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

PROFESSIONAL PAPER 1424—B

USGS
science for a changing world

Availability of Books and Maps of the U.S. Geological Survey

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that may be listed in various U.S. Geological Survey catalogs (**see back inside cover**) but not listed in the most recent annual "Price and Availability List" may be no longer available.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, DC 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Information Services
Box 25286, Federal Center, Denver, CO 80225

OVER THE COUNTER

Books and Maps

Books and maps of the U.S. Geological Survey are available over the counter at the following U.S. Geological Survey Earth Science Information Centers (ESIC), all of which are authorized agents of the Superintendent of Documents:

- **ANCHORAGE, Alaska**—Rm. 101, 4230 University Dr.
- **LAKEWOOD, Colorado**—Federal Center, Bldg. 810
- **MENLO PARK, California**—Bldg. 3, Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**—USGS National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**—Federal Bldg., Rm. 8105, 125 South State St.
- **SPOKANE, Washington**—U.S. Post Office Bldg., Rm. 135, West 904 Riverside Ave.
- **WASHINGTON, D.C.**—Main Interior Bldg., Rm. 2650, 18th and C Sts., NW.

Maps Only

Maps may be purchased over the counter at the following U.S. Geological Survey offices:

- **ROLLA, Missouri**—1400 Independence Rd.
- **STENNIS SPACE CENTER, Mississippi**—Bldg. 3101

Hydrogeologic Framework of the Willamette Lowland Aquifer System, Oregon and Washington

By DENNIS G. WOODWARD, MARSHALL W. GANNETT, *and* JOHN J. VACCARO

REGIONAL AQUIFER-SYSTEM ANALYSIS—PUGET-WILLAMETTE LOWLAND

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1424-B

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON: 1998

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Charles G. Groat, *Director*

Library of Congress Cataloging in Publication Data

Woodward, D. G.
Hydrogeologic framework of the Willamette Lowland Aquifer system, Oregon and Washington : regional aquifer-system analysis--Puget-Willamette Lowland / by Dennis G. Woodward, Marshall W. Gannett, and John J. Vaccaro.
p. cm. -- (U.S. Geological Survey professional paper ; 1424-B)
Includes bibliographical references and index.
Supt. of Docs. no.: I19.16:1424-B
ISBN 0-607-90633-2
1. Groundwater--Oregon--Willamette River Valley Region. 2. Groundwater--Washington (State)--Puget Sound Region. 3. Aquifers--Oregon--Willamette River Valley Region. 4. Aquifers--Washington (State)--Puget Sound Region. I. Gannett, Marshall W. II. Vaccaro, J. J. III. Title. IV. Series.
GB1025.07W66 1998
551.49'09795'3—dc21 98-31986
CIP

For sale by U.S. Geological Survey, Information Services
Box 25286, Federal Center
Denver, CO 80225

FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

CONTENTS

	Page
Foreword	III
Abstract	B1
Introduction	2
Purpose and Approach	2
Geographic Setting	5
Location and Extent	5
Physiography and Soils of the Lowland	5
General Hydrology	9
Climate	9
Surface-Water Resources	9
Previous Hydrogeologic Investigations	13
Hydrogeologic Framework of Aquifer System	16
Framework of Regional Aquifer System	16
Regional Hydrogeologic Units	17
Geometry of Regional Hydrogeologic Units	26
Portland Basin	26
Tualatin Basin	27
Central Willamette Valley	27
Southern Willamette Valley	28
Hydraulic Characteristics	29
Specific Capacity	29
Hydrogeologic Framework of Aquifer System—Continued	
Hydraulic Characteristics—Continued	
Hydraulic Conductivity	B31
Transmissivity	32
Specific Yield	32
Ground-Water Flow System	34
Evolution of Flow System in Willamette Aquifer	34
Water-Level Fluctuations	36
Flow Within Aquifers	44
Flow Between Aquifers	45
Cross-Sectional Flow Models	47
Model Grids and Boundary Conditions	47
Hydraulic Characteristics	49
Simulated Flow System	52
Calculated Water-Budget Components	55
Regional Water Budget	55
Recharge	56
Discharge	58
Water Quality	69
Summary and Conclusions	75
References Cited	80

ILLUSTRATIONS

[Plate is in pocket]

Base map modified from the following sources: hydrography from 1:250,000 topographic quadrangles, 1:100,000 topographic quadrangles and Digital Line Graphs (DLGs), and 1:24,000 topographic quadrangles; counties from 1:500,000 DLGs; roads from 1:250,000 DLGs; cities from Geographic Names Information System data base; and other digital sources. Universal Transverse Mercator projection, Zone 10, North American Datum 1927.

PLATE 1. Map showing generalized water table in the unconsolidated deposits in the Willamette Lowland.

	Page
FIGURE 1–2. Maps showing:	
1. Outline of the study area with major geographic features in the Willamette River drainage basin, Oregon, and adjacent drainages in southwestern Washington	B3
2. Location of Willamette Lowland and structural basins	7
3. Diagrams showing (A) topographic sections west-east across study area and (B) bank section along Willamette River	8
4–5. Graphs and maps showing:	
4. Mean annual and mean monthly precipitation for the study area	10
5. Mean monthly discharge for selected major tributaries of the Willamette River	11
6. Map showing study areas of U.S. Geological Survey Water-Supply Papers and State of Oregon Ground-Water Reports in the Willamette Lowland	15
7. Correlation chart showing the regional relation between generalized geologic units and hydrogeologic units in the Willamette Lowland	17
8. Map showing surficial extent of hydrogeologic units and the Boring Lava	18
9. Diagram showing hydrogeologic sections	19
10–15. Maps showing:	
10. Extent of the Columbia River basalt aquifer	20
11. Altitude of the base of the Willamette confining unit	21
12. Extent and thickness of the Willamette confining unit	23
13. Extent and thickness of the Willamette aquifer	24
14. Extent and thickness of the Willamette Silt unit	25
15. Distribution of specific-capacity values for wells in the Willamette Lowland	30

Page

FIGURE 16. Diagram showing daily precipitation and water-table fluctuations B37
17. Map showing location of selected observation wells 39
18a–d. Hydrographs showing:
18a. Water levels in wells completed in the hydrogeologic units in the Portland Basin and in the Tualatin Basin 40
18b. Water levels in wells completed in the Willamette aquifer, central Willamette Valley 41
18c. Water levels in wells completed in the Willamette aquifer, southern Willamette Valley 42
18d. Water levels in wells completed in the Columbia River basalt aquifer 43
19. Map showing location of wells and head differences between regional hydrogeologic units in the Tualatin Basin 46
20–21. Diagrams showing:
20. Grids and layers for cross-sectional ground-water flow models 48
21. Model grids and layers with pathlines 53
22–26. Maps showing:
22. Distribution of estimated mean annual ground-water recharge for the Willamette Lowland aquifer system 59
23. Distribution and quantity of ground water withdrawn for public supply, 1990 65
24. Distribution and quantity of ground water withdrawn for industrial supply, 1990 66
25. Distribution and quantity of ground water withdrawn for irrigation, 1990 67
26. Distribution and total quantity of ground water withdrawn, 1990 68
27–29 Trilinear diagrams showing:
27. Percentage of major ions in water samples from Tertiary marine rocks 71
28. Percentage of major ions in water samples from the Columbia River basalt aquifer 71
29. Percentage of major ions in water samples from the Willamette aquifer 72
30. Map showing location of wells and a spring that yielded chloride-dominant water samples 73

TABLES

Page

TABLE 1. Discharge characteristics for selected rivers, Willamette Lowland, Oregon and Washington B12
2. Major reservoirs and storage capacity in the Willamette Lowland, Oregon and Washington 14
3. Estimates of hydraulic conductivity for the regional hydrogeologic units, Willamette Lowland, Oregon and Washington 31
4. Estimates of transmissivity and storage coefficient derived from specific-capacity data and aquifer tests in the Willamette Lowland 33
5. Computed values for specific yield and storage volume from previous investigations, Willamette Lowland, Oregon 35
6. Information on model grid systems 49
7. Stream locations, properties, and discharge rates for cross-sectional flow models 50
8. Hydraulic characteristics used in models 50
9. Flow budgets for cross-sectional models 54
10. Comparison of ground-water recharge estimates for different areas in the Willamette Lowland, Oregon and Washington 57
11. Estimates of mean annual recharge on the basis of mean annual precipitation, generalized surficial geology, and land-use and land-cover categories, Willamette Lowland, Oregon and Washington 58
12. Low-flow and high-flow discharge measurements, and seepage quantity and rate for selected Oregon rivers 60
13. Historical ground-water withdrawals in the Willamette Lowland, 1955–75, by area and type of use 63
14. Ground-water withdrawals in the Willamette Lowland, 1990, by area and type of use 64
15. Statistical summary of water-quality characteristics, Willamette Lowland, Oregon and Washington 70
16. Characteristics of selected wells and a spring that yield chloride-dominant water, Willamette Lowland, Oregon and Washington 74

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To Obtain*
acre	0.4047	hectare
acre-foot (acre-ft)	1,233.50	cubic meter
acre-foot per day (acre-ft/d)	1,233.50	cubic meter per day
acre-foot per year (acre-ft/yr)	1,233.50	cubic meter per year
barrel per day (bbl/d)	0.159	cubic meter per day
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per mile ($ft^3/s/mi$)	0.0176	cubic meter per second per kilometer
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
foot (ft)	0.3048	meter
foot per day (ft/d)	0.3048	meter per day
foot per year (ft/yr)	0.3048	meter per year
foot per foot (ft/ft)	1.0	meter per meter
foot per mile (ft/mi)	0.18943	meter per kilometer
foot squared per day (ft^2/d)	0.0929	meter squared per day
gallons per minute (gal/min)	0.06309	liters per second
gallon per minute per foot (gal/min/ft)	0.2070	liters per second per meter
inch (in)	2.54	centimeter
inch (in)	25.4	millimeter
inch per hour (in/hr)	2.54	centimeter per hour
inch per month (in/month)	2.54	centimeter per month
inch per year (in/yr)	2.54	centimeter per year
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
milligrams per liter (mg/L)	1	parts per million, in water

Temperature: To convert temperature given in this report in degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation:

$$°F = 1.8\ °C + 32$$

Temperature: To convert temperature given in this report in degrees Celsius (°C) to degrees Fahrenheit (°F), use the following equation:

$$°C = (°F - 32)/1.8$$

Specific conductance: Is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25 °C).

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

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

DENNIS G. WOODWARD, MARSHALL W. GANNETT, AND JOHN J. VACCARO

ABSTRACT

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

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

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

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

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

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

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

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

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

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

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

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

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

INTRODUCTION

The U.S. Geological Survey began the Regional Aquifer-System Analysis (RASA) program in 1978 in response to congressional concerns about the availability and quality of the Nation's ground water. The purpose of the RASA program is to aid in the effective management of important ground-water resources by providing information on the hydrogeology of regional aquifer systems, as well as analytical capabilities necessary to assess management alternatives (Sun and Johnston, 1994). The regional aquifer systems contained in the Puget-Willamette Lowland were selected to be studied as part of the RASA program (Vaccaro, 1992).

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

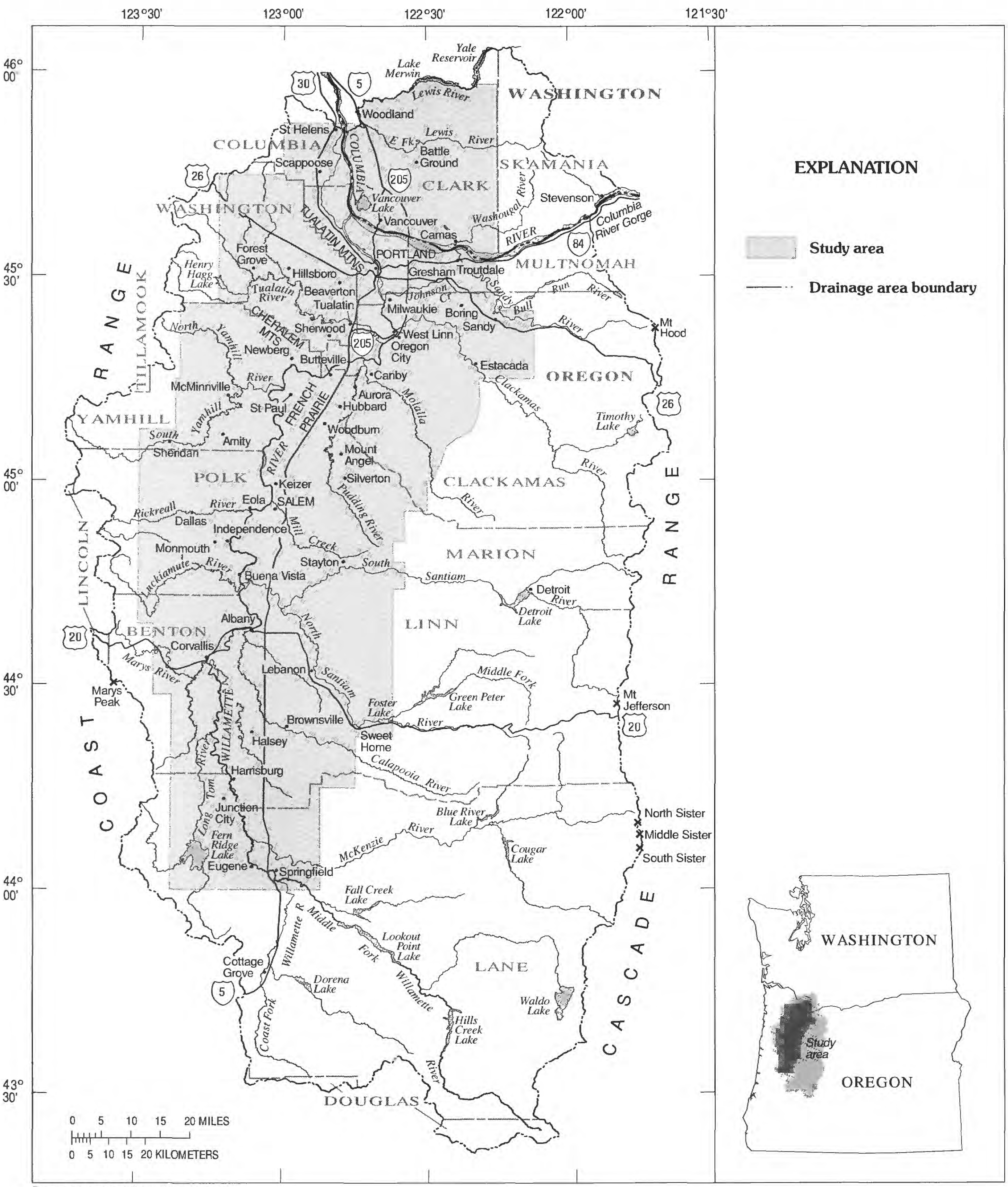
The study area for this report is the Willamette Lowland in Oregon and Washington, which encompasses about 5,680 mi^2 and includes the low-lying parts of the Willamette River drainage in Oregon (referred to as the Willamette Valley) and most of Clark County, Washington (fig. 1). The aquifer system within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

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

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

PURPOSE AND APPROACH

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



Basemap source information on page v.

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

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

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

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

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

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

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

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

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

GEOGRAPHIC SETTING

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

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

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

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

LOCATION AND EXTENT

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

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

PHYSIOGRAPHY AND SOILS OF THE LOWLAND

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

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

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

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

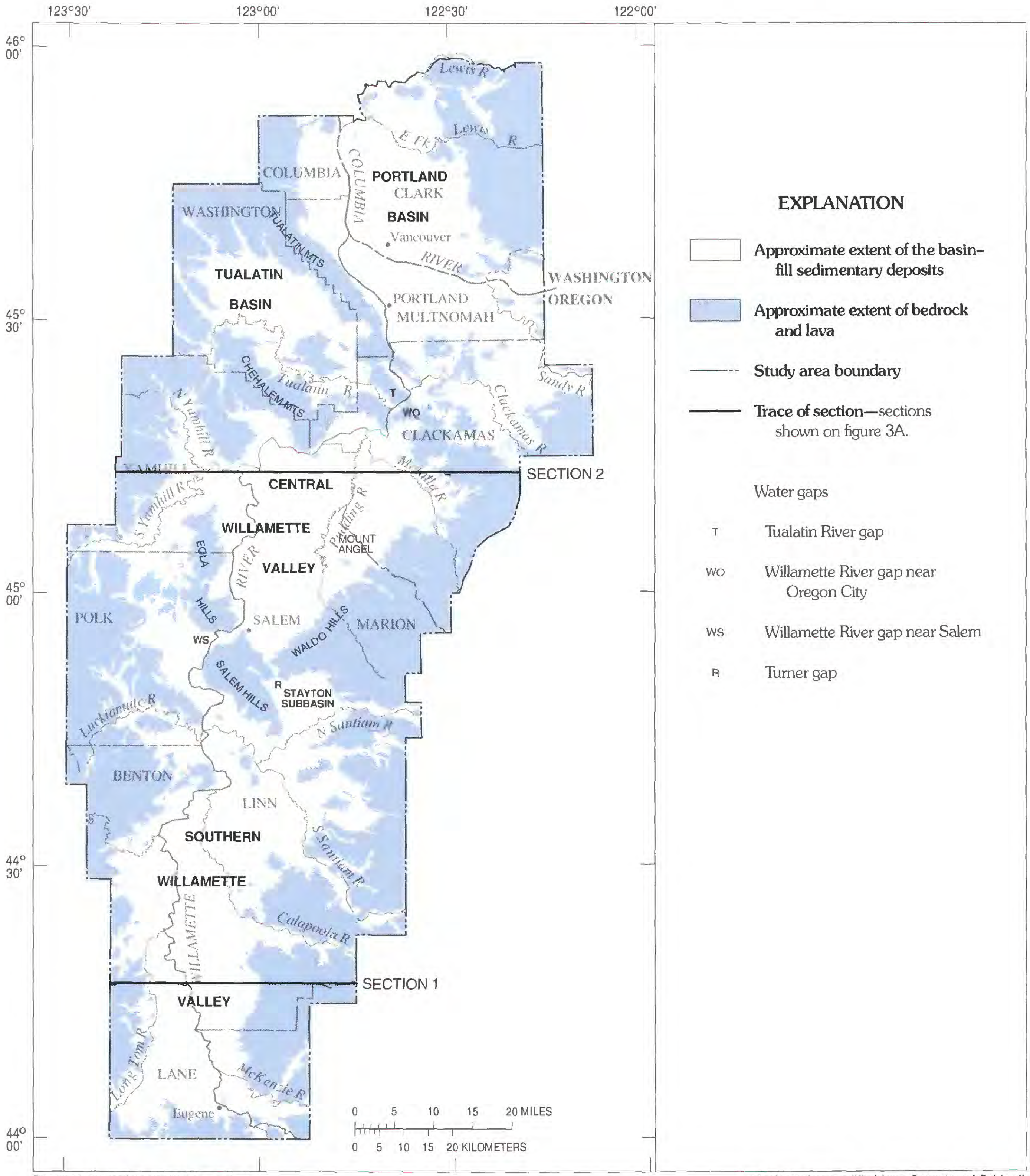
Most of the 187-mile channel of the Willamette River is braided or meandering and flows through a flood plain that ranges from about 0.5 to 4 mi wide. The flood plain contains irregular alluvial terraces and is characterized by many cutoff meanders, oxbow lakes, braided and distributing channels, and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

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

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

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

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



Basemap source information on page v.

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

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

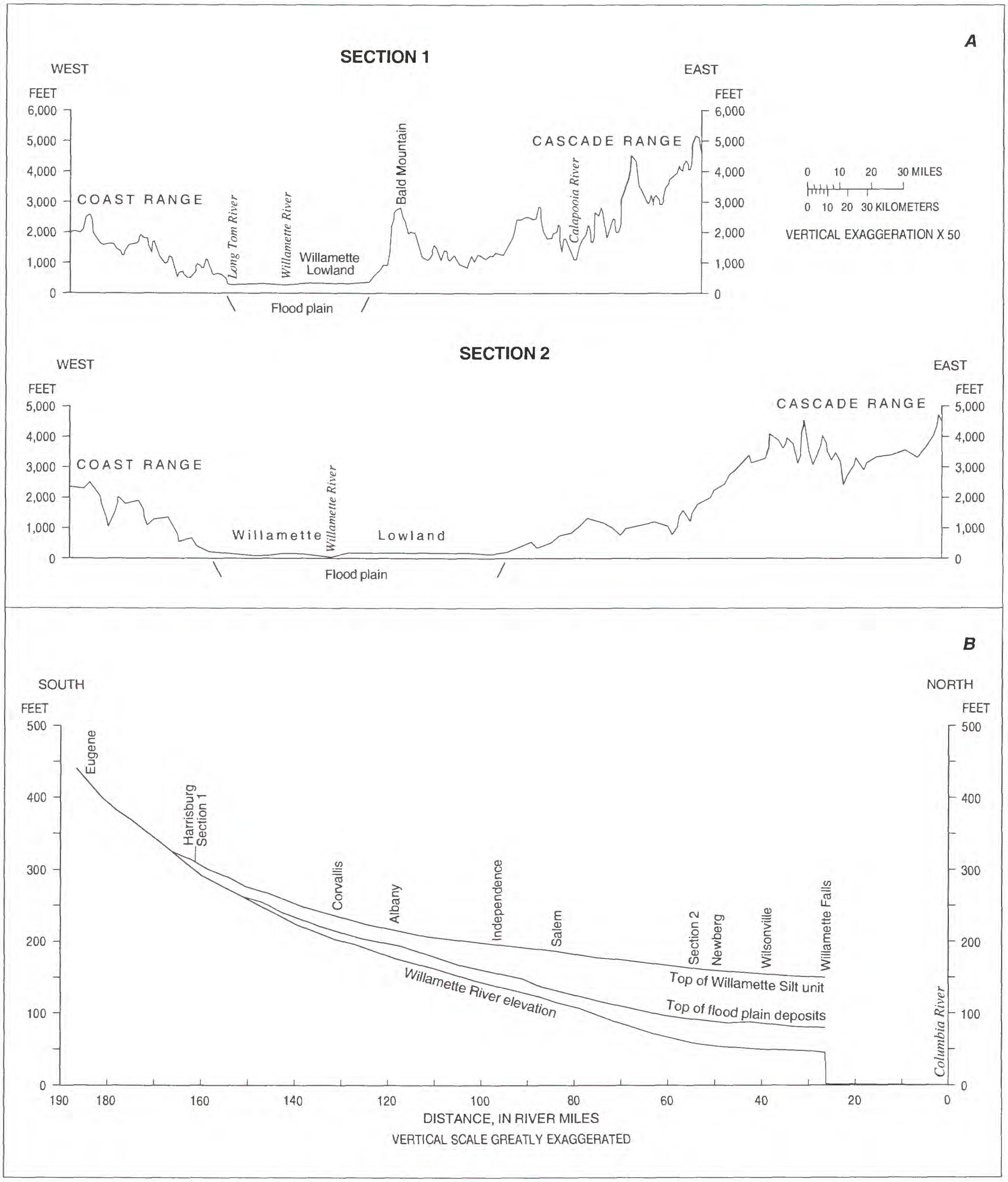


FIGURE 3. (A) Topographic sections west-east across study area and (B) Bank section along Willamette River. (Trace of topographic sections shown on figure 2.)

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

GENERAL HYDROLOGY

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

CLIMATE

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

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

Mean annual maximum air temperatures range from about 60°F (degrees Fahrenheit) in the lowlands to about 47°F in the mountains, and mean annual minimum temperatures range from about 40°F in the lowlands to about 31°F in the mountains. Generally, summer temperatures in the lowlands range from 60 to 90°F and winter temperatures range from 30 to 50°F. The growing season is more than 200 days at lower altitudes and is about 150 days in the higher valleys and foothills.

SURFACE-WATER RESOURCES

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

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

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

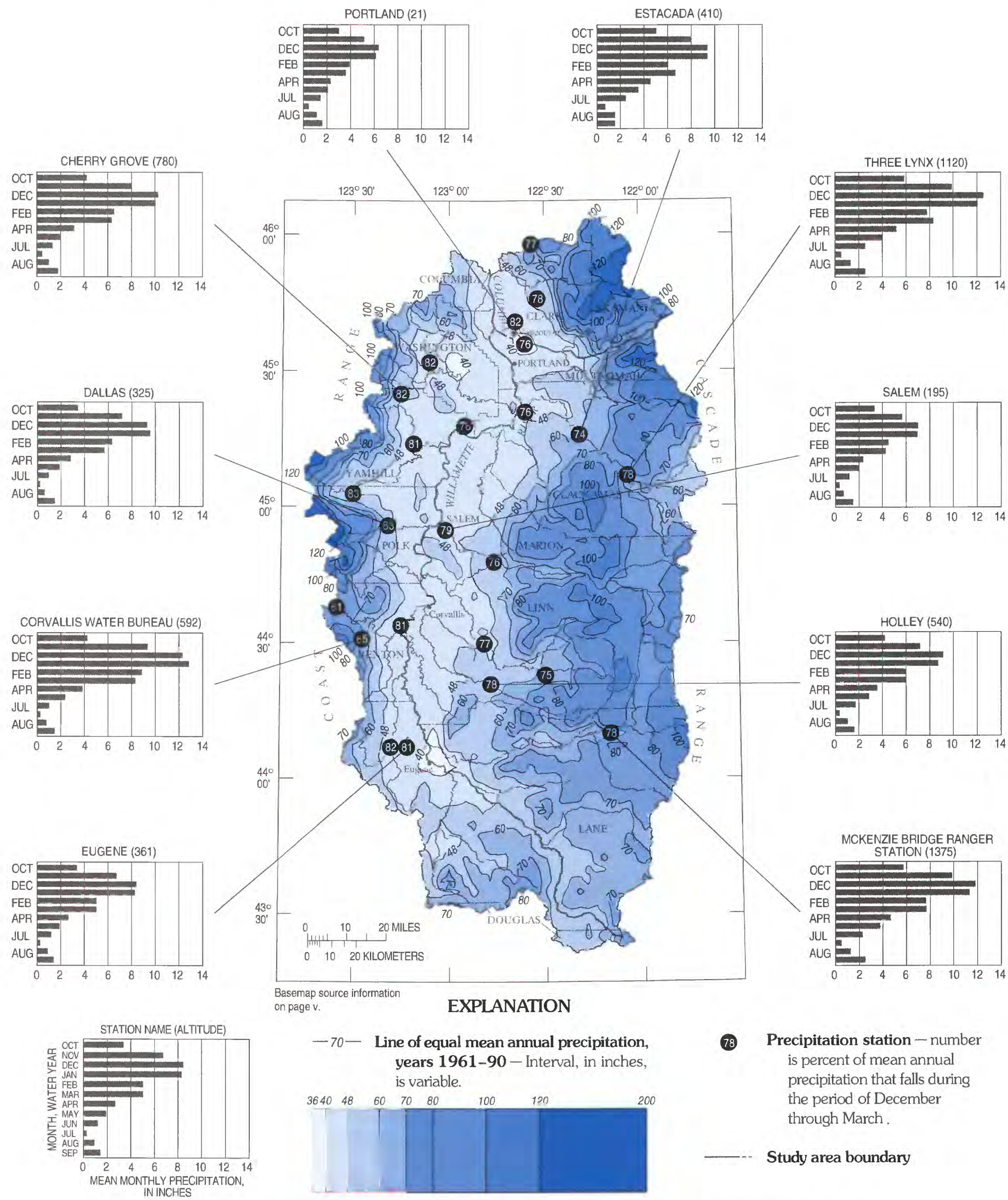


FIGURE 4.—Mean annual and mean monthly precipitation for the study area. (Precipitation data from Taylor, 1993.)

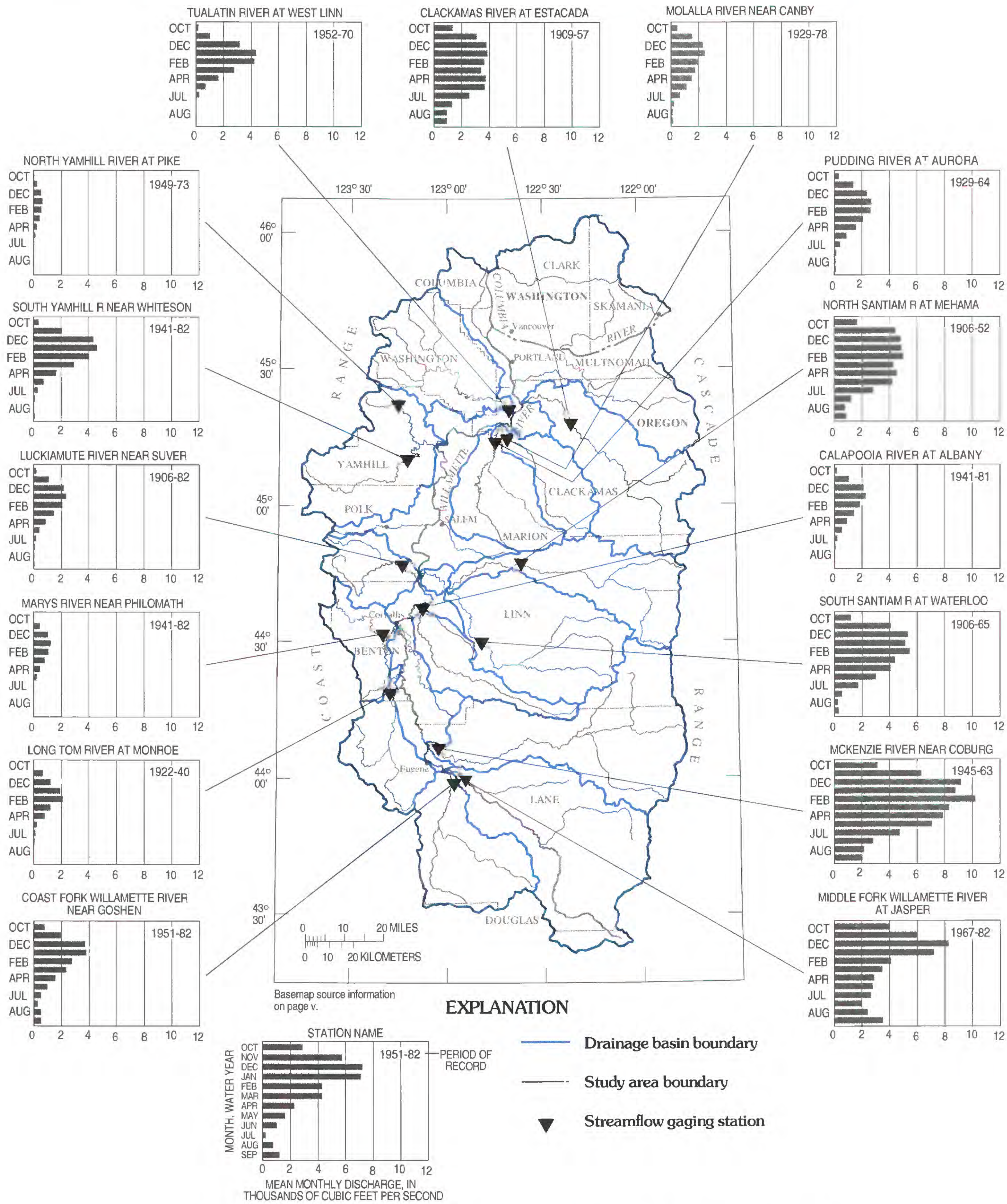


FIGURE 5.—Mean monthly discharge for selected major tributaries of the Willamette River.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

PREVIOUS HYDROGEOLOGIC INVESTIGATIONS

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

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

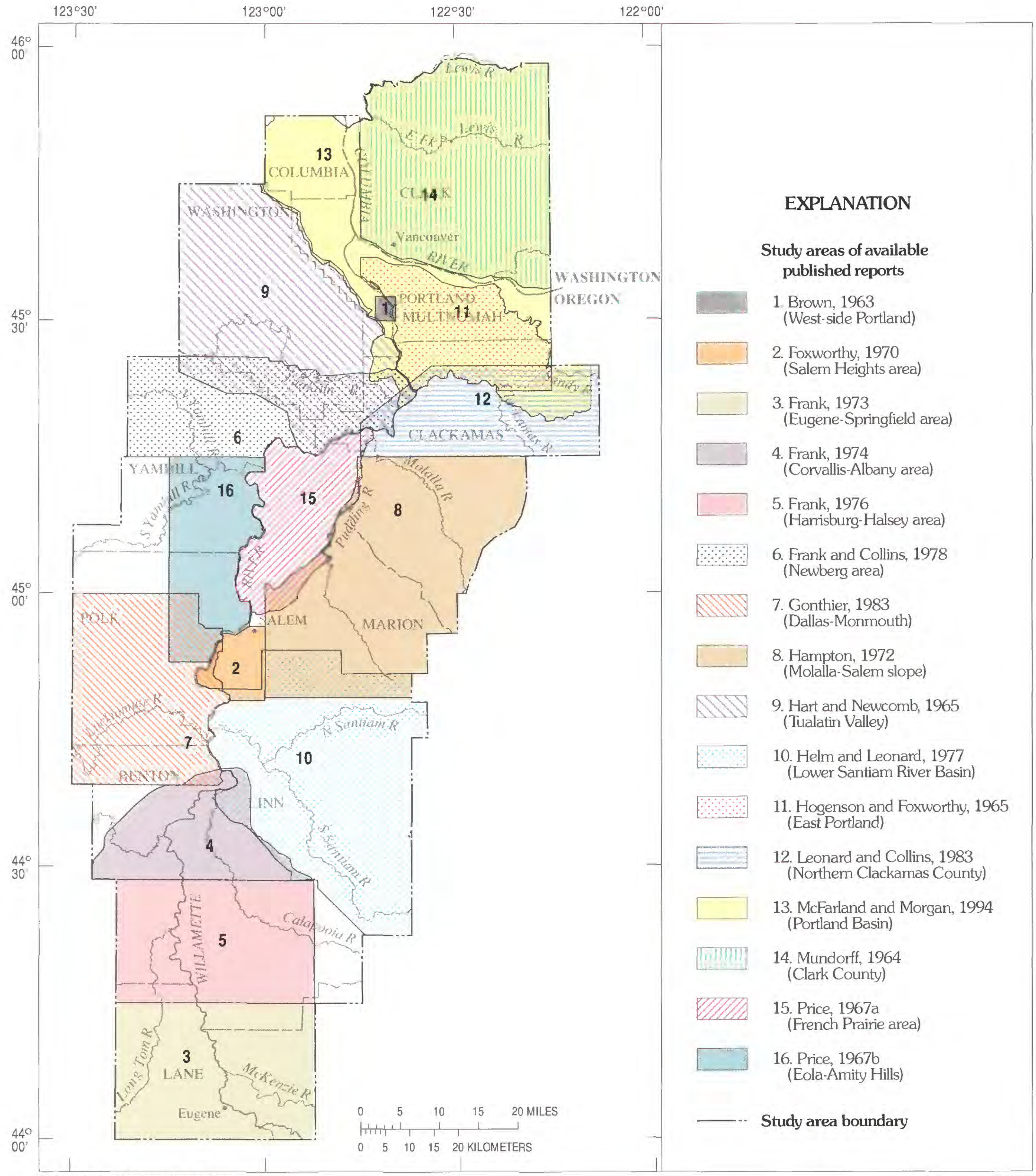
TABLE 2.—*Major reservoirs and storage capacity in the Willamette Lowland, Oregon and Washington*

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

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

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

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



Basemap source information on page v.

