Description of the Ground-Water Flow System in the Portland Basin, Oregon and Washington

United States Geological Survey Water-Supply Paper 2470–A

Prepared in cooperation with Oregon Water Resources Department, City of Portland Bureau of Water Works, and Intergovernmental Resources Center of Clark and Skamania Counties

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 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 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's), 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 office:

- **ROLLA, Missouri**—1400 Independence Rd.

Description of the Ground-Water Flow System in the Portland Basin, Oregon and Washington

By WILLIAM D. MCFARLAND and DAVID S. MORGAN

Prepared in cooperation with
Oregon Water Resources Department,
City of Portland Bureau of Water Works, and
Intergovernmental Resource Center

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2470–A

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

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

Library of Congress Cataloging in Publication Data

McFarland, William D.
Description of the ground-water flow system in the Portland Basin, Oregon and Washington / by William D. McFarland and David S. Morgan.
p. cm. — (U.S. Geological Survey water-supply paper : 2470–A)
"Prepared in cooperation with Oregon Water Resources Department, City of Portland Bureau of Water Works, and Intergovernmental Resource Center."
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2470–A
1. Groundwater flow —Oregon—Portland Region. I Morgan, David S. II. Oregon. Water-Resources Dept. III. Portland (Or.) Water Bureau. IV. Intergovernmental Resource Center. V. Title. VI. Series.
GB1197.7.M397 1996 96–35334
551.49´09795´49—dc20 CIP
ISBN 0-607-87039-7

CONTENTS

PLATES

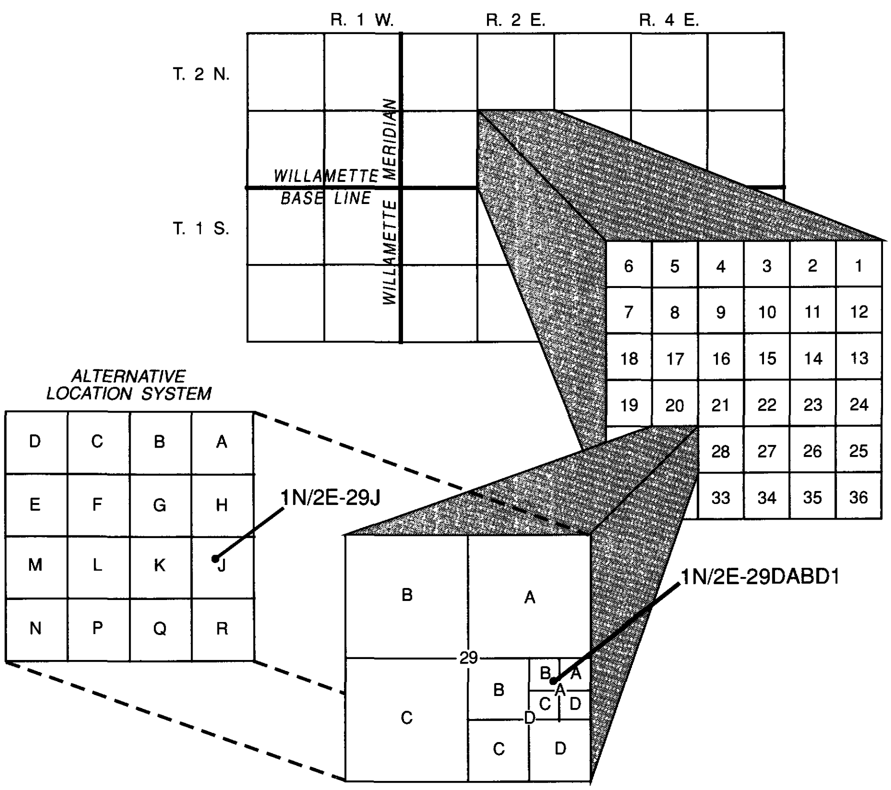
[Plates are in pocket]

FIGURES

TABLES

WELL- AND SPRING-LOCATION SYSTEM

The system used in this report for locating wells and springs is based on the rectangular system for subdivision of public land. The numbers and characters represent successively the township, range, section, and location within the section by quarter section (160) acres), quarter-quarter section (40 acres), quarter-quarter-quarter section (10 acres) and quarter-quarter-quarter-quarter section (2.5 acres). Where necessary, serial numbers are added after the final letter to assure uniqueness of location numbers. An alternative location system, used previously in the State of Oregon and currently in use in the State of Washington, is illustrated below. This system uses a single capital letter to represent the quarter-quarter section (40 acres) in which a well or spring is located.



Description of the Ground-Water Flow System in the Portland Basin, Oregon and Washington

By William D. McFarland *and* David S. Morgan

Abstract

An increasing dependence on ground-water resources in the Portland Basin has made it necessary for State and local governments to evaluate the capability of the ground-water system to meet present and future demands for water. To evaluate this capability, the U.S. Geological Survey, Oregon Water Resources Department, City of Portland Water Bureau, and the Intergovernmental Resource Center engaged in a cooperative hydrogeologic study. This report describes the regional ground-water system and provides a conceptualization of the aquifer system.

The extent, thickness, and boundaries of eight major hydrogeologic units in the basin were mapped. These units include (1) the unconsolidated sedimentary aquifer, (2) the Troutdale gravel aquifer in the Troutdale Formation, (3) confining unit 1, (4) the Troutdale sandstone aquifer in the Troutdale Formation, (5) confining unit 2, (6) the sand and gravel aquifer, and (7) older rocks. The eighth unit is an undifferentiated, fine-grained unit that is mapped where the Troutdale sandstone and sand and gravel aquifers pinch out. In those areas, the contact between confining units 1 and 2 cannot be mapped. Hydraulic-conductivity estimates from aquifer tests and single-well tests indicate that confining unit 1, confining unit 2, and the older rocks have median hydraulic conductivity values of 4, 1, and 0.3 feet per day, respectively. The aquifers have median hydraulic conductivities that range from about 7 to more than 200 feet per day.

Recharge to the ground-water system in the Portland Basin is derived from three sources other than recharge that may occur from streams flowing through the basin: recharge from infiltration of precipitation, runoff to drywells, and on-site waste-disposal systems. Total average yearly recharge from sources other than streams is nearly 1,110,000 acre-feet or about 22 inches.

Water levels in wells in the sedimentary aquifers and seepage measurements for streams indicate that streams are significant discharge areas for the ground-water system. Ground water generally flows from upland areas toward the major streams in the basin, but discharge also occurs from springs. Crystal Springs, located in southeast Portland, are the largest springs in the basin, with a total discharge of more than 5,000 gallons per minute. Springs north of the Columbia River in Washington between Vancouver and Prune Hill discharge about 6,000 gallons per minute.

Withdrawals from wells in the basin also constitute a significant discharge from the ground-water system. In 1988, a total of 120,700 acre-feet of ground water was pumped from the basin for industrial, public-supply, and irrigation uses. Fifty percent of this water was used for industrial purposes, 40 percent for public supply, and 10 percent for irrigation.

Short- and long-term water-level records from wells indicate that the ground-water system may not be in equilibrium in some areas of the basin. Short-term changes indicate that declines may be occurring in southern Clark County, Washington, and Clackamas County, Oregon, at

rates generally ranging from less than 1 to 4 feet per year (1988–89).

INTRODUCTION

Ground water is an important resource for industrial, public-supply, and irrigation use in the Portland Basin. In the Clark County, Washington, part of the basin (fig. 1), water for most use is derived entirely from the ground-water resource. In Columbia, Clackamas, and Multnomah Counties, Oregon, most water for public and industrial use is derived from the city of Portland's Bull Run watershed. For emergency purposes as a backup to the water from the Bull Run watershed, however, the city of Portland uses a well field just east of the city on the south shore of the Columbia River. Although this well field has not been used extensively since its completion in 1986, it can produce more than 100 million gallons per day for an extended period of time if necessary.

Ground water is an abundant resource in the Portland Basin, but managers in both States are concerned about preserving the quantity and quality of the resource. Rapid urban growth in recent years and the associated increased demand for water has resulted in well interference problems, water-level declines, and water-quality problems in the basin. The need for a quantitative understanding of the ground-water flow system to allow for the best management of the resource led to the study described here.

The purpose of this study was threefold: (1) to describe and quantify the ground-water hydrology of the Portland Basin on a regional scale, (2) to quantify the ground-water hydrology to the extent necessary to predict the effects of existing and proposed wells on the basin, and (3) to improve the understanding of the ground-water hydrology to aid in development by the responsible agencies of a regional water-resources allocation plan and in development of a single-well permit process.

This study, begun in January 1987, was initially a cooperative effort between the city of Portland, the Oregon Water Resources Department, and the U.S. Geological Survey, and included the basin only as far north as Salmon Creek (fig. 1) in Clark County, Washington. Shortly thereafter, the Intergovernmental Resource Center, located in Clark County, Washington, became involved in developing a ground-water management plan for Clark County, Washington, and became aware of the Portland Basin study. The Intergovernmental Resource Center determined that the study of the ground-water resources in the basin could help guide their management plan and therefore became the fourth cooperating agency involved in the project. As a result, the study boundary was moved north to include all of Clark County.

Many aspects of the ground-water system were studied and several reports have resulted from this work. Those reports, in addition to this report, include: (1) basic ground-water data (McCarthy and Anderson, 1990), (2) a description of hydrogeologic units (Swanson and others, 1993), (3) estimates of ground-water recharge from precipitation, runoff into drywells, and on-site waste-disposal systems (Snyder and others, 1994), (4) estimates of ground-water pumpage (Collins and Broad, 1993), and (5) an interface between a geographic information system and the U.S. Geological Survey modular ground-water flow model (Orzol and McGrath, 1992).

Purpose and Scope

The purpose of this report is to summarize information in earlier reports and to describe the ground-water flow system in the Portland Basin. This flow system description is then used to formulate a conceptual model to aid in construction of a ground-water flow model of the basin.

Preparation of this report involved the review and use of well records and published maps and reports whenever possible.

Study Methods

All available well records were entered into a data base for use in this study. More than 15,000 wells are included in the data base; about 900 wells were field located for this study and about 600 had been previously field located. Records in the data base for wells not field located contain only basic driller's report information. However, for located wells, additional information such as lithology, water levels, open intervals, and land-surface altitude was entered into the data base.

In the Portland Basin, shallow piezometers were augered near some of the major streams in the basin to study stream/aquifer relations. Also, 179 stream-

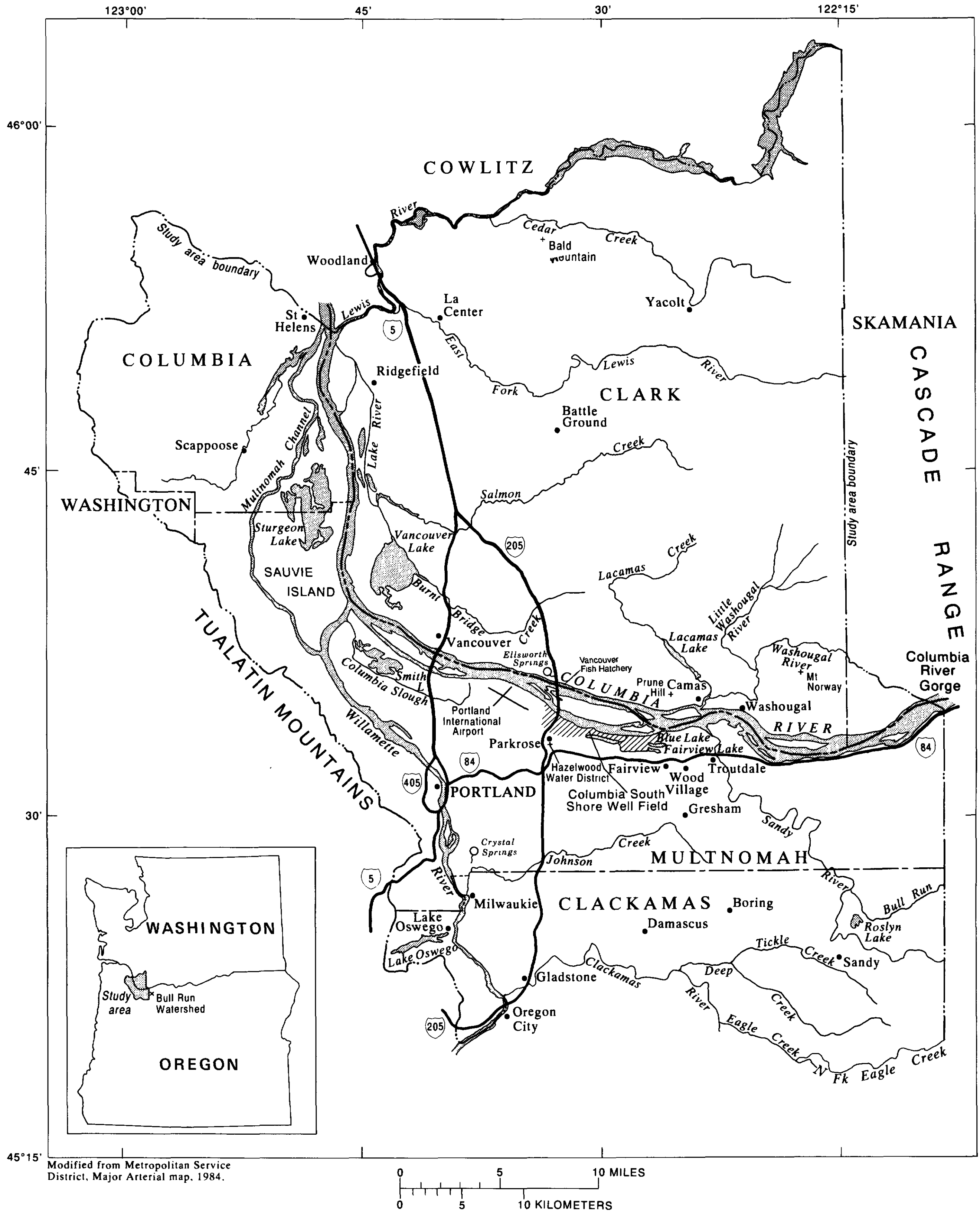


Figure 1. Location of the study area.

discharge measurements were made to estimate low flow and to identify gaining and losing stream reaches.