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

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

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

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

HYDROGEOLOGIC FRAMEWORK OF AQUIFER SYSTEM

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

FRAMEWORK OF REGIONAL AQUIFER SYSTEM

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

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

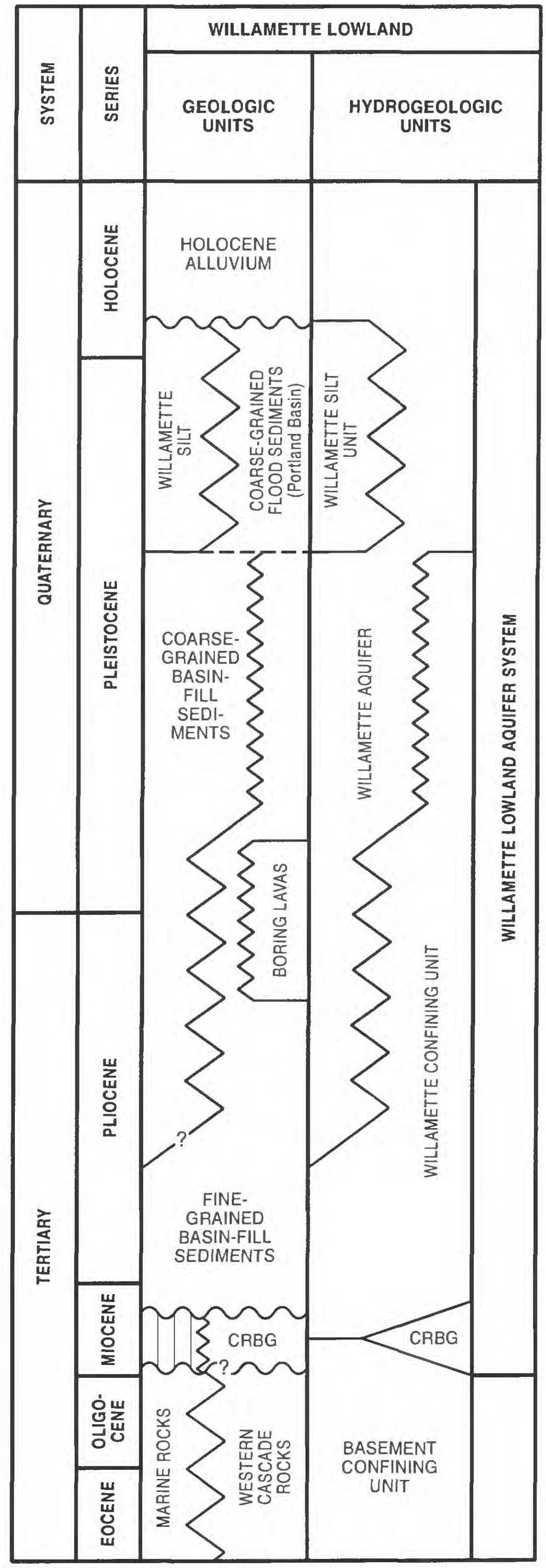
During Pleistocene time, large-volume glacial-outburst floods, originating in western Montana, flowed down the Columbia River drainage and periodically inundated the Willamette Lowland. These floods deposited as much as 250 ft of silt, sand, and gravel in the Portland Basin and as much as 130 ft of silt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

REGIONAL HYDROGEOLOGIC UNITS

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

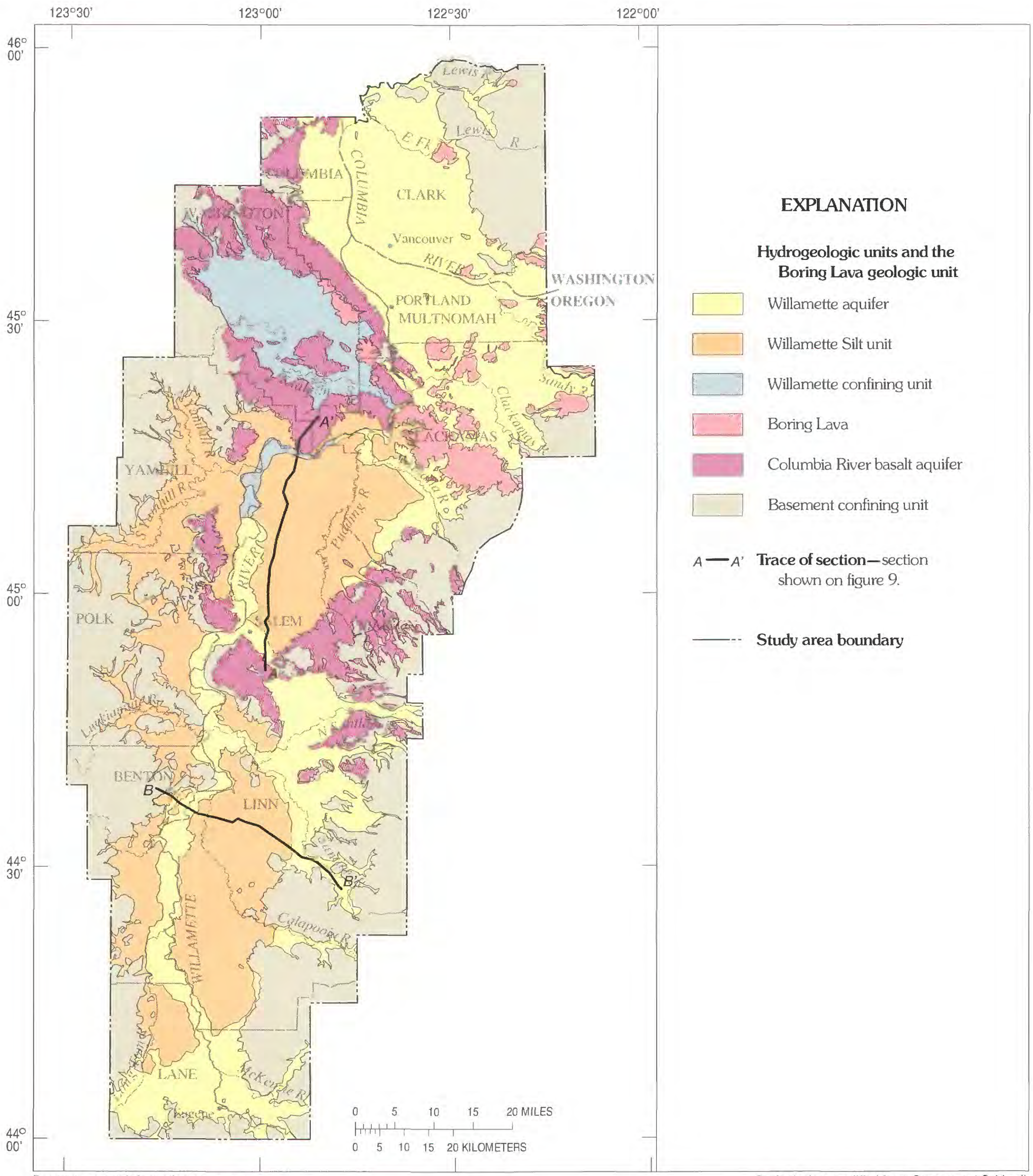
In their work in the Portland Basin, Swanson and others (1993) included the Boring Lava in the Troutdale gravel aquifer (considered to be part of the Willamette aquifer in this regional study). Where the Boring Lava is most extensive in the study area—on the plateau between the Portland Basin and the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

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



NOTE: CRBG = COLUMBIA RIVER BASALT GROUP

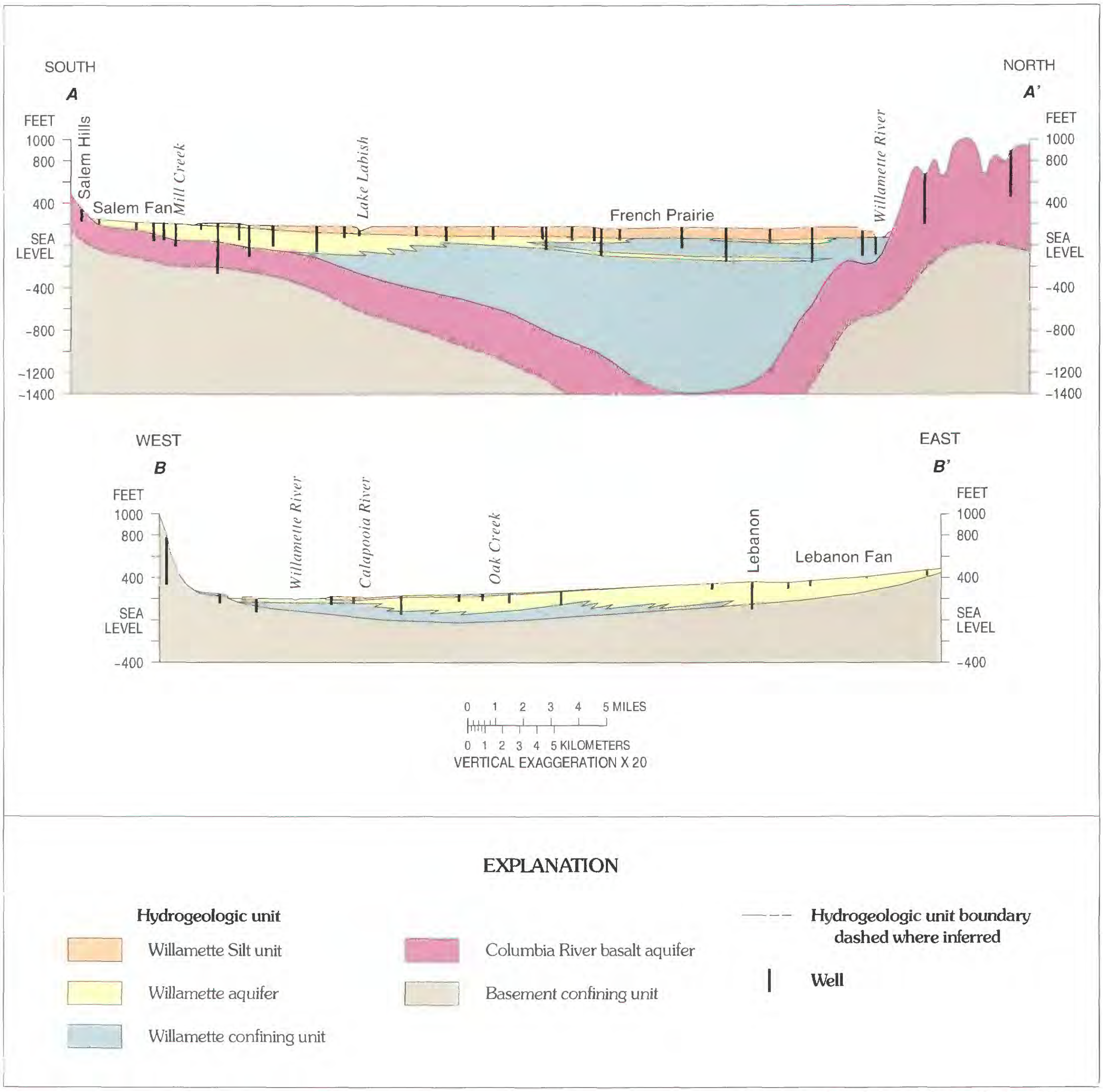
FIGURE 7.—Regional relation between generalized geologic units and hydrogeologic units in the Willamette Lowland.



Basemap source information on page v.

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

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



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

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

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

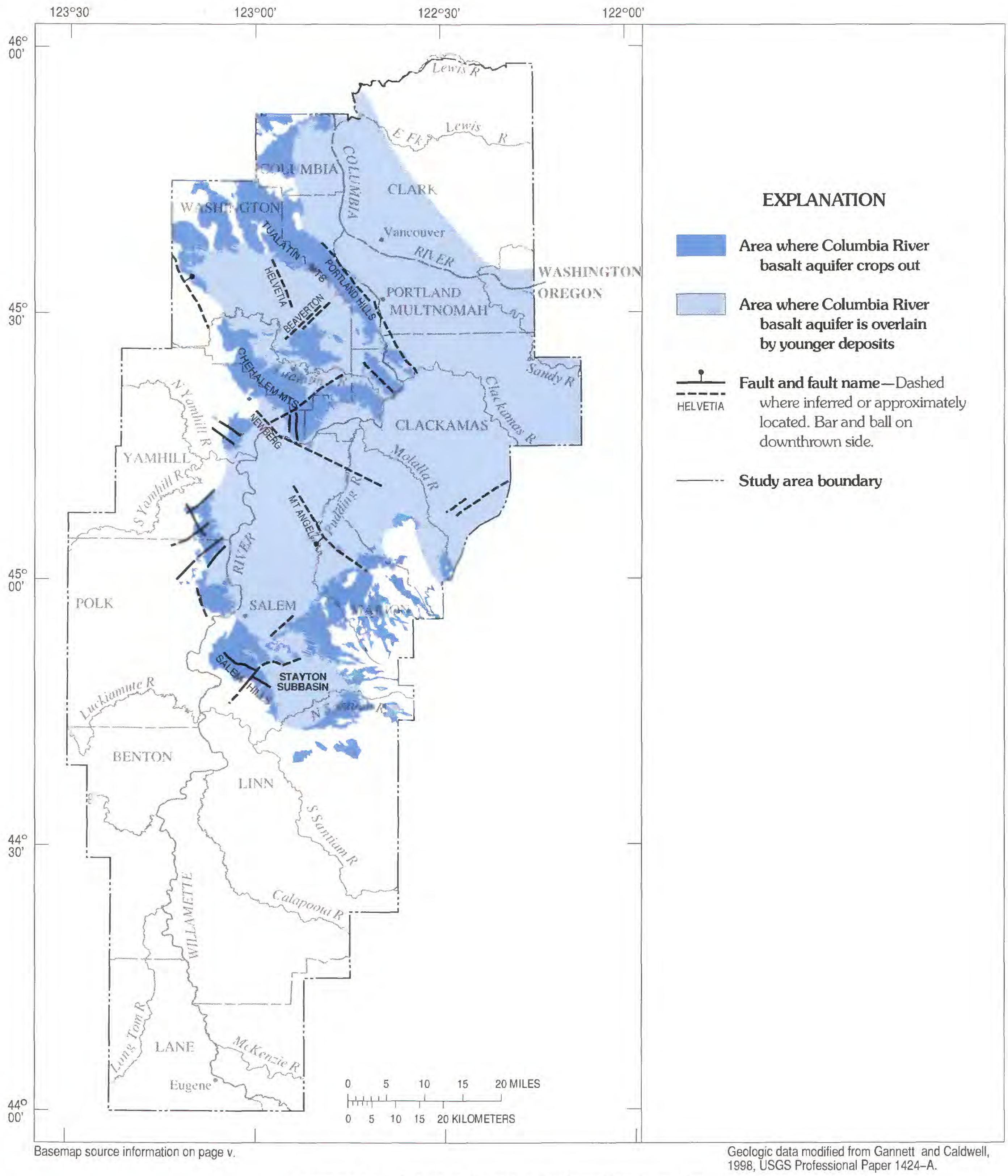
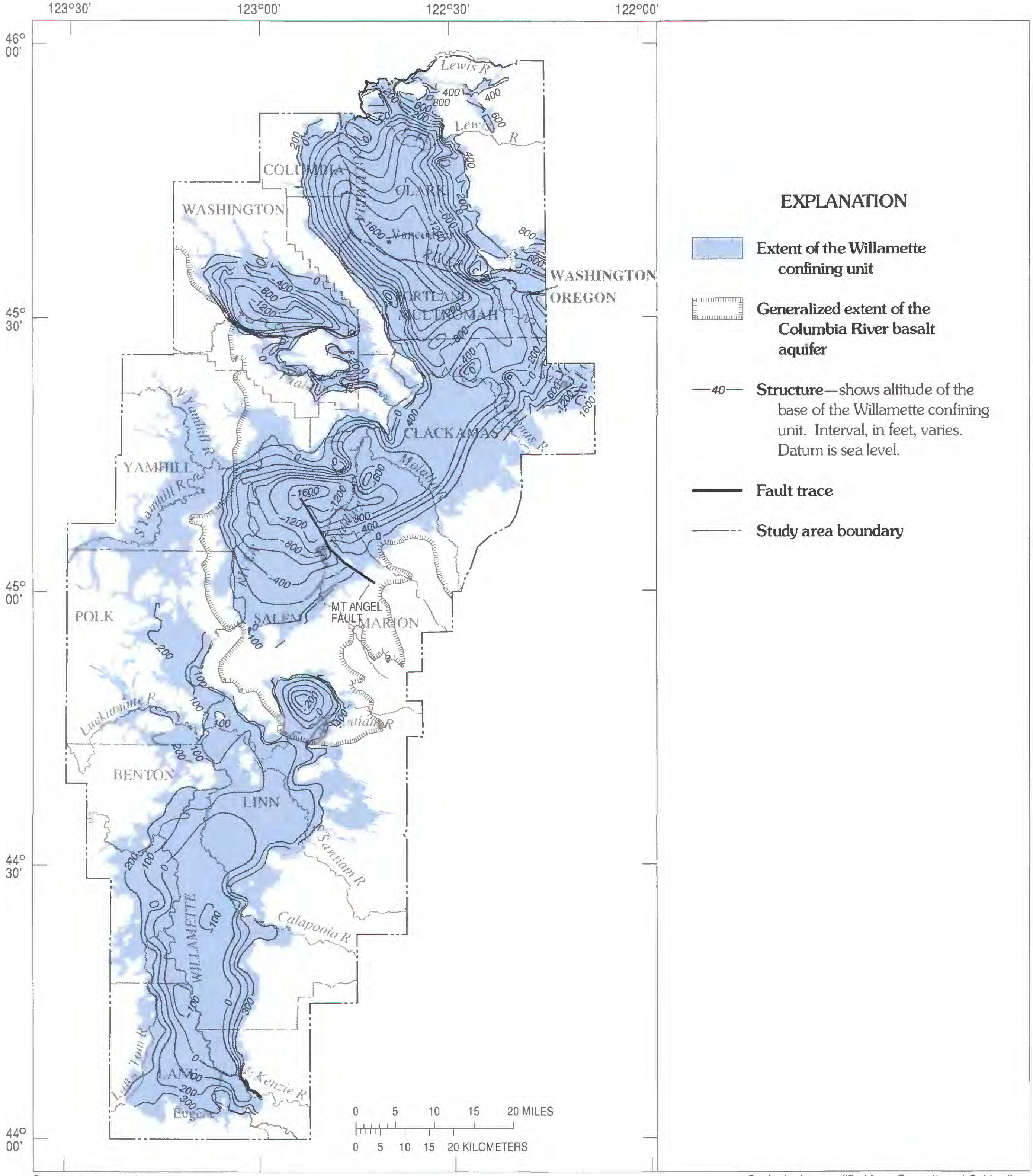


FIGURE 10.—Extent of the Columbia River basalt aquifer.



Basemap source information on page v.

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

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

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

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

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

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

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

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

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

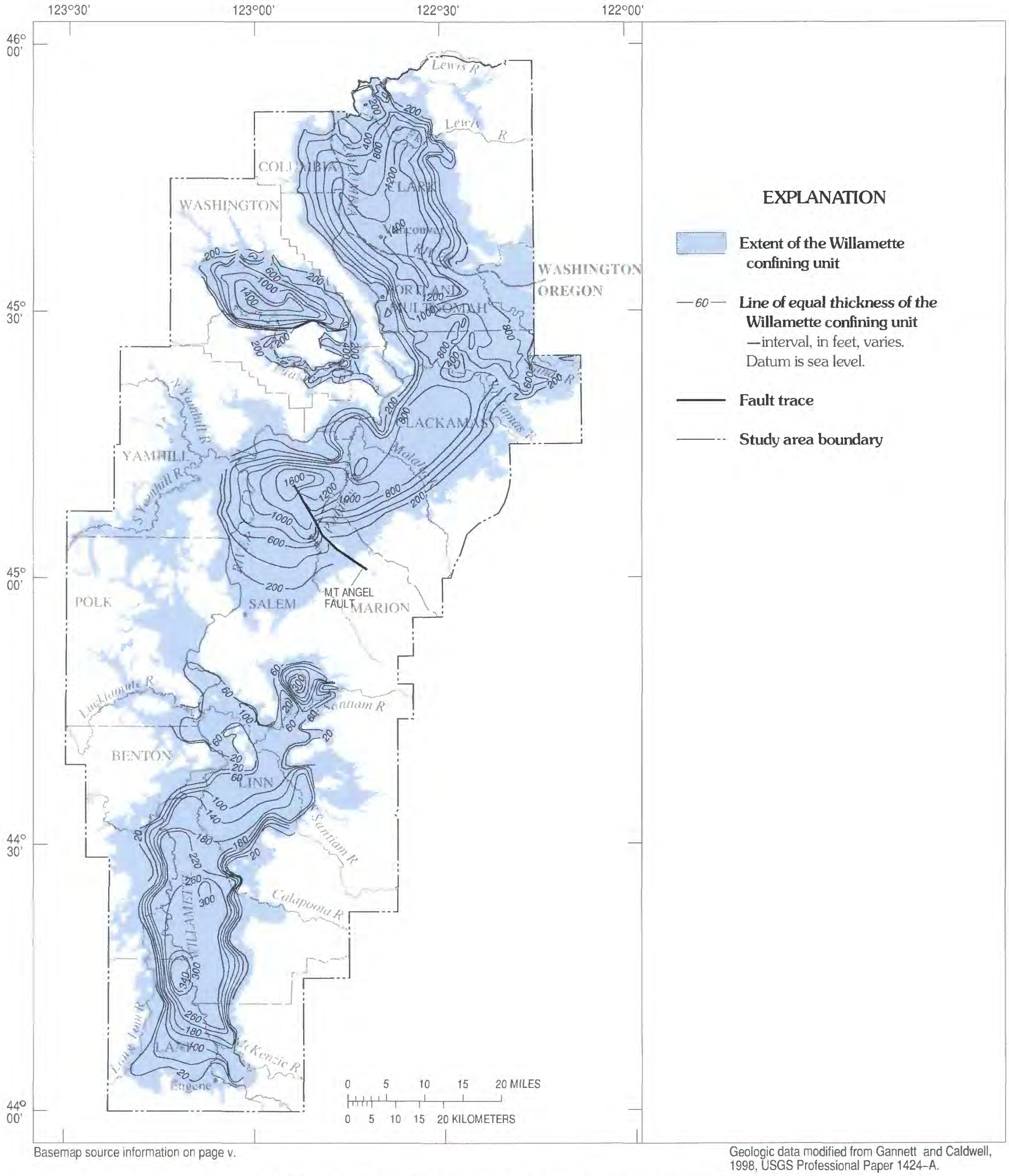
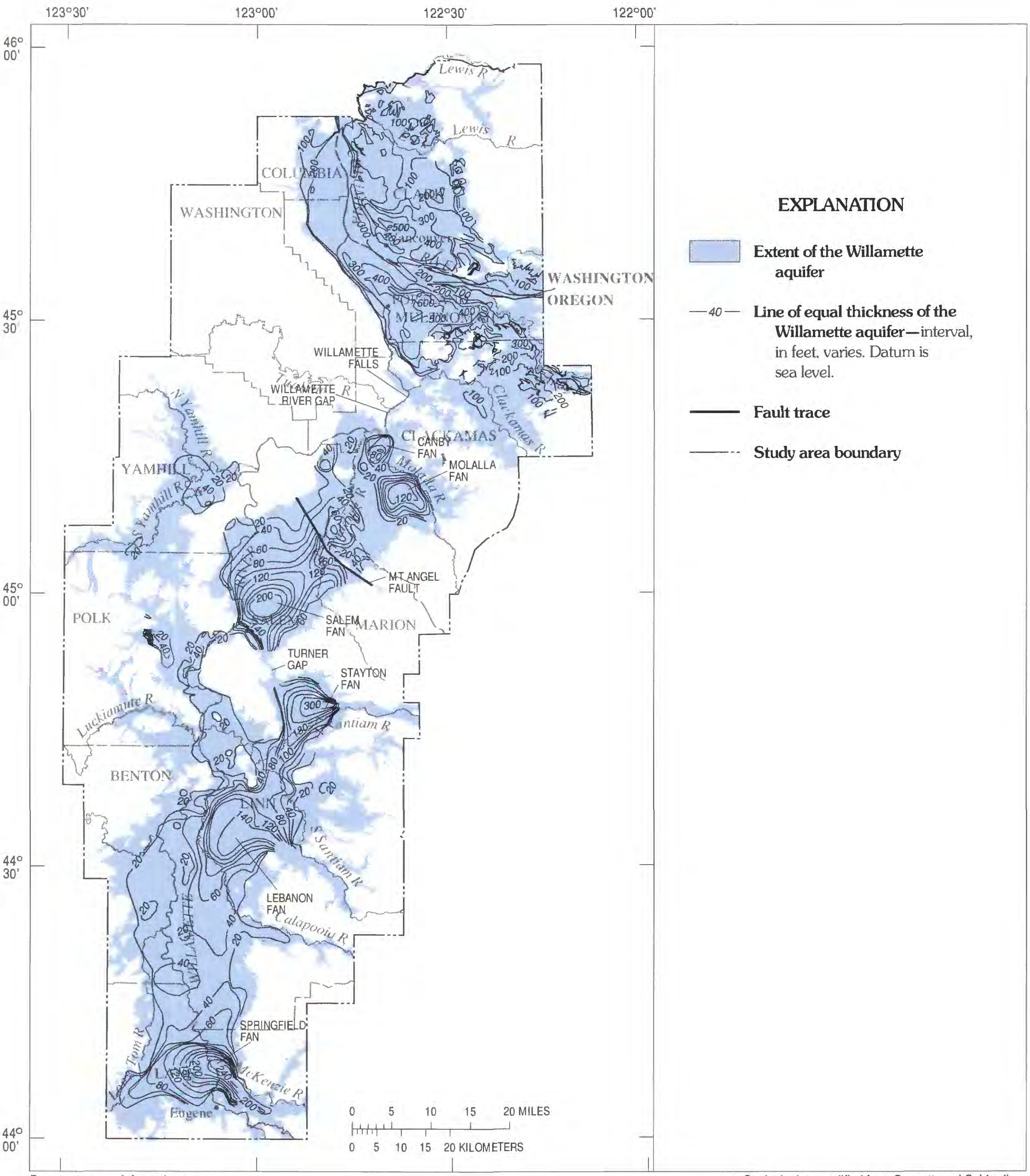


FIGURE 12.—Extent and thickness of the Willamette confining unit.



Basemap source information on page v.

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

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

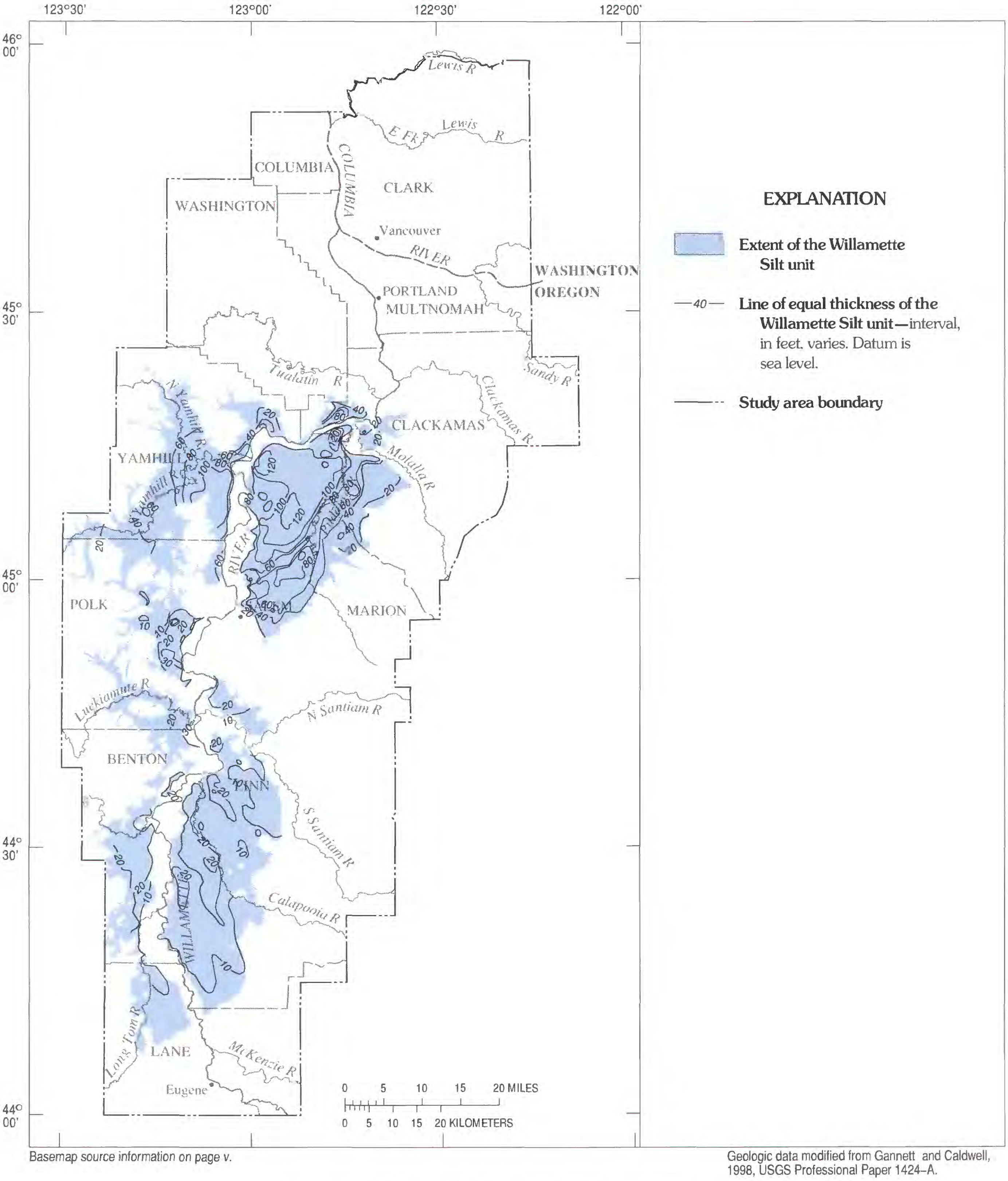


FIGURE 14.—Extent and thickness of the Willamette Silt unit.

GEOMETRY OF REGIONAL HYDROGEOLOGIC UNITS

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

PORTLAND BASIN

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

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

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

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

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

Tualatin Basin

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

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

Central Willamette Valley

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

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

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

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

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

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

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

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

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

Southern Willamette Valley

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

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

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

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

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

The Willamette Silt unit overlies most of the southern Willamette Valley; the unit ranges from 10 to 20 ft, in thickness and generally thins toward the south. The Willamette Silt is too thin to differentiate from Holocene alluvium and other fine-grained surficial materials above an altitude of about 350 ft (for example, between Junction City and Eugene, Oregon; fig. 1), and thus, the southern extent of the unit was selected to correspond to this altitude. As in the central Willamette Valley, the Willamette Silt unit has been eroded from the modern flood plain of the Willamette River.

HYDRAULIC CHARACTERISTICS

An estimate of the magnitude and distribution of horizontal and vertical hydraulic conductivity, transmissivity, and storage coefficient of each aquifer is needed to understand the movement of ground water and, ultimately, to calculate its availability. Hydraulic conductivity is defined as the volume of water that will move in unit time through a unit cross-sectional area under a unit hydraulic gradient at the prevailing kinematic viscosity. Transmissivity is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. The storage coefficient of an unconfined aquifer, such as the Willamette aquifer, is known as the specific yield. Specific yield is defined as the volume of water that an unconfining aquifer releases from storage per unit surface area of aquifer per unit decline in the water table. Additionally, specific capacity, defined as the volume of water pumped per unit time (yield) per unit drawdown, is a good indicator of aquifer yield and also can be used to estimate other hydraulic characteristics.

SPECIFIC CAPACITY

Values of specific capacity are preferred to values of well yield as a measure of aquifer productivity because they account for the loss in head associated with pumping the water. Thus, for a regional assessment of ground-water resources, specific-capacity data are commonly used to compare the water-transmitting properties of hydrogeologic units (Knopman and Hollyday, 1993).

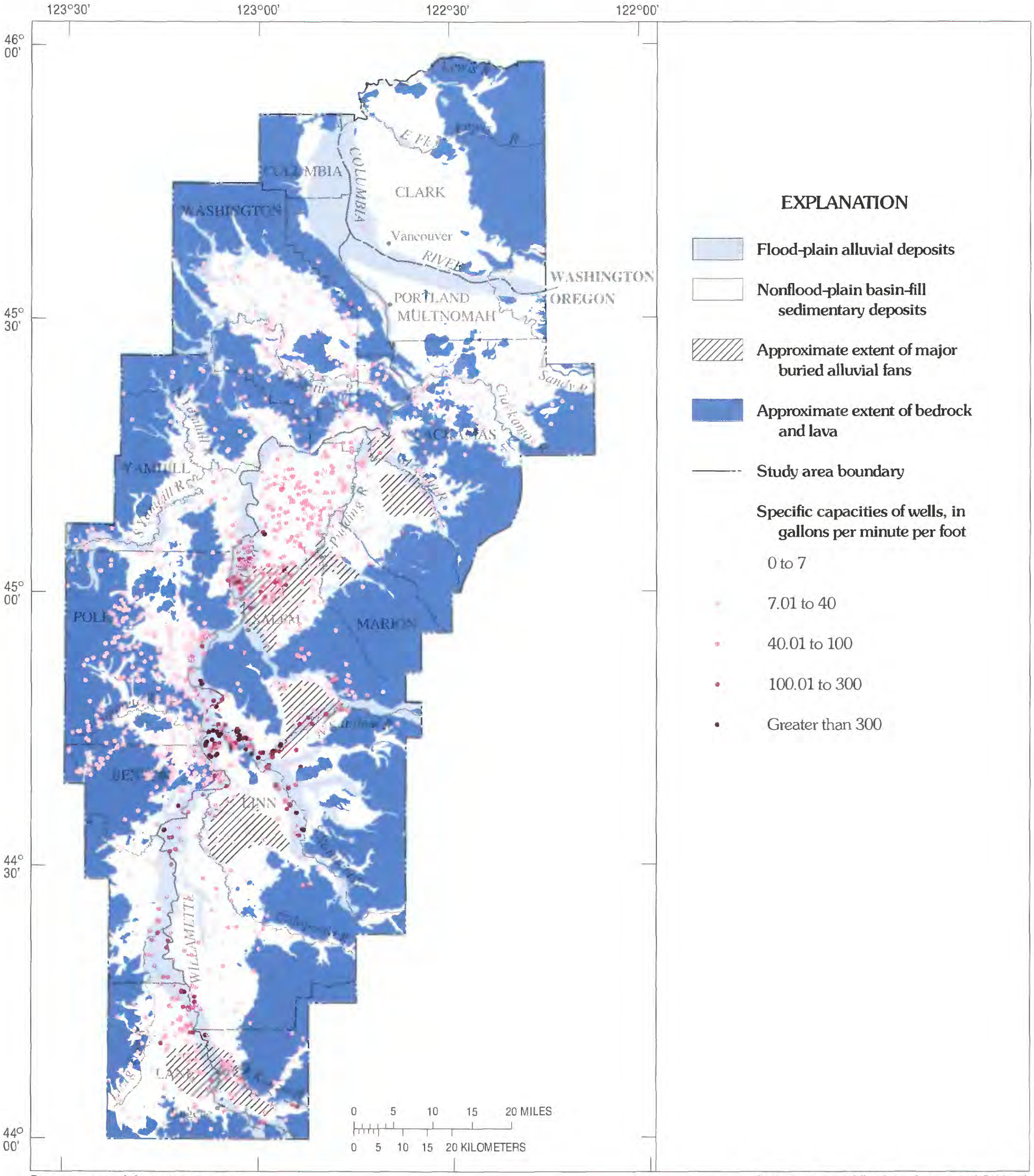
Specific-capacity values of wells generally are available and commonly are used to derive hydraulic conductivity values for an aquifer, although that method is less precise than other methods and factors other than aquifer permeability can influence the specific-capacity value of a well (Walton, 1962). Specific-capacity values are a function of the well depth, casing diameter, duration of well discharge during testing, saturated length of the open interval, well losses, and partial penetration of the well through the saturated thickness of the aquifer.