A map of hydrogeologic-unit outcrops and maps of the tops and thicknesses of each unit were generated for the study area. Detailed geologic mapping (1:24,000 scale) and analysis of drilling samples, geophysical logs, and drillers' reports were used to map the extent, thickness, and lithology of the hydrogeologic units.

Recharge to aquifers in the Portland Basin is from infiltration of precipitation, on-site waste-disposal systems, and runoff to drywells. Recharge to the ground-water system that resulted from infiltration of precipitation was estimated using a Deep Percolation Model developed by Bauer and Vaccaro (1987) for the Columbia River Plateau Regional Aquifer System Analysis Study. Using this method, a recharge analysis was made for three representative subbasins. Sub- sequently, this analysis was used to develop a regression equation to estimate recharge from precipitation for the entire basin. The distribution and discharge rates of on-site waste-disposal systems and drywells were estimated primarily from county and city records or consultants' reports.

Directions of ground-water movement and fluctuations of water levels with time were evaluated by collecting data from field-located wells. A group of approximately 150 wells were measured every other month to evaluate changes in water levels with time. Synoptic water-level measurements were made in approximately 800 wells in spring 1988 and spring 1989. The term synoptic indicates that the measurements were made as simultaneously as possible, within a 2-week period, throughout the basin. These water levels then were used to map the direction of ground-water movement and to map water-level changes in the ground-water system for a 1-year period.

Ground-water use in the basin is primarily for public-supply and industrial purposes. Estimates of use were based on water-system managers' records. Irrigation use is less significant in the basin and was estimated on the basis of crop types and interviews with local irrigators.

Description of the Study Area

The Portland Basin study area in southwestern Washington and northwestern Oregon (fig. 1) includes approximately 1,310 square miles. The Portland Basin is defined as the area bounded by the Tualatin Mountains to the west, the Lewis River to the north, the foothills of the Cascade Range to the east, and the Clackamas River to the south. The Columbia and Willamette Rivers flow through the area and are major discharge areas for the ground-water system.

In the upland areas of the basin, land-surface altitudes are generally 1,200 feet above sea level or less, except to the east along the western Cascade Range, where land-surface altitudes may exceed 3,000 feet. Lowland flood-plain areas of the basin, along the Columbia and Willamette Rivers, have land-surface altitudes between 10 and 20 feet above sea level.

The Cascade Range is an orographic barrier to weather systems moving across Oregon and Washington from west to east. Much of the precipitation from ocean weather systems falls in western Oregon and Washington, and the eastern part of both States is relatively dry. Average annual rainfall in the Portland Basin ranges from about 36 inches per year in the central basin to more than 100 inches per year in the western Cascade Range (Wantz and others, 1983). The long-term average (1929–89) precipitation at Portland International Airport is about 41 inches per year (fig. 2). However, since 1984, annual precipitation at Portland has been 3 to 18 inches below average (National Climatic Data Center, written commun., 1989).

The Portland metropolitan area has a population of approximately 1 million people. Portland, Oregon, is the largest city in the basin and in Oregon; Vancouver is the largest Washington city in the basin. Multnomah and Clackamas Counties in Oregon, and Clark County in Washington, are rapidly growing suburban areas.

Previous Investigations

Geology and ground-water hydrology of parts of the Portland Basin have been studied by several workers. Trimble (1963) mapped the geology of much of the Portland Basin. This report is the most widely used geologic reference for the basin. However, Trimble's mapping did not include the northern one-half of Clark County, north of Salmon Creek. Mundorff (1964) studied the ground-water resources of Clark County and mapped the geology of the entire county. Phillips (1987a, 1987b) compiled much of the existing geologic mapping for the northern part of the basin, primarily in southwestern Washington.

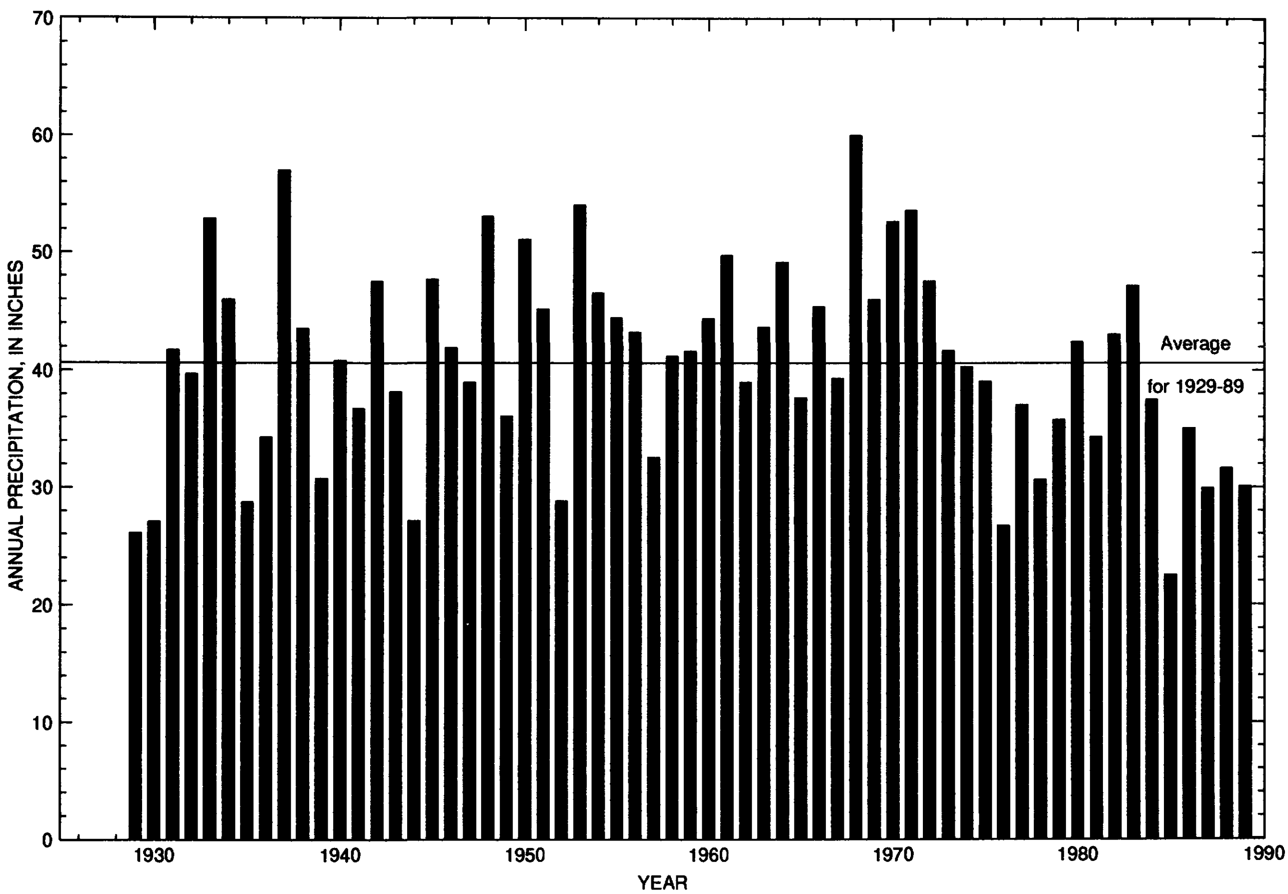


Figure 2. Annual precipitation at Portland International Airport 1929–89.

Mundorff (1964) and Hogenson and Foxworthy (1965) studied the ground-water resources of Clark County, Washington, and eastern Multnomah County, Oregon. Until the present study, these two studies were the primary source of background information on ground-water hydrology in the Portland Basin. Brown (1963) studied effects of water being extracted for heating and cooling purposes in the downtown Portland area. Important background information for northern Clackamas County was obtained from a ground-water study by Leonard and Collins (1983).

Previous studies of the Portland well-field area were important to the success of the Portland Basin study. Willis (1977, 1978) initially described distinct aquifers and confining units in the sedimentary rocks that fill the basin and also described their hydraulic characteristics. McFarland and others (1982) studied the hydrology of the immediate well-field area and constructed preliminary ground-water models. Hartford and McFarland (1989) described the lithology, thickness, and extent of the hydrogeologic units in the east Portland area; their description subsequently provided the basis for extending the description of the same units throughout the basin in this study.

Concurrent Investigations

Turney (1990) sampled ground water in Clark County and defined representative concentrations of inorganic and organic constituents in ground water throughout the county. Variations in concentrations as a function of area, depth, and hydrogeologic unit are described.

In the Sandy-Boring, Oregon area, citizens were concerned that irrigation wells supplying water for nursery operations would affect private water-supply wells. As a result, the Oregon Water Resources Department did a ground-water study in the Sandy-Boring area in northeastern Clackamas County, Oregon. Therefore, little additional data collection was required by the U.S. Geological Survey in that area. Well locations, ground-water use data, and water levels in wells were all supplied by the Oregon Water Resources Department.

Another study in progress was the National Earthquake Hazard Reduction Program Study of the Seattle, Olympia, and Tacoma, Washington, and Portland and Salem, Oregon, metropolitan areas. The purpose of the study was to evaluate the potential for the occurrence of damaging earthquakes in the region. The project was sponsored by the U.S. Geological Survey, Geologic Division. In Washington, this work was done in cooperation with the Washington Department of Natural Resources, and in Oregon with the Oregon Department of Geology and Mineral Industries. As part of this work, extensive geologic mapping of fine-grained unconsolidated sediments was done throughout much of the basin (Madin, 1989).

Acknowledgments

The authors would like to thank the many well owners who allowed U.S. Geological Survey personnel to collect ground-water data on their property. Without the cooperation of those individuals, this project would not have been possible. We are also thankful for the outstanding cooperation of the many State and local governments that assisted with the study. These agencies include the city of Portland Bureau of Water Works, Oregon Water Resources Department, Intergovernmental Resource Center, Washington Department of Ecology, Washington Department of Natural Resources, city of Vancouver, Clark County Public Utility District, and Clark County Public Services.

GEOLOGIC SETTING

The Portland Basin is a structural basin formed by Eocene to Miocene volcanic and marine sedimentary rocks. These rocks include the basalts of Waverly Heights, Goble Volcanics, Skamania Volcanics, Scappoose Formation, Columbia River Basalt Group, and Rhododendron Formation.

Sediments filling the basin are both lacustrine and fluvial. Immediately overlying the bedrock units throughout much of the basin are fine-grained sediments of the Sandy River Mudstone (Trimble, 1963) or the lower member of the Troutdale Formation (Mundorff, 1964). Overlying and interlayered (Swanson and others, 1993) with the Sandy River Mudstone is the Troutdale Formation (Trimble, 1963) or upper member of the Troutdale Formation (Mundorff, 1964), which is the most extensive sedimentary unit in the basin. The Troutdale Formation also is probably the most commonly used aquifer in the basin.

Overlying the older more consolidated sediments in the basin are late Pleistocene sediments that were deposited by alluvial and catastrophic flood events in the basin. These sediments fill the center of the basin and are thickest adjacent to the Columbia and Willamette Rivers. Catastrophic floods during Pleistocene time scoured the older sedimentary units, creating channels that were subsequently filled with thick flood deposits. In some areas, these Pleistocene deposits are very coarse and yield large quantities of water to wells. One of these Pleistocene channels in the Vancouver area was described by Mundorff (1964). Since his work, several other channel filling gravels adjacent to the Columbia River have been drilled and, in some cases, developed for production of ground water.

The Portland Basin is a northwest trending basin with northwest and northeast trending topographic lineations, faults, and folds (Swanson and others, 1993). One of the most prominent structures in the basin is the Tualatin Mountains-Clackamas River Fault that forms the western boundary of the basin. The older volcanic rocks and marine sedimentary rocks in the basin that underlie the basin-fill sediments are offset downward into the basin by poorly defined faults. Small faults and folds also deform these basin-fill sediments.

At the time of this study, a detailed structural geologic map of the Portland Basin was not available, although mapping was in progress by the Oregon Department of Geology and Mineral Industries as part of the Earthquake Hazards Program being conducted by the U.S. Geological Survey, Geologic Division. Detailed structural mapping in the basin will improve our understanding of the ground-water hydrology.

GROUND-WATER SYSTEM

Ground water is an abundant resource in most of the Portland Basin. In the Multnomah County, Oregon, part of the study area, most water needs are adequately supplied from surface-water resources in the Bull Run watershed. In the Vancouver-Clark County, Washington, part of the basin, the water needs are solely dependent on ground-water resources.

Basin-fill sediments are the most easily accessible and widely used water-bearing rocks in the study area. These sediments have been described by previous workers as the Tertiary Sandy River Mudstone and Troutdale Formation, younger Pleistocene to Holocene alluvium, and catastrophic flood deposits of Pleistocene age. In this study, the major water-bearing rocks and confining units within these formations were mapped into eight distinct hydrogeologic units: (1) the unconsolidated sedimentary aquifer, (2) the Troutdale gravel aquifer, (3) confining unit 1, (4) the Troutdale sandstone aquifer, (5) confining unit 2, (6) the sand and gravel aquifer, (7) older rocks, and (8) the undifferentiated fine-grained sediments. All of the units are generally coarser grained near the present channel of the Columbia River.

The ground-water system in the Portland Basin is recharged principally from precipitation and streamflow. In addition, water enters the system at significant rates in some urban areas from runoff into drywells and from on-site waste-disposal systems. Recharge from precipitation is dependent on soil types, land use, and precipitation rates. Recharge to the ground-water system from streams is governed by streambed and aquifer permeabilities and also by hydraulic head gradients between streams and aquifers. In most streams in the Portland Basin, stream stage is lower than the hydraulic head in the uppermost water-bearing unit, indicating that the water-bearing units discharge to the streams. However, reaches of some streams lose water through their streambed because the stage in the stream is higher than the head in the ground-water system.

Drywells are used in urban areas where surficial sediments are permeable enough to channel runoff directly from impervious surfaces into the subsurface. In much of the urban area, storm sewers are not needed because of the widespread use of drywells. Recharge from on-site waste-disposal systems is most significant in the east Multnomah County area where, until recently, all homes and commercial establishments used cesspools to discharge household and other wastes. In that area, cesspools constitute the major source of recharge to the ground-water system. At the present time, the east Multnomah County area is being sewered by order of the Oregon Environmental Quality Commission to protect the quality of ground water. This change will eventually alter the quantity of recharge from cesspools. A significant number of on-site waste-disposal systems also can be found in Clark County, east of Vancouver.

Ground water generally moves from upland areas downgradient to local, intermediate, or regional discharge areas such as streams and springs. The largest springs in the basin are Crystal Springs in southeast Portland, adjacent to the Willamette River, and Ellsworth Springs just east of Vancouver, adjacent to the Columbia River.

Data Collection

Well, spring, and streamflow data were needed to study the ground-water system in the Portland Basin. Wells that have been drilled in the basin provided lithologic and water-level information to map the extent and thickness of the hydrogeologic units and potentiometric surfaces for units throughout the basin. Spring-flow measurements quantify an important component of the discharge from the ground-water system and provide information on ground-water movement. Streamflow measurements were made during low-flow conditions in most streams throughout the basin to identify gaining and losing reaches and to quantify the ground water recharging to or discharging from the aquifer system. The criteria for locating wells and springs are presented below and the data are summarized in McCarthy and Anderson (1990). Low-flow stream-measurement methods and data are presented in this report.

Well Inventory

Representative wells in the Portland Basin were field located by U.S. Geological Survey personnel from January 1987 through June 1988, for the purpose of mapping hydrogeologic units, mapping ground-water-movement directions, and estimating ground-water use in the basin. Approximately 900 wells were field visited during this study, and about 600 wells had been located during previous and concurrent studies. Although well locations are required on State drillers' reports, they may be accurate only to the nearest section, quarter section, or quarter-quarter section. Well location and land-surface altitude were verified for each of the 900 sites.

The deepest well in each section was field located to assist with mapping the hydrogeology. Locating the well allowed an estimate to be made of the land-surface altitude in order to determine the altitude of the hydrogeologic units in the lithologic log for the well. Land-surface altitudes were taken from U.S. Geological Survey 1:24,000 scale topographic maps, generally with 10-foot contour intervals.

Mapping ground-water movement in the basin required some additional well data. Wells completed or screened in particular units were needed for representative water levels in those units completed or screened. Also, additional wells, screened in either shallow or deep units, were located to determine the occurrence of vertical gradients.

Water-rights information was used to select wells for field location. Wells with withdrawal rates greater than 50 gallons per minute or that irrigated more than 10 acres were located to make estimates of ground-water pumpage. Field location was necessary to verify the map location of the well and the hydrogeologic unit from which the water was being withdrawn.

There are some areas of the basin where several wells were located in each section because of the requirements stated above. However, in some upland areas of the basin there may not be any existing wells. There were 1,586 wells located in the basin as a result of this study and previous studies (McCarthy and Anderson, 1990).

Spring Inventory

Forty-two springs and spring-fed streams were located and their discharge measured during this study (McCarthy and Anderson, 1990). Most of these spring discharges were measured in earlier studies by Mundorff (1964) and Hogenson and Foxworthy (1965). In general, spring discharges that previous workers had measured were remeasured during this study; any other springs with discharge greater than 0.1 cubic feet per second also were measured.

Spring discharge measurements were made in 1988. The methods used to measure discharge included current meter, flume, volumetric, and weir measurements. These methods are described in detail by Buchanan and Somers (1984). Some measurements were estimated or reported by owners or other agencies.

Streamflow Measurements

A series of 179 low-flow or seepage measurements were made during fall 1987 and fall 1988 to better understand the relations between ground-water and surface-water sources. The measurements were made in August and September of each year to allow the most accurate measurement of streamflow gains and losses. The 1987 water year was a relatively dry year with only a small amount of precipitation in the early fall (fig. 3). Significant storms in September, just prior to the fall 1988 measurements, could have caused higher streamflows during the 1988 water year measurement period. However, the measurements were made on a stream reach at nearly the same time, so the measurements should reflect the difference in discharge from one site to the next. All tributaries entering a stream reach were measured where possible. Standard surface-water discharge-measurement techniques were used; most measurements were made using current meter or volumetric methods (Buchanan and Somers, 1984).

Data Management

During the course of this study, a large amount of data was compiled and most data reside in, or is linked to, a geographic information system (GIS) data base. Included in the data base are data on wells (both for field located and unlocated wells), thickness of hydrogeologic units, soils, hydrography, precipitation, land subdivision, land-surface altitudes, transportation, land use, spring locations, aquifer test locations, distribution of ground-water use and recharge, and

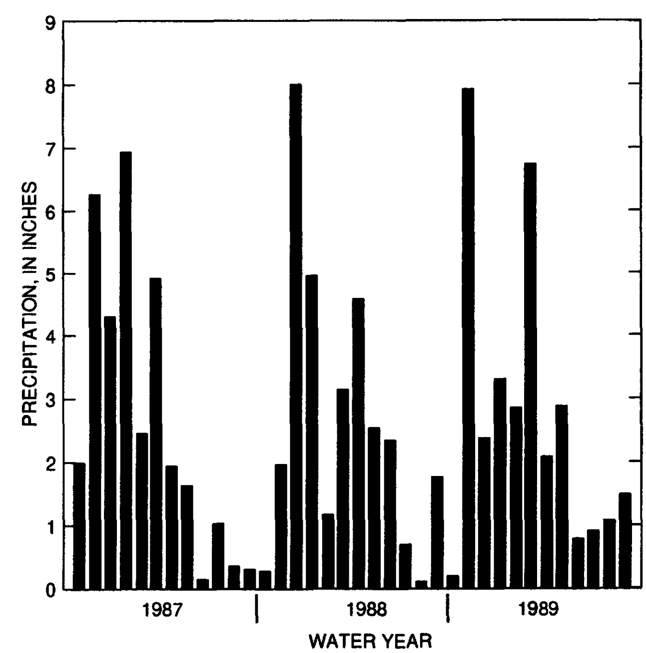


Figure 3. Monthly precipitation at Portland International Airport for water years 1987, 1988, 1989.

several other data types. The data files compiled during the study are primarily in ARC/INFO or INFO format.

Drillers' reports were one of the primary sources of data for the study. Since 1955 in Oregon and 1973 in Washington, drillers have been required to submit reports for each well drilled. In the basin, there are records for more than 15,000 water wells and there are probably several thousand additional wells that are not documented. In this study, the documented wells were entered into a data base for use during the study. For wells that had not been field visited, only basic well information was entered. For wells that were field located, lithologic, open interval, hydrogeologic unit, and altitude information were entered into the data base in addition to the basic well information.

Hydrogeologic Units

The movement of water through a ground-water system and, therefore, the availability of ground water is largely dependent on the extent and thickness of relatively permeable water-bearing rocks (aquifers) and of poorly permeable water-bearing rocks (confining units). These aquifers and confining units are referred to as "hydrogeologic units" in this report because they are mapped on the basis of their geologic and water-bearing characteristics. A hydrogeologic unit may include several geologic units or formations with similar water-bearing characteristics or may include a single part of a geologic unit with a distinct water-bearing characteristic.

In this study, the hydrogeologic units described by Hartford and McFarland (1989) and older hydrogeologic units were mapped throughout the basin (Swanson and others, 1993) using geologic mapping, lithologic descriptions by drillers, geophysical data, examination of drilling samples, specific-capacity tests, and water levels in wells. A detailed discussion of the extent, thickness, and lithology of the units can be found in Swanson and others (1993). The following discussion summarizes their findings.

Eight major hydrogeologic units form the Portland Basin aquifer system. From youngest to oldest these hydrogeologic units include (1) the unconsolidated sedimentary aquifer, (2) the Troutdale gravel aquifer in the Troutdale Formation, (3) confining unit 1, (4) the Troutdale sandstone aquifer in the Troutdale Formation, (5) confining unit 2, (6) the sand and gravel aquifer, and (7) older rocks. The eighth unit, undifferentiated fine-grained sediments, occurs in areas of the basin where the Troutdale sandstone aquifer and the sand and gravel aquifer are absent or where there is insufficient information to characterize the aquifer units within the fine-grained Sandy River Mudstone (or lower member of the Troutdale of Mundorff, 1964). In those areas, confining units 1 and 2 cannot be distinguished on the basis of lithology in drillers' reports and therefore are mapped singly as undifferentiated fine-grained sediments. The location of hydrogeologic units that are exposed at land surface and hydrogeologic sections throughout the basin are shown on plate 1.

For discussion purposes, the aquifer system can be grouped into three major subsystems on the basis of regionally continuous contacts between units or groups of units of distinctly different lithologic and hydrogeologic characteristics (Swanson and others, 1993). These subsystems are the upper sedimentary rocks, lower sedimentary rocks, and older rocks. Maps showing the altitude of the top and thickness of all of the hydrogeologic units in the basin are presented by Swanson and others (1993). The extent and thickness of the major aquifers are shown on plates 2–5 in this report.

Upper Sedimentary Subsystem

The upper sedimentary subsystem overlies the lower sedimentary subsystem throughout most of the basin. The upper sedimentary subsystem is composed of Troutdale gravel of the Troutdale Formation and Cascade Range derived volcaniclastic conglomerate, and locally includes thick deposits of Pliocene and Quaternary High Cascade Volcanics and Boring Lava. The consolidated gravel and volcanic rock are grouped into a Troutdale gravel aquifer, and the late Pleistocene sediments and alluvium are grouped into an unconsolidated sedimentary aquifer.

The unconsolidated sedimentary aquifer is the uppermost hydrogeologic unit in the Portland Basin. The aquifer consists mainly of catastrophic flood deposits of late Pleistocene age that mantle the central part of the basin and of the Holocene Columbia River alluvium. The aquifer also includes water-bearing alluvial deposits that occur along smaller streams in the basin. Additionally, the aquifer includes flood-plain deposits, terrace deposits along major tributaries, and glacial outwash in small basins in northern Clark County, Washington.

The extent and thickness of the unconsolidated sedimentary aquifer are shown on plate 2. The aquifer is thickest under the Columbia River flood plain at Sauvie Island and adjacent areas in Clark County. Drillers' reports in that area indicate that, except for a few wells along the west edge of the study area, all wells were completed in unconsolidated sand and sandy gravel. The deepest wells on Sauvie Island are from 250 to 300 feet deep. Elsewhere in the basin, the aquifer is generally between 50 and 100 feet thick with local accumulations of catastrophic flood deposits of more than 250 feet. Locally, stream alluvium and low terrace deposits are generally from 20 to 60 feet thick. Unconsolidated glacial outwash deposits underlying Chelatchie Prairie and the Yacolt area in Washington are as much as 200 feet and approximately 100 feet thick, respectively.

In some parts of the basin, deposits mapped as the unconsolidated sedimentary aquifer are unsaturated; however, in other areas the unit is saturated, consists of alluvium or coarse-grained catastrophic flood deposits, and is the most productive aquifer in the Portland Basin. Mundorff (1964) described a major alluvial aquifer adjacent to the Columbia River near Washougal, Camas, and Vancouver, Washington. In those areas, public-supply and industrial wells generally yield from 1,000 to 6,000 gallons per minute with less than 10 feet of drawdown. The city of Portland has developed wells in similar deposits in Oregon, just north of Blue Lake, for municipal water supply. In that area, public-supply wells have been tested at rates of up to 10,000 gallons per minute with less than 25 feet of drawdown. Similar, highly productive, coarse-grained catastrophic flood deposits in the unconsolidated sedimentary aquifer that have not yet been developed also may be present beneath Sauvie Island. Wells completed in finer grained catastrophic flood deposits typically yield as much as 150 gallons per minute (Mundorff, 1964).

The unconsolidated sedimentary aquifer is less productive in other areas of the basin but, nonetheless, is an important water-bearing unit. In Chelatchie Prairie and the Yacolt area in northern Clark County, wells completed in fluvial and glacial outwash gravels yield as much as 600 gallons per minute. Along the Clackamas, Sandy, East Fork of Lewis, and Lewis Rivers, wells in poorly consolidated terrace gravels yield from 10 to 40 gallons per minute. Holocene alluvium underlying the Columbia River and Willamette River flood plains are principally clayey silt and sand that yield from 5 to 40 gallons per minute. Coarser deposits can yield 100 to 200 gallons per minute.