About 1,200 specific-capacity values for the Willamette aquifer were derived from two data sets that included values for most of the Willamette Valley south of the Portland Basin. The U.S. Geological Survey's national data base contained 1,050 wells with the necessary information, and the Oregon Water Resources Department had similar information for 142 wells in its files of water appropriation permits.

The following is a summary of specific-capacity data from these data bases:

Specific capacity, in gallons per minute per foot of drawdown	National data base		State data base
	Number of wells	Well locations	Number of wells
>300	47	46 wells in modern flood plains of large perennial streams; 1 well in alluvial fan.	6
100–300	75	73 wells in modern flood plains of large perennial streams; 2 wells in alluvial fans.	19
40–100	91	76 wells in modern flood plains of large perennial streams; 7 wells in alluvial fans; 8 wells outside fans or flood plains.	21
7–40	366	91 wells in modern flood plains; 61 wells in alluvial fans; 214 wells outside fans or flood plains (many of these wells are in the French Prairie area).	57
0–7	471	Almost all of these wells are located outside fans or flood plains.	39

The preceding chart indicates that for the Willamette aquifer (excluding the Portland Basin), the flood-plain deposits compose the most productive parts of the aquifer, the buried alluvial fans are the next most productive, and the least productive deposits of the aquifer are those that do not contain the flood-plain or alluvial-fan deposits (fig. 15).



Basemap source information on page v.

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

FIGURE 15.—Distribution of specific-capacity values for wells in the Willamette Lowland.

Because only a few specific-capacity data were available for the Columbia River basalt aquifer, the well yields also are discussed here in order to obtain some understanding of aquifer yield. According to Foxworthy (1970), who studied the Columbia River basalt aquifer in the Salem Heights area (fig. 6), the wells that have large yield in that area probably tap a confined zone in the lower part of the aquifer; this zone yields as much as 1,000 gal/min (gallons per minute) to wells that have specific capacities of at least 11 gal/min/ft (gallons per minute per foot). By contrast, most of the wells that tap basalt zones that are not part of the main confined aquifer produce less than 200 gal/min and have specific capacities of about 2 gal/min/ft or less. Brown (1963) reported that the specific capacity of wells completed in the basalt aquifer in western Portland range from 0.6 to 21 gal/min/ft, and well yields vary from 50 to 1,000 gal/min. Frank and Collins (1978) reported that the yield of wells completed in the Columbia River basalt aquifer in the Newberg, Oregon, area range from 15 to 1,000 gal/min.

HYDRAULIC CONDUCTIVITY

A large range of horizontal hydraulic conductivity values exists for all units in the Willamette Lowland aquifer system (table 3) because of variations in the lithology, stratigraphy, grain size, consolidation, and cementation of the deposits. The large range in values for the Willamette aquifer is due primarily to the grain-size distribution of the different units composing the aquifer, the occurrence of interbedded fine-grained deposits, and the presence of semiconsolidated to partly cemented sand and gravel beds, the latter being associated with older geologic units in the aquifer (Mundorff, 1964; Glenn, 1965). Hydraulic conductivity values for the Holocene flood-plain alluvium and the outburst-flood deposits in the Portland Basin, the coarsest-grained and best-sorted deposits in the Willamette aquifer, generally range from 10 to 2,000 ft/d (feet per day) and have a median of 240 ft/d (Morgan and McFarland, 1996). These same deposits have a median value of 170 ft/d in the central Willamette Valley (Gonthier, 1983). Conductivity values for the major, buried, gravel-dominated alluvial fans are similar to those for the flood-plain alluvium, whereas values for the remaining part of the Willamette aquifer deposits generally range from about 1 to 100 ft/d and have median values of 19 ft/d in the central Willamette Valley (Gonthier, 1983) and about 10 ft/d in the Portland Basin (Morgan and McFarland, 1996).

The large range of hydraulic conductivity values for the Columbia River basalt aquifer, from about 0.001 to 750 ft/d, is due primarily to the geologic structure and the number of interflow zones penetrated by the wells used to estimate the value. For example, in a relatively flat topographic setting where vertical head gradients are upward, a deep well completed in the aquifer may have a larger apparent conductivity than a similar well completed in an upland setting, where the vertical gradient is downward. Hansen and others (1994) indicated that structural deformation of the Columbia River Basalt Group, such as that in anticlines (which are typically expressed as uplands), not only may juxtapose interflow zones but also appears to close or restrict connected pore space. The conductivities determined for each setting could be greatly increased or decreased depending on the number of interflow zones that are present, or the number of zones open to the well bore. Based on the analyses of Hansen and others (1994) and Morgan and McFarland (1996), median hydraulic conductivity values for the undeformed and for the structurally affected basalts are about 1 to 3 ft/d and about 0.001 to 0.1 ft/d, respectively.

TABLE 3.—*Estimates of hydraulic conductivity for the regional hydrogeologic units, Willamette Lowland, Oregon and Washington*
[--, unknown]

Hydrogeologic unit	Number of values	Hydraulic conductivity, in feet per day: Median	Range
Willamette Silt unit	5	0.1	0.01–8
Willamette aquifer	[1]90	240	0.03–7,000
	[2]1,178	110	3–440
	[3]268	7	0.03–1,500
	[4]2,094	15	3–200
Willamette confining unit	[5]113	2	0.01–90
Columbia River basalt aquifer [6]	--	1	0.001–750

[1] Values based on well data for unconsolidated sedimentary aquifer, from Morgan and McFarland (1996).

[2] Values based on model calibration for unconsolidated sedimentary aquifers, from Morgan and McFarland (1996).

[3] Values based on well data for Troutdale Gravel aquifer, from Morgan and McFarland (1996).

[4] Values based on model calibration for Troutdale Gravel aquifer, from Morgan and McFarland (1996).

[5] Values based on well data for coarse-grained deposits, from Morgan and McFarland (1996).

[6] Values from Hansen and others (1994).

Wells that withdraw water from the Willamette confining unit generally are completed in medium- to coarse-grained interbedded zones locally contained in this unit. Available hydraulic conductivity values for this confining unit are representative of these coarser zones and are not typical of the unit as a whole. For the Portland Basin, Morgan and McFarland (1996) calculated hydraulic conductivity values from 113 specific-capacity tests from wells completed in the productive zones of the confining bed, and reported that values ranged from 0.01 to 90 ft/d and averaged about 2 ft/d. A median value characterizing the entire Willamette confining unit, however, may be smaller than the 2 ft/d value associated with the coarser zones.

Although the water table exists in the Willamette Silt unit throughout much of the Willamette Lowland, this unit is generally not used as an aquifer. Therefore, hydraulic conductivity values estimated from well tests completed in this unit are lacking. Based on laboratory analyses of cores from five wells, however, Price (1967a) reported that the hydraulic conductivity of the silt ranged from 0.01 to 8 ft/d (table 3).

TRANSMISSIVITY

Transmissivity values for the Willamette aquifer and the Columbia River basalt aquifer compiled for this study had a large range—from less than 100 to 665,000 ft^2/d (square feet per day). Transmissivity values also were calculated for this study. Two techniques were used to calculate transmissivity values: using data from aquifer tests and using data from specific-capacity determinations. Although transmissivity values calculated from aquifer tests are considered more reliable, few aquifer tests have been conducted in the study area. Estimates of transmissivity derived from aquifer tests are shown in table 4, and as expected, values for the flood-plain deposits in the Willamette aquifer are larger than values for buried alluvial deposits. Also shown in table 4 are seven sets of estimates derived from both specific-capacity and aquifer-test data using methods described by Ferris and others (1962) and Theis (1963); generally, estimates derived from the aquifer-test data gave larger transmissivity values.

Because so few aquifer tests have been conducted in the Willamette Lowland, transmissivities also were estimated from specific capacities at 503 wells listed in the U.S. Geological Survey data base that met the following criteria: (1) the well has a diameter of at least 8 inches, (2) the pumping test lasted for at least 2 hours, (3) the well depth is known, and (4) the well location is known. These criteria were selected to minimize the effects of well loss and to best determine the geologic deposit in which the well is completed.

The following chart is an analysis of transmissivity estimates derived from specific-capacity data from 324 of the 503 wells in the Willamette Lowland that had values greater than 1,000 ft^2/d.

Transmissivity, in feet squared per day	Number of wells	Well locations
>100,000	12	12 wells in modern flood plains of large perennial streams;
60,000–100,000	12	12 wells in modern flood plains of large perennial streams;
30,000–60,000	18	17 wells in modern flood plains of large perennial streams; 1 well in an alluvial fan;
10,000–30,000	42	32 wells in modern flood plains; 4 wells in alluvial fans; 5 wells outside fans or flood plains (1 in basalt);
1,000–10,000	240	89 wells in modern flood plains; 29 wells in alluvial fans; 122 wells outside fans or flood plains.

The preceding transmissivity information indicates that for the Willamette aquifer, the flood-plain deposits have the largest transmissivities, the buried alluvial fans have the next largest transmissivities, and the least transmissive parts of the aquifer are those that do not contain the flood-plain or alluvial-fan deposits. These findings corroborate those of the hydraulic conductivity analysis previously mentioned. Average transmissivities from the 324 wells were calculated for those wells completed in each type of deposit (table 4).

SPECIFIC YIELD

For many of the previous investigations in the Willamette Valley, the following technique was used to estimate the specific yield of the Willamette aquifer: The specific yield values shown in the next chart were assigned to thicknesses of unconsolidated materials described in drillers' logs, and the products of the specific yield times thickness were summed over different intervals and divided by total thickness.

Material	Specific yield in percent
Gravel, sand and gravel, and related coarse, gravelly deposits	25
Sand, medium to coarse, loose	20–25
Sand, fine, tight, and in lenses; sand containing clay lenses	15–20
Clay and gravel; gravel containing clay binder; conglomerate; cemented gravel; and clay containing gravel lenses	10–15
Clay, silt, and related fine-grained deposits	3–5

TABLE 4.—*Estimates of transmissivity and storage coefficient derived from specific-capacity data and aquifer tests in the Willamette Lowland*

[gal/min, gallons per minute; gal/min/ft, gallons per minute per foot; ft^2/d, square feet per day; --, no data]

Well number	Pumping rate (gal/min)	Specific capacity (gal/min/ft)	Transmissivity, specific capacity [1] (ft^2/d)	Transmissivity, formula [2] (ft^2/d)	Storage coefficient, specific yield (percent)
		Willamette aquifer—flood plain deposits			
16S/4W-25ccd	1,200	--	--	78,000	--
16S/4W-36bbc	1,230	--	--	79,000	--
16S/4W-36bbd	1,210	--	--	76,000	--
15S/4W-17aad	300	75	20,000	--	--
15S/4W-28bad2	550	466	120,000	270,000	5.0
14S/4W-06cdc	300	16.7	4,400	--	--
13S/5W-35abc	400	40	11,000	--	--
162 wells	--	--	[3] 29,735	--	--
		Willamette aquifer—buried alluvial deposits			
04S/2W-02acbz	64	2.3	--	12,000	.07
15S/4W-32cab4	980	41	11,000	6,200	--
16S/3W-30dba	300	41	11,000	36,000	--
16S/3W-32dbd1	235	17	4,600	2,700	.02
17S/2W-26ccal	875	86	23,000	67,000	6.0
13S/3W-18bbc2	310	4.9	1,300	--	--
13S/3W-28cab	165	2.4	600	--	--
14S/3W-05baa	400	5.7	1,500	--	--
14S/3W-07ddc	75	2.8	700	600	--
14S/4W-01dab2	200	3.0	800	--	--
14S/4W-21dac	650	16.1	4,300	4,900	--
15S/4W-16adc	300	2.5	700	--	--
34 wells [4]	--	--	[3] 4,540	--	--
127 wells [5]	--	--	[3] 3,010	--	--
		Columbia River basalt aquifer			
02S/2W-1J1	--	--	--	3,080	--
1 well	--	--	10,460	--	--

[1] Transmissivity calculated using specific-capacity data.
[2] Transmissivity calculated using aquifer-test data.
[3] Average transmissivity value.
[4] Wells completed in buried alluvial fans.
[5] Wells completed in buried alluvium not in fans or flood plains.

Using this technique, the specific yield for identified segments of the Willamette aquifer previously was estimated for many areas in the Willamette Valley (table 5). As might be expected, the specific yield (17 to 19 percent) for the coarse, well-sorted flood-plain deposits (Qyal and Qal less than 50 ft deep) was larger than the specific yield (9 to 17 percent) for the buried alluvial deposits (Qoal and Qal more than 50 ft deep). Additionally, the overall specific yield values decreased slightly with depth—for depths less than 50 ft, the average specific yield ranged from 13 to 18 percent and averaged 16 percent, whereas for depths from 50 to 100 ft, the average specific yield ranged from 9 to 15 percent and averaged about 11.5 percent.

GROUND-WATER FLOW SYSTEM

The ground water in the Willamette Lowland aquifer system generally occurs under unconfined (water-table) conditions, except for the deeper parts of the Columbia River basalt aquifer. The generalized water table in the Willamette Lowland has been mapped (pl. 1) to show the regional configuration of the flow system during late summer to early fall conditions, when the water table is at the seasonal low. Water-level data listed in many previous reports were included so that an adequate areal distribution could be achieved (Foxworthy and others, 1964; Frank and Johnson, 1970, 1972, 1975; Hampton, 1963; Helm, 1968; Price, 1961; Price and Johnson, 1965; Sceva and DeBow, 1966). Because the ground-water flow in the Columbia River basalt aquifer is varied and complex and there is a lack of regional water-level data (both areal and vertical), the flow system of this aquifer is only briefly described. However, typical ground-water-level fluctuations are shown by representative hydrographs presented in this report.

EVOLUTION OF FLOW SYSTEM IN WILLAMETTE AQUIFER

The regional pattern of horizontal ground-water flow in the Willamette aquifer is largely controlled by overall structural setting and by the location of major surface drainages. In turn, the present positions of the drainages in the Willamette Lowland south of the Portland Basin (the Willamette Valley) are controlled in at least two ways by the location of the buried alluvial fans. In the first way, the locations of the buried alluvial fans are evidenced at the land surface by higher altitudes that deflect streams downslope. Thus, the Willamette River generally occupies the western part of the Willamette Valley. The second way depends on the sediment deposition, erosion, and transport during emplacement and post-emplacement times of the alluvial fans.

During the Quaternary, periodic alpine glaciations resulted in the deposition of extensive alluvial fans where glacial streams entered the Willamette Valley (Glenn, 1965). The coarse gravels and sands that compose the alluvial fans were transported by high-energy streams draining the Cascade Range. These fans, with the exception of the Springfield and Canby fans, were covered by the Willamette Silt. For the past approximately 11,000 years, major streams in and adjacent to the Willamette Lowland have had the energy level sufficient to erode and transport silt and sand-sized particles. For example, the suspended sediment in the Willamette River at Portland, Oregon, was measured near peak flow on January 18, 1990, when the discharge was 53,100 ft^3/s and the estimated discharge during the 10 previous days averaged 102,800 ft^3/s (Hubbard and others, 1991). The sediment concentration was only 21 mg/L (milligrams per liter), and the load was computed at 2,800 tons per day; even during these peak flows, about 97 percent of the suspended sediment was finer than 0.062 mm (millimeter) (silt and clay). Klingeman and Emmett (1982) refer to the Willamette River as a gravel-bed river, whose bed also contains many cobbles. They sampled the river at Salem and delineated an armor layer that has an average grain size ranging from 38 to 58 mm (very coarse gravel). On occasion, the major streams have sufficient energy to erode and transport gravel, but they have not been able to significantly erode into the coarser sediments in the alluvial fans.

Consequently, the resulting topography of the major drainage networks is one of steep-sided incisions down through the Willamette Silt that stop at the underlying coarser alluvial gravels; erosion then proceeds by lateral side-cutting. Balster and Parsons (1968) noted that near the top of the deep valley fill, a partially cemented coarse gravel deposit occurs at about the present level of the Willamette River. A series of hydrogeologic sections by Gannett and Caldwell (1998) also show that the major river channels in the lowland have incised the Willamette Silt and just penetrate the Willamette aquifer. This explains why Piper (1942) referred to many of the stream channels as "trenches" and why Glenn (1965) described the permanent streams draining the Willamette Lowland typically as having steep-walled, flat-floored valleys that are larger than the present streams require and flood plains that are floored by coarse gravels. Therefore, the present positions of the major individual drainages have been controlled by the alluvial fans as follows.

TABLE 5.—*Computed values for specific yield and storage volume from previous investigations, Willamette Lowland, Oregon*

[Qal, alluvium, flood deposits; Qyal, alluvium, young; Qoal, alluvium, older; --, range or area not given; WT, water table]

Deposit	Depth zone (feet)	Average specific yield (percent)	Range of specific yield (percent)	Area (acres)	Storage volume (acre-feet)
		Eugene-Springfield [1]			
Qal	10–100	15.2	13.1–19.2	--	1,400,000
Qal	100–150	12.9	--	--	700,000
		Harrisburg-Halsey [2]			
Qyal	10–30	19	17–20	30,000	110,000
Qoal	10–50	13	11–18	90,000	470,000
Qoal	50–80	12	11–14	30,000	110,000
Qoal	50–100	9	8–9	25,000	110,000
		Corvallis-Albany [3]			
Qyal	10–35	19	18–21	25,000	120,000
Qoal	10–50	14	11–16	60,000	320,000
Qoal	50–100	11	7–17	47,000	310,000
		French Prairie area [4]			
Qal	10–100	17.1	15.4–19.1	134,000	2,000,000
Qal	100–200	16.9	13.2–23.8	134,000	2,140,000
		Stayton Subbasin			
Qal	WT–50	17	--	42,140	300,000
Qal	50–100	14	--	42,140	320,000
		Leon-Albany plain			
Qal	WT–50	18	--	81,690	450,000
Qal	50–100	15	--	81,680	570,000
		Interbasin area			
Qal	WT–50	17	--	19,000	120,000
Qal	50–100	10	--	19,000	90,000
		Ankeny Bottom area			
Qal	WT–50	18	--	23,420	150,000
Qal	50–100	10	--	23,420	100,000
		Molalla-Salem Slope (valley plain and adjacent areas) [5]			
Qal	WT–100	14.6	11–18	118,800	1,245,000
Qal	100–200	13.6	7–19	118,800	1,618,000

[1] Frank, 1973.
[2] Frank, 1976.
[3] Frank, 1974.
[4] Price, 1967a.
[5] Hampton, 1972.

1. The Willamette River channel occupies the western margin of the Willamette Valley, and, where not influenced by shallow bedrock, the Willamette River tends to hug the western edge of the flood plain. This orientation of the river may be a result of tectonic factors (for example, more differential uplift in the Cascade Range, tilting of the valley floor, and so on). However, the geologic history and geometry and extent of the fans mapped in this study indicate that the Lebanon and Salem fans have forced the Willamette and proto-Willamette Rivers to the western margin of the valley.
2. Amazon Creek has been forced along the western margin of the Springfield fan, downstream from where the creek enters the lowland.
3. The lower Calapooia River, downstream from its confluence with Spoon Creek, has been forced along the western margin of the Lebanon fan.
4. The South Santiam River has been forced westward by the southern margin of the Stayton fan. It is possible that in the past, the South Santiam flowed east of the Salem Hills and joined the North Santiam to flow through Turner gap. However, during the time the North Santiam River deposited the Stayton fan, the South Santiam River may have been forced westward by the Stayton fan into the southern part of the Salem Hills, where the river was able to erode through the marine sedimentary rocks not capped by the Columbia River Basalt Group.
5. The North Santiam River has been a prominent factor in the evolution of the flow regime in the central part of the Willamette Valley. The North Santiam River, and possibly the South Santiam River, may have flowed northward through the Turner gap and then continued northward through the channel presently called Lake Labish (now primarily occupied by the Pudding River). Piper (1942, p. 12) and McDowell (1991) maintain that this channel was once occupied by an ancestral Willamette River but was abandoned by that stream early in the epoch of trenching. However, water-table contours (pl. 1) indicate a flow pattern that suggests the presence of a permeable buried channel that trends from near the Turner gap to the Labish channel. Furthermore, the shape of the Salem fan (fig. 13) suggests that its redeposited tail trends along this buried channel. Glenn (1965) states that in the lower part of the Labish channel, the Pudding River flows in a circuitous channel cut into coarse sands and fine gravel where the river enters the channel. Therefore, it is more physically plausible that as the Salem fan grew and the energy of the stream decreased, the fan eventually choked off flow along the Labish channel. This forced the flow of the Santiam River along the southwestern margin of the Salem fan to the Willamette River drainage, the same course now followed by Mill Creek. This proposed evolution is commensurate with the fact that the present Mill Creek flood plain north of the Turner gap is much larger than the present stream requires and is floored by coarse gravels. Eventually, the Stayton fan began to develop, forcing the North Santiam River to flow along the southeastern and southern margin of the fan and diverting the flow south of the Salem Hills again to rejoin the South Santiam.
6. The Molalla River occupies a flood plain 1 mi to 2 mi wide that has a veneer of coarse gravel. The river has been forced northward along the eastern side of the Molalla fan; north of that fan the river has been forced westward along the southern margin of the Canby fan.

In conclusion, prominent alluvial fans were deposited by high-energy streams where they debouched onto the Willamette Lowland from the Cascade Range. Coarse sands and gravels in the fans were reworked and redeposited along the distal parts of the fans by high-energy streams. The Willamette Silt was deposited in the lowland up to an altitude of about 350 ft above sea level and buried some of the coarse fan sediments. The major rivers have eroded through the Willamette Silt down to near their former base level. However, because of low-energy conditions, the present rivers in the study area cannot erode significantly into the coarse sediment on the alluvial fans, and they are forced, primarily by lateral sidecutting, to occupy channels downgradient (primarily west and southwest) of the fans. Thus, the coarse sands and gravels beneath the modern flood plains of the major streams in the lowland are primarily reworked and resorted Pleistocene sediments.

WATER-LEVEL FLUCTUATIONS

Ground water in the Willamette aquifer generally occurs under unconfined conditions, and the potentiometric surface of the aquifer is the water table. Fluctuations of the water table represent changes in ground-water storage. The water table is a dynamic surface that moves up and down in concert with local and regional ground-water recharge and ground-water discharge trends. These trends are largely controlled by precipitation, river- and reservoir-stage, and well-withdrawal patterns. Generally, water-level fluctuations are analyzed on the basis of two time periods—seasonal (sometimes called annual) variations and long-term variations.

Throughout the Willamette Lowland, seasonal fluctuations of the water table commonly are a delayed response to the seasonal fluctuations in precipitation.

Only a small part of the precipitation falling on the lowland contributes directly to surface runoff, because much of the lowland is flat-lying and the overlying soils have large infiltration rates. Additionally, because about 80 percent of the annual precipitation falls during the cold winter months when evaporative demand is small, only a small part of the precipitation falling during this period evaporates. Therefore, most of the winter precipitation infiltrates and percolates to the water table. Finally, the relatively small quantity of precipitation that falls during the summer (about 6 percent of the mean annual total) is held as soil moisture and is extracted from the shallow subsurface through evapotranspiration.

The relation between daily precipitation recorded at Salem, Oregon, during 1960 and 1961 and the seasonal fluctuations of the water table in a 123-ft deep well completed in the Willamette aquifer (fig. 16) was noted by Price (1967a) and is considered to be representative of the lowland. The well is located about 5 mi east of the Willamette River and about 8 mi north of Salem, Oregon. Ground-water levels start to decline with the onset of the growing season. Some precipitation can recharge the Willamette aquifer during the early spring, but after about April or May, water levels decline. That is, as the rainy season dissipates during March and April, the water table begins to fall because of a decrease in ground-water recharge and an increase in both evapotranspiration and ground-water pumpage. Little or no recharge to the Willamette aquifer from local precipitation occurs during the summer, and the water table is lowest during the late summer and the fall. The water table generally reaches a regional low during the period from August through mid-November. The rainy season begins in the fall with a

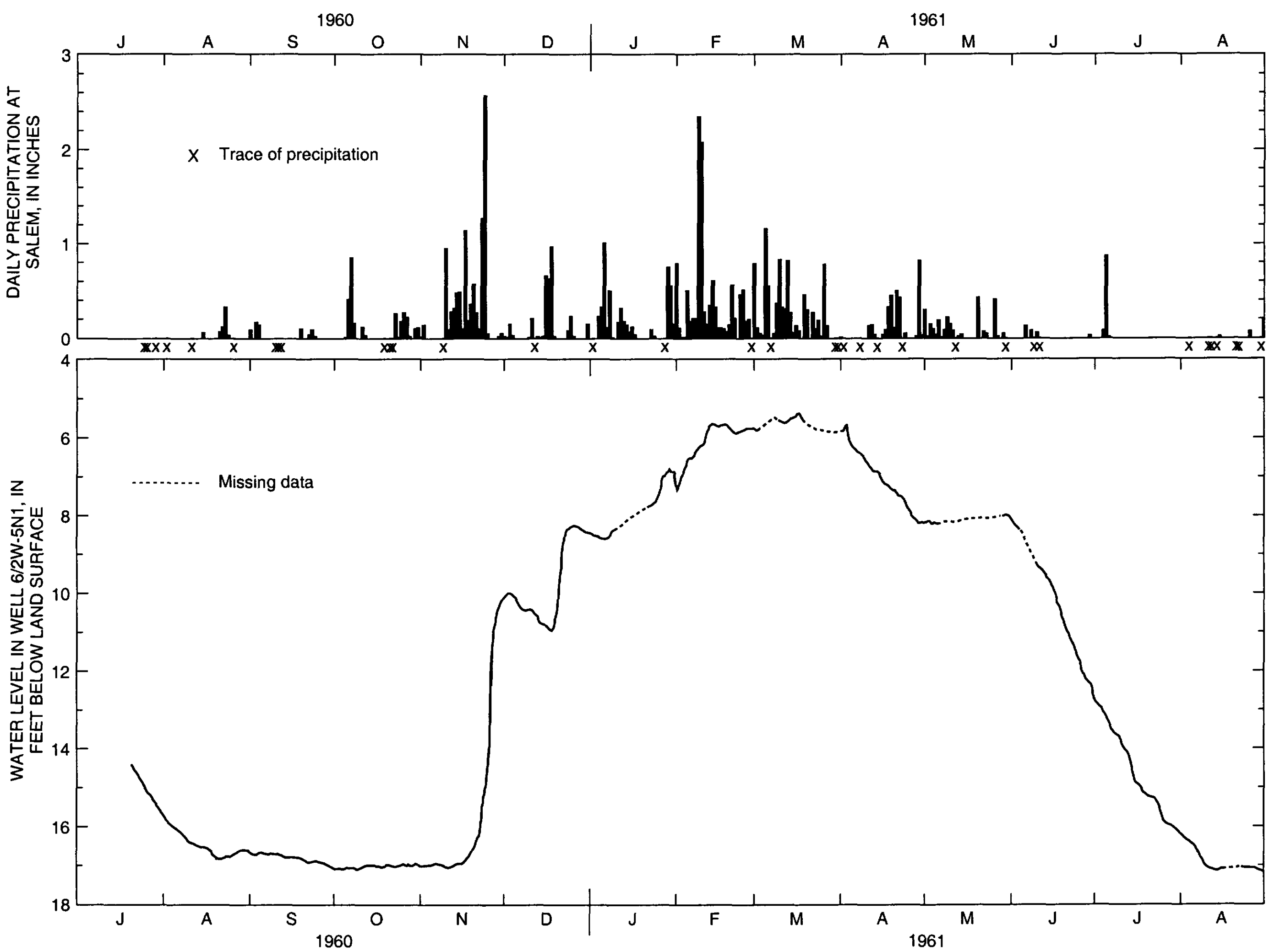


FIGURE 16.—Daily precipitation and water-table fluctuations. (Well located in Township 6 south, Range 2 west, Section 5. From Price, 1967a, p. 48.)

concurrent decrease in evaporative demand because of decreasing temperatures. It generally takes about 2 weeks after the initial rains (depending on the field capacity of the soil and the intensity and duration of the rain) before the water table begins to rise. Thus, the effects of the rainy season and the decreased evapotranspiration in October are reflected in the water-table rises during November and December (fig. 16). Overall, the recovery of water levels each winter to approximately the same level indicates that the aquifer is supported by recharge primarily from the direct infiltration of local precipitation and that, generally, recharge balances discharge.

The precipitation/water-level relation aspects were initially noted by Piper (1942), who reported that from 1928 to 1936, both the minimum and maximum yearly range in water-table fluctuation—3.5 and 28 ft—occurred in the southern Willamette Valley under unconfined conditions and that the fluctuations were natural. Piper attributed the sharp rise in ground-water levels in December and January almost entirely to the infiltration of rain that falls in the immediate vicinity, and he ascribed the steady decline after April largely to continuous unwatering of the alluvial deposits (the Willamette aquifer) as the ground water moves horizontally toward and into the streams.

Ground-water flow patterns in the Willamette aquifer also are closely linked to the stage in the major streams in the lowland. Piper (1942) first noted that in the younger alluvium along the Willamette River and its principal tributaries, the fluctuations of ground water closely follow the fluctuations of stream stage. He suggested that the ground-water level in this alluvium was determined more by a backwater effect of rising and falling river stage than by extensive percolation from the river into the alluvium and the reverse, and that, ordinarily, the water table sloped toward the river. However, when the rainy season begins, the stage of the Willamette River and ground-water levels both rise. The rise in the water table is caused partly by the direct infiltration of precipitation and partly by seepage of water from the major streams into the highly permeable alluvium adjacent to the stream channels.

Seasonal fluctuations of the water table from the selected wells shown in figure 17 are evident on hydrographs shown in figures 18a–d. Seasonal fluctuations in the Willamette aquifer in the flood plains of major streams are moderated by the stage of the stream, and these fluctuations generally range from about 3 to 7 ft (fig. 18a). Seasonal fluctuations of the water table in the Willamette aquifer away from major streams generally range from about 8 to 15 ft (figs. 18a–c).

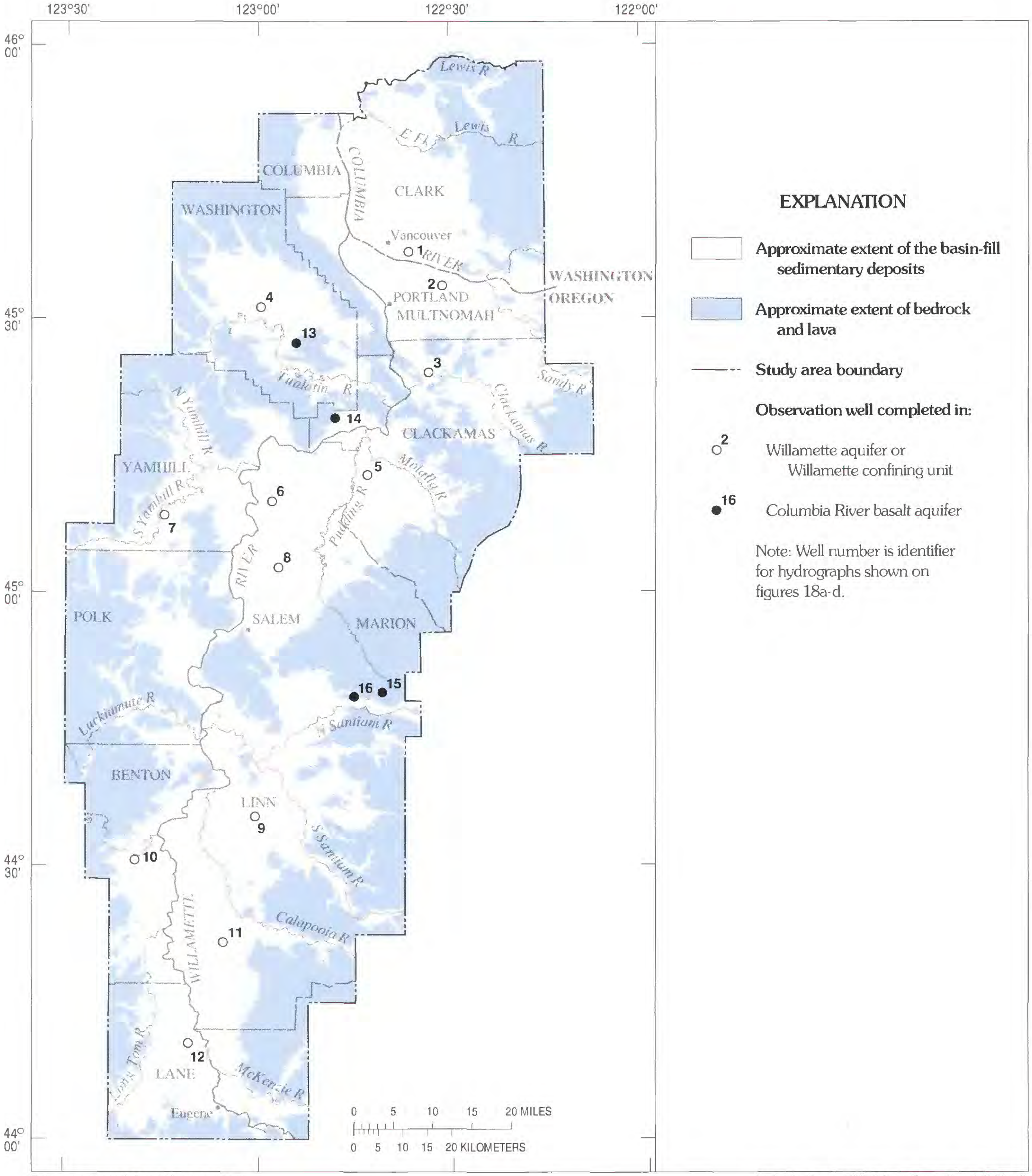
Seasonal water-table fluctuations of the Willamette aquifer in the Portland Basin have been described using 50 hydrographs for the period 1987–90 (McCarthy and Anderson, 1990). The average fluctuation from the high level in spring to the low level in late summer to early fall was 5.6 ft.

In the central Willamette Valley, the average depth-to-water during the winter remained relatively constant in each of the four long-term hydrographs shown on figure 18b until about 1984–85. At that time, the winter water levels began to decline to about 5 ft below the long-term average. Depths-to-water ranged from about 10 to 15 ft for the three shallow wells and was about 30 ft for the deep well (completed in a deeper, semiconfined part of the aquifer). The average depth-to-water during the summer to fall period generally fluctuates within a range of 5 ft, except for some years when a probable increase in pumping may have further effected declines (fig. 18b).