The Troutdale gravel aquifer generally overlies confining unit 1 or the undifferentiated fine-grained sediments and underlies the unconsolidated sedimentary aquifer. The contact between this unit and underlying fine-grained units marks a distinct change in depositional environment in the basin and separates the upper and lower sedimentary subsystems.

The Troutdale gravel aquifer is composed of several geologic formations of poorly to moderately cemented conglomerate and sandy conglomerate, but also includes thick local accumulations of lavas and a mantling soil horizon. The conglomerate part of the aquifer extends basinwide and includes the upper part of the Troutdale Formation of Trimble (1963) and Mundorff (1964); Cascade Range derived volcaniclastic conglomerate chiefly mapped as Springwater Formation, Walters Hill Formation, and Gresham Formation by Trimble (1963); and is included in the informal upper member Troutdale Formation of Mundorff (1964). Within the basin, local accumulations of Boring Lava underlie, interlayer, and overlie the Cascade Range derived volcaniclastic conglomerate and are mapped as part of the Troutdale gravel aquifer for this study. East of the Sandy River, an eastward-thickening sheet of Cascade lavas also is included in the Troutdale gravel aquifer. In many areas, the upper part of the Troutdale gravel aquifer is weathered to a thick, clayey soil. In upland areas above an altitude of 300 feet, the weathered upper part may be as much as 100 feet thick. Weathered loess deposits of clay and silt also occur in the upper part of the Troutdale gravel aquifer and may be 10 to 20 feet thick. The extent and thickness of the Troutdale gravel aquifer are shown on plate 3.

Boring Lava and vent rocks are included in the Troutdale gravel aquifer. Boring Lava is dark-gray to light-gray colored and commonly forms columnar and platy joints. Some flows are similar in appearance to Columbia River Basalt Group rocks, but many of them can be distinguished by their coarser or less dense texture. These rocks are most extensive in Oregon, southeast of Portland. Boring Lava also occurs locally in Clark County at Prune Hill, at Mount Norway, Bear Prairie, Green Mountain, and Battle Ground Lake. In some areas of the basin, Boring Lava caps hills and may not be saturated; however, one exception is in the Mount Norway area where the Boring Lava supplies sufficient water to domestic wells. Boring Lava vents intrude basin-fill sediments and may influence ground-water flow where they are present.

The Troutdale gravel aquifer is generally thickest where the Boring Lava or the Cascade Volcanics are included in the unit. These areas are generally in the southern and southeastern parts of the basin (pl. 3) where the unit is more than 800 feet thick. Throughout much of the basin, however, the aquifer ranges from 100 feet to 400 feet in thickness.

The Sandy River, Little Sandy River, Bull Run River, and much of the Clackamas and East Fork Lewis Rivers have cut completely through the Troutdale gravel aquifer, exposing underlying units along their canyon walls. The Columbia River has eroded the Troutdale gravel aquifer from the eastern boundary of the study area to the vicinity of Rocky Butte and then from about 2 miles north of the Willamette and Columbia River confluence to the northern boundary of the study area.

The Troutdale gravel aquifer is an important and productive aquifer in the Portland Basin, in which many public-supply, industrial, and domestic wells are completed. Most wells will yield a minimum of 50 gallons per minute, and carefully constructed wells can yield more than 2,000 gallons per minute.

Lower Sedimentary Subsystem

The lower sedimentary subsystem extends nearly basinwide and overlies the older rocks. It is composed of (1) interbedded consolidated silt, sand, and clay that are characteristic of Trimble's (1963) Sandy River Mudstone and Mundorff's (1964) lower member of the Troutdale Formation, and (2) interlayered vitric sandstone and quartzite-pebble-bearing basaltic conglomerate that characterize the Troutdale Formation in the lower Sandy River canyon-type area. The lower sedimentary subsystem was divided into two aquifers and two confining units in the southeastern part of the basin, where the vitric sandstone and channel gravel deposits of the ancestral Columbia River interlayer with the Sandy River Mudstone. Where data permit, the lower sedimentary subsystem is mapped into confining unit 1, the Troutdale sandstone aquifer, confining unit 2, and the sand and gravel aquifer. Toward the western side of the basin, the Troutdale sandstone and sand and gravel aquifers become finer grained and apparently pinch out (pl. 1). In these areas, confining unit 2 and confining unit 1 are not distinguishable from each other, and the lower sedimentary subsystem is mapped as undifferentiated fine-grained sediments. Throughout most of the basin, the contact between confining unit 1 or the undifferentiated fine-grained sediments with the overlying Troutdale gravels is easily mapped.

Confining unit 1 is the uppermost unit in the lower sedimentary subsystem. The contact between this unit and the overlying Troutdale gravel aquifer is recognizable throughout the basin where adequate well data or outcrop data are available. Confining unit 1 consists of medium- to fine-grained arkosic sand, silt, and clay, with some vitric sand beds. Confining unit 1 is generally less than 200 feet thick, but is more than 260 feet thick in well 3N/2E-30BBD. In the Portland well-field area, the updip edge of the confining unit has been eroded by the Columbia River. Confining unit 1 is generally a poor water-bearing unit, except where sand lenses provide adequate water for domestic use. The unit is not used as a source of water throughout most of the basin. Confining unit 1 limits vertical flow in the aquifer system and in many areas confines the Troutdale sandstone aquifer.

Confining unit 1 is defined as an individual unit only where the Troutdale sandstone aquifer is present. Outside that area, the unit is part of a thick sequence of undifferentiated fine-grained sediments from the top of the confining unit to the top of the older rocks. The confining unit does not occur in all areas where the Troutdale sandstone aquifer is present, and, therefore, the aquifer may be in direct contact with the overlying unconsolidated sedimentary and Troutdale sandstone gravel aquifers in some areas of the basin.

The Troutdale sandstone aquifer consists of coarse vitric sandstone and conglomerate with lenses and beds of fine to medium sand and silt. The aquifer is underlain by confining unit 2 and overlain by confining unit 1 throughout much of its extent. Where the aquifer is not present, the two confining units cannot be differentiated.

Hartford and McFarland (1989) described the Troutdale sandstone aquifer as consisting of two lithologic subunits; the upper two-thirds is chiefly vitric sandstone and the lower one-third is conglomerate. The upper, vitric sandstone subunit consists of moderately to well-sorted angular to subround coarse sand of black to dark-brown olivine basalt glass and dark-gray olivine basalt. Lenses of sandy silt and clay are interlayered with the vitric sandstone. The lower, conglomerate subunit consists of quartzite-bearing basaltic conglomerate with a matrix of vitric sand and micaceous lithic arkose. The extent and thickness of the Troutdale sandstone aquifer are shown on plate 4.

The Troutdale sandstone aquifer is generally from 100 to 200 feet thick, but may reach a thickness of 400 feet in the southeastern part of the basin. The thickest part of the aquifer is east of the Sandy River, close to the source area for the sediments that compose the unit. The aquifer is generally thinner to the west and northwest and interfingers with undifferentiated fine-grained sediments near the center of the basin (pl. 1).

Sandstones and conglomerates of the Troutdale sandstone aquifer are excellent water-bearing units just west of the mouth of the Columbia River Gorge and, to a lesser degree, in the Damascus and Boring, Oregon areas. Large capacity wells in the Portland well field yield as much as 2,500 gallons per minute. Other smaller capacity municipal, industrial, and irrigation wells open to the Troutdale sandstone aquifer may yield more than 500 gallons per minute.

Confining unit 2 overlies the sand and gravel aquifer and underlies the Troutdale sandstone aquifer where the two aquifers are present. Hartford and McFarland (1989) describe confining unit 2 in the Portland well field as grayish olive-green clay and silt with lenses of silt and fine- to medium-grained basaltic sand. Outcrops of this unit are limited to the southeastern part of the basin along the Clackamas and Sandy Rivers in Oregon.

Confining unit 2 is used for a water supply only where more permeable units are not present. Lenses of silt and fine-grained sand 2 to 6 feet thick in the unit can supply water for domestic use. Confining unit 2 limits vertical movement in the aquifer system and partly confines the sand and gravel aquifer.

The sand and gravel aquifer is the lowermost hydrogeologic unit in the lower sedimentary subsystem. Where it is present, this aquifer is defined by the total sediment thickness between the top of the aquifer and the top of the older rocks. This sediment interval consists principally of sandy gravel, silty sand, sand, and clay. Where it is described in the Portland well field (Hartford and McFarland, 1989), the sand and gravel aquifer has a relatively coarse upper subunit and a predominately fine-grained lower subunit that extends to the base of the sedimentary rock section. This hydrogeologic unit is considered a relatively coarse-grained facies of the Sandy River Mudstone and Mundorff's (1964) lower member of the Troutdale Formation.

In general, available well data suggest that the sand and gravel aquifer is coarsest near the present Columbia River channel. Sand and sandy gravel beds were probably deposited by an ancestral Columbia River. The extent and thickness of the sand and gravel aquifer are shown on plate 5.

The sand and gravel aquifer is developed chiefly by public-supply systems along the south shore of the Columbia River between Interstate Highway 5 and the Sandy River. Portland Bureau of Water Works supply wells that are open solely to the sand and gravel aquifer can yield 2,000 to 3,000 gallons per minute. One Troutdale public-supply well, open only to the sand and gravel aquifer, was tested at a discharge of 590 gallons per minute with 52 feet of drawdown after 24 hours. Several domestic wells, in the low hills between the Washougal River and Columbia River, draw water from a sandy conglomerate that is included in the sand and gravel aquifer. These wells yield from 5 to 30 gallons per minute.

In southern Clark County, Washington, four deep wells have been drilled to depths from 847 to 1,000 feet to determine whether the productive sand and gravel aquifer developed in the Portland well field occurs north of the Columbia River. The city of Vancouver drilled the first deep well in 1985, at the Ellsworth Springs site (2N/2E-33CDA(P)) with the goal of obtaining additional public drinking-water supplies. The well was drilled to a depth of 1,063 feet and penetrated the Troutdale gravel aquifer, confining unit 1, Troutdale sandstone aquifer, and confining unit 2.

A unit similar to the sand and gravel aquifer also was encountered at approximately 650 feet below sea level. Although mapping by Swanson and others (1993) did not extend the sand and gravel aquifer to include this well, data from the Ellsworth well and from new wells support mapping the aquifer northward 1 to 2 additional miles.

Two aquifers were tested in the Ellsworth well. The deeper aquifer appears to be the sand and gravel aquifer and the upper aquifer is the Troutdale gravel aquifer. The sand and gravel aquifer was tested at 110 gallons per minute for just more than 1 hour with approximately 3 feet of drawdown. The Troutdale gravel aquifer was tested at 150 gallons per minute for approximately 3.5 hours with approximately 57 feet of drawdown (Robinson and Noble, 1985). From these tests, Robinson and Noble (1985) estimated that the deeper aquifer could yield as much as 2,000 gallons per minute, and the shallow aquifer could yield 500 gallons per minute or less in a properly constructed production well.

In early 1990, the city of Vancouver drilled a test well approximately 2 miles northeast of the Ellsworth well (2N/2E-27BBC(D)) to a depth of 1,200 feet. The well provided additional information on the extent of the hydrogeologic units and the northern extent of the sand and gravel aquifer. This well apparently penetrated all of the hydrogeologic units, including the sand and gravel aquifer at an altitude of 574 feet below sea level. The well was tested at rates of up to 625 gallons per minute for 24 hours with a drawdown of 52 feet. The results of the tests suggested that the sand and gravel aquifer is capable of yielding more than 2,000 gallons per minute from properly completed production wells (Robinson and Noble, 1990).

Two additional deep wells were drilled at the Vancouver Fish Hatchery (1N/2E-3AC(G)) by the Washington Department of Game in 1990. These wells were drilled to replace the water supply lost from the declining spring discharge at the hatchery. The first well was a 922-foot test well and the second a 873-foot production well. Both of these wells penetrated the sand and gravel aquifer at approximately 600 feet below sea level. The Troutdale sandstone aquifer is difficult to identify in these wells because only thin (10- to 20-foot) layers of vitric sandstone are present. The wells appear to be in an area close to the western extent of the Troutdale sandstone aquifer (pl. 4).

The undifferentiated fine-grained sediments are mapped where aquifers in the lower sedimentary subsystem are not present or well information is insufficient to map them. The sediments generally overlie older rocks and underlie the Troutdale gravel aquifer. These fine-grained sediments are lithologically similar to confining unit 1 and confining unit 2. The unit may include some sediments older than Mundorff's (1964) lower member Troutdale Formation in northern Clark County. The unit is generally a poor water-bearing formation. However, in northern Clark County it is an important local source of water. Where the unit contains extensive beds of sand, its capacity to yield water may be equivalent to that of the sand and gravel aquifer.

Older Rocks Subsystem

The older rocks subsystem includes Miocene and older volcanic and marine sedimentary rocks, generally of low permeability, that underlie and bound the basin-fill sediments in the Portland Basin. The contact between the older rocks and basin-fill sediments often can be easily interpreted in wells that penetrate the older rocks. With the exception of the Columbia River Basalt Group and the Rhododendron Formation, these older rocks are poor aquifers and, in most areas, supply water in quantities adequate only for domestic use. These rocks are not a primary source of water in many parts of the study area. Much of the area where the older rocks occur at land surface is sparsely populated forest uplands, with some farmland or urbanized areas served by public water supplies. Where they are covered by basin-fill sediments, the older rocks generally are too deep to be used as a water supply under the current demand for water. The distribution of these older rocks by geologic formation is shown in figure 4.