In the southern Willamette Valley, the average depth-to-water during the winter (when the water table is highest) has remained relatively constant, as shown by the information of the four long-term hydrographs on figure 18c. These depths ranged from about 3 to 6 ft below land surface. With the exception of lower water levels during 1973–75, the average depth-to-water during the summer to fall period (when the water table is lowest) has remained relatively constant since the early 1960's (fig. 18c).

Ground water in the Columbia River basalt aquifer generally occurs under unconfined conditions near the land surface (where the basalt outcrops) and is confined at depth. Four long-term hydrographs (fig. 18d) are representative of water-level fluctuations in the Columbia River basalt aquifer in the lowland.

Well 01S/02W-26BDC (fig. 17, well number 13) was drilled in the early 1960's on a basalt outcrop west of Cooper Mountain in the Tualatin Basin. The progressive water-level decline in this well until the early 1970's (fig. 18d, well number 13) typifies the water-level declines in this area due to extensive pumping for irrigation. According to Bartholomew and DeBow (1970), ground-water levels in the Cooper Mountain-Bull Mountain area declined as much as 12 ft/yr (feet per year) and more than a total of 40 ft from the early 1960's to 1974. In order to stabilize water levels and to prevent further depletion of the basalt aquifers, the Cooper Mountain-Bull Mountain area was declared a critical ground-water area by the Oregon State Engineer in 1974, and restrictions were placed on both pumping and the construction of new wells. Additionally, in 1974, when the Wolf Creek Irrigation Project began supplying water for irrigation from the Tualatin River, the use of ground water for irrigation further decreased. As a result, water levels in the basalt aquifer in that area began to rise. However, hydrographs from the remaining wells shown on figure 18d indicate a progressive, long-term water-level decline.



Basemap source information on page v.

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

FIGURE 17.—Location of selected observation wells.

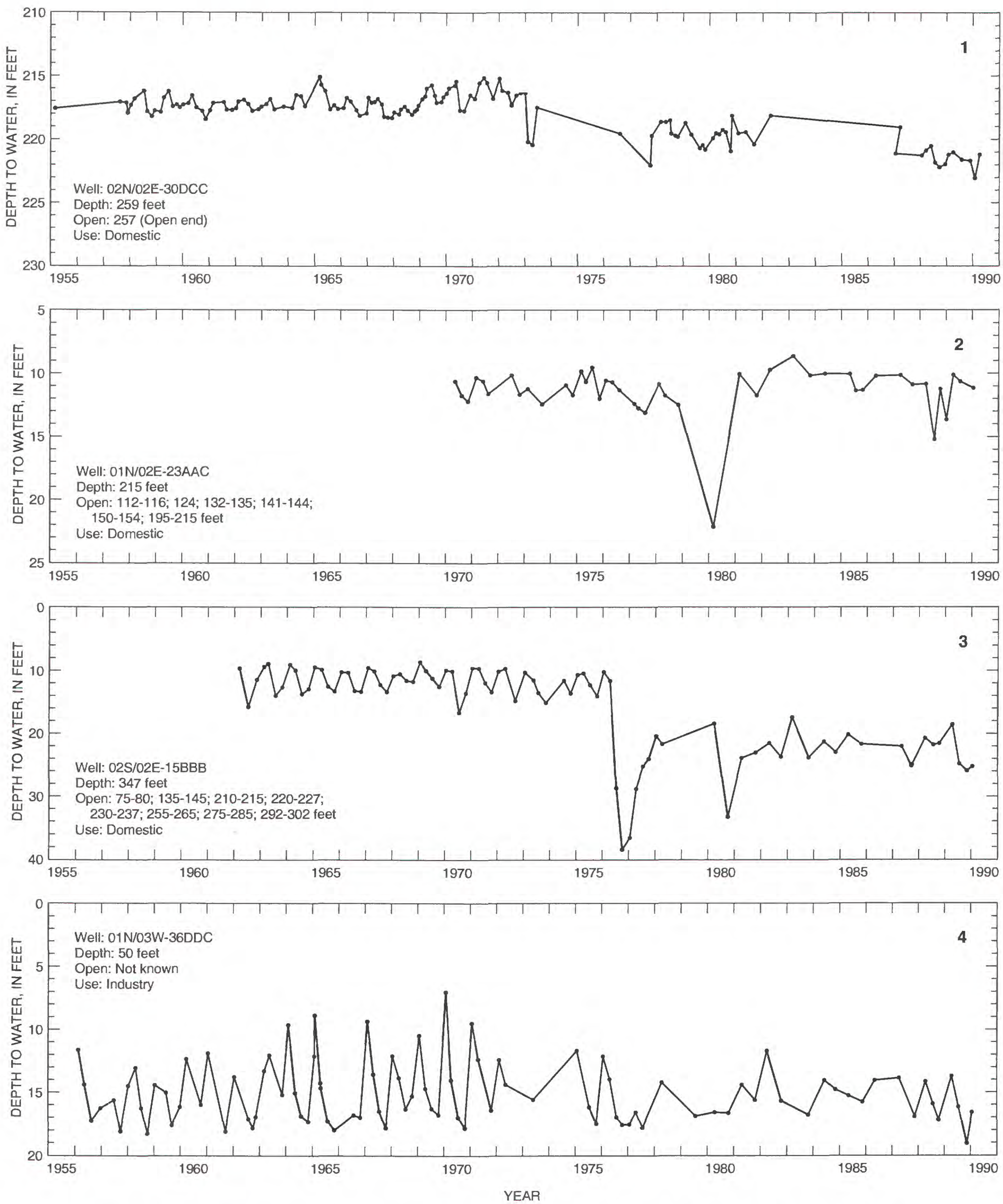


FIGURE 18a.—Water levels in wells completed in the hydrogeologic units in the Portland Basin and in the Tualatin Basin. Graph number (1-16) is also well number on figure 17.

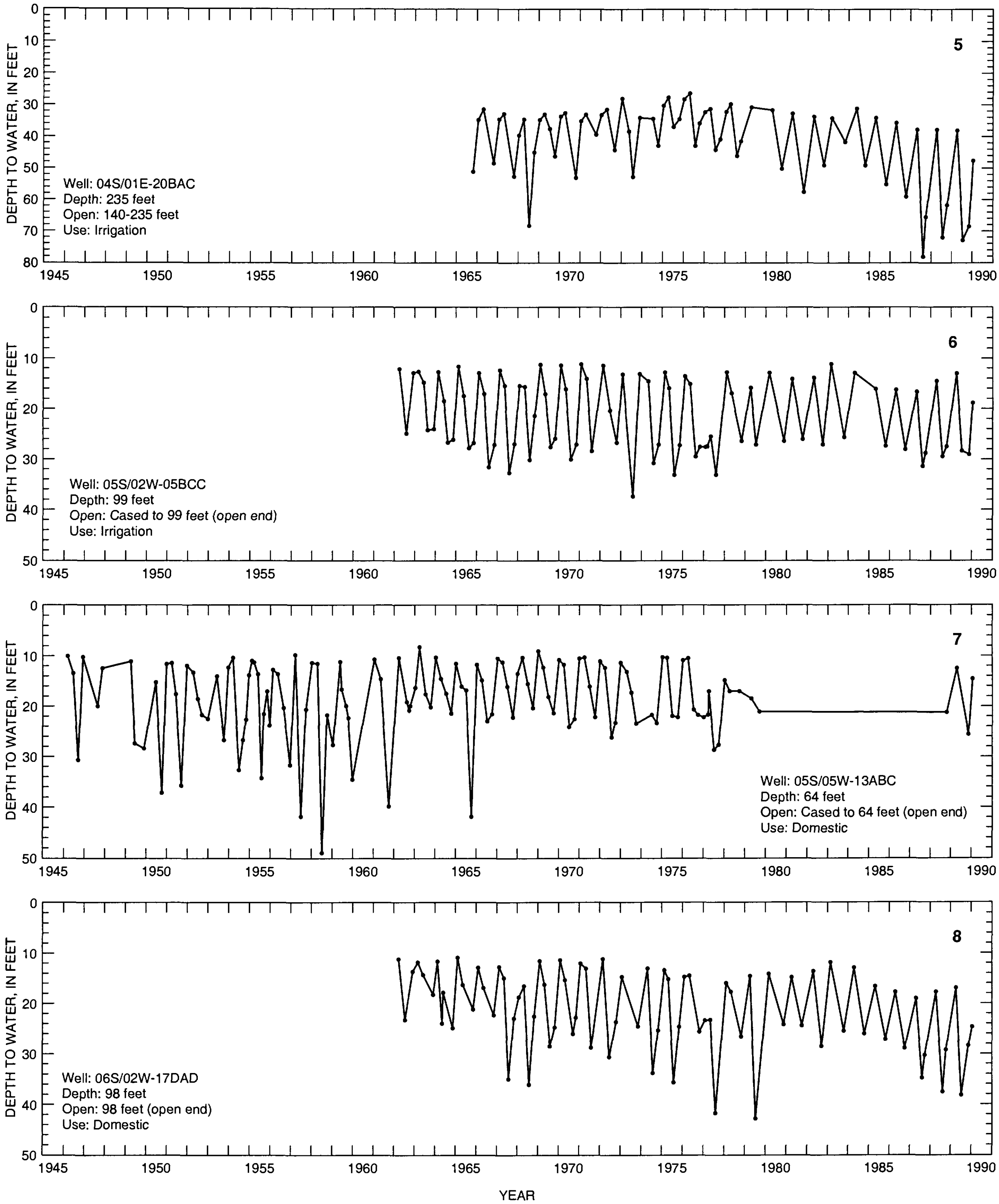
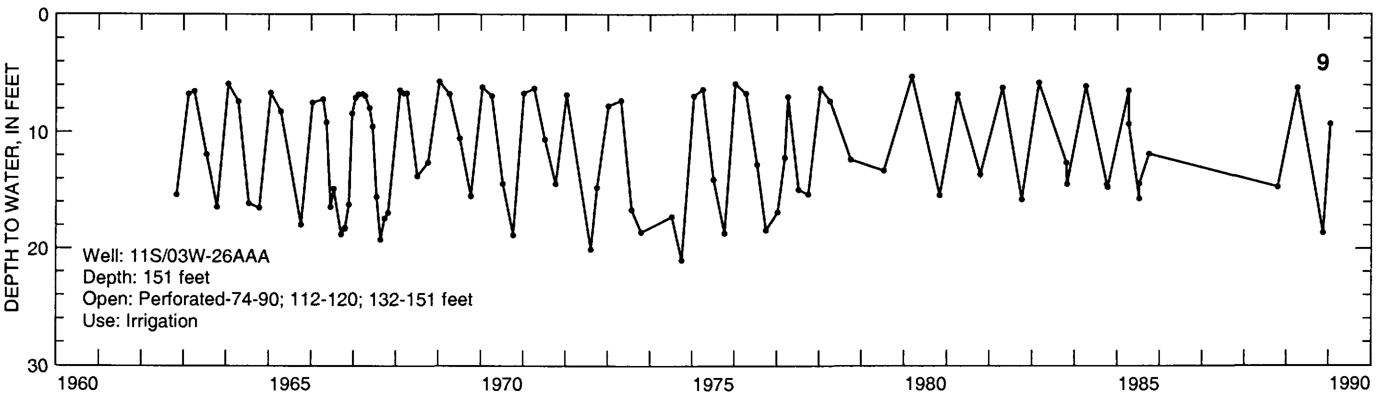
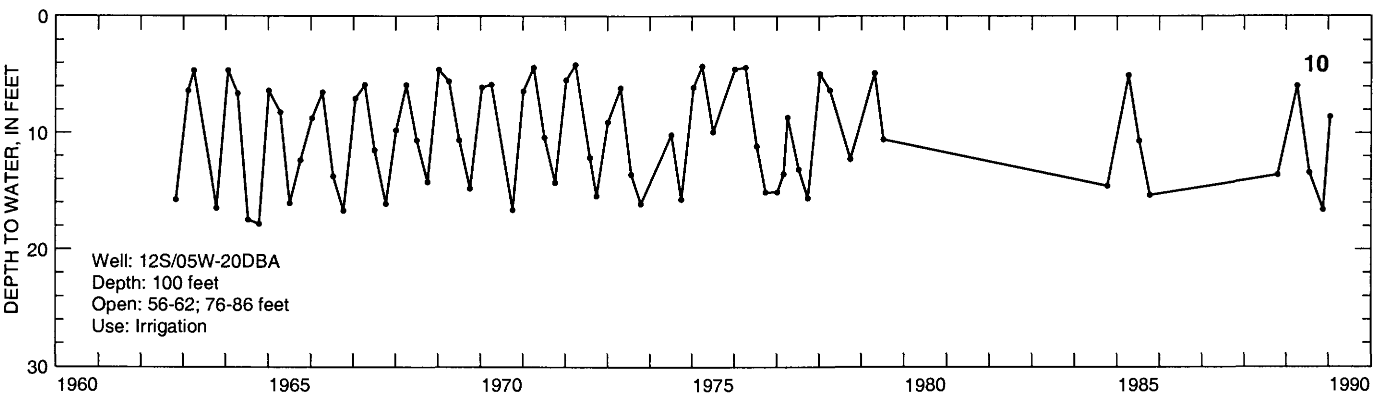
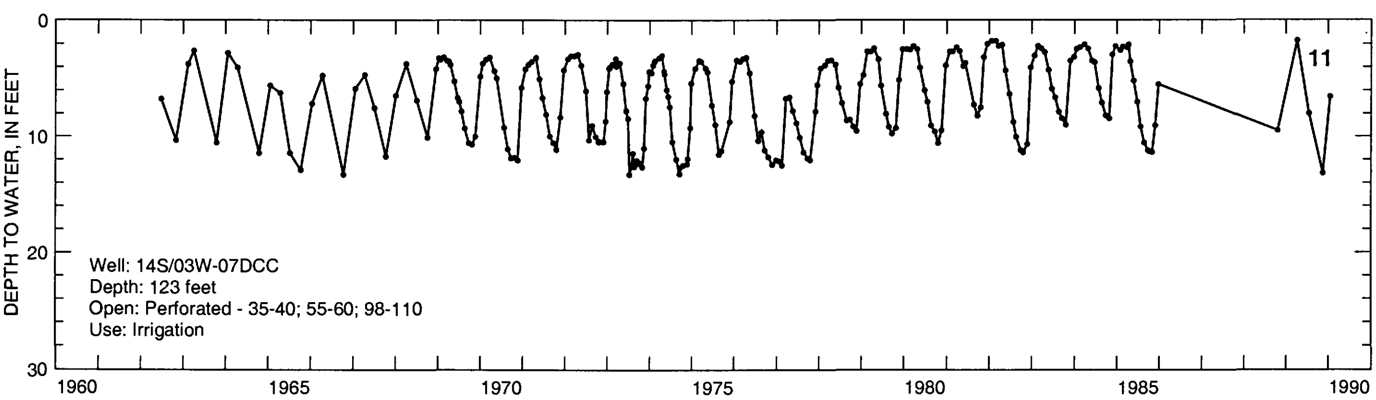


FIGURE 18b.—Water levels in wells completed in the Willamette aquifer, central Willamette Valley. Graph number (1-16) is also well number on figure 17.







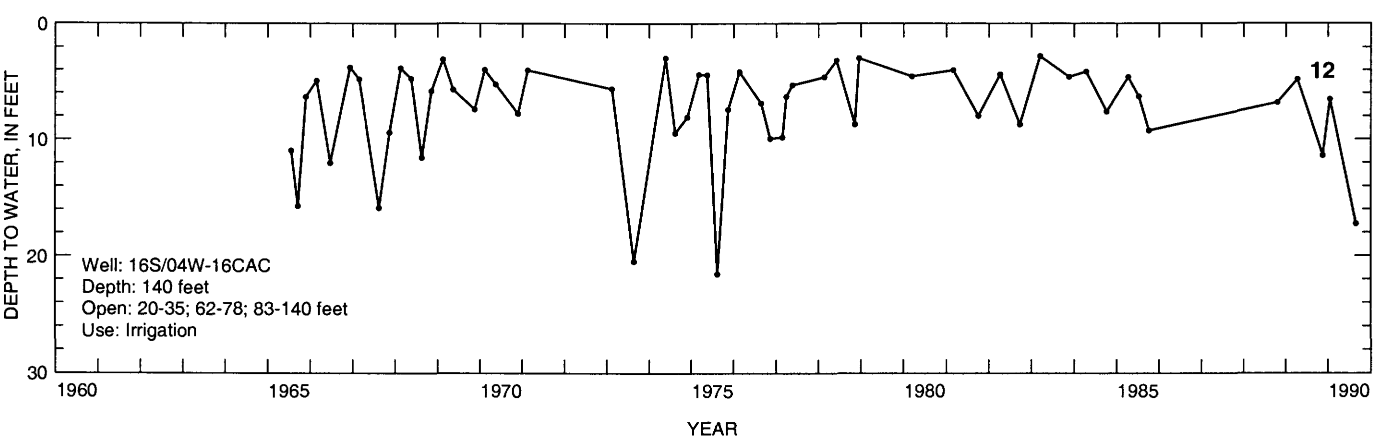


FIGURE 18c.—Water levels in wells completed in the Willamette aquifer, southern Willamette Valley. Graph number (1-16) is also well number on figure 17.

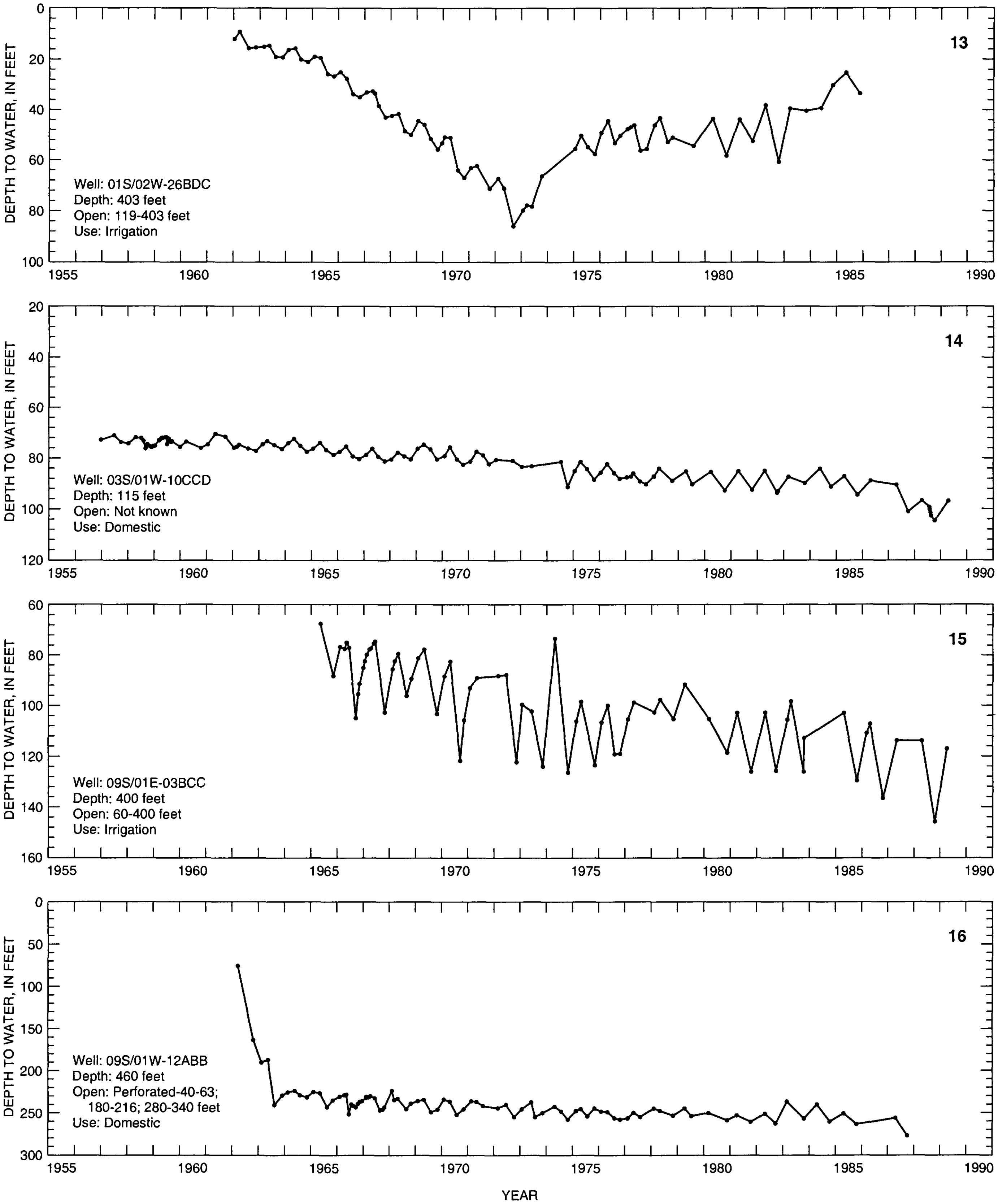


FIGURE 18d.—Water levels in wells completed in the Columbia River basalt aquifer. Graph number (1-16) is also well number on figure 17.

FLOW WITHIN AQUIFERS

During the winter and spring, when the regional water table is highest, some wells completed in the Willamette aquifer begin to flow (water levels rise above land surface); these wells usually cease to flow during the summer. In order to eliminate this variation in ground-water flow patterns caused by precipitation variability, water-level measurements collected during the summer and fall, when the water table is lowest, were used to map the water table (pl. 1). The water table mapped in plate 1 coincides with the potentiometric surface of the Willamette aquifer, except in the Tualatin Basin, where it coincides with the potentiometric surface of the Willamette confining unit, and in certain areas in the northern part of the central Willamette Valley, where it coincides with the surface of the Willamette Silt and confining units.

The water-table map (pl. 1) shows an overall pattern of ground-water flow to the major streams, indicating that the base flow of these streams is sustained by ground-water discharge. The direction of ground-water movement is approximately perpendicular to the water-table contours, and the change in the water-table altitude along a perpendicular line, divided by the distance for the change, is the hydraulic gradient. For a given hydraulic conductivity and porosity, the velocity of ground water is proportional to the hydraulic gradient. The horizontal hydraulic gradient ranges from more than 60 ft/mi (0.01 ft/ft [foot per foot]) near the western part of the central Willamette Valley to less than 2 ft/mi (0.0004 ft/ft) in the flood plain of the Willamette River north of Salem, Oregon. On the basis of average values of the hydraulic gradient and the hydraulic characteristics of the Willamette aquifer, the velocity of water moving through the aquifer ranges from about 3 to 30 ft/d, which is typical for sand and gravel aquifers.

The configuration of the water-table contours is controlled by several factors, including the geometry of the aquifer, the distribution of the thickness and hydraulic conductivity of the aquifer, the discharge of ground water into streams, the recharge to the aquifer from streams, the recharge by the infiltration of water through permeable soils, and the withdrawal of ground water by wells (Gutentag and Weeks, 1980). For example, flattening of the gradient indicated by the widely spaced contours, such as those in the flood plain of the Willamette River, is due to the large hydraulic conductivity of the flood-plain deposits.

Upgradient flexures of the water-table contours at a stream indicate ground-water flow toward, and discharge to, the stream; this generally is the dominant flow pattern in the lowland. Downgradient flexures in water-table contours crossing streams generally indicate water movement from the stream into the aquifer; this flow pattern exists near the apex of some of the buried alluvial fans. This local flow pattern was also observed by Piper (1942), who noted a flowing well located near the apex of the Lebanon alluvial fan in the southern Willamette Valley; the well usually ceased to flow during the summer. The lack of flexures in water-table contours crossing streams generally indicates that the aquifer and stream are not hydraulically connected.

In the southern Willamette Valley, regional ground-water flow is primarily toward the northwest (away from the Cascade Range), toward a buried channel that underlies most of the Willamette River, and toward a buried channel that hugs the western extent of the lowland and underlies reaches of Amazon Creek-Long Tom River-Muddy Creek. The hydraulic gradient generally is small, ranging from about 4 ft/mi (0.0008 ft/ft) in the flood plain of the Willamette River to about 20 ft/mi (0.004 ft/ft) down the Stayton fan.

In the central Willamette Valley, regional ground water moves primarily in an east-northeasterly to west-southwesterly direction and flows toward the Willamette River and the Pudding River-Labish channel. A regional ground-water divide exists beneath the central part of the French Prairie area. The hydraulic gradient is variable, ranging from less than 2 ft/mi (0.0004 ft/ft) in the flood plain of the Willamette River to more than 60 ft/mi (0.001 ft/ft) along the eastern part of the area; the gradient also is steep where the flood plain of the Willamette River is deeply incised.

Ground water in the Tualatin Basin moves from the periphery of the basin toward the central area and moves toward the streams. The gradient generally is steep, probably because the water table is in the Willamette confining unit, which consists of deposits that have small hydraulic conductivity.

Regional ground-water movement in the Portland Basin is toward the major rivers—particularly the Columbia, Willamette, and Clackamas Rivers. The hydraulic gradient generally ranges from about 5 to 50 ft/mi (0.001 to 0.01 ft/ft) and averages about 30 ft/mi (0.006 ft/ft). The steepest water-table gradients occur near the rivers along the incised flood plains of the Columbia and Willamette Rivers.

Hansen and others (1994) describe ground-water movement in the Columbia River Basalt Group for the Columbia Plateau RASA, located in central Washington, north-central Oregon, and small parts of northwestern Idaho. Generally, interflow zones (consisting of the basalt flow top in combination with the superposed flow base) support most of the horizontal ground-water movement, whereas most of the ground-water movement is vertical in the basalt flow centers. Additionally, the interflow zones in the basaltic sequence comprise numerous thin, semiconfined aquifers that have horizontal and vertical variations in physical and hydraulic characteristics (Hansen and others, 1994). Beeson and others (1989b) have delineated as many as 23 separate basalt flows in a part of the Tualatin Basin. Thus, it is possible that each interflow zone could have a distinct potentiometric surface, depending on the hydraulic connection between interflow zones. For this reason, and because of the sparse water-level information available from wells completed in the Columbia River basalt aquifer, water levels in this aquifer are described only in general terms.

Water-level data for the Columbia River basalt aquifer indicate that throughout most of the study area the vertical component of flow is downward. The well construction history and related change in water levels for well 09S/01N-12ABB (fig. 17 and fig. 18d, well number 16) indicate the vertical head change with depth. The magnitude of this change is considered representative for much of the area. The well was initially drilled in 1955 to a depth of 104 ft; the initial water level was at a depth of 52 ft below land surface and stabilized at a depth of 91 ft. Six years later, the well was deepened to 227 ft, and the static water level was about 85 ft; in 1963, the well was deepened to about 460 ft and the water level finally stabilized at a depth of about 226 ft. The water levels for the latter deepening indicate about a 141-ft vertical head change over about a 243-ft depth interval, or a downward vertical head gradient of about 0.58 ft/ft. Generally, the transition from vertical downward flow to upward flow in the basalts appears to be rather abrupt and occurs near regional discharge areas and near known faults and folds; this is similar to an observation of Hansen and others (1994) for the Columbia River Basalt Group on the Columbia Plateau. The hydrologic effects on flow between aquifers because of the variations of head with depth in the Columbia River basalt aquifer are described in more detail in the next section.

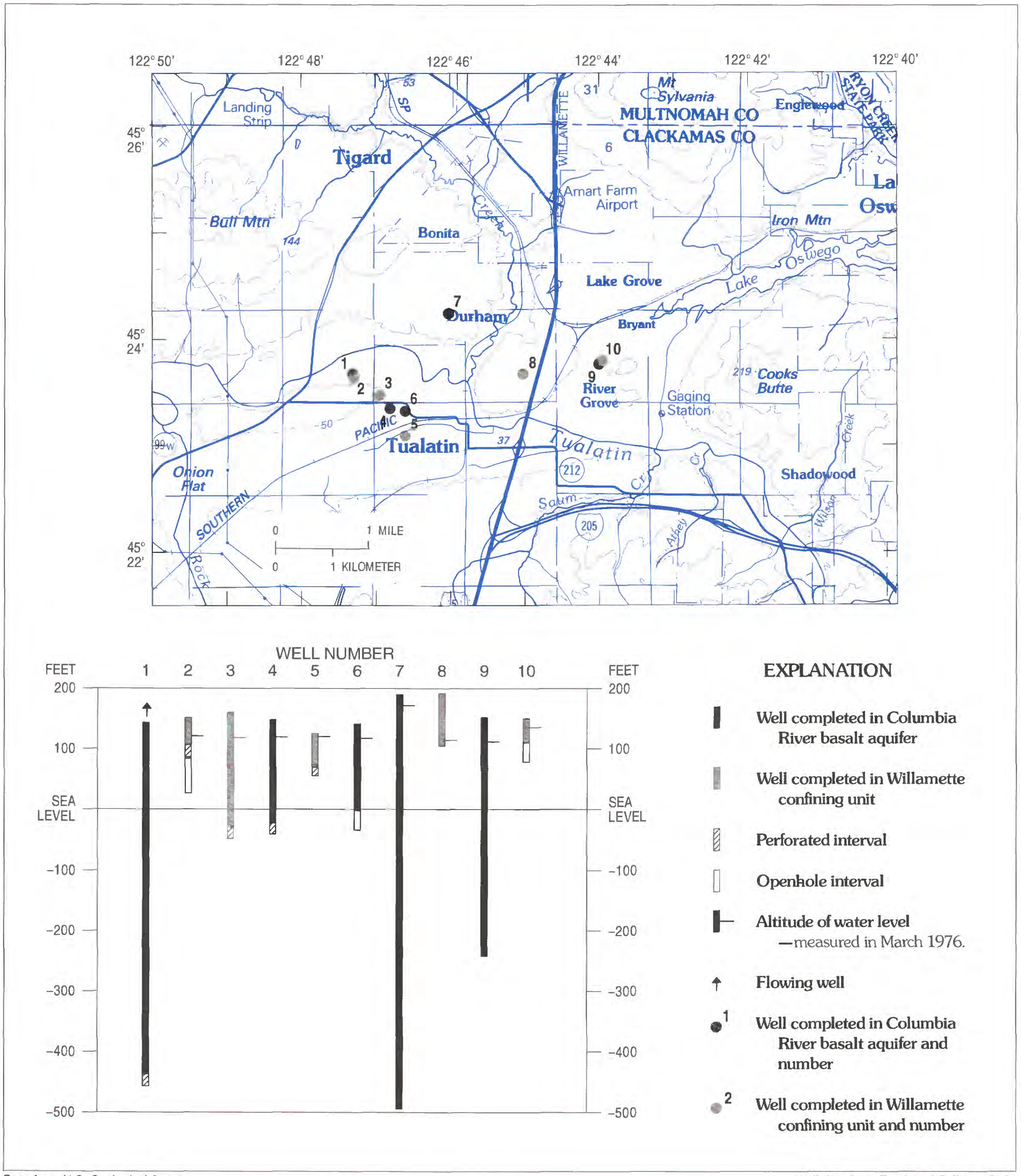
FLOW BETWEEN AQUIFERS

Saline ground water in the deeper Tertiary marine rocks is confined by the Willamette confining unit and the Columbia River basalt aquifer and has a large, vertically upward, flow component. Many of the deep petroleum test wells drilled in the study area experienced flowing saline water when the marine rocks were penetrated at depth (Newton, 1969). For example, formation tests on marine sands in the bottom of Texaco's "Cooper Mt. 1" yielded flows of salt water with rates as much as 700 barrels per day, and formation tests of Spencer sands in "Miller 1" at a depth from 2,374 to 2,425 ft produced a 2,200-ft rise of salt water. In the Newberg, Oregon area, mineralized water from underlying marine sedimentary rocks may move upward in response to the lowering of head due to pumping ground water from the basalt (Frank and Collins, 1978); further, the possibility of the upward movement of saline water was greater in a synclinal or downwarped area, where such movement can occur by way of tension cracks or through a fault zone. Additionally, where the Willamette confining unit is thin or absent, there is an increased possibility of inducing upward movement of saline ground water.

In their study of the Columbia River Basalt Group in the Columbia Plateau RASA, Hansen and others (1994) noted that throughout most of that area the vertical component of ground-water flow was downward, except near discharge areas (generally located in topographic lows); anomalies to this overall pattern were caused by geologic structures (faults and folds) and by intensive pumping. Newcomb (1961, 1965, 1969), Davies-Smith and others (1988), and F.A. Packard (U.S. Geological Survey, written commun., 1989) noted that, in some instances, major faults and sharp folds within the Columbia River Basalt Group were impediments to horizontal ground-water flow and created anomalous, vertically upward flow in the basaltic aquifer. Wells completed in the Columbia River Basalt Group just upgradient of some major faults and folds yielded a more evolved water type, typical of deeper aquifers (Steinkampf, 1989).

In the Willamette Lowland, the occurrence of flowing wells drilled in the Columbia River basalt aquifer is well documented. Hogenson and Foxworthy (1965) described a 310-ft flowing basalt well east of Portland; the well flowed at a rate of 40 gal/min to a height of about 30 ft above land surface. Hart and Newcomb (1965) documented many flowing wells in their study of the Tualatin Basin and further speculated that vertically permeable parts of fault zones may serve as discharge routes from the basalt to the overlying alluvial materials or to the surface. In places, the Columbia River basalt aquifer at depths beneath the valley fill contains ground water that rises in wells above the level of the water table. Hart and Newcomb (1965) further noted that wells that tap the confined water with the greatest head above the water table are located around the sides of the Tualatin Basin floor.

An indication of head differences between regional hydrogeologic units in the lowland is shown for 10 wells drilled in the Tualatin Basin within 1.5 mi of the city of Tualatin, Oregon (fig. 19). Five of the wells are completed in permeable zones in the Willamette confining unit, and the other five wells are completed in the underlying Columbia River basalt aquifer; water levels in each well were measured during March 1976 (Frank and Collins, 1978).



Base from U.S. Geological Survey
1:100,000 Oregon City quadrangle

Well data from Frank and Collins, 1978
USGS Ground Water Report No. 27.

FIGURE 19.—Location of wells and head differences between regional hydrogeologic units in the Tualatin Basin.

Head relations shown on figure 19 indicate that (1) the local water table is between an altitude of 114 and 121 ft, (2) the heads in the shallow basalt wells (No. 4 and No. 6) correspond with the water table, (3) the heads in the deep basalt wells (No. 1 and No. 7) are higher than the water table, indicating vertically upward flow near the Tualatin River, and (4) the head in basalt well No. 9 is lower than the head in well No. 10, which is completed in the overlying Willamette confining unit. Thus, over a relatively short distance, predominantly horizontal flow (no vertical head difference), vertically upward flow, and vertically downward flow are shown by the water levels for these 10 wells.

CROSS-SECTIONAL FLOW MODELS

Cross-sectional numerical flow models were constructed for two selected sections of the Willamette Lowland aquifer system in order to test a conceptual model of the ground-water flow system, to test estimates of hydraulic properties, and to provide information on the ground-water flow budget. Although the models were not rigorously calibrated, the simulated heads and discharges to streams compared favorably with observed heads and discharges, indicating that the conceptualization of the flow system and estimates of hydraulic properties were reasonable.

The two models, represented as sections M1-M1′ and M2-M2′ on figure 20, are approximately parallel to flow paths, as determined from the generalized water-table map (pl. 1). Section M1-M1′ extends from the vicinity of Silverton, west to the crest of the Eola Hills (which is north of Salem), and is considered to represent conditions in much of the central Willamette Valley, where basin-fill deposits are underlain by the Columbia River basalt aquifer. Section M2-M2′ extends from Peterson Butte (which is south of Lebanon), roughly west to the Willamette River between Corvallis and Albany; west of the Willamette River section would be essentially the reverse of M2-M2′. Section M2-M2′ is considered to be representative of the southern Willamette Valley, where basin-fill deposits directly overlie the basement confining unit.

Ground-water flow was simulated under steady-state conditions using the finite-difference ground-water flow model (MODFLOW) of McDonald and Harbaugh (1988). Flow paths were calculated and plotted using the programs MODPATH and MODPATH-PLOT by Pollock (1989). Flow budgets for individual aquifer units were determined using the program ZONEBUDGET of Harbaugh (1990).

MODEL GRIDS AND BOUNDARY CONDITIONS

The model grids for both sections are presented on figure 20, traces of the modeled sections are shown on plate 1, and information about the grids are summarized in table 6. Horizontal subdivision of the sections was based on the resolution of water-table altitude data, spacing of streams, and the scale of major topographic features. A constant cell length (column) of 1,500 ft and width (row) of 1 ft was selected for both sections. Vertical subdivision was based on the regional hydrogeologic units discussed earlier in this report. Each unit was represented by one model layer, except in section M1-M1′, where the thick Willamette confining unit was represented by four layers. The layer thickness was variable; the thickness of each model cell was based on the average thickness of the corresponding hydrogeologic unit at that location. For the four layers representing the Willamette confining unit in section M1-M1′, the layers were defined so that the thickness was equal.

The upper boundary of both sections was the water table and was modeled as a free surface. The uppermost active layer generally corresponded to the Willamette Silt unit (layer 1) or the Willamette aquifer (layer 2). The Columbia River basalt aquifer (layer 7) is the uppermost active layer at both ends of section M1-M1′. The uppermost active cells received a recharge flux that was determined by using a regression relation based on precipitation and elevation that had been determined by Snyder and others (1994) for the Portland Basin. Where the Columbia River basalt aquifer was the uppermost unit, a recharge rate of 14 in/yr was used; although this rate is lower than predicted by the regression relation, it is considered reasonable because of the small vertical hydraulic conductivity and generally steep topography of the basalt. Recharge ranged from 14.0 to 21.2 in/yr in section M1-M1′ and from 18.4 to 19.9 in/yr in the section M2-M2′.

The bottom of both sections was the top of the basement confining unit and was modeled as a no-flow boundary. There is undoubtedly some flow from the basement confining unit into the overlying units; however, because of its small hydraulic conductivity, the volume of this flow is likely to be small relative to the total flow in the system. Additionally, data are not available to quantify inflow from the basement confining unit and this formulation follows the conceptual model used to delineate the aquifer system described previously in the report.

Lateral boundaries (the ends of the sections) were also modeled as no-flow boundaries. Section M1-M1′ extends in both directions to the contact between the Columbia River basalt aquifer and the basement confining unit. Basin-fill deposits abut the basement confining units on the east end of section M2-M2′.

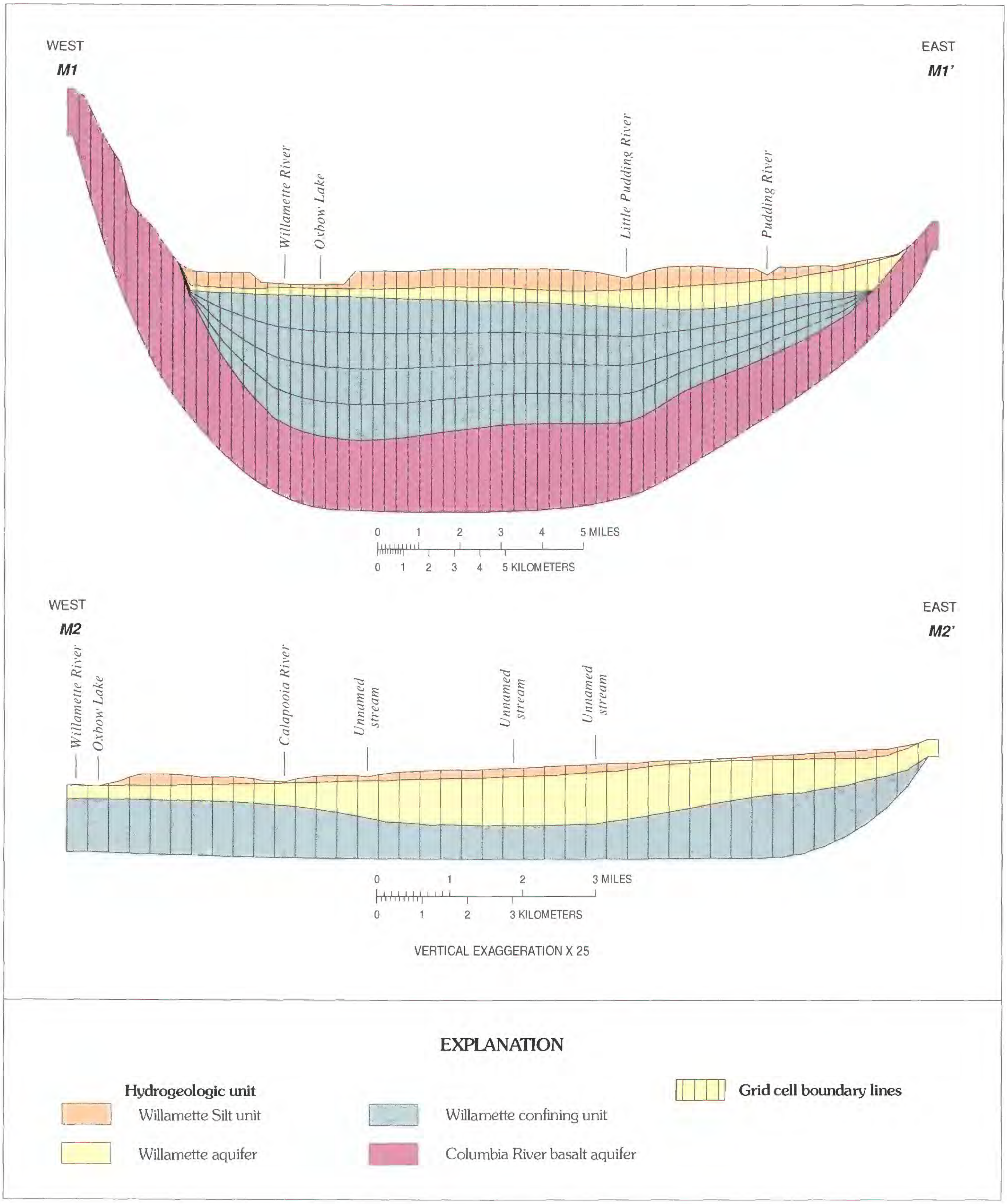


FIGURE 20.—Grids and layers for cross-sectional ground-water flow models.

TABLE 6.—*Information on model grid systems*

Model Characteristic	Section [1]	
	M1-M1′	M2-M2′
Length (miles)	21	12
Number of layers	7	3
Column width (feet)	1,500	1,500
Number of columns	74	42
Minimum active cell thickness (feet)	5	6
Maximum active cell thickness (feet)	440	180
Number of drain cells	17	9

[1] Model grid system shown on figure 20.

These basement confining unit contacts were modeled as no-flow boundaries. The western end of section M2-M2′ is bounded by the Willamette River. Because there is often vertical, or nearly vertical flow directly beneath major streams, this boundary was assumed to be a flow line and, therefore, a no-flow boundary. Because the model sections generally parallel ground-water flow paths, the sides of the models approximate flow lines and were represented as no-flow boundaries.

The evapotranspiration package of the flow model was used to simulate ground-water discharge by evapotranspiration because ground-water levels are near land surface over large parts of both sections. The parameters required by the package are the maximum evapotranspiration rate and extinction depth. These parameters were assumed to be uniform across both sections and were estimated assuming that the dominant land cover is grass (grown for seed), grain, pasture, or some combination of the three. The maximum evapotranspiration rate (18 in/yr) was estimated as the portion of crop-water requirements (30 in/yr) not satisfied by available precipitation. Available precipitation (12 in/yr) is the total precipitation (45 in/yr) minus the quantity lost to runoff (15 in/yr) and deep percolation (18 in/yr). Runoff estimates were from Oster (1968), and crop-water requirements were obtained from Cuenca and others (1992). The extinction depth was assumed to be approximately equal to the maximum rooting depth for the dominant crop types; the value used in the models was 5 ft.

Several streams traverse each model section and were modeled using the drain package of the model, as opposed to the river package. Both packages represent head-dependent flux boundaries; however, with the river package, water can move into or out of the aquifer depending on the head relation. With the drain package, water is allowed only to move out of the aquifer to the drain. In both cross-sectional models, most of the streams gain water from the aquifer. The only streams that did not receive water from the aquifer were small intermittent drainages. Because it is unlikely that these small intermittent streams would be flowing without ground-water inflow, they were modeled as drains to prevent them from providing water to the aquifer. Although the drain package was used to simulate the streams, the term "stream" will be used to describe them in the remainder of this discussion. Streams were placed in the Willamette Silt unit (layer 1) or, if the silt was absent due to erosion, in the Willamette aquifer (layer 2). Information on streams in both models is given in table 7. Stream elevations and channel widths were estimated from 1:24,000-scale topographic maps.

HYDRAULIC CHARACTERISTICS

The horizontal hydraulic conductivity of the hydrogeologic units (table 8) was initially estimated on the basis of information from a number of sources. The hydraulic conductivity of the Willamette Silt unit was based on values presented by Price (1967a) and on published values for similar materials (Bureau of Reclamation, 1985; Driscoll, 1986). Hydraulic conductivity estimates for the Willamette aquifer were based on analysis of specific-capacity data from well logs and published values for similar materials. Conductivity values derived from ground-water flow modeling of the Portland Basin (Morgan and McFarland, 1996) were used to estimate the conductivity of the Willamette confining unit, as well as the vertical anisotropy in the entire basin-fill section. The horizontal hydraulic conductivity and vertical anisotropy of the Columbia River basalt aquifer was estimated on the basis of the results of Morgan and McFarland (1996), Hansen and others (1994), and analysis of specific-capacity data from well logs. In calculating the initial streambed hydraulic conductances, it was assumed that streambed properties were the same as the hydraulic properties of the cell containing the stream node.

In general, the estimated hydraulic characteristics for the Willamette Silt unit, 1 ft/d horizontal hydraulic conductivity and 0.01 ft/d vertical hydraulic conductivity, produced satisfactory modeling results (table 8). With the exception of the vertical conductances beneath streams, changing these parameters did not dramatically change model results. In order to reduce calculated heads in the silt unit and the underlying Willamette aquifer adjacent to major streams, it was necessary to increase vertical conductances between the silt and the underlying aquifer in cells with streams by about one order of magnitude.

TABLE 7.—*Stream locations, properties, and discharge rates for cross-sectional flow models*

[ft, feet; ft²/d, square feet per day; ft³/d, cubic feet per day]

Name	Layer	Column	Altitude (ft)	Conductance (ft^2/d)	Discharge (ft^3/d)
		Section M1-M1′			
Unnamed	7	1	1,000	0.063	0
Unnamed	7	4	780	.093	0
Unnamed	7	6	450	.097	0
Unnamed	7	7	400	.085	0
Unnamed	1	13	165	.00571	0
Unnamed	1	14	165	.00571	0
Willamette River	2	19	95	120.00	65.3
Oxbow Lake	2	22	90	30.00	95.7
Patterson Creek	1	29	128	1.00	7.3
Unnamed	1	37	180	.0125	0
Little Pudding River	1	48	138	25.00	58.7
Woods Creek	1	50	148	1.50	6.9
Unnamed	1	51	185	.0111	0
Unnamed	1	56	148	.75	7.9
Pudding River	1	60	145	25.00	100.8
Unnamed	1	63	191	.025	0
Unnamed	7	73	287	.0025	3.5
		Section M2-M2′			
Willamette River	2	1	193	35.71	16.0
Oxbow Lake	2	2	193	28.57	31.8
Calapoola River	2	11	209	33.33	67.3
Unnamed	2	15	218	4.00	37.6
Unnamed	1	22	245	6.00	10.1
Unnamed	1	26	257	10.00	19.5
Unnamed	1	34	282	2.50	3.8
Unnamed	1	35	288	0	0
Unnamed	1	39	303	.09	0

TABLE 8.—*Hydraulic characteristics used in models*

Hydrogeologic unit	Initial estimate, (in feet per day)		Final estimate, (in feet per day)	
	Horizontal conductivity	Vertical conductivity	Horizontal conductivity	Vertical conductivity
Willamette Silt	1	0.01	1	0.01
Willamette aquifer	200	2	200–600	2
Willamette confining unit	5	.05	5	.1
Columbia River basalt aquifer	5	.017	2.5	.025

The physical basis for increasing conductances beneath streams is explained in the discussion on streambed conductance adjustments later in this section.

The initial estimates of the hydraulic characteristics of the Willamette aquifer, a horizontal hydraulic conductivity of 200 ft/d and a vertical conductivity of 2 ft/d, gave satisfactory results. Overall, changing these parameters did not have a large effect on the simulated flow system. This may be because of the large contrast between the hydraulic properties of the aquifer and the adjacent units. Increasing the horizontal hydraulic conductivity of the Willamette aquifer to 600 ft/d beneath the Willamette River flood plain improved the fit between simulated and observed heads in the Willamette Silt unit adjacent to the flood plain. This was a reasonable adjustment because specific-capacity data (table 4) indicate that hydraulic conductivities of the aquifer gravels in the flood plain are substantially larger than elsewhere, presumably because of reworking by stream action (see previous discussion in the "Hydraulic Characteristics" section of report).

The initial estimate of horizontal hydraulic conductivity for the Willamette confining unit, 5 ft/d, gave reasonable results and was not changed. Although the initial vertical hydraulic conductivity of 0.05 ft/d was doubled to reduce vertical gradients, water-level data from wells suggest that vertical gradients generally are small in the Willamette Lowland. The vertical hydraulic conductivity of the Willamette confining unit, which separates the Columbia River basalt aquifer from the Willamette aquifer in section M1-M1′, was found to have a significant influence on vertical gradients between the Columbia River basalt aquifer and the Willamette aquifer.

The initial estimates of horizontal and vertical hydraulic conductivity of the Columbia River basalt aquifer, 5 ft/d and 0.017 ft/d, respectively, had to be adjusted to match simulated and observed heads. With the original values, excessive upward vertical gradients were simulated beneath the center of the basin—simulated heads in the Columbia River basalt aquifer were more than 100 ft above land surface. As described and shown previously (fig. 19), flowing artesian wells are uncommon in the Columbia River basalt aquifer except near the margins of the basalt uplands. Most of the simulated large, upward gradients were reduced by decreasing the horizontal hydraulic conductivity in the basalt by a factor of 2, increasing the vertical conductivity of the basalt from 0.017 ft/d to 0.025 ft/d, and increasing the vertical conductivity of the overlying Willamette confining unit as mentioned previously.

Satisfactory model results were obtained only after selectively increasing conductances of streambeds in the silt by up to 50 times the initial estimates. Large conductance values are considered reasonable because of the range in streambed materials and because of the reworking and sorting of streambed materials by stream action after their deposition by glacial-outburst floods, thereby increasing their hydraulic conductivity. As mentioned previously, this latter process has certainly occurred in the Willamette aquifer along the Willamette River flood plain and has probably occurred in other units as well.

Estimates of hydraulic characteristics of the hydrogeologic units were adjusted to match the simulated and observed heads and discharge quantities in both models. Because of the limited ability of cross-sectional models to simulate a three-dimensional flow system and the general lack of field measurements, the models were not rigorously calibrated. However, the simulated heads and discharge quantities are reasonable given the available data. The water-table surface shown on plate 1 represents water levels at their lowest annual altitude. Water levels fluctuate 5 to 20 ft/yr in the area of section M1-M1′ (Price, 1967a) and 2 to 14 ft/yr in the vicinity of section M2-M2′ (Frank, 1974; Helm and Leonard, 1977); these fluctuations were described previously in the "Water-Level Fluctuations" section. Water levels simulated by the steady-state models represent average annual water-level altitudes and should be higher than the altitude shown on plate 1, but within the range of observed seasonal fluctuations. With the exception of a few cells in both models, simulated heads in the top active model layers were above the altitudes on plate 1, within the observed range of seasonal fluctuations, and below ground level. Simulated heads in the non-water table model layers were consistent with what is known about vertical head differences and hydraulic gradients in the area.

Simulated ground-water discharge to streams was compared to estimates from Price (1967a) and from Laenen and Risley (1997), whose information is described more thoroughly in the "Discharge" section later in this report. Discharge quantities were only available for the Willamette River in both model sections and for the Pudding River in section M1-M1′. Laenen and Risley (1997) found that ground-water discharge to the Willamette River was highly seasonal. Seepage measurements during the summer of 1992 indicated little or no ground-water inflow to the Willamette River main stem. Measurements during the spring of 1993, by contrast, indicated that the main stem gained approximately 2,000 ft^3/s between river mile (RM) 55 and 195.

Ground-water discharge to the Willamette River in the vicinity of section M1-M1′ was estimated from seepage measurements made in September 1993 (Laenen and Risley, 1997). The M1-M1′ section crosses the river near RM 72. Ground-water inflow to the river from RM 78.5 to RM 55 was approximately 476 ft^3/s, which equals a discharge of about 331 $ft^3/d/ft$ (cubic feet per day per foot) of river length. Thus, average annual discharge to the river calculated by the 1-ft-wide model should be between 0 and 331 ft^3/d (cubic feet per day). Simulated steady-state discharge to the Willamette River and a hydraulically connected oxbow lake in section M1-M1′ was 161 ft^3/d, which is reasonable.

On the basis of hydrograph analysis, Price (1967a) estimated that ground water discharges to the Pudding River between RM 40.7 and RM 8.2 at a rate of 146,000 acre-ft/yr (acre-feet per year), or an average annual discharge of about 101 $ft^3/d/ft$ of river length. Because the estimate is based on a stream hydrograph, it integrates discharge to the Pudding River as well as its tributaries. In section M1-M1′, which crosses the Pudding River near RM 46, upstream from the section analyzed by Price (1967a), simulated discharge to the Pudding River and its tributaries was about 178 $ft^3/d/ft$. Given the uncertainty in applying Price's (1967a) discharge estimates, this is a reasonable match.

The only discharge estimate available for section M2-M2′ is for the Willamette River and is based on seepage measurements made in June 1993 during high springtime discharge (Laenen and Risley, 1997). Section M2-M2′ crosses the Willamette River near RM 127. Ground-water inflow between RM 119.3 and RM 141.7 was estimated to be 931 ft^3/s or about 680 $ft^3/d/ft$ of river length. Because the river is one of the model boundaries and similar ground-water conditions are assumed to exist on both sides of the river, ground-water inflow calculated by the model should be about one-half the estimate or between 0 and 340 ft^3/d. Simulated steady-state discharge to the Willamette River and a hydraulically connected oxbow lake from section M2-M2′ is about 48 ft^3/s. The 340 ft^3/d represents the probable spring peak in ground-water discharge, the simulated average annual value of 48 ft^3/d is considered reasonable. Discharge quantities to all streams are listed in table 7.

Simulated Flow System

The major factors controlling the ground-water flow system are recharge, evapotranspiration, geometry of hydrogeologic units, distribution and magnitude of horizontal and vertical hydraulic conductivity in the units, and locations and properties of streams and their beds. To help visualize the simulated movement of water, the particle-tracking and plotting programs MODPATH and MODPATH-PLOT were used. These programs calculate and plot the paths of imaginary particles of water as they move through the flow system. These paths represent flow lines through the modeled system. Flow lines through both model sections (fig. 21) were plotted by tracing the paths of imaginary water particles from the point where they recharge the ground-water system at the water table to the point where they discharge from the system through streams or evapotranspiration. For the sections shown on figure 21, one particle was started at the water table in the center of each cell and tracked to its discharge location.

Water recharging the Willamette Silt unit moves vertically downward into the Willamette aquifer, where flow is primarily horizontal toward streams, the primary discharge point (fig. 21, section M1-M1′). A small part of the water moving in the Willamette aquifer may move into the underlying Willamette confining unit, where its movement includes a larger vertical component. Water in the Willamette confining unit moves upward and back into the Willamette aquifer near and beneath streams to which the water ultimately discharges. Water in the Columbia River basalt aquifer moves horizontally and downward from recharge areas in uplands toward the central parts of the basin, then upward from the basalt into the overlying units.

The Willamette Silt unit is recharged mainly through infiltration of precipitation (table 9). Most of the water moves into the underlying Willamette aquifer within several hundred feet of where it enters the saturated zone (fig. 21, section M2-M2′). Simulated downward vertical hydraulic gradients between the Willamette Silt unit and the Willamette aquifer in areas away from streams range from approximately 0.014 to 0.15 ft/ft. Horizontal hydraulic gradients within the Willamette Silt unit range from 4×10^{-5} to 0.015 ft/ft. Where the water table is above the rooting depth of plants, some of the water discharges through evapotranspiration. Some water moves upward into the Willamette Silt unit from the underlying Willamette aquifer beneath and adjacent to streams (fig. 21). Streams in the Willamette Silt unit, such as the Pudding and Calapooia Rivers, are principal locations of ground-water discharge. Upward vertical hydraulic gradients beneath these streams range from about 0.017 to 0.13 ft/ft.

Although water enters the Willamette aquifer from both the overlying and the underlying units, most enters it through the overlying Willamette Silt unit (table 9).

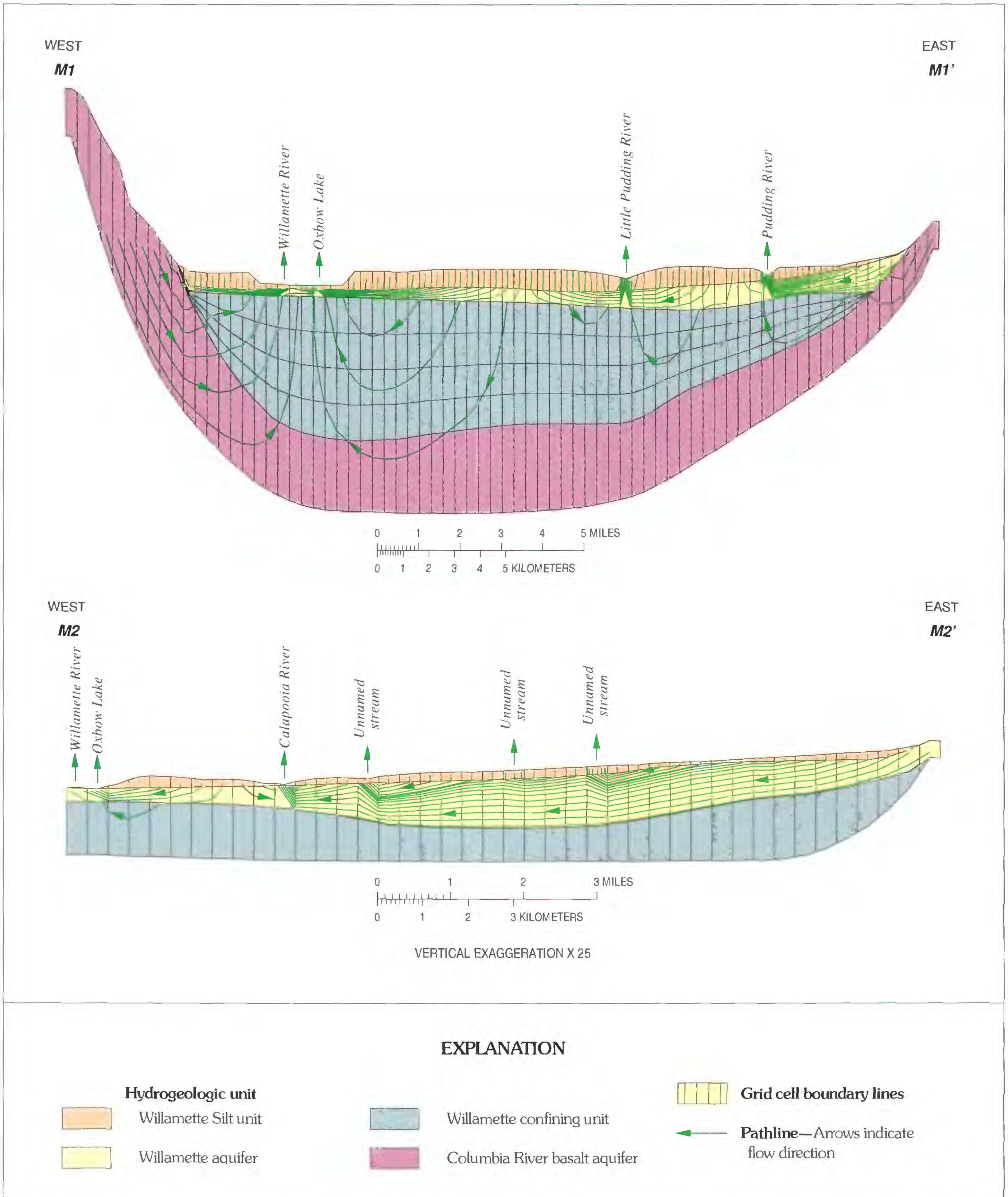


FIGURE 21.—Model grids and layers with pathlines. (The pathlines represent the paths of water particles that start at the water table in the center of the uppermost active cells and travel to their discharge points.)

TABLE 9.—*Flow budgets for cross-sectional models*

[--, not applicable]

Hydrogeologic Unit	Flow from, in cubic feet per day						Flow to, in cubic feet per day						
	Recharge	Willamette Silt	Willamette aquifer	Willamette confining unit	Columbia River basalt aquifer	Total in	Evapotranspiration	Streams	Willamette Silt	Willamette aquifer	Willamete confining unit	Columbia River basalt aquifer	Total out
Section M1-M1′													
Willamette Silt unit	323	--	159	0	0	482	53	182	--	247	0	0	482
Willamette aquifer	32	247	--	69	0	348	1	161	159	--	27	0	348
Willamette confining unit	0	0	27	--	46	73	0	0	0	69	--	4	73
Columbia River basalt aquifer	48	0	0	4	--	52	6	1	0	0	45	--	52
Model net total	403	--	--	--	--	--	60	343	--	--	--	--	403
Section M2-M2′													
Willamette Silt unit	225	--	19	0	--	244	72	33	--	139	0	--	244
Willamette aquifer	46	139	--	6	--	191	13	153	19	--	6	--	191
Willamette confining unit	0	0	6	--	--	6	0	0	0	6	--	--	6
Model net total	271	--	--	--	--	--	85	186	--	--	--	--	271

Water in the Willamette aquifer moves horizontally toward streams and discharges to streams with which it is hydraulically connected. However, some water moves from the Willamette aquifer into the overlying Willamette Silt unit beneath streams to which the silt is hydraulically connected. Although a small volume of water moves into the underlying Willamette confining unit (table 9), most of this water moves back into the Willamette aquifer downgradient. Simulated horizontal hydraulic gradients in the Willamette aquifer range from 5×10^{-5} to 0.006 ft/ft and average about 0.002 ft/ft.

Water moves into the Willamette confining unit from the overlying Willamette aquifer and, when present, from the underlying Columbia River basalt aquifer (table 9). Where the Columbia River basalt unit underlies the confining unit, water from the basalt accounts for most of the flow through the confining unit. Water moving in the confining unit eventually discharges to the Willamette aquifer, usually in the vicinity of major streams.

The Columbia River basalt aquifer is recharged primarily through infiltration of precipitation where the unit is exposed at land surface (table 9; fig. 21, section M1-M1′). The model results indicate that a small volume of water also enters the basalt from the overlying Willamette confining unit. As modeled, no water can enter the basalt from the underlying marine rocks of the basement confining unit because the contact between the units is represented by a no-flow boundary. However, as previously described, locally, some water probably flows from the marine rocks. Some wells drilled deep into the basalt in the Portland and Tualatin Basins encounter saline water that generally is thought to originate in the marine rocks (as will be discussed in the "Water Quality" section). Water discharges from the basalt primarily to the overlying Willamette confining unit.

Calculated Water-budget Components

Water movement in both modeled sections is similar, with a few notable differences. Calculated flow budgets for both models are presented in table 9. In section M1-M1′, stream discharge accounts for 85 percent of the total discharge, and evapotranspiration accounts for 15 percent. In section M2-M2′, stream discharge accounts for 69 percent of the total discharge, and evapotranspiration accounts for 31 percent. The larger estimated evapotranspiration in section M2-M2′ is accounted for by the flatter topography in this section, which results in a generally higher water table.

Flow budgets within the Willamette Silt unit are slightly different for the two modeled sections. Simulations indicate that 80 to 83 percent of the recharge from precipitation occurs in the Willamette Silt unit and the remainder occurs either in the Willamette aquifer or in the Columbia River basalt aquifer. These percentages are a function of the exposed surface areas of the units and input recharge rates. Of the water entering the Willamette Silt unit through recharge in section M1-M1′, approximately 76 percent discharges to the Willamette aquifer, 16 percent discharges to evapotranspiration, and 8 percent discharges directly to streams. Of the recharge to the Willamette Silt unit in section M2-M2′, approximately 62 percent discharges to the Willamette aquifer, 32 percent is discharged by evapotranspiration, and 6 percent discharges to streams. These values again reflect higher evapotranspiration in section M2-M2′.

Flow budgets in the Willamette aquifer also are different for each section. Of the water that enters the Willamette aquifer in section M1-M1′, 71 percent is derived from the Willamette Silt unit, 20 percent comes from the underlying Willamette confining unit, and 9 percent is from recharge. Of the water that enters the Willamette aquifer in section M2-M2′, 73 percent is derived from the Willamette Silt unit, 3 percent comes from the Willamette confining unit, and 24 percent is from recharge. The largest differences between the two sections is the larger amount of water moving upward from the Willamette confining unit in section M1-M1′.

The volume of water moving through the Willamette confining unit depends on the presence or absence of the underlying Columbia River basalt aquifer. In section M2-M2′, where the Columbia River basalt aquifer is absent, the only water moving through the confining unit is water moving downward from the overlying Willamette aquifer; this water eventually moves upward back into that overlying unit. This quantity represents only about 2 percent of the total flow in section M2-M2′ (table 9). In section M1-M1′, water that enters the Columbia River basalt aquifer through recharge in the basalt uplands moves into the overlying Willamette confining unit and eventually discharges to the Willamette aquifer. The quantity of water moving from the basalt represents 62 percent of the total flow in the Willamette confining unit and about 11 percent of the total flow in section M1-M1′ (table 9).

REGIONAL WATER BUDGET

Long-term hydrographs for observation wells completed in the Willamette aquifer confirm that, on a regional basis, the aquifer is in equilibrium—the water table rises each winter/spring to about the same altitude. Therefore, long-term recharge is equal to long-term discharge, and the changes in storage are minimal. However, estimating or quantifying the various components of both ground-water recharge and ground-water discharge can provide a better understanding of the overall hydrology of the aquifer system. For example: (1) how much ground water in the southern Willamette

Valley is being pumped from the Willamette aquifer for agricultural irrigation, (2) how much is discharged to the Willamette River from Eugene to Harrisburg, Oregon, and (3) what is the annual recharge to the Willamette aquifer?

The regional water budget consists of ground-water recharge and discharge. Recharge, as described in the next section, principally is derived from the infiltration of precipitation and is the major factor controlling ground-water availability. Secondary sources of recharge are lateral inflow to the aquifer system and leakage from surface-water bodies (the latter of which is described in the "Discharge" section because of its relation to ground-water discharge). Discharge occurs by leakage to surface-water bodies, by evapotranspiration, and by ground-water pumpage. Depending on the location, some or all these components may compose part of the water budget.

RECHARGE

Water is recharged to the Willamette Lowland aquifer system primarily through the direct infiltration of precipitation on the lowland and also by (1) lateral inflow from alluvial aquifers associated with stream valleys outside the study area, (2) subsurface inflow from the adjacent basement confining unit along the periphery of the lowland, (3) seepage from streams and reservoirs during periods of high stage, (4) irrigation return flow, and (5) runoff into drywells and from on-site waste-disposal systems.

Estimates of ground-water recharge have been calculated for many of the areal ground-water studies conducted in the Willamette Lowland—the Portland Basin by Snyder and others (1994), the Tualatin Basin by Hart and Newcomb (1965), the French Prairie area by Price (1967a), the Molalla-Salem Slope area by Hampton (1972), the Dallas-Monmouth area by Gonthier (1983), the Corvallis-Albany area by Frank (1974), the Harrisburg-Halsey area by Frank (1976), and the Eugene-Springfield area by Frank (1973). Additionally, Foxworthy (1970) estimated that the natural recharge to the basalt aquifers (the Columbia River basalt aquifer) of the Salem Hills is derived entirely from local precipitation. All the studies recognized that recharge was predominantly derived from the infiltration and subsequent percolation of precipitation to the water table.

The most widely used method for estimating areal ground-water recharge involves (1) calculating the area of the unconsolidated deposits, (2) determining the average seasonal water-table fluctuation in those deposits, and (3) multiplying the product of the first two values by an estimate of the average specific yield of the deposits. This computation provides the net volume of ground water causing the areal water-table rise. Dividing that volume by the area of the deposits provides a minimum estimate of ground-water recharge from all sources. A different approach was used by Snyder and others (1994), who estimated ground-water recharge in the Portland Basin from precipitation, from runoff into drywells, and from on-site waste-disposal systems. Snyder and others (1994) determined that precipitation contributed about 95 percent of the mean annual recharge by using two techniques conjunctively to estimate recharge from precipitation—a deep percolation model developed by Bauer and Vaccaro (1987) and regression analysis.

Results of these areal recharge calculations suggest that the gross mean annual ground-water recharge in the lowland ranges from 13 to 18 inches (about 33 to 47 percent of the mean annual precipitation, table 10). The results also indicate that recharge in the reworked flood-plain deposits averages about 58 percent of the mean annual precipitation, and recharge in the other deposits in the lowland averages about 42 percent. For this study, estimates of mean annual recharge to the Willamette Lowland aquifer system were derived by using the information presented in table 10 and the results from other investigations.

Four classes of surficial hydrogeologic units were first defined: (1) flood-plain deposits, mainly of the Willamette aquifer, covering 788 mi^2; (2) the remaining part of the Willamette aquifer, the Willamette Silt unit, and the Willamette confining unit, covering 2,316 mi^2; (3) the Columbia River basalt aquifer and the Boring Lava, covering 740 mi^2; and (4) the basement confining unit, covering 1,835 mi^2. The classes do not directly correspond to the extents of the regional hydrogeologic units because the classes include small, generally discontinuous areas that were not defined as part of a particular regional unit. For example, areas of basin-fill deposits that either were not hydraulically connected to the main part of the corresponding regional unit or were situated in the uplands may not have been included as part of the Willamette aquifer or confining unit but were included in one of the first two classes defined above. Similarly, small areas of the Columbia River Basalt Group that were isolated from the rest of the nonbedrock deposits by basement rocks were not included as part of the Columbia River basalt aquifer but were included in class 3 above.