The Skamania Volcanics, Goble Volcanics, and basalts of Waverly Heights are all dense altered volcanic rocks with little capacity to store or transmit water. Wells in these units yield about 5 to 10 gallons per minute. As residential development moves into the foothills of the Cascade Range, the Skamania Volcanics and, to a lesser degree, the Goble Volcanics are being increasingly used as a source of water. Wells drilled into the fractured zones and to the soil/rock interface may be the best producers.

Marine sedimentary rocks, such as the Scappoose Formation, also have limited water-bearing capabilities and in some areas contain saline water. Saline water has been encountered along the western edge of Sauvie Island and also along the Willamette River west of Milwaukie. Most wells in these older rocks generally have yields of from 5 to 10 gallons per minute.

The Columbia River Basalt Group is used as an aquifer along the western and, to a lesser extent, southern boundaries of the Portland Basin where it crops out or is not overlain by thick sedimentary rock aquifers. Large capacity wells in the Columbia River Basalt Group typically are open to several hundred feet of the unit in order to penetrate one or more productive interflow zones. In the study area, several wells completed in the Columbia River Basalt Group are capable of producing more than 1,000 gallons per minute.

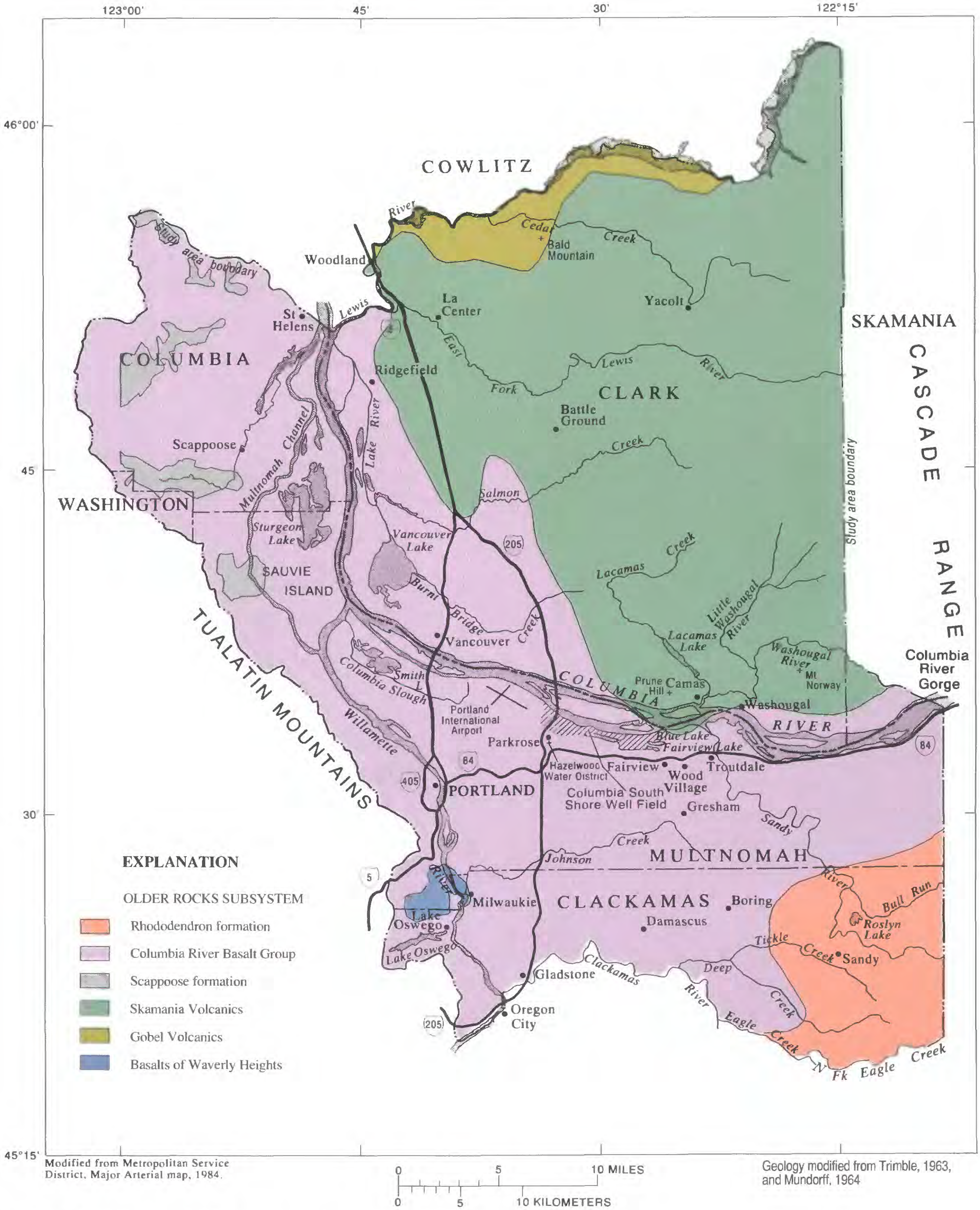


Figure 4. Distribution of older rocks in the Portland Basin.

Although the Columbia River Basalt Group has the capability in places to produce large quantities of ground water, its limited capacity to store water is evident in many parts of western Oregon. Water-level declines have occurred in several upland areas of the Willamette Valley in Oregon as a result of overdevelopment of aquifers in the basalts.

The Rhododendron Formation underlies the extreme southeastern part of the study area and produces ground water for domestic use and small-scale irrigation. The Rhododendron Formation is composed principally of lava flows and consolidated volcanic debris. Leonard and Collins (1983) reported that the most productive wells were completed in material described as lava or rock by drillers. Well yields of 5 to 25 gallons per minute are typical for the Rhododendron Formation.

Hydraulic Characteristics

A detailed quantitative analysis of any ground-water system requires that the hydraulic characteristics of the system be mapped and described. Because the aquifer system in the Portland Basin is a layered, three-dimensional system, it was necessary to describe the hydraulic characteristics of the ground-water system in both the horizontal and vertical directions.

The hydraulic characteristics of aquifers and confining units in the Portland Basin were initially determined from multiple well-aquifer tests, single-well tests, and from published data. Multiple well-aquifer tests provide the best data for determining values for hydraulic conductivity and storage coefficient. In the Portland Basin, tests with multiple observation wells are usually done only on high-capacity wells used for public-supply, irrigation, or industrial uses. Standard time-drawdown or distance-drawdown analytical techniques were used with observation well data to estimate hydraulic-parameter characteristics.

In the Portland Basin, single well tests are usually "specific-capacity" tests in which the well is pumped for a period of 1 to 4 hours and the drawdown is measured at the end of the pumping period. Specific capacity, which is the yield of the well divided by the drawdown in the well, is an estimate of the productivity of the aquifer and can be used to estimate the transmissivity and subsequently the hydraulic conductivity. To estimate transmissivity, the effective diameter of the well, discharge rate, drawdown, duration of pumping, and storage coefficient must be known. The most accurate estimates of storage coefficient are from the analysis of multiple well tests where water levels in one or more wells are observed while a nearby well is pumped.

Specific-capacity data are generally available for most drilled wells and are listed on the driller's report. Specific-capacity data give the best areal distribution of data, but the multiple well tests give the most reliable estimates of hydraulic properties.

More than 55 multiple well-aquifer tests throughout the Portland Basin were used to estimate transmissivity and storage coefficient. Storage-coefficient values from the multiple well tests were then used for input in calculating transmissivity from specific-capacity data in those areas devoid of multiple well-test data.

Storage coefficients determined from the aquifer tests and published information were used to assign values of storage to each of the hydrogeologic units. Average storage coefficients for each unit were as follows: unconsolidated sedimentary aquifer, 0.003; Troutdale gravel aquifer, 0.0008; confining unit 1, 0.00005; Troutdale sandstone aquifer, 0.00024; confining unit 2, 0.00005; sand and gravel aquifer, 0.0004; and older rocks, 0.0001. Where these units are at the land surface, water in them can be under water-table conditions. Under water-table conditions, specific yield is commonly in the range of 0.05–0.20.

A method published by Vorhis (1979) was used to calculate transmissivity values from specific capacity. The method is based on the Theis equation and assumes that well inefficiency is negligible. Values of horizontal hydraulic conductivity were calculated from transmissivities by dividing transmissivity by the total thickness of the aquifer, as determined from the mapped thickness of each hydrogeologic unit. The variability of hydraulic conductivity (fig. 5) ranged over five orders of magnitude. The older rocks in the basin have the lowest median hydraulic conductivity, approximately 0.3 feet per day, and 50 percent of the values are between 0.05 and 1.5 feet per day. The total range of hydraulic conductivity for the older rocks unit is from less than 0.001 to about 200 feet per day. This wide variability is probably due to the low primary hydraulic conductivity of these older rocks and the localized areas of high secondary hydraulic conductivity as a result of faulting. Also, in rocks like the Columbia River Basalt Group, the most permeable zones may be between basalt flows, and wells that have relatively small open intervals may not intersect these interflow zones.

Two other units with relatively low median hydraulic conductivities are the two confining units. The median value for confining unit 2 is about 1 foot per day and the median value for confining unit 1 is about 4 feet per day. The range of values is similar for the two confining units (fig. 5). Confining unit 1 may have a slightly higher median hydraulic conductivity value due to the common occurrence of sand lenses in the unit, especially in northern Clark County.

The four sedimentary aquifers in the basin have the highest median hydraulic conductivities. The unconsolidated sedimentary aquifer has the highest median value of hydraulic conductivity (200 feet per day) and also the greatest variation in values (0.03 to 70,000 feet per day). It is the most permeable aquifer, as well as the most heterogeneous unit. The Troutdale gravel aquifer, Troutdale sandstone aquifer, and the sand and gravel aquifer all have similar median values of about 7 to 16 feet per day. The Troutdale sandstone and the sand and gravel aquifer have low variation in hydraulic conductivity relative to some of the other

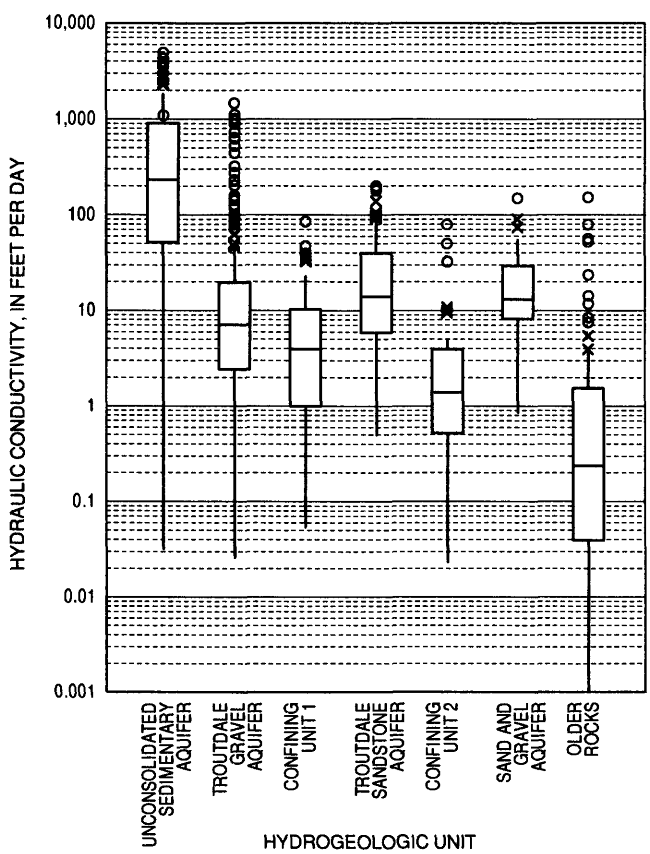


Figure 5. Statistical distribution of hydraulic conductivity for hydrogeologic units in the Portland Basin.

units. The Troutdale gravel aquifer, however, has values of hydraulic conductivity ranging over six orders of magnitude.

Because of the depositional characteristics of the basin-fill sediments in the Portland Basin, the horizontal and vertical hydraulic conductivities of aquifers and confining units may differ by orders of magnitude. Generally, hydraulic conductivity is greatest in the horizontal direction because of the horizontal orientation of fine-grained sediments

Field measurement of vertical hydraulic conductivity was not within the scope of this study. Therefore, vertical hydraulic conductivity was estimated as part of the ground-water model-calibration process.

Recharge

Recharge to the aquifer system in the Portland Basin is primarily by infiltration of precipitation. However, within the urbanized parts of the basin other sources contribute significant amounts of water locally to the aquifer system. The two most significant urban sources of recharge are runoff from impervious surfaces to drywells (sumps) and effluent from on-site waste-disposal systems. About 20 percent of the basin is urbanized.

Recharge from agricultural irrigation was not estimated. Although locally important, recharge from irrigation is insignificant on a regional scale. The total quantity of water used for agricultural purposes in the Portland Basin is about 18 cubic feet per second from ground water (Collins and Broad, 1993) and an estimated 25 cubic feet per second from surface water (Broad and Collins, 1996). Logically, after losses for interception, soil-moisture storage, and evapotranspiration, the quantity of recharge from agricultural irrigation would be expected to be small (Snyder and others, 1994). The exclusion of irrigation results in a more conservative estimate (or underestimate) of recharge. Recharge gains and losses from streams and rivers also were not included in this study, because the ground-water flow model will be used to facilitate these estimates.