The areal distribution of the mean annual precipitation for the study area was then overlaid on the extent of each of these surficial hydrogeologic units, and a precipitation value was defined for each part of each unit that was between contour lines of equal precipitation. For the flood-plain deposits, 58 percent of the precipitation was assumed to become ground-water recharge; for the remaining parts of the Willamette aquifer, the Willamette Silt unit, and the Willamette confining unit, 42 percent was assumed to become recharge. A linear

TABLE 10.—*Comparison of ground-water recharge estimates for different areas in the Willamette Lowland, Oregon and Washington*

Area[1]	Average annual precipitation (inches)	Average annual recharge (inches)	Average annual recharge, as percent of precipitation
Portland Basin	45	18	40
Tualatin Basin	44	16–17	36–39
Central Willamette Valley			
French Prairie	41	18	44
Molalla-Salem Slope	43	18	42
Southern Willamette Valley			
Dallas-Monmouth	40	13	33
Corvallis-Albany	38	18	47
Flood-plain deposits			60
Other deposits			44
Harrisburg-Halsey	40	17	43
Flood-plain deposits			57
Other deposits			39
Eugene-Springfield	40	13	33

[1] Areas shown on figure 2.

regression equation that relates mean annual precipitation to ground-water recharge to the Columbia River Basalt Group, developed by Bauer and Vaccaro (1990), was used to estimate recharge to the basalt and lava. No estimates of recharge were made for the basement confining unit and areas covered by large surface-water bodies.

The estimates of recharge were then modified in two ways: (1) they were reduced in selected areas to account for the effects of land use and land cover, and (2) the estimates of recharge for the part of the Portland Basin included in the analysis of Snyder and others (1994) were used in place of the estimates derived during this study. To account for land-use and land-cover effects, recharge was set to 0.0 for impervious (urban) areas, reduced by 75 percent for built-up areas, and reduced by 50 percent for residential (high-density) areas. These reductions are the same as those used for the Puget Sound aquifer system during this RASA study (Vaccaro and others, 1998). The areal extent of these three land-cover categories was identified by using digital land-use and land-cover data (U.S. Geological Survey, 1990). The estimates of recharge by Snyder and others (1994) were then substituted for part of the Portland Basin because they were more detailed. These estimates include not only ground-water recharge from precipitation, but also recharge from the runoff to dry wells and from on-site waste-disposal systems; therefore, these estimates include nonzero values for relatively impervious areas and values in built-up and residential areas that are larger than values used for the rest of the study area. Because the Portland Basin includes most of the population and urban centers that overlie the aquifer system, the recharge estimates for the urban, built-up, and residential categories (table 11) are, in the main, representative of the estimates for the Portland Basin.

The results of the analysis (table 11 and fig. 22) show that about 21,346 ft^3/s (51.1 in/yr) of precipitation falls in the study area, of which about 13,186 ft^3/s (46.6 in/yr) falls on the aquifer system (table 11). Of the latter quantity, about 5,462 ft^3/s (19.3 in/yr) is estimated to recharge the aquifer system (table 11). The regional estimate of mean annual recharge is about 42 percent of the mean annual precipitation on the aquifer system and includes a 280 ft^3/s reduction due to land-use and land-cover effects. Excluding recharge derived from sources other than precipitation, recharge varies seasonally from about 0.05 in/month (inches per month) in the summer to about 3 to 6 in/month in the winter. Additionally, annual recharge values exhibit large interannual variations (Snyder and others, 1994). Because most of the low streamflow (during August) in the Willamette River is accounted for by streams entering the lowland, the mean annual recharge helps support base flow from about December through July.

TABLE 11.—*Estimates of mean annual recharge on the basis of mean annual precipitation, generalized surficial geology, and land-use and land-cover categories, Willamette Lowland, Oregon and Washington*

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

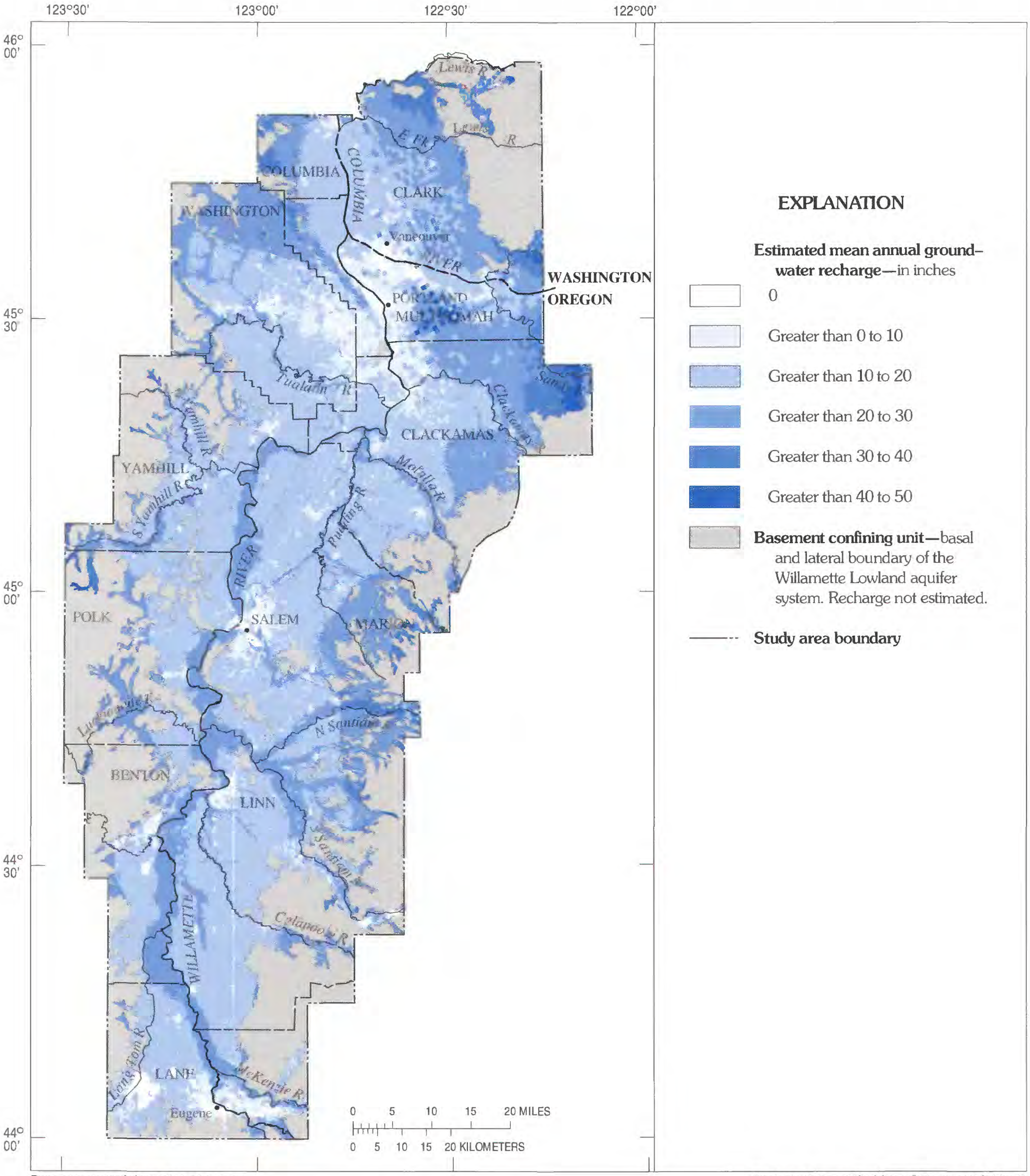
Surficial geology[1]	Land use and land cover	Area (mi^2)	Recharge (in/yr)[2,3]	Precipitation (in/yr)	Recharge (ft^3/s)[2,3]	Precipitation (ft^3/s)
Flood-plain deposits of the Willamette aquifer	Undeveloped and nonbuilt-up	641	24.1	44.2	1,138	2,089
	Residential	13	12.7	43.3	12	42
	Built-up	35	13.3	45.0	34	114
	Urban	99	8.1	43.7	60	319
	All categories	788	21.4	44.2	1,244	2,564
Willamette aquifer (excluding flood-plain deposits), Willamette Silt unit, and the Willamette confining unit	Undeveloped and nonbuilt-up	1,833	19.7	46.0	2,661	6,214
	Residential		28	14.1	44.8	2,992
	Built-up	352	14.5	46.3	376	1,199
	Urban	103	3.6	43.8	27	334
	All categories	2,316	18.1	45.9	3,093	7,839
Columbia River basalt aquifer and Boring Lava	Undeveloped and nonbuilt-up	650	22.0	51.8	1,055	2,480
	Residential	5	12.6	44.6	4	14
	Built-up	76	11.5	46.0	64	259
	Urban	9	3.1	44.3	2	30
	All categories	740	20.7	51.1	1,125	2,783
Subtotal		3,844	19.3	46.6	5,462	13,186
Basement confining unit	Undeveloped and nonbuilt-up	1,780		60.0		7,947
	Residential	3		47.2		9
	Built-up	48		52.5		187
	Urban	4		48.6		17
	All categories	1,835		60.4		8,160
Total		5,679	19.7	51.1	5,462	21,346

[1] Includes small discontinuous areas that were not included as part of the regional hydrogeologic units.
[2] Includes estimates derived by Snyder and others (1994) for the Portland Basin.
[3] Recharge not estimated for basement confining unit or areas covered by large surface-water bodies.

DISCHARGE

Water is discharged from the Willamette Lowland aquifer system primarily by flow to surface-water bodies (streams, reservoirs, and springs) and secondarily by evapotranspiration and pumpage through wells.

Regionally, ground water flows toward streams and is discharged to the streams through springs and seeps. This ground-water discharge fully supports the baseflow of streams that head in the lowland and sustains the flow of the other streams. Discharge measurements were made on the Willamette, McKenzie, and Santiam Rivers to estimate ground-water seepage into and out of the rivers; low-flow measurements were obtained during August and September 1992, and high-flow measurements were obtained during June and September 1993 (Antonius Laenen, U.S. Geological Survey, written commun., 1993). Results of the discharge measurements are shown in table 12. The discharge of tributary inflows and outflows was also measured so that ground-water seepage along specific stream reaches could be estimated.



Basemap source information on page v.

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

FIGURE 22.—Distribution of estimated mean annual ground-water recharge for the Willamette Lowland aquifer system.

TABLE 12.—*Low-flow and high-flow discharge measurements, and seepage quantity and rate for selected Oregon rivers*

[ft^3/s, cubic feet per second; $ft^3/s/mi$, cubic feet per second per mile; -, seepage out of river; +, seepage into river; --, not estimated]

River	Measuring point, in river miles	Measured discharge (ft^3/s)	Seepage (ft^3/s)	4 percent error in discharge (ft^3/s)	Seepage rate ($ft^3/s/mi$)
		LOW-FLOW			
		(Measurements made during August 17–28, 1992)			
Willamette River	195	2,380	--	95	--
	192.8	2,120	-258	85	117.3
	187	2,300	+ 59	92	--
	175	3,490	- 43	140	--
	169.6	3,810	+305	152	56.5
	161	3,770	- 22	151	--
	149.8	3,640	-119	146	--
	141.7	3,580	- 59	143	--
	134.4	3,700	+137	148	--
	120.1	4,206	+497	168	34.8
	119.3	4,220	- 33	169	--
	108.4	4,009	-194	160	17.8
	94.2	5,524	-5	221	--
	84	5,680	+ 95	227	--
	71.7	5,547	-211	222	--
	61.3	5,547	+ 17	222	--
	55	5,358	-179	214	--
		(Measurements made during September 1–3, 1992)			
North Santiam River	28.5	541	--	22	--
	23.5	353	- 62	14	12.4
	14.5	324	+ 11	13	--
	11.7	332	+8	13	--
South Santiam River	7.7	1,124	--	45	--
	3.3	1,005	-126	40	28.6
Santiam River	9.6	1,480	--	59	--
	6	1,382	- 98	55	27.2
	0	1,504	+ 72	60	12.0
		(Measurements made during August 17–28, 1992)			
McKenzie River	47	1,684	--	67	--
	7	1,220	-116	49	2.9

Errors associated with discharge measurements were about 3 percent of the measured discharge and, because upstream reservoirs were periodically releasing water during the August survey period, an additional 1 percent error was assumed in order to account for that variable flow. Additionally, evapotranspiration losses were considered to be 1 $ft^3/s/mi$ (cubic foot per second per mile) along the Willamette River, and these losses were factored into the seepage estimates. Only seepage estimates that exceeded the 4 percent error limit were considered to be credible.

The seepage estimates listed in table 12 indicate that at least three reaches of the Willamette River had significant seepage during the August 1992 low-flow period. From RM 195 to 192.8, the river lost about 258 ft^3/s or 117.3 $ft^3/s/mi$ to the Willamette aquifer; this reach is in a narrow valley incised into bedrock, and the bed sediment probably consists of coarse-grained alluvium. From RM 175 to 169.6, the river gained about 305 ft^3/s or 56.5 $ft^3/s/mi$ from the aquifer; this reach crosses the distal part of the Springfield fan (fig. 13). From RM 134.4 to 120.1, the river gained about 497 ft^3/s or

TABLE 12.—*Low-flow and high-flow discharge measurements, and seepage quantity and rate for selected Oregon rivers—Continued*

River	Measuring point, in river miles	Measured discharge (ft^3/s)	Seepage (ft^3/s)	4 percent error in discharge (ft^3/s)	Seepage rate ($ft^3/s/mi$)
		HIGH-FLOW			
		(Measurements made during June 21–30, 1993)			
Willamette River	195	2,416	--	97	--
	187	2,792	-324	112	40.5
	177.5	2,893	+ 44	116	--
	169	7,168	+328	287	38.6
	166.5	6,169	-998	247	399.2
	161	7,087	+896	253	162.9
	155	6,390	-729	256	121.5
	149.8	7,018	+633	281	121.7
	145	7,215	-183	289	--
	141.7	6,919	-299	277	90.6
	134.4	6,967	+ 21	279	--
	127.5	7,254	+6	290	--
	119.3	7,846	+293	314	--
	114	7,788	- 59	312	--
	108	7,516	-274	301	--
	101	11,563	+957	463	136.7
	94.2	11,589	- 83	464	--
	89	11,670	+170	467	--
	84	11,798	- 40	--	--
		(Measurements made during September 21–22, 1993)			
Willamette River	84	10,470	--	419	--
	78.5	10,345	-207	414	--
	71.7	10,380	+ 66	415	--
	65	10,160	-212	406	--
	61.3	10,510	+330	420	--
	55	10,660	+156	426	--
	51.5	11,160	+423	446	--
	46.5	11,000	-156	440	--
	39	11,470	+475	459	63.3
	31.1	11,090	-538	444	68.1
	28	11,530	+285	--	--

34.8 $ft^3/s/mi$ from the aquifer; this reach runs adjacent to the distal extent of the Lebanon fan and is the terminus of long ground-water flow paths that traverse the southern Willamette Valley (pl. 1).

Five reaches on the other rivers listed in table 12 had significant seepage during the low-flow surveys. Of particular interest is the reach on the North Santiam River from RM 28.5 to 23.5, where about 62 ft^3/s or 12.4 $ft^3/s/mi$ was lost to the Willamette aquifer; this reach traverses the proximal part of the Stayton fan. Thus, the seepage estimates indicate that during low-flow periods, streams crossing the proximal part of the buried alluvial fans lose water to the aquifer, whereas streams crossing the distal part of the fans gain water from the aquifer.

During the June 1993 high-flow period, at least eight reaches of the Willamette River had significant seepage (table 12). From RM 187.0 to 195.0, the river lost about 324 ft^3/s or 40.5 $ft^3/s/mi$ to the Willamette aquifer; this reach also lost water to the aquifer during the low-flow period. From RM 169.0 to 177.5, the river gained about

328 ft^3/s or 38.6 $ft^3/s/mi$ from the aquifer; this reach crosses the distal part of the Springfield fan and also gained water from the aquifer during the low-flow period. The next four significant seepage reaches are contiguous reaches in the southern Willamette Valley, spanning from RM 149.8 to 169.0. From RM 166.5 to 169.0, the river lost about 998 ft^3/s or 399.2 $ft^3/s/mi$ to the Willamette aquifer; from RM 161.0 to 166.5, the river gained about 896 ft^3/s or 162.9 $ft^3/s/mi$ from the aquifer; from RM 155.0 to 161.0, the river lost about 729 ft^3/s or 121.5 $ft^3/s/mi$ to the aquifer; and from RM 149.8 to 155.0, the river gained about 633 ft^3/s or 121.7 $ft^3/s/mi$ from the aquifer. The alternating loss-gain-loss-gain reaches could result from water moving downstream and alternating between surface flow and subsurface flow in the coarse alluvial aquifer associated with the present flood plain. The last significant seepage reach on the Willamette River, from RM 101.0 to 108.0, gained 957 ft^3/s or 136.7 $ft^3/s/mi$ from the aquifer; this reach is immediately downstream from the juncture of the Santiam and the Willamette Rivers, and ground-water underflow associated with the Santiam River probably accounts for most of the discharge gain.

A considerable volume of ground water in the Willamette Lowland is discharged by evapotranspiration from both the soil root zone and the aquifer system in areas where the water table is near the land surface. Evaporative demand is highest in the summer, when the temperature is highest, and transpiration is highest during the crop-growing season. Annual evaporation from class A pans in the Willamette Valley ranges from about 30 to 40 inches. The mean annual class A pan evaporation at the Fern Ridge Reservoir (fig. 1) is 38.30 inches, and about 87 percent of the annual total occurred from April through September (Frank, 1973); the equivalent reservoir-evaporation value (considered to be a factor of 0.70 times the pan evaporation) is 26.83 inches. Potential evapotranspiration in the study area decreases with altitude from about 25 in/yr in the lowland to about 20 in/yr on the upper slopes. By contrast, the estimated evapotranspiration tends to increase slightly with altitude, because increased rainfall allows more moisture to evaporate from the soil. For soils with a 2-inch holding capacity, the estimated evapotranspiration increases from 12 inches in the lowland to 16 inches at higher altitudes, and for soils with a 6-inch holding capacity, evapotranspiration ranges from 15 to 18 inches (Pacific Northwest River Basins Commission, 1970b).

According to Price (1967a), evapotranspiration from all sources in the Willamette Valley, as estimated by the U.S. Army Corps of Engineers, was about 20 in/yr, or about 62.5 percent of the average potential evapotranspiration at Corvallis, Oregon. Price, however, suggested that evapotranspiration in the French Prairie area probably was closer to 22 in/yr, and that along the flood plains of the Willamette River and its major tributaries, evapotranspiration approximated the rate of evaporation from open-water bodies. Snyder and others (1994) estimated annual evapotranspiration in the Portland Basin (excluding evapotranspiration from the ground-water system) to range from about 14 to 20 in/yr. Additionally, on the basis of the results of the cross-sectional ground-water flow models, about 15 to 16 in/yr of evapotranspiration is supported by the aquifer system.

Fresh and abundant water was a major factor in the early development of the Willamette Valley. Historically, ground-water use generally was from shallow, dug wells that were used for domestic and stock purposes in areas distant from streams. Piper (1942) noted that the total withdrawal of ground water during 1928–36 from the southern Willamette Valley was small and that withdrawals from the central Willamette Valley during the same period may have been comparable. The withdrawals were made from numerous rural wells for household use, wells belonging to a few community water systems serving a few thousand people, and wells providing supplemental irrigation of a few thousand acres of land.

Generally, ground-water withdrawals have increased annually as population and other water demands have increased. Agricultural irrigation, originally supplied by surface water, increased slowly in the Willamette Valley—about 1,000 acres were irrigated by 1911, 3,000 acres by 1920, 5,000 acres by 1930, and 27,000 acres by 1940 (Pacific Northwest River Basins Commission, 1971b). However, the growth of irrigation in the valley since World War II has been substantial, particularly irrigation supplied by ground water. In 1965, 243,660 acres were irrigated in the Willamette Valley, and about 101,400 of those acres were irrigated with ground water.

Previous estimates of ground-water withdrawals in the Willamette Lowland were made for each of the areal ground-water studies noted on figure 6. These estimates were aggregated by type of water use for each of the basins (table 13) but, from 1955 to 1975, the accounting period of water use for each study varied. The aggregated total ground-water withdrawal for this timespan (323,380 acre-ft/yr) is similar to Foxworthy's (1979) estimate of 1970 ground-water pumpage (380,800 acre-ft) from the Willamette Lowland ground-water system (including most of Clark County, Washington). Some of the difference between the two estimates is because the aggregated withdrawals listed in table 13 for the Portland Basin were estimated for the period 1955–60, but withdrawals for that area had increased by 1970.

TABLE 13.—*Historical ground-water withdrawals in the Willamette Lowland, 1955–75, by area and type of use*

[Withdrawals in acre-feet per year; --, not estimated due to small quantity]

Area[1]	Period of use	Public, domestic supply	Industrial supply	Irrigation supply	Total
Portland Basin	1955–60	17,350	120,000	37,000	174,350
Clark County, Washington	1955	14,650	84,000	9,000	
East Portland	1960	2,700	18,000	28,000	
West-side Portland	1958	--	18,000	--	
Tualatin Basin	1955	1,830	150	1,700	3,680
Central Willamette Valley	1960–75	12,660	2,250	34,500	49,410
North Clackamas County	1972	3,600	--	2,300	
Molalla-Salem Slope	1966	3,100	--	8,600	
French Prairie	1960	2,100	1,100	17,000	
Newberg	1975	2,800	900	1,800	
Eola-Amity Hills	1964	1,060	250	4,800	
Southern Willamette Valley	1967–75	15,880	5,390	74,670	95,940
Dallas-Monmouth	1975	2,030	340	7,170	
Lower Santiam River	1967	3,200	2,000	30,000	
Corvallis-Albany	1971	1,200	2,300	10,500	
Harrisburg-Halsey	1974	1,050	250	13,000	
Eugene-Springfield	1968	8,400	500	14,000	
Total for lowland		47,720	127,790	147,870	323,380

[1] Areas shown on figure 2; except for Clark County, Washington, all areas are located in Oregon.

However, even after allowing for the differences in the period of use, the distribution and quantity of the ground-water withdrawals indicate some patterns. During the 20-year period from the mid-1950's to the mid-1970's (table 13), about 45 percent of the total ground water withdrawn was used for irrigation supplies, about 40 percent was used for industrial supplies, and the remaining 15 percent was used for public, domestic, and stock supplies. About 50 percent of the irrigation withdrawals occurred in the southern Willamette Valley. Geographically, about 54 percent of the total withdrawals occurred in the Portland Basin (where industrial supply was the predominant water use), and about 30 percent occurred in the southern Willamette Valley (where irrigation supply was the predominant water use). The withdrawal of ground water for industrial uses and for the heating and cooling of buildings in downtown Portland, Oregon, has increased greatly since 1955 (Brown, 1963).

Collins and Broad (1996) were the first to systematically quantify the areal distribution of ground-water withdrawals for the entire Willamette Lowland, and their estimates are presented in the following discussion. These 1990 estimates of ground-water withdrawals were aggregated by type of water use (public supply, industrial supply, and irrigation supply) and were distributed throughout the Willamette Lowland on a quarter-township basis (an area of approximately 9 mi^2). Collins and Broad (1996) did not differentiate withdrawals by aquifer; however, the Willamette aquifer is the most widely and extensively used aquifer in the lowland. Generally, the Columbia River basalt aquifer is used extensively only in the Tualatin Basin (where the Willamette aquifer is not present), near the periphery of the central Willamette Valley (where the Willamette aquifer is thin), and in its outcrop area.

Public supply includes ground water pumped by municipal water systems, by nonmunicipal water systems that serve five or more residences (housing developments, apartment complexes, or mobile-home parks), and by private, self-supplied domestic wells. Many of the largest and most populated cities in the Willamette Valley depend on surface-water supplies for municipal water—Portland, Beaverton, Hillsboro, Forest Grove, Oregon City, Lake Oswego, McMinnville, Salem, Corvallis, Albany, and Eugene. However, a total of as many as 48 municipal water systems, with 194 active wells, withdrew about 63,343 acre-ft of ground water during 1990 (87 ft^3/s). About 6,225 acre-ft of ground water was pumped by nonmunicipal water systems, and an estimated 40 acre-ft of water was pumped by private wells for domestic use. Portland has a municipal well field for use as a standby or emergency supply, but did not use this well field during 1990. In 1990, the total withdrawal of ground water for public supply was estimated to be 69,608 acre-ft (96 ft^3/s) (table 14); the distribution of these withdrawals is shown on figure 23. About 56 percent of the ground water used for public supply in 1990 was pumped from the Portland Basin. Of that quantity, the city of Vancouver, Washington, withdrew 23,395 acre-ft of ground water in 1990 (32 ft^3/s) (Collins and Broad, 1996) or about 34 percent of the total public supply.

Industrial supply includes ground water pumped by private wells for manufacturing and processing goods and for commercial uses, such as heating and cooling. Industrial withdrawals, estimated from about 120 wells, totaled 72,154 acre-ft (100 ft^3/s) in 1990 (table 14). About 92 percent of this quantity was withdrawn from the Portland Basin (fig. 24); wood-processing plants and aluminum smelters are the largest industrial ground-water users in the area.

Irrigation supply includes ground water withdrawn for farms, agricultural and horticultural crops, and golf courses. About 8,100 irrigation wells are estimated to be in operation in the Willamette Lowland (Collins and Broad, 1996). A variety of crops is irrigated with either surface water or ground water (and a few with both). In 1990, 194,457 acre-ft (268 ft^3/s) of ground water was withdrawn for irrigation supplies (table 14). More ground water was pumped for irrigation in the central Willamette Valley area than in all the other areas combined (fig. 25).

Throughout the Willamette Lowland, an estimated 336,219 acre-ft (464 ft^3/s) of ground water was withdrawn in 1990 for all uses (table 14). Of that amount, about 37 percent was withdrawn from the central Willamette Valley, 33 percent from the Portland Basin, 27 percent from the southern Willamette Valley, and 3 percent from the Tualatin Basin (fig. 26; table 14). For comparison, this quantity (464 ft^3/s; 1.7 in/yr) is about 4 percent of the mean annual precipitation falling on the aquifer system, about 1 percent of the mean annual flow of the Willamette River, and about 8 percent of the estimate of the mean annual recharge to the aquifer system.

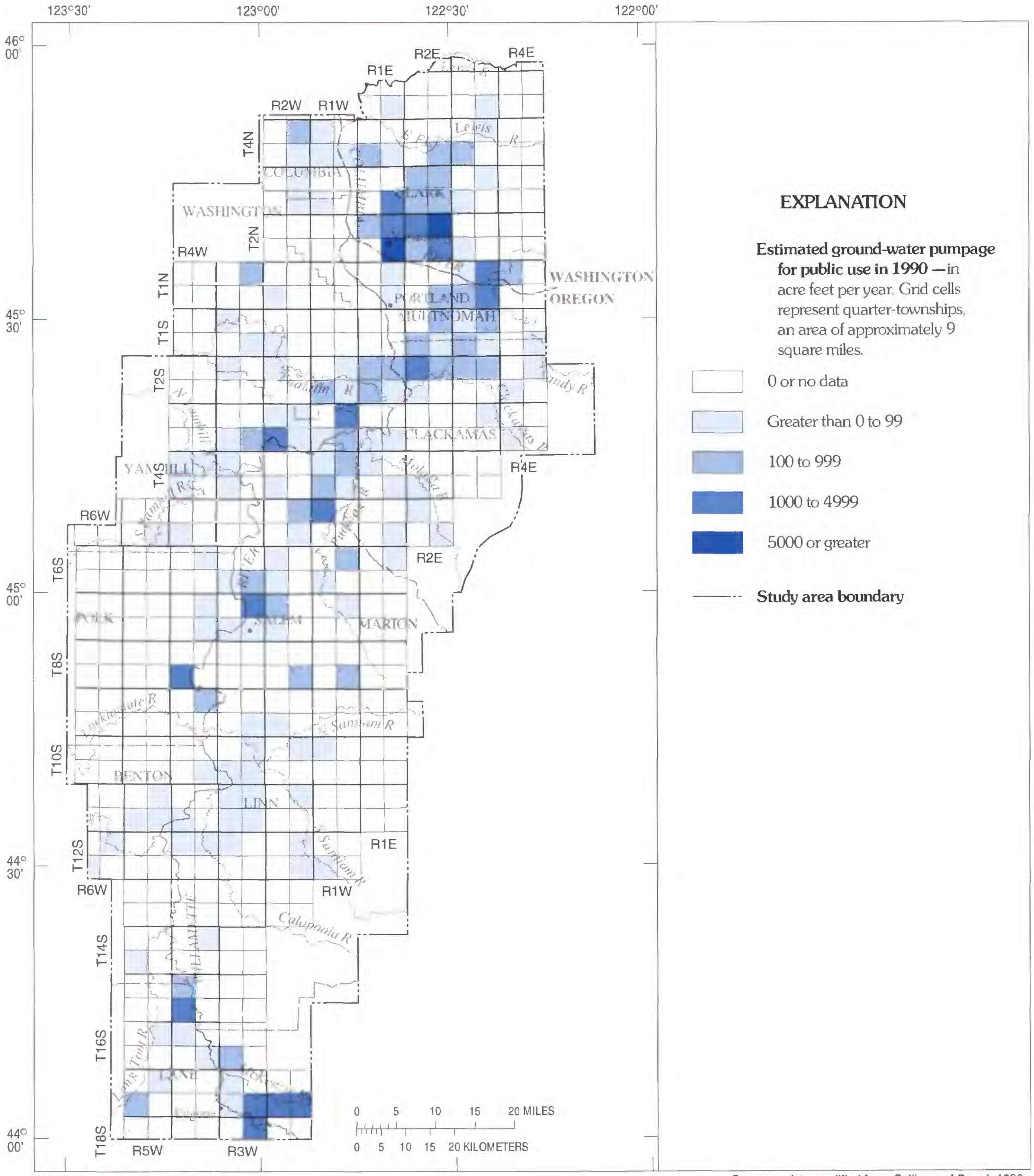
Trends in the quantity, use, and distribution of withdrawals in the last 25 years or more are shown by a comparison of tables 13 and 14. Although estimated total ground-water withdrawals throughout the lowland for the 1955–75 period and for 1990 are about the same, the distribution and use patterns are markedly different.

TABLE 14.—*Ground-water withdrawals in the Willamette Lowland, 1990, by area and type of use (Source: Collins and Broad, 1996)*

[withdrawals in acre-feet per year]

	Type of use			
Area[1]	Public supply	Industrial supply	Irrigation supply	Total
Portland Basin	38,654	66,603	7,032	112,289
Tualatin Basin	3,786	1,119	4,366	9,271
Central Willamette Valley	11,740	3,065	110,140	124,945
Southern Willamette Valley	15,428	1,367	72,919	89,714
Total withdrawals	69,608	72,154	194,457	336,219

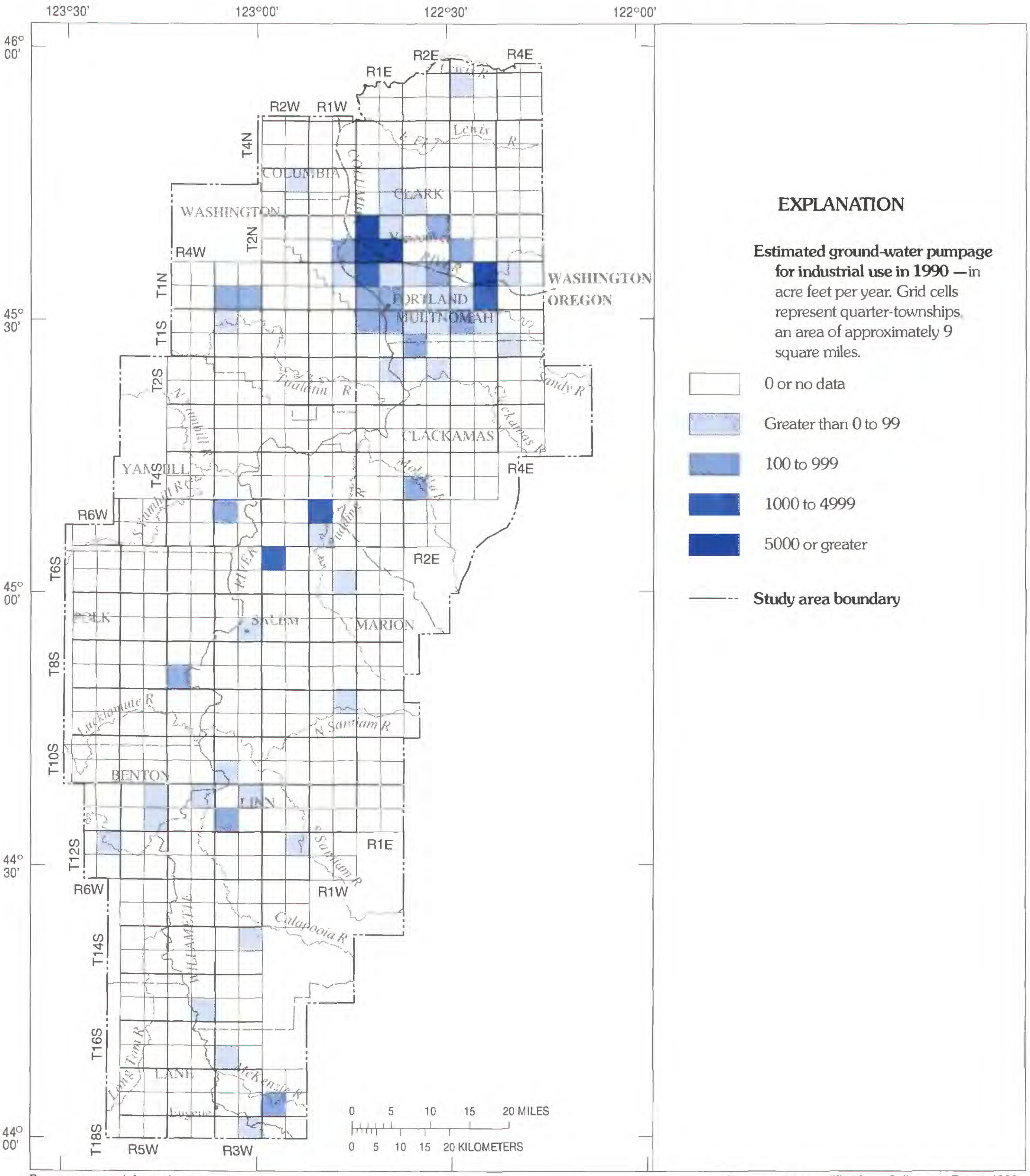
[1]Areas shown on figure 2.



Basemap source information on page v.

Pumpage data modified from Collins and Broad, 1996. USGS Water-Resources Investigations Report 96-4111.

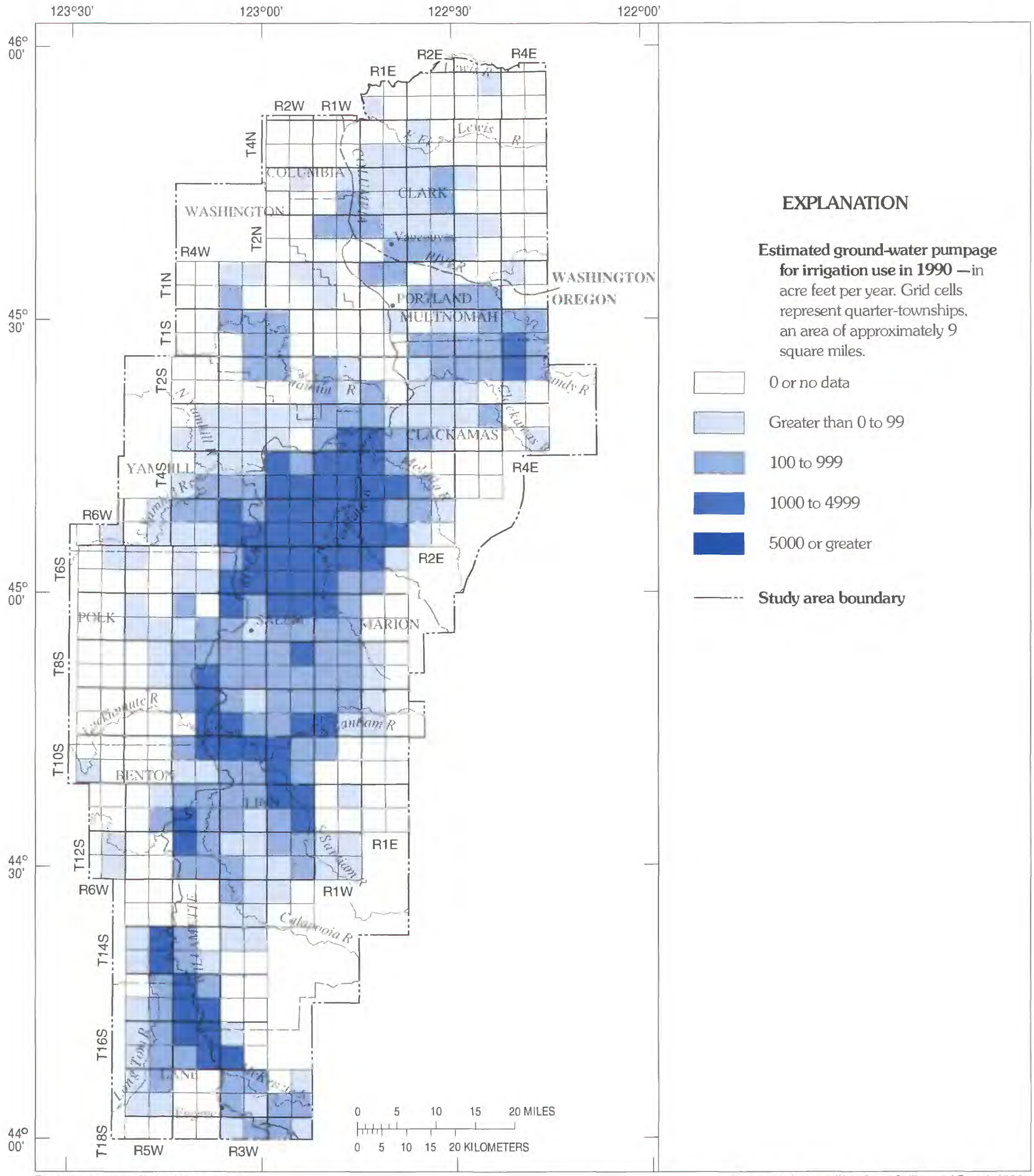
FIGURE 23.—Distribution and quantity of ground water withdrawn for public supply, 1990.



Basemap source information on page v.

Pumpage data modified from Collins and Broad, 1996, USGS Water-Resources Investigations Report 96-4111.

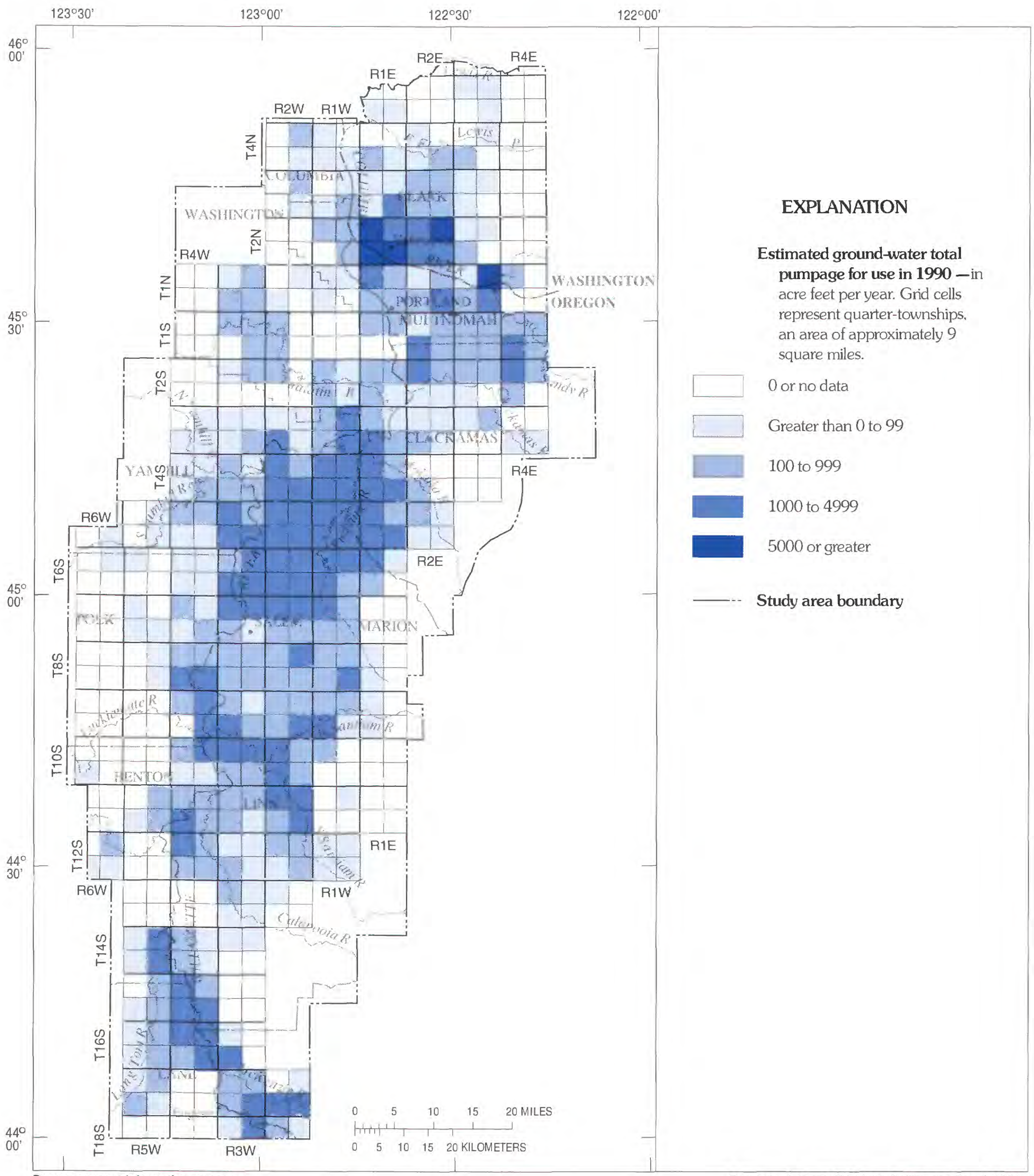
FIGURE 24.—Distribution and quantity of ground water withdrawn for industrial supply, 1990.



Basemap source information on page v.

Pumpage data modified from Collins and Broad, 1996, USGS Water-Resources Investigations Report 96-4111.

FIGURE 25.—Distribution and quantity of ground water withdrawn for irrigation, 1990.



Basemap source information on page v.

Pumpage data modified from Collins and Broad, 1996, USGS Water-Resources Investigations Report 96-4111.

FIGURE 26.—Distribution and total quantity of ground water withdrawn, 1990.

The large increase in population in the Portland Basin in the last 35 years has resulted in the conversion of rural farmland to urban and suburban developments; as a result, public and domestic water use has grown, while irrigation water use has declined. Industrial water use has declined mainly due to the decrease in wood-processing and milling activities. Although total ground-water withdrawals in the Tualatin Basin increased by about 150 percent from 1955 to 1990, only about 3 percent of the total withdrawals in the lowland during 1990 occurred in that basin. In the central Willamette Valley, the acreage of irrigated agriculture has increased markedly in the last 25 years, as has the withdrawal of ground water from an increased number of irrigation wells. As of 1990, almost 57 percent of the total irrigation withdrawals occurred in this part of the lowland (table 14), whereas, in 1975, only about 23 percent of the irrigation withdrawals occurred in the central Willamette Valley (table 13). The use of ground water for irrigation use in the southern Willamette Valley has remained about the same during the last 25 years (tables 13 and 14).

WATER QUALITY

Most of the shallow ground water throughout the Willamette Lowland is of good chemical quality and is suitable for most uses. Abundant recharge from the infiltration of precipitation assures a reliable source of fresh ground water in the shallow permeable deposits. Ground-water-quality problems, however, have been documented throughout the lowland. Most of these problems can be attributed to natural factors. Arsenic-rich ground water in the Fisher Formation in the southwestern part of the southern Willamette Valley (Goldblatt and others, 1963) and the widespread occurrence of saline ground water, primarily from Tertiary marine rocks, are examples of ground water that naturally contains excessive concentrations of undesirable constituents. Numerous, localized cases of anthropogenic contamination of ground water have been noted in the lowland, particularly in the Portland Basin.

The minimum, median, and maximum concentrations or values of selected constituents and properties from 11 snow samples (Laird and others, 1986) and from 314 ground-water samples (previously collected throughout the study area) are listed in table 15. The ground-water samples were aggregated by aquifer unit and general rock type. The low median values for all the constituents and properties from the Willamette and Columbia River basalt aquifers confirm that good-quality ground water exists throughout most of the lowland. The most notable water-quality characteristics shown in table 15 are the high maximum values for concentrations of calcium, sodium, chloride, and dissolved solids in samples collected from the Tertiary marine rocks (and to a lesser extent, from the Columbia River basalt aquifer).

Trilinear (Piper) diagrams of 58 ground-water samples from marine rocks in the lowland show a mixed character, with three major types: a chloride-dominant (chloride exceeds 60 percent of total anions) water type is most prevalent (27 samples), followed by a sodium-bicarbonate type (15 samples), and a calcium-magnesium-bicarbonate type (9 samples) (fig. 27). Potable ground water can be obtained from the Tertiary marine rocks, as evidenced by the chemical analyses from 32 of the 58 samples compiled for this study that had total dissolved solids concentrations of less than 500 mg/L.

Median values of all constituents and properties for the samples from the Columbia River basalt and the Willamette aquifers are similar, although maximum concentrations of calcium, sodium, and chloride are more than 10 times higher in samples from the basalt aquifer, while maximum concentrations of bicarbonate and sulfate are at least 2 times higher in samples from the Willamette aquifer (table 15). On the basis of 75 water samples, ground water in the Columbia River basalt aquifer is predominantly a calcium-magnesium-bicarbonate water type, except for the few previously mentioned samples that were a calcium-sodium-chloride water type (fig. 28). Steinkampf (1989), in his work on the Columbia Plateau RASA study, found that the ground water type in the Columbia River Basalt Group aquifers is primarily calcium-magnesium-bicarbonate and sodium-bicarbonate; the former type was found in upgradient and recharge areas, and the latter type was found downgradient and deeper in the system.

Ground water in the Willamette aquifer generally is chemically homogeneous and is predominantly a calcium-magnesium-bicarbonate type (fig. 29), although a few samples are a chloride-dominant (calcium-magnesium-chloride) water type. The 181 analyses from the Willamette aquifer were grouped by geographic setting for analysis of lateral differences of water chemistry —the east side of the Willamette River versus the west side, the northern part of Willamette Valley versus the southern part, and the peripheral part of the valley versus the central part. However, no geographic differences in the water chemistry of the Willamette aquifer were noted.

The occurrence of saline (chloride-dominant) ground water in the Willamette Valley has caused problems and speculation for many years. Little chloride is introduced to the study area by precipitation, according to the analyses of 11 samples of snow chemistry collected by Laird and others (1986) in the Cascade Range from drainage basins adjacent to the study area.

TABLE 15.—*Statistical summary of water-quality characteristics, Willamette Lowland, Oregon and Washington*

[Concentrations in milligrams per liter unless otherwise indicated; <, less than; --, no data]; µS/cm, microsiemens per centimeter at 25 degrees Celsius]

Statistic and number of analyses[1]	Silica	Iron	Manganese	Calcium	Magnesium	Sodium	Potassium	Bicarbonate	Sulfate	Chloride	Boron	Arsenic	Dissolved solids	Specific conductance (µS/cm)	pH units
Cascade Range snow survey (11 samples analyzed)															
Minimum	--	--	--	0.017	<0.003	<0.01	0.01	--	0.1	0.07	--	--	--	2.38	5.2
Median	--	--	--	.038	.013	.09	.01	--	.12	.22	--	--	--	2.97	5.6
Maximum	--	--	--	.061	.037	.16	.3	--	.16	.4	--	--	--	6.1	5.7
Analyses	--	--	--	11	11	11	--	--	11	--	--	--	--	11	11
Willamette aquifer (181 samples analyzed)															
Minimum	8	0	0	.6	.1	1.1	.2	3	0	0	0	0	15	14	537
Median	42	.05	.01	19.5	9	9	1.6	107	3.1	4.4	.02	0	170	227	7.3
Maximum	68	16	1.9	170	36	170	9.5	418	130	400	.41	.03	800	1,520	9.5
Analyses	181	164	122	181	181	181	181	181	181	181	113	101	191	175	177
Columbia River basalt aquifer (75 samples analyzed)															
Minimum	15	0	0	25	0	4	0	13	0	1	0	0	67	68	6.2
Median	43	.07	0	17	5.3	12	1.3	114	1.8	10	.11	0	182	182	7.5
Maximum	72	16.5	.69	4,290	83	2,350	122	201	64	11,600	1.1	.001	18,500	29,600	9.5
Analyses	75	56	36	75	75	75	75	75	75	75	22	4	75	52	75
Tertiary marine rocks (58 samples analyzed)															
Minimum	4	0	0	1.3	0	32	.1	3	0	1.6	0	0	57	52	4.9
Median	23	.16	.05	24	4.3	115	1.3	133	9	120	.36	0	426	728	7.7
Maximum	56	19	.58	11,500	210	4,060	64	503	500	26,000	2.8	.5	41,800	49,700	9.6
Analyses	58	58	40	58	58	58	58	58	56	58	48	48	56	57	58

[1]Data for ground-water samples compiled from published U.S. Geological Survey reports listed on figure 6, and snow data from Laird and others (1986).

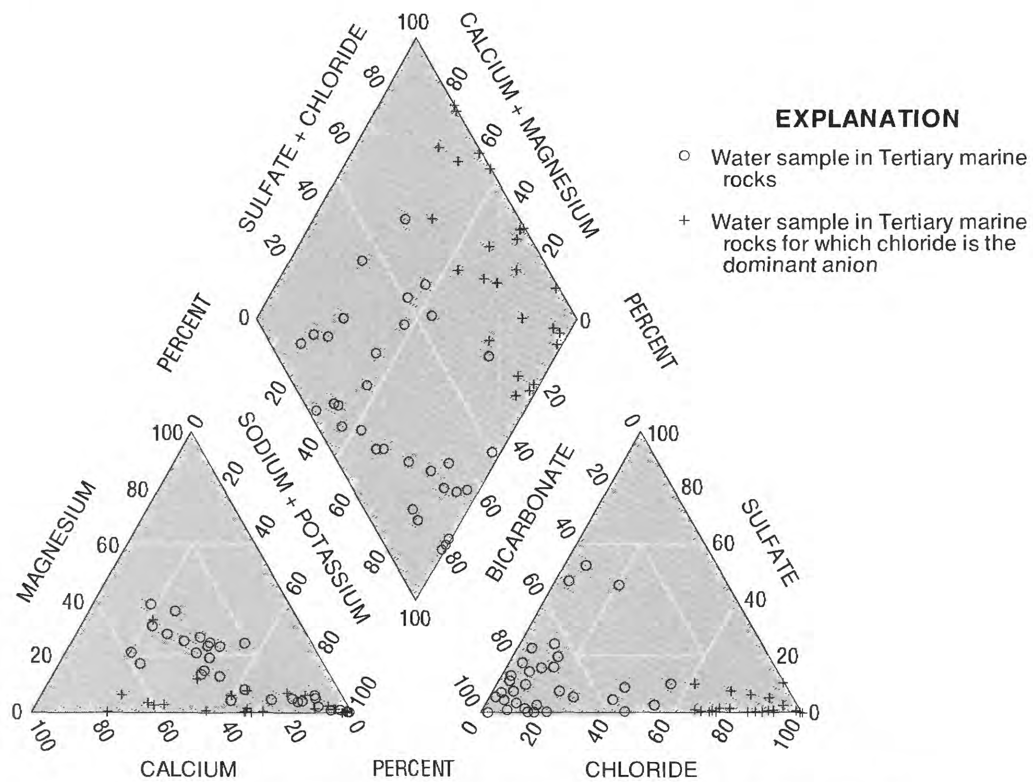


FIGURE 27.—Percentage of major ions in water samples from Tertiary marine rocks.

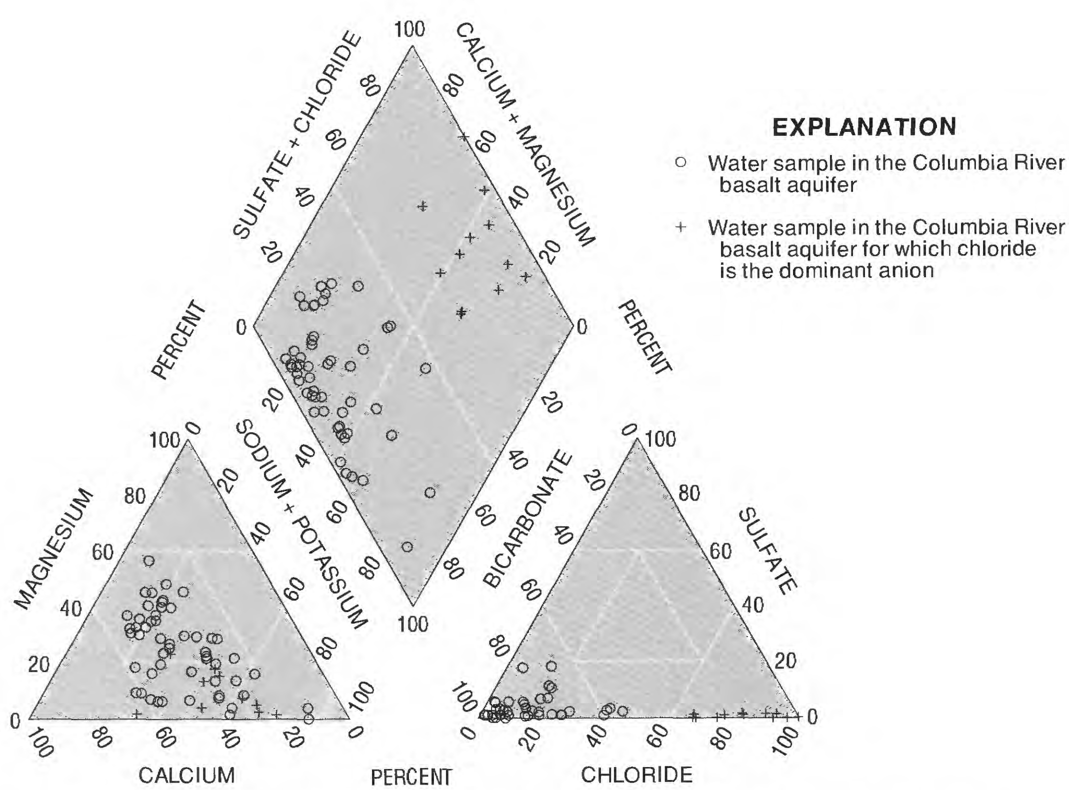


FIGURE 28.—Percentage of major ions in water samples from the Columbia River basalt aquifer.

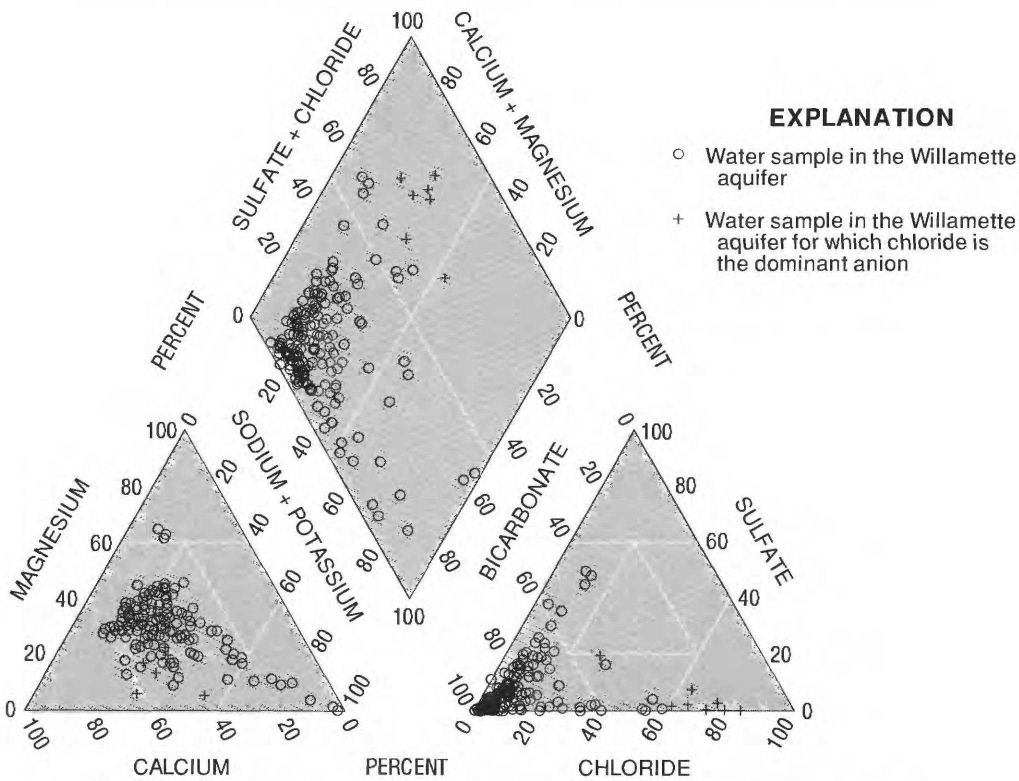
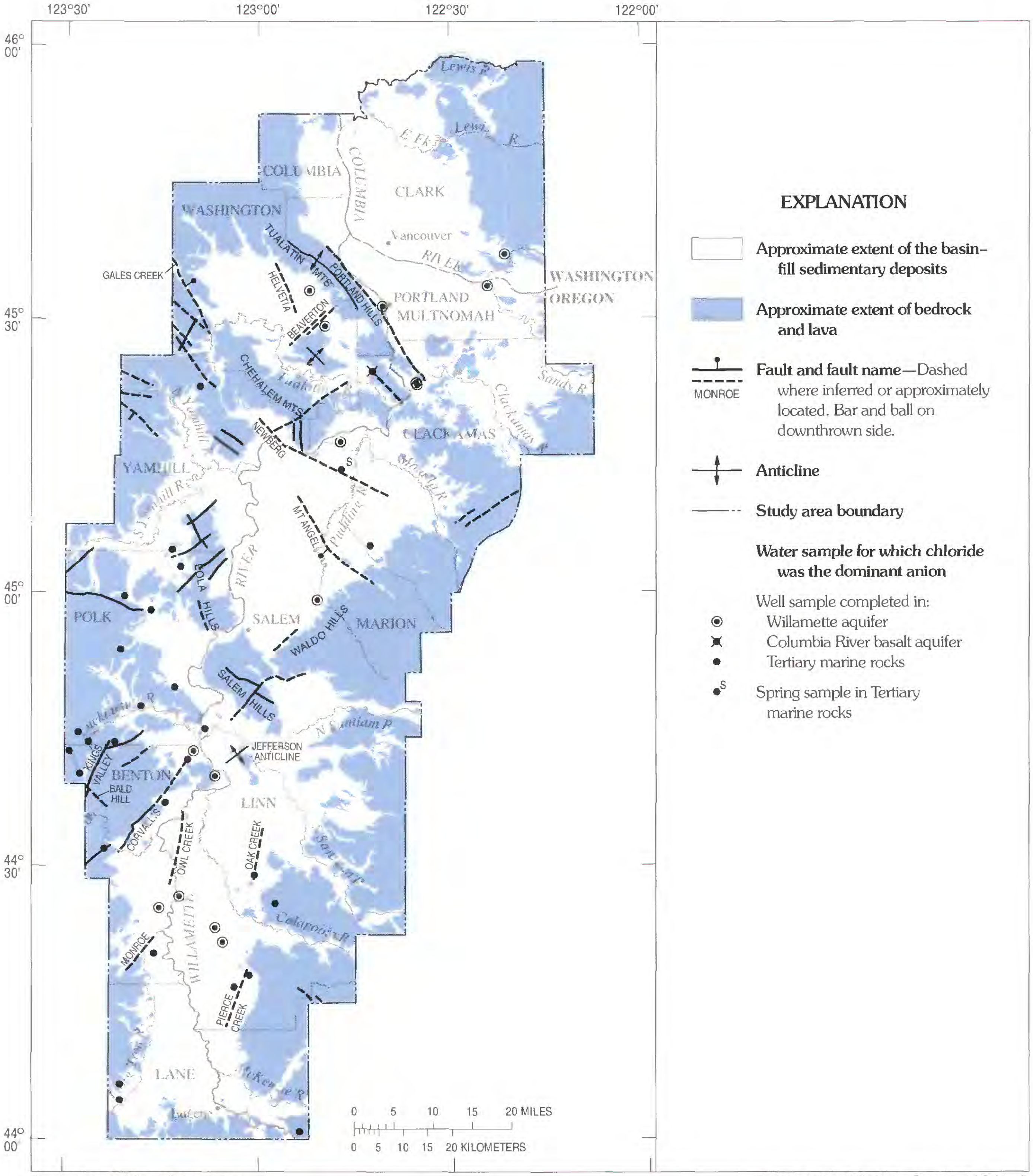


FIGURE 29.—Percentage of major ions in water samples from the Willamette aquifer.

The median chloride concentration was 0.22 mg/L, and the maximum was 0.4 mg/L (table 15). Some chloride could be introduced into shallow ground water by fertilizer and pesticide application or from septic and sewage systems. However, saline ground water in the lowland was noted long before fertilizers and pesticides were applied or septic and sewage systems were used. Halite dissolution and magmatic outgassing also could provide chloride in the subsurface, but no halite deposits are known in the area, and chloride from magmatic outgassing is considered to be negligible in the area. Piper (1942) reported that saline ground water was likely to be found in the Coast Range foothills bordering the western side of the valley or within the sedimentary rocks in the western half of the central lowland.

In order to gain a better understanding of the factors that determine the occurrence of the saline water, more information was compiled for the 42 wells and 1 spring that yielded samples of chloride-rich water (see figs. 27 to 29), and the well locations were plotted on a map showing the traces of known faults in the lowland (fig. 30). Although most of these faults were delineated on the basis of bedrock exposures, and the mapped extent coincides with the bedrock outcrop, it is probable that many of these mapped faults extend beyond the bedrock outcrop and disrupt the bedrock beneath the basin-fill sediments. Information defining the well depth, type of finish (screened, open end, open hole, or perforated casing), and depth of the open interval was compiled for each of the 42 wells and 1 spring (table 16), along with any association of the well and spring location with known or suspected faults.

Chloride-dominant water was found in 27 of the 58 samples from wells in the marine rocks (fig. 27 and table 16); those samples generally were either from deep wells or from wells drilled near major faults (fig. 30 and table 16). In discussing information for 25 wells drilled for petroleum exploration in the lowland, Newton (1969) reported that porous marine sands were found to be saturated with salt water in each of these deep wells, and that all tests made on the marine sands yielded connate water (water trapped in sediments at the time of their deposition). In addition, many of the petroleum test wells drilled in the study area yielded flowing saline water when the marine rocks were penetrated at depth. Thus, saline ground water in the deeper Tertiary marine rocks is confined and in certain locations has a pronounced vertical upward flow.



Basemap source information on page v.

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

FIGURE 30.—Location of wells and a spring that yielded chloride-dominant water samples.

TABLE 16.—*Characteristics of selected wells and a spring that yield chloride-dominant water, Willamette Lowland, Oregon and Washington*

[oe, open end; p, perforated casing; o, open hole; ?, unknown; --, no data]

Well number (township/range-section)	Well depth, in feet	Finish, and open interval, in feet	Remarks
		Willamette aquifer completions	
1N/3E-23B1	183	oe,183	None
10S/4W-10cdb1	37	p,31–37	Near probable extension of Corvallis fault
10S/4W-25ddd1	30	p,23–30	Near crest of the Jefferson anticline
13S/4W-17bac	60	p,53–58	Near eastern bluff of Willamette River flood plain
13S/5W-23dac	51	p,45–47	Near probable extension of Owl Creek fault
14S/3W-7ddc	123	p,35–110	Near crest of the Harrisburg anticline
14S/4W-1aab2	125	p,35–119	Near crest of the Harrisburg anticline
		Columbia River basalt aquifer completions	
2N/4E-31acb	200	?,190–200	None
1N/1E-34cab	690	?,324–690	On Portland Hills fault
1N/2W-24J1	550	?,480–515	Near Helvetia fault
1S/1W-17A2	1,507	o,1100–1507	Near Beaverton fault
2S/1E-8R1	607	o,58–607	Near probable unnamed fault
2S/2E-20F1	692	o,169–692	On Portland Hills fault
2S/2E-20K1	250	--	On Portland Hills fault
3S/1W-27R1	1,004	o,682–1004	Near probable extension of unnamed fault
7S/1W-6R1	225	p,75–225	Near probable extension of unnamed fault
		Tertiary marine rock completions	
2S/4W-23N1	92	--	Near Gales Creek fault
4S/1W-15H2	spring	--	Near unnamed fault
6S/1E-5B1	185	o,175–185	None
6S/4W-6F1	2,985	--	Abandoned oil-test well
6S/4W-17K1	270	o,32–270	Near unnamed suspected fault
7S/5W-6bdd	47	o,19–47	Near Salt Creek
7S/5W-15acc1	129	o,21–129	Near probable extension of unnamed fault
8S/4W-31dda1	122	p,92–122	None
8S/5W-7bbb	97	o,40–97	None
9S/4W-35aa	--	--	Near probable extension of Corvallis fault
9S/5W-16abc	535	o,21–535	Deep completion
9S/6W-31dba	85	o,18–85	None
10S/4W-16dcc	134	p,72–81	Near Corvallis fault
10S/6W-1cac	105	o,42–105	Near Kings Valley fault
10S/6W-5dad2	80	o,20–80	None
10S/6W-30ddb	180	o,55–180	Near probable extension of Bald Hill fault
10S/7W-12dcc	88	o,63–88	Near probable extension of Bald Hill fault
11S/5W-13acb	255	oe,255	Near intersection of Corvallis and Calapooia River faults
12S/3W-35adc2	110	p,84–92	On Oak Creek fault
12S/6W-15aac	605	o,18–605	On Corvallis fault
13S/2W-17cdd	90	--	None
14S/5W-23bcb1	140	--	Adjacent to Oliver Butte
15S/3W-2bbb	200	--	Near Pierce Creek fault
15S/3W-9cba	60	p,48–58	Near Pierce Creek fault
17S/6W-12ddc	124	o,40–124	None
17S/6W-24ddc	233	--	None
18S/2W-11dbc	505	o,20–505	Deep completion

Caldwell (1993) used oxygen-18/oxygen-16 and deuterium/hydrogen isotopic ratios, in conjunction with chloride, bromide, and iodide concentrations ratios, to determine that the source of the chloride-dominant water from selected springs and from deep wells completed in marine rocks was marine connate water. Connate ground water in the deeper Tertiary marine rocks commonly contains concentrations of calcium, sodium, and chloride at least an order of magnitude higher than ground water in the Willamette aquifer or in the shallow part of the Columbia River basalt aquifer (table 15).

In contrast, sodium-bicarbonate and calcium-magnesium-bicarbonate type waters from the marine rocks are found only in relatively shallow (generally less than 100-ft deep) wells drilled on or near the outcrop of the marine rocks. The calcium-magnesium-bicarbonate water type from the shallow marine rocks is quite similar to the same type water found in shallow wells completed in the Columbia River basalt and Willamette aquifers.

The chloride-dominant water in the Columbia River basalt aquifer was found in 9 of the 75 samples compiled for this study (table 16), and most of these samples are associated with either deep wells or wells located on or near major faults (fig. 30 and table 16). Many previous investigations have noted saline water in the basalt and have associated it with faults and fold-induced fractures. Newcomb (1972) reported that the basalt of the Columbia River Basalt Group in the Willamette Valley contained calcium-sodium-chloride waters that are rising into the basalt from underlying sedimentary rocks west of the Cascade Range. Hogenson and Foxworthy (1965) described the geochemistry of water from a deep well (2S/2E-20F1) drilled in the east Portland part of the Portland Basin. The well, which penetrated marine sediments beneath the basalt from 685–692 ft, yielded fresh water from the basalt at a depth of 200 ft, but in the principal water-bearing zone (the lower 10 ft of the basalt, depth of 675–685 ft), the water was too saline to use. Another nearby well (2S/2E-20K1) penetrated fractured basalt and produced saline water, and Hogenson and Foxworthy (1965, p. 45–46) postulated that the fractured rock penetrated by the well "represents a general zone of fracturing that extends across several of the basalt layers and serves as a conduit for the upward-leaking saline water." These wells were drilled adjacent to the Portland Hills fault (fig. 30 and table 16), and the fractured zone is undoubtedly associated with this fault. Where the overlying basalt has been fractured or stretched during folding, it may have more abundant and more open joints and fractures that allow saline water to migrate upward. Brown (1963) noted that in west Portland, the saline water in the sedimentary rocks underlying the basalt was an unusual type, referred to as calcium-sodium chloride water. Nearly all water samples from the belt of strongly folded basalt at the foot of the West Hills have shown some saline water of this type. Hart and Newcomb (1965) reported that in the Tualatin Basin, permeable parts of fault zones could allow some water of poor quality to rise from the older rocks that underlie the basalt.

Chloride-dominant water from the Willamette aquifer was found in 7 samples (table 16), 6 of which were from wells drilled in the southern Willamette Valley. Most of the wells were drilled near probable faults or near the crests of anticlines (fig. 30). Miller and Gonthier (1984) reported that in some areas, saline ground water from underlying marine rocks in the Willamette Valley discharges upward to the overlying basin-fill aquifer, resulting in localized saline water. Caldwell (1993) speculated that a series of saline springs and a deep oil-test well that produced saline ground water from the marine rocks occurred along a northeast-trending fault. The series of perennial springs discharges water near Salt Creek at a rate up to 5 gal/min, with chloride concentrations as high as 27,000 mg/L.