In this study, major components of recharge were estimated and are described in detail by Snyder and others (1994). Recharge from infiltration of precipitation was estimated by applying a computer model to estimate deep percolation of precipitation within three representative subbasins in the study area.

The recharge estimates from these three subbasins were then analyzed using a multivariate linear regression of climatic and physical factors used in the model to derive an equation for calculating recharge for any part of the study area. Drywell locations were compiled from existing inventories, and estimates of recharge were based on collection area, precipitation, runoff, and evapotranspiration. Estimates of recharge from on-site waste-disposal systems were made using an inventory of the distribution and capacity of septic systems and cesspools as provided by local government agencies. These components of recharge, precipitation, drywells, and on-site waste-disposal systems were then summed to determine the total recharge from these sources (Snyder and others, 1994).

Recharge from precipitation was estimated using a deep percolation model (Bauer and Vaccaro, 1987), regression analysis, and regionalization of the results to the grid cells of the ground-water model. Recharge from precipitation for three selected subbasins within the study area was calculated using a modified version of the deep percolation model—a model that is based on physical processes that include soil moisture, soil evaporation, plant transpiration, surface-water runoff, snow cover, and interception and evaporation of precipitation from foliar cover.

The deep percolation model was modified for this study to better reflect the prevailing conditions of the basins being modeled. These modifications included increasing the number of available soil types, adjusting growth curves for local plant types, calculating impervious area from land-use type, and routing of a part of incident precipitation to runoff on the basis of the percentage of impervious area.

The deep percolation model was not used to calculate recharge from precipitation over the entire study area because of the numerous simulations that would be required and the lack of necessary data in many of the drainage basins. The subbasins selected for detailed analysis with the deep percolation model were Salmon and Cedar Creeks in Washington and Johnson Creek in Oregon. These three subbasins were selected because each represented different climatic, topographic, and land-use conditions found in the basin. Other important factors in the selection of these subbasins were that drainage basins could easily be defined, extended records of daily stream discharge were available, and nearby weather-station data were available (daily precipitation and temperature data).

Estimated average recharge in the Salmon Creek subbasin was 27.1 inches per year, or 45 percent of the 60-inch average annual precipitation per year. Average recharge in Cedar Creek subbasin was 51.5 inches per year, or 51 percent of the average annual precipitation of 100 inches. Average recharge in the Johnson Creek subbasin was estimated at 19.9 inches per year, or 36 percent of the average annual subbasin precipitation of 55 inches (Snyder and others, 1994).

A multivariate regression analysis was done on the results of the deep percolation model in the three subbasins to derive an equation for calculating the average annual recharge from precipitation for any part of the study area using readily determined climatic and physical parameters. A stepwise regression, where independent variables are added or subtracted one at a time, was done to derive the recharge equation. The dependent variable was average annual recharge as calculated by the deep percolation model and the independent variables included average annual precipitation, runoff, impervious area, land-surface altitude, slope, aspect, soil depth, available soil-water capacity, soil texture, root depth, transpiration, interception capacity, and foliar cover. The stepwise regression indicated that the best equation to calculate average annual recharge is one that uses average annual precipitation, percentage of impervious area, and land-surface altitude. The equation Snyder and others (1994) used to regionalize recharge is:

$$RCHG = (0.48212)PRCP - (0.35418)IMPRV + (0.0097444)ALT - 4.7906, \tag{1}$$

where

$RCHG$ = recharge, in inches per year;

$PRCP$ = precipitation, in inches per year;

$IMPRV$ = impervious area, in percent;

ALT = altitude of land surface, in feet.

The adjusted R-squared (the coefficient of determination adjusted for the number of independent variables used in the regression) is 0.91, which indicates that 91 percent of the variation in recharge, as determined by the deep percolation model, can be explained by precipitation, impervious area, and altitude of land surface (Snyder and others, 1994, p. 16).

This equation was the basis for regionalizing average annual recharge for the Portland Basin. A part of the study area was discretized into a rectilinear grid identical to that selected for later use in a numerical ground-water model for the basin. This discretization allowed the direct transfer of average annual recharge data to the ground-water model. This grid, consisting of 3,040 cells with a 3,000 foot spacing, is evident in the plot of total average annual recharge shown in figure 6. The y-axis of this grid is oriented 28.8 degrees west of north. Gridded precipitation, impervious area, and elevation were used to calculate recharge from precipitation for each of the cells.

The estimated volumetric rate of recharge from precipitation (including recharge from precipitation over water-surface areas) in the 3,000 foot ground-water model grid is 1,500 cubic feet per second. The average recharge from precipitation for the model grid cells ranges from 0 to 49 inches per year with a mean of 20.8 inches per year (Snyder and others, 1994).

Recharge from runoff to large diameter drywells (sumps) was estimated from available records from county, municipal, State, and Federal agencies. Within the 88-square-mile urban area inventoried, nearly 5,700 drywells were found. Almost two-thirds of this total (3,720) are in Multnomah County, where the mean drywell density of 84 per square mile is nearly twice the 46 drywells per square mile in Clark County (Snyder and others, 1994).

In this study, a mass-balance approach was used to estimate the percentage of average annual precipitation lost to detention storage and eventually to evaporation, and the remaining amount of recharge available to recharge the ground-water system. The mass balance was calculated using a model in which the amount of water available for recharge was estimated as the daily precipitation in excess of detention storage, with storage being depleted at the daily pan-evaporation rate. Average detention storage capacity of impervious surfaces in the study area was estimated by Laenen (1980) to be at approximately 0.05 to 0.10 inches. Daily pan-evaporation and precipitation data were obtained from the North Willamette Agricultural Experiment Station, 15 miles south of downtown Portland. Average precipitation at that site is 42 inches per year and pan evaporation is 44 inches per year (Snyder and others, 1994).

Using these detention storage, climatic, and pan-evaporation data, it was found that about 74 percent of the average annual precipitation falling on impervious surfaces would run off to drywells (where drywells were used). In urban areas where drywells are present, the estimated average volume rate of recharge from drywells is 61.7 cubic feet per second, of which nearly one-half, or 27.1 cubic feet per second, occurs in Clark County. Rates of drywell recharge in the 3,000 foot ground-water model grid cells range from 0.1 to 26 inches per year, with a mean of 9.4 inches per year (Snyder and others, 1994).

On-site waste-disposal systems (septic tanks and cesspools) are used in many parts of the study area to dispose of commercial and domestic wastewater. Effluent from these systems, like surface runoff shunted to drywells, bypasses most or all of the near-surface, unsaturated-zone processes of evapotranspiration, filtration, and bio-retardation. This makes these on-site waste-disposal systems an efficient avenue for recharge to the aquifer system in local areas.

On-site waste-disposal systems are concentrated mostly in urban areas, whereas recharge from these systems in rural areas is less significant. The mid-Multnomah County, Oregon, area has the highest density of on-site waste-disposal systems in the Portland Basin, with approximately 50,000 residential and commercial systems within a 39-square-mile area. This area is currently being sewered to eliminate on-site waste-disposal systems by the year 2003. Another large unsewered urban area is located in the vicinity of Burnt Bridge Creek in Clark County, Washington, which is similar in size (approximately 7,500 systems) to the unsewered area in Multnomah County.

Annual recharge volume for each residential on-site waste-disposal system was estimated to be 117 gallons per day on the basis of an average of 2.6 persons per household and a per capita discharge of 45 gallons per day (Snyder and others, 1994). In order to estimate an average effluent-discharge-volume rate for commercial on-site waste-disposal systems, it was assumed that if residential systems produced 117 gallons per day, then the 50,459 residential systems functioning in Multnomah County, Oregon, in 1985 generated 5.9 million gallons per day of the 16.7 million gallons per day estimated total discharge in that area. Therefore, it was assumed the remaining 10.8 million gallons per day was generated by the 3,133 commercial systems at an individual average rate of 3,400 gallons per day (Snyder and others, 1994).

The average volume rate of recharge from on-site waste-disposal systems for the study area was estimated to be 27.2 cubic feet per second, of which 4.7 cubic feet per second was in Clark County, Washington. Average rates of recharge in the 3,000 foot

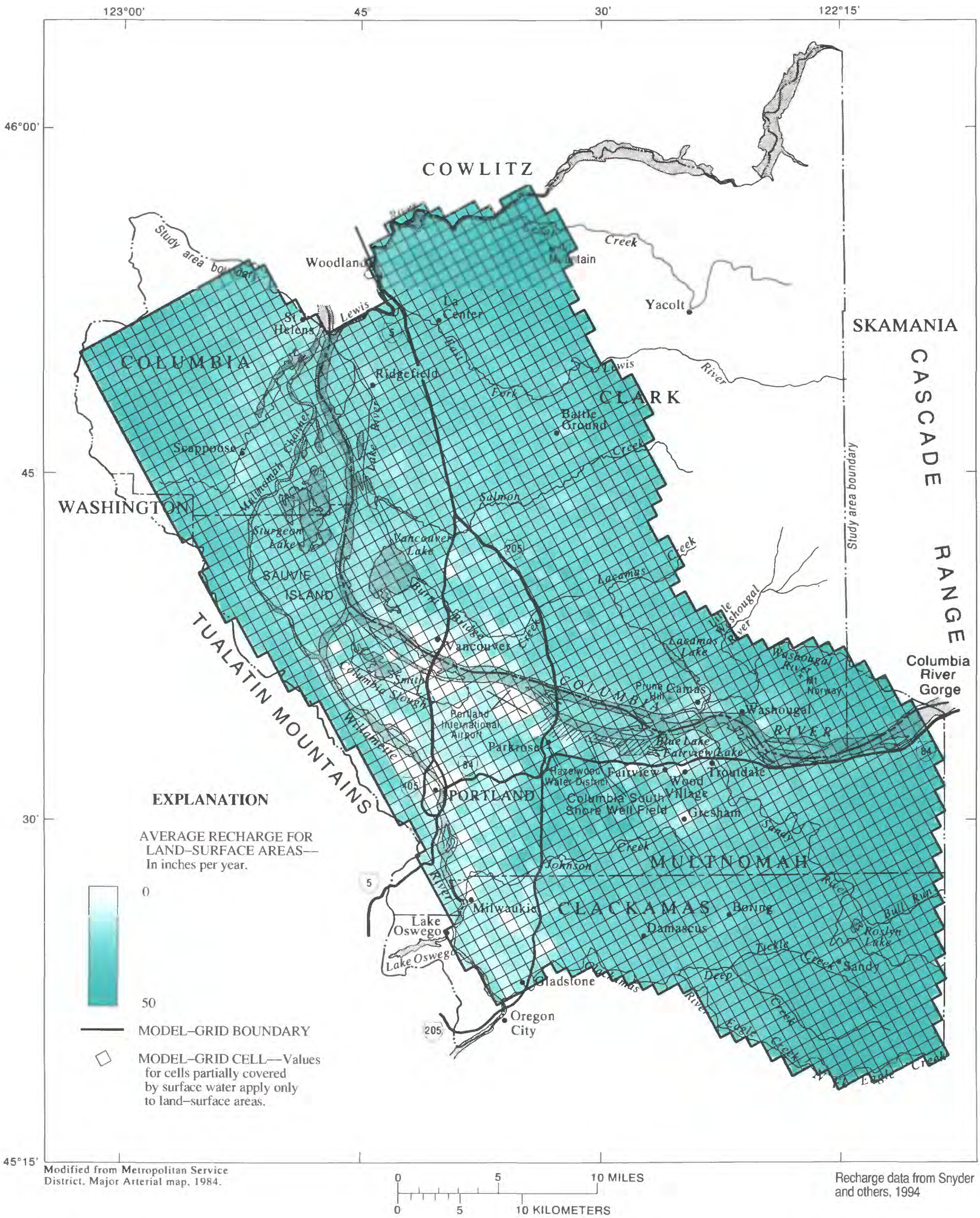


Figure 6. Distribution of average annual effective recharge from the infiltration of precipitation, runoff to drywells, and on-site waste-disposal systems.

ground-water model grid cells, where on-site waste-disposal systems are present, range from 0.1 to 26 inches per year, with a mean of 5.0 inches per year. In local urban areas, the combined recharge from runoff to drywells and from on-site waste-disposal systems may exceed 40 inches per year.

The average volume rate of recharge from all sources in the gridded area (981 square miles), including precipitation, drywells, and on-site waste-disposal systems, is 1,590 cubic feet per second or about 1,150,000 acre-feet per year. The average rate of recharge from these sources is 22.0 inches per year in the model grid area. An average of 20.8 inches per year of this recharge is from infiltration from precipitation. The distribution of the average rate of recharge is shown in figure 6.

The lowest recharge occurs along and between the Columbia and Willamette Rivers, where recharge is zero or slightly greater. The Tualatin and western Cascade Mountains have the greatest recharge rates in the grid area, about 49 inches per year. Localized areas of recharge also occur within the urban areas of Multnomah County, Oregon, and Clark County, Washington, as a result of drywells and on-site waste-disposal systems.

On a regional scale, the dominant component of recharge is infiltration of precipitation, which accounts for 94 percent of total recharge. Regional recharge from drywells is about 4 percent and from on-site waste-disposal systems is less than 2 percent of the total recharge. However, within the areas of inventoried drywells, recharge from precipitation is 45 percent of the total recharge in that area, drywell recharge makes up 38 percent of the recharge, and 17 percent is from on-site waste-disposal systems (Snyder and others, 1994).

Ground-Water Movement

Ground water generally moves from upland areas, such as the Tualatin Mountains, Boring Hills, or western Cascade Range, toward the major discharge points in the basin, such as the Columbia, Willamette, Lewis, and Clackamas Rivers. Upland areas generally have strong downward components of movement and can be classified as "recharge areas;" lowland areas generally have strong upward components of movement and can be classified as "discharge areas." In the Portland Basin, discharge areas are generally limited to narrow zones along the major streams.

Previous workers (Mundorff, 1964; Hogenson and Foxworthy, 1965) discussed the occurrence of "perched water" in the Portland Basin. Perched water as defined by Mundorff (1964) is where a zone of saturation is perched on the strata of low permeability above the main water table. A body of ground water is not considered to be perched unless there is unsaturated material between it and the main body of ground water. These areas described as perched ground-water bodies are areas with strong downward components of movement or recharge areas as described above.

Perched ground water is common in the shallowest water-bearing units throughout much of the Portland Basin. However, few wells tap these perched aquifers because small seasonal variations in water levels can significantly reduce the saturated thickness of the water-bearing zone. In some areas of the basin, wells that produce from these perched zones actually become dry during the summer months, when there is an increased need for water and reduced recharge.

Contour maps of water levels for the unconsolidated sedimentary aquifer, Troutdale gravel aquifer, Troutdale sandstone aquifer, and the sand and gravel aquifer are shown on plates 2–5. These maps show water levels in the aquifers during spring of 1988. Water levels shown for 1988 may reflect some residual drawdown from the pumping because the city of Portland pumped their well field heavily in September, October, and November 1987. Maps of ground-water flow directions were not constructed for the confining units because wells completed in those units are much less common than in the aquifers.

The saturated thickness of the unconsolidated sedimentary aquifer (pl. 2) probably changes throughout the year owing to seasonal fluctuations in recharge to the ground-water system. During the spring, the thickness of the zone of saturation is greatest and in the late summer and early fall water levels are lowest and, therefore, the saturated thickness is reduced. Fluctuations in the water table may cause the aquifer to be saturated only during the spring, because this aquifer is relatively thin in many areas; for this reason, many shallow wells penetrate a layer of variable saturated thickness.

Areas where the unconsolidated sedimentary aquifer may be seasonally unsaturated are shown on plate 2. These areas were delineated by subtracting the depth to water from the total thickness of the aquifer unit.

Depth to water was mapped on the basis of data from wells less than 100 feet deep throughout the basin. Vertical gradients in the basin made it necessary to select the shallowest wells possible to represent the water table and therefore the depth to water. All wells less than 100 feet deep, from the data base of more than 15,000 located and unlocated wells, were used to calculate minimum depth to water for specific areas.

For areas where adequate shallow well data were not available, a regression between land-surface altitude and the water-table altitude for wells in the basin was used to approximate the depth to water. The approach used was similar to that used by Williams and Williamson (1989). Data from 165 field-located wells less than 100 feet in depth were used to regress land-surface altitude against water-table altitude to derive the following linear equation:

$$SWLA = (0.98 \times LSA) - 19.5, \quad (2)$$

where

LSA = land-surface altitude at the well, and

$SWLA$ = static water-level altitude in the well.

The R-squared (coefficient of determination) for the regression is 0.997. Only the field-located wells were used because they have relatively accurate land-surface and static water-level altitudes as compared to the wells that were not field located. Equation 2 was then used with gridded land-surface altitude to calculate depth to water using the equation:

$$DTW = GLSA - \mathrm{ABS}\,\left|[(GLSA \times 0.98) - 19.5]\right|, \quad (3)$$

where

DTW = estimated depth to water for a grid cell, and

$GLSA$ = gridded land-surface altitude.

The gridded land-surface-altitude data for the area were derived for 3,000 by 3,000 foot grid areas that were later used for a ground-water model. The average altitude for each cell or area was estimated from the digital line graphs of the 1:100,000 scale topographic maps for the study area. Then, equation 3 was used to calculate the average depth to water for each gridded area. Where land-surface altitudes were less than 25 feet, however, equation 3 did not provide reasonable results. This inaccuracy may have been related to inaccuracies in estimating land-surface altitudes from 1:24,000 scale maps. In these cases, an alternate approach was used to assign depth to water for grid cells or areas with average land-surface altitudes less than 25 feet. Depth to water in these areas was set to 5 feet, which is reasonable for shallow wells completed in the unconsolidated sedimentary aquifer along the Columbia and Willamette flood plains.

In Oregon, the ground water in the unconsolidated sedimentary aquifer flows from an altitude of more than 200 feet in the Gresham area toward the Columbia and Willamette Rivers to the west and north (pl. 2). The shape of the water table in this aquifer appears to be a subdued facsimile of the topography. Hydraulic gradients in the terraces between Gresham and Mount Scott to the west are as little as 25 feet per mile. This area was referred to by Hogenson and Foxworthy (1965) as the "Portland terraces." Along the break in slope between the Portland terraces and the flood plains of the Columbia and the Willamette Rivers, the water table in the unconsolidated sedimentary aquifer has a much steeper hydraulic gradient—as much as 300 feet per mile (pl. 2). Hydraulic gradients in this aquifer beneath the flood plains of the Columbia and Willamette Rivers are just a few feet per mile.

The water table in Multnomah County east of the Portland city limits may be largely controlled by recharge from on-site waste-disposal systems as well as runoff to drywells. The installation of municipal sewer systems in east Multnomah County may cause measurable changes in the water table by decreasing the quantity of recharge from these two sources.

In Clark County, Washington, ground water in the unconsolidated sedimentary aquifer flows from more than 250 feet above sea level along the eastern extent of the aquifer (pl. 2) toward the Columbia River and other major streams. Gradients are generally steepest beneath the break in slope between the terraces and the Columbia River flood plain. A mound in the water table occurs just west of Orchards, where water levels are more than 250 feet above sea level. This mound may be a result of slightly lower hydraulic conductivities in the unconsolidated sedimentary aquifer or could be due to greater recharge to the ground-water system from on-site waste-disposal systems or drywells.

Salmon Creek and the East Fork Lewis River are significant discharge areas for the unconsolidated sedimentary aquifer. North of Salmon Creek in Clark

County, Washington, the water table is relatively complex due to the complex surface-water drainage in the area.

Parts of the unconsolidated sedimentary aquifer in the Yacolt and Chelatchie Prairie Basins and along the Lewis River near the northern border of Clark County are isolated from the rest of the Portland Basin. The aquifer can be an important source of water owing to the relatively low hydraulic conductivity of the underlying older rocks.

Water levels in the unconsolidated sediments in the Yacolt area are more than 650 feet above sea level, and ground-water movement is generally from northwest to southeast downgradient to Yacolt Creek. Ground-water movement in the unconsolidated sediments in the Chelatchie Prairie area is generally from east to west, and the water table slopes from more than 500 feet above sea level to 400 feet above sea level.

Water-level data for the Troutdale gravel aquifer have the best areal coverage and, therefore, provide the best definition of ground-water flow directions, as compared with the other aquifers (pl. 3). In addition, Mundorff (1964) published a water-level contour map for Clark County that represents the 1949 to 1950 period for the Troutdale gravel aquifer. These two maps allow a comparison of water levels between two time periods, separated by 40 years.

Water levels in the Troutdale gravel aquifer in the spring of 1988 were highest in the southeastern part of the study area, near Sandy, Oregon, where water levels are more than 900 feet above sea level. East of the Sandy River, water levels are more than 1,400 feet above sea level; however, limited data are available in that area. In that area, the Troutdale gravel aquifer includes thick accumulations of High Cascades Lavas. The Sandy River has completely eroded the Troutdale gravel aquifer, separating the aquifer east of the Sandy River from the aquifer west of the Sandy River.

In the area of the Boring Hills, which extends from Mount Scott just southeast of Portland to the Boring area, a ground-water divide is present (pl. 3). Ground-water levels along this divide are as high as 500 to 600 feet above sea level, although some of these water levels could be considered perched. The Boring Lavas that underlie the Boring Hills and are included in the Troutdale gravel aquifer may cause water levels to remain elevated in that area. The regional water levels may not exceed 400 feet above sea level, but few data are available to support this supposition. To the north of the divide, ground water moves toward the Columbia River, and to the south of the divide ground water moves toward the Clackamas River. Throughout the rest of the Oregon side of the study area, ground water moves toward the Willamette and Columbia Rivers.

In Clark County, Washington, the Troutdale gravel aquifer does not include large amounts of Boring or High Cascades Lavas. Water levels are highest in the Mount Norway area, where they exceed 900 feet above sea level (pl. 3). Ground water in the Troutdale gravel aquifer moves southward toward the Columbia River. Throughout the rest of Clark County, water levels generally are highest in the eastern part of the county, along the western flank of the Cascades; ground water moves toward the Columbia River, East Fork Lewis and Lewis Rivers, and Salmon Creek. Mundorff's (1964) map of water levels in the upper member of the Troutdale Formation (pl. 6) shows similar ground-water flow directions; however, some contours have shifted to the north in the past 40 years. This shift is most evident from the 150 foot contour just west of Prune Hill. Comparison of plates 3 and 6 show that this contour is positioned 1.5 to 2 miles to the northeast of the same contour for the 1949–50 map. This comparison would suggest that some stress to the aquifer system had caused the change in water levels, and that the decline possibly has been 10 feet or more. The 100 foot contour also has moved approximately 0.5 miles to the northeast.

In the Troutdale sandstone aquifer, water levels are highest near Sandy, Oregon, and are more than 700 feet above sea level (pl. 4). From the area of high water levels, ground water moves generally to the northwest toward the Columbia River. Water levels are mounded in the vicinity of the Boring Hills, just east of Damascus, Oregon, and water levels in the Troutdale sandstone aquifer also show that ground water moves toward the Clackamas River. Tickle, Deep, and Noyer Creeks cut deeply through the Troutdale gravel aquifer in the Sandy-Boring area. Ground-water flow directions within the Troutdale gravel aquifer in that area are controlled by these streams, and a significant quantity of seepage occurs along the canyon walls, which are a major discharge area for aquifers in the area. Seepage measurements along the streams show gains of approximately 1 to 2.5 cubic feet per second per stream mile in the Sandy-Boring area (table 3, following "Selected References").

In the vicinity of Gresham, Oregon, the movement of ground water in the Troutdale sandstone aquifer is almost directly northward toward the Columbia River. Hydraulic gradients in that area range from about 50 to 100 feet per mile.

The erosional character of the Troutdale sandstone aquifer appears to have a controlling influence on the ground-water movement directions and the discharge from the aquifer. The eastern, updip edge of the sandstone aquifer near the Columbia River has been eroded by the Columbia River and forms an upstream, V-shaped, outcrop pattern. The Blue Lake area is part of this eroded area. Water levels in the Troutdale sandstone aquifer indicate that the Blue Lake area also may be an important discharge area for this aquifer (pl. 4). Water levels in the aquifer become equivalent to the water levels in the unconsolidated sedimentary aquifer, which is in hydraulic connection with the Columbia River.

East of the Sandy River in Oregon, water-level data for the Troutdale sandstone aquifer are sparse; ground-water movement is probably toward the Sandy and Columbia Rivers.

In Clark County, Washington, the Troutdale sandstone aquifer has the highest water levels in the northeastern and eastern extent of the unit. Water levels are more than 200 feet above sea level and the primary ground-water movement direction is to the southwest toward the Columbia River.

Ground-water flow directions in the sand and gravel aquifer generally are toward the Columbia River (pl. 5). In east Multnomah County, Oregon, movement is generally toward the vicinity of Blue and Fairview Lakes on the south shore of the Columbia River. The highest water levels in that area are approximately 30 feet above sea level at the southwestern extent of the unit, and movement is generally to the northeast. The lowest water levels are north of Blue Lake, where the water levels in the sand and gravel aquifer are equivalent to Columbia River stage.

The discharge of ground water from the sand and gravel aquifer in the Blue Lake area probably results from the erosional contact of the aquifer with younger sediments that are in hydraulic connection with the Columbia River. North of Blue Lake, confining unit 1, the Troutdale gravel aquifer, confining unit 2, and the Troutdale sandstone aquifer have been removed by erosion, and the sand and gravel aquifer is in direct contact with the unconsolidated sedimentary aquifer, where the contact is between 100 and 200 feet below land surface.

Piezometers in the Blue Lake area indicate that water from the sand and gravel aquifer discharges to the unconsolidated sedimentary aquifer. The deepest piezometers in the sand and gravel aquifer have higher hydraulic heads than the hydraulic head in the unconsolidated sedimentary aquifer.

Along the southeastern extent of the sand and gravel aquifer, along the Sandy River and east of the Sandy River, sparse data indicate water levels as high as 130 feet above sea level. Ground water in the sand and gravel aquifer is assumed to move toward the Columbia and Sandy Rivers.

Where the sand and gravel aquifer occurs south of the Washougal River in Washington, ground water moves southwestward toward the Columbia River. Water levels range from more than 500 feet above sea level beneath Mount Norway to near river levels adjacent to the river.

Water-level data in the older rocks are available only near the edge of the basin. In general, the water levels indicate movement toward the major discharge areas in the basin. Where the Columbia River Basalt Group has been tapped in the southeastern part of the basin, water levels are significantly lower than water levels in the overlying sediments.