In summary, shallow ground water in the Willamette Lowland generally is of good chemical quality and is suitable for most uses. Saline ground water in the lowland is possibly marine connate water in origin, exists at depth in Tertiary marine rocks, and migrates upward along faults and tight folds. The saline water in the Willamette and Columbia River basalt aquifers, as well as the more dilute chloride-dominant ground-water in shallow marine rocks, generally occurs near faults or folds and results from the mixing of shallow meteoric water with deep formation water brought near the surface along the fault zones.

SUMMARY AND CONCLUSIONS

The Willamette Lowland in Oregon and Washington encompasses about 3,700 square miles and includes the low-lying parts of the Willamette River drainage in Oregon and in most of Clark County, Washington. The Willamette Valley constitutes about 90 percent of the lowland. About 70 percent of the population of Oregon and all of the population of Clark County, Washington, reside in the Willamette Lowland; the burgeoning population is increasing the demand for available water.

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

Most of the 187-mile channel of the Willamette River is braided or meandering and flows through a flood plain that ranges from about 0.5 to 4 miles wide. The lowest flood-plain surface of the Willamette River is underlain by coarse or moderately coarse alluvium. Steep, near-vertical bluffs composed of the Willamette Silt separate the flood-plain surface from the lowland surface; the relief of the bluffs increases in the downstream direction and ranges from about 0 feet near Harrisburg, where the two surfaces merge, to about 80 feet near Wilsonville. Soils in the lowlands generally are silty and sandy and have a subsoil structure that allows rapid infiltration and tends to prevent surface runoff.

Mean monthly precipitation data from selected weather stations in the study area indicate that (1) about 80 percent of the mean annual precipitation falls from October through March, and (2) the mean annual precipitation ranges from about 37 inches near Portland to more than 80 inches along parts of the western and eastern boundary of the study area. The rainy season initiates the high-flow period of November through April for streams (accounting for from 70 to 90 percent of the mean annual discharge).

The mean annual discharge of the Willamette River at Portland is 32,180 cubic feet per second, or about 40 inches per year, from the 11,100-square-mile drainage area. Almost all of the Willamette's discharge is derived from 15 major tributaries. However, discharge of the river does not represent natural runoff because (1) streamflow is regulated by many reservoirs, and (2) many municipal and agricultural irrigation systems divert water.

The major eastern tributaries of the Willamette River (totaling about 60 percent of the Willamette River Basin) drain the Cascade Range and account for about 75 percent of the mean annual discharge of the Willamette Basin. The major western tributaries drain the Coast Range and its foothills and account for about 17 percent of the mean annual discharge. The Coast Fork Willamette River drains the upland south of the Willamette Valley, where the Cascade and Coast Ranges merge, and accounts for about 5 percent of the mean annual discharge.

The differences in magnitude between Coast Range derived discharge and Cascade Range derived discharge are largest during low-flow periods. The mean August discharge of the seven major eastern tributaries below the confluence of the Coast and Middle Forks of the Willamette River is about 25 times larger than that of the six western tributaries. The mean August discharge of the McKenzie River (2,150 cubic feet per second) is about 48 percent of the mean August discharge of all the other tributaries combined (4,510 cubic feet per second); much of the sustained discharge by the McKenzie River during the low-flow period probably is derived from meltwater from glaciers in the drainage basin.

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

The aquifer system in the Willamette Lowland is composed of five hydrogeologic units, from oldest to youngest: (1) the basement confining unit, (2) the Columbia River basalt aquifer, (3) the Willamette confining unit, (4) the Willamette aquifer, and (5) the Willamette Silt unit. The areal extent of the aquifer system is about 3,665 square miles, and the lateral extent of the principal aquifer units is defined by the area underlain by Recent alluvium, Pliocene-to-Pleistocene basin-fill sediments and volcanics, and upper Tertiary volcanics.

The basement confining unit includes all the stratigraphic units that underlie the Columbia River Basalt Group lavas in the northern part of the lowland and the basin-fill deposits in the southern part, and it forms the lateral and basal boundary to the Willamette Lowland aquifer system. The basement confining unit is composed of Tertiary marine sedimentary rocks and Eocene volcanic rocks of the Coast Range, and volcanic rocks of the western Cascade Range.

The Columbia River basalt aquifer overlies the basement confining unit over 2,500 square miles of the northern part of the Willamette Lowland and consists of accordantly layered basalt flows of the Columbia River Basalt Group. The thickness of the aquifer is typically several hundred feet, but locally it is as much as 1,000 feet thick. The aquifer is overlain by basin-fill deposits over about 1,900 square miles; and it crops out over an area of about 600 square miles in the uplands that separate the southern and the central Willamette Valley, the Portland Basin, and the Tualatin Basin.

The Willamette confining unit covers about 3,100 square miles, crops out over an area of about 225 square miles, and consists primarily of fine-grained distal alluvial-fan and low-gradient stream deposits. The sediment of the Willamette confining unit is commonly described by drillers as blue clay, sandy clay, or shale. The thickness of the Willamette confining unit ranges from 0 to more than 1,600 feet. In the Tualatin

Basin, the upper part of the Willamette confining unit is composed of the Willamette Silt because the intervening Willamette aquifer is absent. The Willamette confining unit overlies the Columbia River basalt aquifer in the northern part of the lowland and overlies the basement confining unit in the southern part.

The Willamette aquifer is the principal aquifer unit in the Willamette Lowland. The unit covers about 2,700 square miles and ranges in thickness from less than 20 to more than 600 feet. The Willamette aquifer is exposed over an area of about 1,640 square miles and consists primarily of coarse-grained proximal alluvial-fan and braided-stream deposits. In the Portland Basin, the Willamette aquifer consists of as much as 600 feet of silt, sand, and gravel. The greatest thicknesses and coarsest materials of the Willamette aquifer outside of the Portland Basin occur in six major alluvial fans that were deposited where major streams from the Cascade Range enter the Willamette Lowland.

The Willamette Silt unit generally is equivalent to the Willamette Silt that was deposited throughout much of the Willamette Lowland by late Pleistocene glacial-outburst floods. The unit extends over about 1,200 square miles and ranges in thickness from 0 to more than 130 feet. Except for the Portland Basin, the flood deposits consist primarily of silt and fine sand of relatively uniform lithology.

The aquifer system in each basin, although hydraulically connected through a series of restrictive water gaps, is distinctive. The Columbia River basalt aquifer underlies most of the Portland Basin. Its upper surface, which forms a deep bowl-like depression, is as deep as 1,600 feet below sea level in the center of the basin. The aquifer is as much as 1,000 feet thick. The Willamette confining unit also underlies most of the Portland Basin and is as much as 1,400 feet thick. The Willamette aquifer in the Portland Basin includes the basin-filling deposits above the Willamette confining unit, and generally ranges in thickness from about 100 feet to 400 feet, but locally is more than 600 feet thick.

In the Tualatin Basin, the Columbia River basalt aquifer and the Willamette confining unit are the only regional hydrogeologic units above the basement confining unit. The Columbia River basalt aquifer underlies the entire basin, is about 1,200 feet below sea level in the center of the basin, and is up to 1,000 feet thick. In the Tualatin Basin, the entire basin-fill section is composed predominantly of silt and clay, with only minor sand and gravel, and has been assigned to the Willamette confining unit. The unit has a maximum thickness of more than 1,400 feet.

All five hydrogeologic units occur in the central Willamette Valley. The Columbia River basalt aquifer underlies the entire central Willamette Valley, except for small areas along the far eastern margin, where it thins out against the underlying basement confining unit. The top of the basalt is as much as 1,600 feet below sea level in the deepest part of the basin. The thickness of the Columbia River basalt aquifer varies throughout the central Willamette Valley, ranging from about 300 feet to as much as 600 feet. A number of faults have been mapped in the central Willamette Valley, some of which offset the aquifer, and numerous other faults have been mapped in the uplands surrounding the basin where the aquifer outcrops. The Willamette confining unit reaches a maximum thickness of 1,600 feet. The Willamette aquifer in the central Willamette Valley ranges in thickness from 0 feet to more than 200 feet and contains three major alluvial fans—the Salem fan, the Molalla fan, and the Canby fan. The Salem fan is from 6 to 8 miles wide and forms a gravel deposit as much as 200 feet thick. In the southern part of the Salem fan, the Willamette confining unit is absent, and the Willamette aquifer directly overlies Columbia River basalt aquifer. The Molalla fan is from 4 to 6 miles wide and forms a gravel deposit as much as 120 feet thick. The Canby fan, in the northern part of the basin just south of the Willamette River gap, is about 2 miles wide and forms a gravel deposit as much as 100 feet thick. The Willamette Silt unit overlies most of the central Willamette Valley. The unit has a maximum thickness of about 130 feet near the center of the basin and generally thins toward the south and near the margins of the basin.

In the southern Willamette Valley, all of the regional hydrogeologic units are present; however, the Columbia River basalt aquifer occurs only in the Stayton Subbasin. The Willamette confining unit overlies the Columbia River basalt aquifer in the Stayton Subbasin and overlies the basement confining unit throughout the rest of the valley, except beneath the heads of the alluvial fans where the confining unit is absent. The Willamette confining unit is thinner in the southern Willamette Valley than elsewhere in the Willamette Lowland, ranging from less than 20 to about 340 feet thick. The Willamette aquifer ranges from less than 20 to as much as 240 feet thick in the southern Willamette Valley and contains three large fans—the Springfield fan, the Lebanon fan, and the Stayton fan. The Springfield fan forms a deposit predominantly of sand and gravel as much as 240 feet thick and 8 to 9 miles wide. The Lebanon fan consists of coarse sediment deposited primarily by the South Santiam River, is about 8 to 10 miles wide, and includes deposits predominantly of sand and gravel as much as 140 feet thick. The Stayton fan is from 6 to 8 miles wide and has a maximum thickness of about 300 feet. The Willamette aquifer is much thinner (averaging only about 20 to 40 feet thick) between the alluvial fans of the southern Willamette Valley than in the central Willamette Valley. The Willamette Silt unit covers most of the southern Willamette Valley; the unit ranges in thickness from 10 to 20 feet and generally thins toward the south.

The regional pattern of horizontal ground-water flow in the Willamette aquifer is largely controlled by the locations of major surface drainages. In turn, the present positions of the drainages in the Willamette Valley are controlled by the locations of the buried alluvial fans that were deposited by high-energy streams where they debouched onto the Willamette Lowland from the Cascade Range. Coarse sands and gravels in the fans were reworked and redeposited by high-energy streams along the distal parts of the fans. The Willamette Silt was deposited in the lowland up to an altitude of about 350 feet above sea level, and it buried some of the coarse fan sediments. The major rivers have eroded through the Willamette Silt down to near their former base level. However, because of the low-energy conditions, these rivers cannot erode significantly into the coarse sediment on the alluvial fans and are "forced," primarily by lateral sidecutting, to occupy channels downgradient of the fans. Thus, the coarse sands and gravels beneath the modern flood plains of the major streams in the lowland are primarily reworked and resorted Pleistocene sediments.

Ground water in the Willamette aquifer generally occurs under unconfined conditions, and the potentiometric surface of the aquifer is the water table. Because much of the lowland is flat-lying and the overlying soils have large infiltration rates, only a small part of the precipitation falling on the lowland contributes directly to surface runoff. Additionally, because about 80 percent of the mean annual precipitation falls during the cold winter months, when evaporative demand is small, only a small part of the precipitation that falls during this period evaporates. Therefore, most of the winter precipitation infiltrates and percolates to the water table, and a regional high in the water table generally occurs during December through March.

The regional water-table map shows an overall pattern of ground-water flow to the major streams, indicating that the base flow of these streams is sustained by ground-water discharge. The hydraulic gradient of the Willamette aquifer ranges from more than 60 feet per mile (0.01 foot per foot) near the western part of the central Willamette Valley to less than 2 feet per mile (0.0004 foot/foot) in the flood plain of the Willamette River north of Salem, Oregon. On the basis of average values of the hydraulic gradient and the hydraulic characteristics of the Willamette aquifer, the velocity of water moving through the aquifer ranges from about 3 to 30 feet per day, which is typical for sand and gravel aquifers.

Ground water in the Columbia River basalt aquifer generally occurs under unconfined conditions near the land surface where the basalt outcrops and becomes more confined with depth. Although water-level data for the Columbia River Basalt aquifer indicate that throughout most of the study area the vertical component of flow is downward, vertical upward flow is apparent in some areas. The transition from vertical downward flow to upward flow in the basalts generally appears to be rather abrupt and occurs near regional discharge areas and near known faults and folds.

Long-term hydrographs for observation wells completed in the Willamette aquifer confirm that, on a regional basis, the aquifer is in equilibrium—the water table rises each winter and spring to about the same altitude. Thus, long-term recharge is equal to long-term discharge. Water is recharged to the Willamette Lowland aquifer system primarily through the direct infiltration of precipitation on the lowland. Previous areal recharge calculations made throughout the study area suggest that the gross, mean annual ground-water recharge in the lowland ranged from 13 to 18 inches, or about 33 and 47 percent of the mean annual precipitation; the calculation results also indicated that recharge in the reworked flood-plain deposits averaged about 58 percent of the mean annual precipitation, and recharge in the other deposits in the lowland averaged about 42 percent.

An analysis of ground-water recharge from precipitation showed that about 21,346 cubic feet per second (51.1 inches per year) of precipitation falls in the study area, of which about 13,186 cubic feet per second (46.6 inches per year) falls on the aquifer system. Of the latter quantity, about 5,462 cubic feet per second (19.3 inches per year) is estimated to recharge the aquifer system. The regional estimate of mean annual recharge is about 42 percent of the mean annual precipitation and includes a 280 cubic feet per second reduction due to land-use and land-cover effects. Excluding recharge derived from sources other than precipitation, recharge varies seasonally from about 0.05 inch per month in the summer to about 3 to 6 inches per month in the winter. Because most of the low streamflow (during August) in the Willamette River is accounted for by streams entering the lowland, the mean annual recharge principally supports base flow from about December through July.

Water is discharged from the Willamette Lowland aquifer system primarily by (1) flow to surface-water bodies (streams, reservoirs, and springs), but also by (2) evapotranspiration, and (3) pumpage through wells. Regionally, ground water flows toward streams and is discharged to the streams through springs and seeps. This ground-water discharge fully supports the base flow of streams that head in the lowland and partially supports the base flow of the other streams. Low-flow discharge measurements were conducted during August through September 1992 on the Willamette, McKenzie, and Santiam Rivers to determine minimum ground-water seepage into and out of the rivers. The low-flow seepage estimates suggest that streams crossing the proximal part of the buried alluvial fans lose water to the aquifer, and streams crossing the distal part of the fans gain water from the aquifer.

A considerable volume of ground water in the Willamette Lowland is discharged by evapotranspiration from both the soil root zone and the aquifer system in areas where the water table is near the land surface. Snyder and others (1994) estimated annual evapotranspiration in the Portland Basin to range from about 14 to 20 inches per year. Additionally, on the basis of the results of the cross-sectional ground-water flow models, about 15 to 16 inches per year of evapotranspiration is supported by the aquifer system.

Numerical models based on a conceptual model of the ground-water flow system described in this report reasonably simulated observed heads and discharge quantities, thereby supporting the proposed conceptual model. Satisfactory simulation results were obtained with only minor adjustments to most initial estimates of hydraulic parameters. The greatest adjustments were to conductances of streambeds in the Willamette Silt unit. The simulations allowed for a generalized quantitative analysis of ground-water flow within the system and provided insight into the relative magnitudes of various boundary fluxes. Simulation results indicate that most ground water discharges from the system to tributary drainages and not to the main stem of the Willamette River, corresponding to the results of Morgan and McFarland (1996) for the Portland Basin. Evapotranspiration may account for up to 32 percent of the ground-water discharge. Most ground-water flow occurs in the Willamette Silt unit and the Willamette aquifer, principally in the upper several tens to few hundred feet of the system. Ground-water movement through the Willamette confining unit, which is greatest where that unit overlies the Columbia River basalt aquifer, accounts for up to 10 percent of the total flow in the system. Water that recharges the basalt through precipitation is discharged mainly to the Willamette confining unit.

Estimates of ground-water withdrawals for 1990 were aggregated by type of water use (public supply, industrial supply, and irrigation supply) and were distributed throughout the Willamette Lowland on a quarter-township basis. Although many of the largest and most populated cities in the Willamette Valley depend on surface-water supplies for municipal water, a total of as many as 48 municipal water systems, with 194 active wells, withdrew as much as 63,343 acre-feet (87 cubic feet per second) of ground water during 1990. About 56 percent of the ground water used for public supply in 1990 was pumped from the Portland Basin. Of that quantity, the city of Vancouver, Washington, withdrew 23,395 acre-feet (32 cubic feet per second) of ground water in 1990 or about 34 percent of the total public supply. Industrial withdrawals, estimated from 120 wells, totaled 72,154 acre-feet (100 cubic feet per second) in 1990, of which about 92 percent was withdrawn from the Portland Basin. Wood-processing plants and aluminum smelters are the largest industrial ground-water users in the area. About 194,457 acre-feet (268 cubic feet per second) of ground water was withdrawn for irrigation supplies in 1990. More ground water was pumped for irrigation in the central Willamette Valley area than in all the other areas combined.

Throughout the Willamette Lowland, an estimated 336,219 acre-ft (464 cubic feet per second) of ground water was withdrawn in 1990 for all uses. About 37 percent of the ground water withdrawn in 1990 was from the central Willamette Valley. For comparison, this quantity is about 4 percent of the mean annual precipitation that falls on the aquifer system, about 1 percent of the mean annual flow of the Willamette River, and about 8 percent of the estimate of the mean annual recharge to the aquifer system.

Most of the shallow ground water throughout the Willamette Lowland is of good chemical quality and is suitable for most uses. Abundant recharge from the infiltration of precipitation assures a reliable source of fresh ground water in the shallow permeable deposits. Trilinear (Piper) diagrams of 58 ground-water samples from marine rocks in the lowland show a mixed character, but a chloride-dominant (chloride exceeds 60 percent of total anions) water type is prevalent (27 samples), followed by a sodium-bicarbonate type (15 samples) and a calcium-magnesium-bicarbonate type (9 samples). Potable ground water can be obtained from the Tertiary marine rocks, as evidenced by the chemical analyses from 32 of the 58 samples compiled for this study that had total dissolved solids concentrations of less than 500 milligrams per liter.

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

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

REFERENCES CITED

Allison, I.S., 1953, Geology of the Albany Quadrangle, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 37, 20 p.

Balster, C.A., and Parsons, R.B., 1968, Geomorphology and soils, Willamette Valley, Oregon: Corvallis, Oregon, Oregon State University, Agricultural Experiment Station Special Report 265, 31 p.

Balster, C.A., and Parsons, R.B., 1969, Late Pleistocene stratigraphy, southern Willamette Valley, Oregon: Northwest Science, v. 43, p. 116–129.

Bartholomew, W.S., and DeBow, Robert, 1970, Ground-water levels, 1967–1968: State of Oregon, Ground Water Report No. 15, 122 p.

Bauer, H.H., and Vaccaro, J.J., 1987, Documentation of a deep percolation model for estimating ground-water recharge: U.S. Geological Survey Open-File Report 86–536, 180 p.

Bauer, H.H., and Vaccaro, J.J., 1990, Estimates of ground-water recharge to the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, for predevelopment and current land-use conditions: U.S. Geological Survey Water-Resources Investigations Report 88–4108, 37 p., 4 pls.

Beeson, M.H., Tolan, T.L., and Madin, I.P., 1989a, Geologic map of the Lake Oswego quadrangle, Clackamas, Multnomah, and Washington Counties, Oregon: Oregon Department of Geology and Mineral Industries Map GMS-59, scale 1:24,000, 1 sheet.

Beeson, M.H., Tolan, T.L., and Anderson, J.L., 1989b, The Columbia River Basalt Group in western Oregon—Geologic structures and other factors that controlled flow emplacement patterns, *in* Reidel, S.P., and Hooper, P.R., eds., Volcanism and tectonism in the Columbia River Flood Basalt Province: Geological Society of America Special Paper 239, p. 223–246.

Beeson, M.H., Tolan, T.L., and Madin, I.P., 1991, Geologic map of the Portland quadrangle, Multnomah and Washington Counties, Oregon, and Clark County, Washington: Oregon Department of Geology and Mineral Industries Geological Map Series GMS-75, scale 1:24,000.

Brown, S.G., 1963, Problems of utilizing ground water in the west-side business district of Portland, Oregon: U.S. Geological Survey Water-Supply Paper 1619–O, 42 p.

Bureau of Reclamation, 1985, Ground Water Manual: Denver, Colorado, United States Government Printing Office, 480 p.

Caldwell, R.R., 1993, Geochemistry, alluvial facies distribution, hydrogeology, and groundwater quality of the Dallas-Monmouth area, Oregon: Portland, Oregon, Portland State University, Department of Geology, Master's Thesis, 198 p.

Collins, C.A., and Broad, T.M., 1993, Estimated average annual ground-water pumpage in the Portland Basin, Oregon-Washington: U.S. Geological Survey Water-Resources Investigations Report 91–4018, 24 p.

——— 1996, Ground-water pumpage in the Willamette Lowland regional aquifer system, Oregon and Washington, 1990: U.S. Geological Survey Water-Resources Investigations Report 96–4111, 27 p.

Cuenca, R.H., Nuss, J.L., Martinez-Cob, Antonio, Katul, G.G., and Gonzalez, J.M., 1992, Oregon crop water use and irrigation requirements: Corvallis, Oregon, Oregon State University, Extension Miscellaneous 8530, 184 p.

Daly, Christopher, and Neilson, R.P., 1992, A continuous topographic approach to modeling the distribution of precipitation in mountainous terrain, *in*, Jones, M.E., and Laenen, Antonius, (eds.), Interdisciplinary Approaches in Hydrology and Hydrogeology: American Institute of Hydrology, p. 437–454.

Davies-Smith, Ann, Bolke, E.L., and Collins, C.A., 1988, Geohydrology and digital simulation of the ground-water flow system in the Umatilla Plateau and Horse Heaven Hills area, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 87–4268, 72 p.

Driscoll, F.G., 1986, Groundwater and wells: St. Paul, Minnesota, Johnson Division, 1089 p.

Foxworthy, B.L., 1970, Hydrologic conditions and artificial recharge through a well in the Salem Heights area of Salem, Oregon: U.S. Geological Survey Water-Supply Paper 1594–F, 56 p.

——— 1979, Summary appraisals of the Nation's ground-water resources—Pacific Northwest region: U.S. Geological Survey Professional Paper 813–S, 39 p.

Foxworthy, B.L., Hogenson, G.M., and Hampton, E.R., 1964, Records of wells and springs, water levels and chemical quality of ground water in the east Portland area, Oregon: State of Oregon, Ground Water Report No. 3, 79 p.

Frank, F.J., 1973, Ground water in the Eugene-Springfield area, southern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 2018, 65 p.

——— 1974, Ground water in the Corvallis-Albany area, central Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 2032, 48 p.

——— 1976, Ground water in the Harrisburg-Halsey area, southern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 2040, 45 p.

Frank, F.J., and Collins, C.A., 1978, Groundwater in the Newberg area, northern Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 27, 77 p.

Frank, F.J., and Johnson, N.A., 1970, Selected ground-water data in the Eugene-Springfield area, southern Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 14, 70 p.

——— 1972, Ground-water data in the Corvallis-Albany area, central Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 17, 46 p.

——— 1975, Ground-water data in the Harrisburg-Halsey area, central Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 22, 48 p.

Friday, John, and Miller, S.J., 1984, Statistical summaries of streamflow data in Oregon, Volume 2. Western Oregon: U.S. Geological Survey Open-File Report 84–454, 250 p.

Gannett, M.W., and Caldwell, R.R., 1998, Geologic framework of the Willamette Lowland aquifer system, Oregon and Washington: U.S. Geological Survey Professional Paper 1424–A, 32 p., 8 pl.

Glenn, J.L., 1965, Late Quaternary sedimentation and geologic history of the North Willamette Valley, Oregon: Corvallis, Oregon, Oregon State University, Geology Department, Ph.D. dissertation, 231 p.

Goldblatt, E.L., Van Denburgh, A.S., and Marsland, R.A., 1963, The unusual and widespread occurrence of arsenic in well waters of Lane County: Eugene, Oregon, Lane County Department of Public Health, 24 p.

Gonthier, J.B., 1983, Groundwater resources of the Dallas–Monmouth area, Polk, Benton, and Marion Counties, Oregon: State of Oregon, Ground Water Report No. 28, 50 p.

Griffin, W.C., Watkins, F.A., Jr., and Swanson, H.A., 1956, Water resources of the Portland, Oregon, and Vancouver, Washington, area: U.S. Geological Survey Circular 372, 45 p.

Gutentag, E.D., and Weeks, J.B., 1980, Water table in the High Plains aquifer in 1978 in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Hydrologic Investigations Atlas HA–642.

Hampton, E.R, 1963, Records of wells, water levels, and chemical quality of ground water in the Salem-Molalla slope area, northern Willamette Valley, Oregon: State of Oregon, Ground Report No. 2, 174 p.

——— 1972, Geology and ground water of the Molalla-Salem Slope area, northern Willamette Valley, Oregon: U.S. Geological Survey Water -Supply Paper 1997, 83 p.

Hansen, A.J., Vaccaro, J.J., and Bauer, H.H., 1994, Ground-water flow simulation of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 91–4187, 81 p., 15 pl.

Harbaugh, A.W., 1990, A computer program for calculating subregional water budgets using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 90–392, 46 p.

Hart, D.H., and Newcomb, R.C., 1965, Ground water of the Tualatin Valley, Oregon: U.S. Geological Survey Water-Supply Paper 1697, 172 p.

Hartford, S.V., and McFarland, W.D., 1989, Lithology, thickness, and extent of hydrogeologic units underlying the east Portland area, Oregon: U.S. Geological Survey Water-Resources Investigations Report 88–4110, 23 p.

Helm, D.C., 1968, Records of wells, water levels, and chemical quality of water in the lower Santiam River Basin, middle Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 13, 186 p.

Helm, D.C., and Leonard, A.R., 1977, Ground-water resources of the lower Santiam River Basin, middle Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 25, 75 p.

Hogenson, G.M., and Foxworthy, B.L., 1965, Ground water in the east Portland area, Oregon: U.S. Geological Survey Water-Supply Paper 1793, 78 p.

Hubbard, L.E, Herrett, T.A., Kraus, R.L., and Kroll, C.G., 1991, Water resources data for Oregon, Water year 1990—Volume 2. Western Oregon: U.S. Geological Survey Water-Data Report OR–90–2, 336 p.

Jones, M.A., in press, Geological framework of the Puget Lowland aquifer system, Washington and Canada: U.S. Geological Survey Professional Paper 1424–C.

Klingeman, P.C., 1973, Indications of streambed degradation in the Willamette Valley: Corvallis, Oregon, Oregon State University, Water Resources Research Institute Report WRRI–21, 99 p.

Klingeman, P.C., and Emmett, W.W., 1982, Gravel bedload transport processes, *in*, Hey, R.D., Bathurst, J.C., and Thorne, C.R., eds., Gravel-bed rivers: New York, John Wiley and Sons Ltd., p. 141–179.

Knopman, D.S., and Hollyday, E.F., 1993, Variation in specific capacity in fractured rocks, Pennsylvania: Ground Water, v. 31, no. 1, p. 135–145.

Laird, L.B., Taylor, H.E., and Lombard, R.E., 1986, Data on snow chemistry of the Cascade-Sierra Nevada Mountains: U.S. Geological Survey Open-File Report 86–81, 25 p.

Laenen, Antonius, and Risley, J.C., 1997, Development and application of a precipitation-runoff and streamflow-routing model for the Willamette River Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 95–4284, 197 p.

Leonard, A.R., and Collins, C.A., 1983, Ground water in the northern part of Clackamas County, Oregon: State of Oregon, Ground Water Report No. 29, 85 p.

Loy, W.G., 1976, The Atlas of Oregon: Eugene, Oregon, University of Oregon, 26 p.

McCarthy, K.A., and Anderson, D.B., 1990, Ground-water data for the Portland Basin, Oregon and Washington: U.S. Geological Survey Open-File Report 90–126, 56 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 14 chapters.

McDowell, P.F., 1991, Quaternary stratigraphy and geomorphic surfaces of the Willamette Valley, Oregon, *in*, Morrison, R.B., ed., Quaternary Nonglacial Geology—Conterminous U.S.—Boulder, Colorado: Geological Society of America, The Geology of North America, v. K–2, p. 156–164.

McFarland, W.D., 1983, Description of aquifer units in western Oregon: U.S. Geological Survey Open-File Report 82–165, 35 p.

McFarland, W.D., and Morgan, D.S., 1996, A description of the ground-water flow system in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Supply Paper 2470–A, 58 p., 7 pl.

Miller, T.L., and Gonthier, J.B., 1984, Oregon ground-water quality and its relation to hydrogeologic factors—a statistical approach: U.S. Geological Survey Water-Resources Investigations Report 84–4242, 88 p.

Morgan, D.S., and McFarland, W.D., 1996, A regional ground-water flow model of the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Supply Paper 2470–B, 77 p. 9 pl.

Morgan, D.S., and Weatherby, D.G., 1992, Bibliography of hydrogeology for the Willamette Valley, Oregon: U.S. Geological Survey Water-Resources Investigations Report 91–473, 138 p.

Mundorff, M.J., 1964, Geology and ground-water conditions of Clark County, Washington, with a description of a major alluvial aquifer along the Columbia River: U.S. Geological Survey Water-Supply Paper 1600, 268 p.

Newcomb, R.C., 1961, Storage of ground water behind subsurface dams in Columbia River Basalt, Washington, Oregon, and Idaho: U.S. Geological Survey Professional Paper 383–A, 15 p.

——— 1965, Geology and ground-water resources of the Walla Walla River Basin, Washington-Oregon: Olympia, Washington, Water-Supply Bulletin 21, Washington State Division of Water Resources, 151 p.

——— 1969, Effect of tectonic structure on the occurrence of ground water in the basalt of the Columbia River Group of The Dalles area, Oregon and Washington: U.S. Geological Survey Professional Paper 383–C, 33 p.

——— 1972, Quality of the ground water in basalt of the Columbia River Group, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Supply Paper 1999–N, 71 p.

Newton, V.C., Jr., 1969, Subsurface geology of the lower Columbia and Willamette Basins, Oregon: State of Oregon Department of Geology and Mineral Industries, Oil and Gas Investigations No. 2, 121 p.

Oster, E.A., 1968, Patterns of runoff in the Willamette Basin, Oregon: U.S. Geological Survey Hydrologic Investigations Atlas HA-274, 1 pl.

Pacific Northwest River Basins Commission, 1970a, Comprehensive framework study of water and related lands, Appendix IV,—Land and mineral resources: Vancouver, Washington, 383 p.

——1970b, Comprehensive framework study of water and related lands, Appendix V, Vol. 2—Water resources: Vancouver, Washington, 1022 p.

——1971a, Comprehensive framework study of water and related lands, Appendix VII—Flood control: Vancouver, Washington, 396 p.

——1971b, Comprehensive framework study of water and related lands, Appendix IX—Irrigation: Vancouver, Washington, 343 p.

——1971c, Comprehensive framework study of water and related lands, Appendix XII—Water quality and pollution control: Vancouver, Washington, 531 p.

Piper, A.M., 1942, Ground-water resources of the Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 890, 194 p.

Pollock, D.W., 1989, Documentations of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89–381, 188 p.

Price, Don, 1961, Records of wells, water levels and chemical quality of ground water in the French Prairie-Mission Bottom area, northern Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 1, 314 p.

——1967a, Geology and water resources in the French Prairie area, northern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 1833, 97 p.

——1967b, Ground water in the Eola-Amity Hills area, northern Willamette Valley, Oregon: U.S. Geological Survey Water-Supply Paper 1847, 66 p.

Price, Don, and Johnson, N.A., 1965, Selected ground-water data in the Eola-Amity Hills area, northern Willamette Valley, Oregon: State of Oregon, Ground Water Report No. 7, 55 p.

Sceva, J.E., and DeBow, Robert, 1966, Ground-water levels, 1965: Salem, State of Oregon, Ground Water Report No. 9, 111 p.

Schlicker, H.G., and Deacon, R.J., 1967, Engineering geology of the Tualatin Valley region, Oregon: Oregon Department of Geology and Mineral Industries Bulletin 60, 51 p.

Snyder, D.T., Morgan, D.S., and McGrath, T.S., 1994, Estimation of ground-water recharge from precipitation, runoff into dry wells, and on-site waste-disposal systems in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 92–4010, 33 p.

Steinkampf, W.C., 1989, Water-quality characteristics of the Columbia Plateau aquifer system, Washington, Oregon, and Idaho: U.S. Geological Survey Water-Resources Investigations Report 87–4242, 37 p.

Sun, R.J., and Johnston, R.H., 1994, Regional aquifer-system analysis program of the U.S. Geological Survey, 1978–1992: U.S. Geological Survey Circular 1099, 126 p.

Swanson, R.D., McFarland, W.D., Gonthier, J.B., and Wilkinson, J.M., 1993, A description of hydrogeologic units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90–4196, 37 p.

Taylor, G.H., 1993, Normal annual precipitation: Oregon State University, Oregon Climate Service, Corvallis, Oregon, map.

Thwaites, R.G., 1904, Original journals of the Lewis and Clark Expedition, 1804–06: New York, Antiquarian Press Ltd., unpaginated.

Trimble, D.E., 1963, Geology of Portland, Oregon and adjacent areas—A study of Tertiary and Quaternary deposits, lateritic weathering profiles, and of Quaternary history of part of the Pacific Northwest: U.S. Geological Survey Bulletin 1119, 119 p.

Turney, G.L., 1990, Quality of ground water in Clark County, Washington, 1988: U.S. Geological Survey Water-Resources Investigations Report 90–4149, 97 p.

U.S. Geological Survey, 1990, Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps—Data Users Guide: Reston, Virginia, U.S. Geological Survey, National Mapping Program, Technical Construction, Data Users Guide 4, 33 p.

U.S. Weather Bureau, 1964, Mean annual precipitation, 1930–57, State of Oregon: Portland, Oregon, U.S. Soil Conservation Service Map M–4161.

——1965, Mean annual precipitation, 1930–57, State of Washington: Portland, Oregon, U.S. Soil Conservation Service Map M–4430.

Vaccaro, J.J., 1992, Plan of study for the Puget-Willamette Lowland regional aquifer-system analysis, western Washington and western Oregon: U.S. Geological Survey Water-Resources Investigations Report 92–4189.

Vaccaro, J.J., Hansen, A.J., and Jones, M.A., 1998, Hydrogeologic framework of the Puget Sound aquifer system, Washington and British Columbia: U.S. Geological Survey Professional Paper 1424–D, 77 p., 1 pl.

Walton, W.C., 1962, Selected analytical methods for well and aquifer evaluation: Illinois State Water Survey Bulletin 49, 81 p.

Werner, K.S., 1990, I. Direction of maximum horizontal compression in western Oregon determined by borehole breakouts, II. Structure and tectonics of the northern Willamette Valley, Oregon: Corvallis, Oregon, Oregon State University, master's thesis, 159 p.

Yeats, R.S., Graven, E.P., Werner, K.S., Goldfinger, Chris, and Popowski, Thomas, 1991, Tectonics of the Willamette Valley, Oregon: U.S. Geological Survey Open-File Report 91–441, 46 p.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1999 — 773-460 / 21002 Region No. 8