Discharge

Ground-water discharge in the Portland Basin is primarily to springs, streams, and wells. Springs in the basin are most common along the Columbia and Willamette Rivers, but springs also occur along other major streams in the basin. In many areas, the springs occur where the contact between the unconsolidated sedimentary aquifer and less permeable underlying material occurs at the land surface. Streams are important discharge areas throughout most of the basin, with the exception of the east Multnomah County, Oregon area, where the sediments are extremely permeable and little ground-water discharge to streams occurs.

Pumpage from wells is also an important component of discharge from the ground-water system. In Clark County, Washington, ground water is the primary source of drinking water. In the Oregon part of the basin, most of the water for public use comes from the Bull Run watershed. There are also significant uses of ground water for backup municipal, irrigation, and domestic-water supplies.

Springs

Mundorff (1964) described springs in Clark County, Washington, along the Columbia River and showed the importance of these springs in terms of discharge from the ground-water system. He measured all major spring discharge between Vancouver, Washington, and Prune Hill, located just west of Camas, Washington, in the spring of 1949. Mundorff found that approximately 35 cubic feet per second of ground water was discharged near the contact between the unconsolidated sedimentary aquifer and the Troutdale gravel aquifer in that area. The largest springs in Clark County are Ellsworth Springs.

Hogenson and Foxworthy (1965) also measured spring discharge in the basin in Oregon; however, spring discharge did not appear to be as significant as on the Washington side of the Columbia River. Springs do occur on the south side of the Columbia River between the Portland International Airport and Troutdale, Oregon. The largest springs in the Portland Basin are Crystal Springs, which are located along the Willamette River in Oregon. These springs were not measured by Hogenson and Foxworthy, and little historic discharge data are available for them.

In this study, discharge measurements were made on all known springs in the basin with discharge greater than 0.1 cubic feet per second. Forty-two springs were measured, mainly along the Columbia and Willamette Rivers. Historic measurements and measurements during this study are listed in table 1. Locations for the springs are given by McCarthy and Anderson (1990).

The most significant changes in spring discharges have occurred in Clark County. In this study, most of the spring discharges measured in 1949 by Mundorff (1964) were remeasured. The spring discharges that could not be measured do not have 1988 measurements in table 1. Only one spring-fed stream (1N/2E-3K) measured by Mundorff (1964) is not listed in the table. That stream was a significant part (about 39 percent) of the total 35 cubic feet per second measured by Mundorff. The stream was not measured in this study owing to uncertainty that the stream was entirely fed by springs. For this reason, only the Fish Hatchery spring (1N/2E-3ACC1(G)), which discharges into that stream, was measured. The springs measured in 1949 in Clark County had a total discharge of 11,110 gallons per minute (25 cubic feet per second), and measurements made during this study gave a total dis- charge of 6,470 gallons per minute (14.5 cubic feet per second)—a decrease in spring flow of approximately 42 percent since 1949.

The ratio of the change in spring flow from 1 949 to measurements made during this study (table 1) show that a few springs did not have significant changes in discharge. These springs include 1N/2E-2DCB1(Q), 1N/2E-3BCA1(E), 1N/2E-3DAA1(J), and 2N/3E- 7DAA1(J). One spring, 1N/2E-4AAC1(A) had a slightly higher discharge than the discharge estimated by Mundorff in 1949. The remaining springs measured in Clark County had decreased discharge rates. The spring located at 1N/3E-7BDB1(F) and the Fish Hatchery spring (1N/2E-3ACC1(G)) had the greatest decreases in discharge. The current discharge at these springs is less than 5 percent and less than 20 percent, respectively, of the discharge in 1949.

The decreases in spring discharge and also the degradation of the quality of water discharged from springs in Clark County has affected some of the major uses of spring water in the county. Ellsworth Springs has not had a significant change in discharge during the past 40 years, but there have been increased nitrate concentrations measured at the springs. Beginning in the late 1800's, the city of Vancouver used Ellsworth Springs as a source of drinking water (Arvid Grant and Associates, 1974). The city of Vancouver used approximately 4 million gallons per day from the springs to supply as much as 20 percent of its peak demand. As development east of Vancouver took place, the water quality at the springs deteriorated (increased nitrate concentrations) such that the springs could no longer be used for a public supply of drinking water. Vancouver discontinued use of the springs in September of 1973. This loss of the springs caused the city of Vancouver to rely more heavily on wells as a source of water.

The springs at the Vancouver Fish Hatchery were at one time the sole source of water for rearing fish. However, in recent years, the discharge at the springs has declined significantly (table 1). Due to this lack of available spring discharge, the Washington Department of Game was forced to drill supply wells to keep the hatchery in operation. At least two wells that were drilled upgradient from the hatchery had poor yields, and finally a well more than 1,000 feet deep, which supplied an adequate supply of water, was drilled at the hatchery site.

In the Oregon part of the study area in 1988, the total discharge from the measured springs (table 1) was 7,205 gallons per minute (16 cubic feet per

Table 1. Spring discharge

[*, location number from Mundorff (1964); **, location number from Hogenson and Foxworthy (1965); e, estimated discharge measurement; --, owner or spring name unknown; Q, discharge; gal/min, gallons per minute; Ellsworth Springs discharge is total of three springs listed]

Number					Discharge measurement			
Spring location	Spring identification	Owner	Spring name	Altitude	Q (gal/min)	Date	Remarks	Ratio of discharge 1949 to 1988
			Clark County, Washington					
1N/2E-2CBA1(M)	108	--	--	50	1,760	4/11/49	1N/2E/2M1s*	0.5
					898	5/24/88		
1N/2E-2DCA1(Q)	107	--	--	50	675	4/11/49	1N/2E-2Q1s*	.51
					346	5/24/88		
1N/2E-2DCB1(Q)	106	A.W. King	--	100	280	4/11/49	1N/2E-12C1s*	.96
					269	5/25/88		
1N/2E-3ACC1(G)	110	Washington Dept. of Game	--	70	e1,200–1,500	4/--/49	1N/2E-3G1s*	0.14–0.18
					213	9/24/90		
1N/2E-3BCA1(E)	112	--	--	60	e200	4/11/49	1N/2E-3E1s	1.01
					202	4/10/88		
1N/2E-3BDC1(F)	111	--	--	45	610	4/11/49	1N/2E-3F1s*	
1N/2E-3DAA1(J)	109	Wood	--	50	665	4/18/49	1N/2E-3J2s*	1.03
					682	5/24/88		
1N/2E-4AAC1(A)	113	McMillian	--	100	200	4/11/49	1N/2E-4B2s*	1.25–1.50
					e250–300	5/10/88		
1N/2E-4ABA1(B)	114	Baranovitch	--	100	1330	4/11/49	1N/2E-4B1s*	--
1N/2E-4BBB1(D)	116	Laderas	--	100	e75	4/15/49	1N/2E-4D1s*	.67
					50	5/10/88		
1N/2E-12ABA1(B)	105	Groenwalt	--	150	e225	4/11/49	1N/2E-12B1s*	--
1N/3E-7BBD1(D)	104			50	550	4/11/49	1N/3E-7E1s*	.46
					256	5/25/88		
1N/3E-7BDA1(F)	101	--	--	60	520	4/19/49	1N/3E-7G1s*	.51
					269	5/25/88		
1N/3E/7BDA2(F)	102	--	--	60	185	4/18/49	1N/3E-7F2s*	.32
					60	5/25/88		
1N/3E-7BDB1(F)	103	--	--	60	100	4/18/49	1N/3E-7F1s*	.045
					4.5	5/25/88		
2N/3E-7DAA1(J)	118	Kendal	--	150	e100	4/15/49	2N/2E-31J1s*	1.07
					107	5/10/88		
2N/2E-32DCA1(Q)	117	Jordan	--	145	e50	4/15/49	2N/2E-32Q1s*	.44
2N/2E-33CAC1(L)	119	City of Vancouver	Ellsworth Springs	220	2,085	10/15/45	2N/2E-33L1s*	1.34
2N/2E-33CAD1(L)	115	City of Vancouver	Ellsworth Springs	220			2N/2E-33Pls*	
2N/2E-33CBB1(M)	120	City of Vancouver	Ellsworth Springs	220	2,790	4/28/88	2N/2E-33M1s*	
			Clackamas County, Oregon					
1S/1E-36ADB(H)	17	--	Minthorne Spring	88	800	9/9/88		
1S/1E-36BDA1(F)	21	Joe Paulanski	Spring Creek	87	539	9/9/88		
2S/1E-1CCB1(N)	19	Gregory Dollowitch	Courtney Spring East	167	9	7/25/88		
2S/3E-9CAD1(L)	20	--	Elliott Springs	410	33	7/26/88		
			Multnomah County, Oregon					
1S/2E-23BAB1(D)	1	--	--	7	700	--/--/59	1N/2E-23D1s**	
1N/3E-25BCC1(E)	2	D & D Bennett Co.	Spence Spring	70	335	2/12/57	1N/3E-26H2s**	.35
					116	7/14/88		
1N/3E-25CBC1(M)	3	City of Troutdale	--	155	75	7/12/88	--	

Table 1. Spring discharge—Continued

Number					Discharge measurement			
Spring location	Spring identification	Owner	Spring name	Altitude	Q (gal/min)	Date	Remarks	Ratio of discharge 1949 to 1988
			Multnomah County, Oregon—Continued					
1N/3E-26ACC1(G)	6	Union Pacific Railroad	Stromboli Spring	60	135 81	2/12/57 7/18/88	1N/3E-26G1s**	.6
1N/3E-26AAD1(A)	4	Harvey Rossi	Rossi Spring	65	20 183	2/12/57 7/13/88	1N/3E-26H3s**	.89
1N/3E-26ADD2(H)	5	Union Pacific Railroad	--	50	5 5	2/12/57 7/14/88	1N/3E-26H4s**	1.0
N/3E-34AAD1(A)	7	City of Wood Village	Arata Spring	248	8 20	7/18/88 5/28/37	1N/3E-34A2s**	
1N/3E-35BBC1(D)	8	County of Multnomah	--	265	20 22	5/28/37 7/18/88	Total corresponds to 1N/3E-35D1s*	1.1 1.3
1N/3E-35BBC2(D)	9	County of Multnomah	--	270	23 30	5/28/37 7/18/88		
1S/1E-13CACC1(L)	12	City of Portland	Crystal Springs	85	675	11/18/88		
S/1E-13CBDA1(M)	11	City of Portland	Crystal Springs	2	900	11/18/88		
1S/1E-13CCAD1(N)	13	City of Portland	Crystal Springs	75	1,000	11/18/88		
1S/1E-13CCDA1(N)	14	City of Portland	Crystal Springs	70	500	11/18/88		
1S/1E-13CDBC1(P)	15	Eastmoreland Golf	Crystal Springs	75	360	11/18/88		
1S/1E-13DABB(J)	22	Reed College	Crystals Springs	110	359	12/28/88		
S/1E-13DBAD1(K)	10	Andris	Crystal Springs	108	359	11/28/88		
1S/1E-24BABB1(C)	16	Eastmoreland Golf Course	Crystal Springs	85	900	11/18/88		
1S/2E-19CDA1(P)	18	--	Errol Springs	110	251	8/11/88		

second). Most of this discharge was at Crystal Springs, a group of at least eight large springs in 1S/1E-13. The discharge at Crystal Springs has not been regularly monitored in the past, and the measurements done during this study accurately document the spring locations and discharge for the first time. The discharge at Crystal Springs in 1988 was 5,300 gallons per minute (11.8 cubic feet per second).

Crystal Springs was proposed for use by the city of Portland in 1886 to supplement the public drinking-water system for the city. However, the proposal was rejected in favor of establishing the Bull Run watershed. The springs were never used as a drinking-water supply. In 1872, an engineer estimated that the discharge of Crystal Springs was at least 8 million gallons per day (12.4 cubic feet per second). In comparison with these older measurements, measurements during this study show that the discharge of the springs has probably remained approximately the same. However, nitrate concentrations measured by the U.S. Geological Survey in 1977 were 7.1 milligrams per liter, which is close to the recommended maximum contaminant level of 10 milligrams per liter established by the EPA. Therefore, any future use of the water from Crystal Springs may not be limited by the quantity of water available but by the quality.

Some springs in Oregon show changes in discharge rates from measurements done by Hogenson and Foxworthy (1965). The greatest decrease occurred at Spence Spring in 1N/3E-25BCC1(E) where the discharge in 1988 was 35 percent of the discharge in 1957 (table 1). Stromboli Spring, 1N/3E-26ACC1(G), was the only other spring with a significant decrease in discharge. All other springs remained about the same where data were available for comparison.

Spring discharge in Oregon also appears to occur along the Columbia Slough, in the flood plain of the Columbia River. The slough drains farm and industrial land in the flood plain and is the final discharge area for stormwater systems in east Multnomah County, Oregon. Hogenson and Foxworthy (1965) measured one spring that discharges into the slough (1N/2E-23BB1S(D)) at 700 gallons per minute and noted that several other springs issue into the slough. They also indicated that the discharge from the springs was dependent on Columbia River stage. The measurement of discharge to and from the slough was not within the scope of this study. In the absence of either synoptic or long-term measurements of discharge in the slough, and because of the complex relation between springs, storm runoff, and Columbia River seepage, determining the magnitude and duration of spring discharge to the Columbia Slough was beyond the scope of this study.

Streams

The largest component of ground-water discharge in the Portland Basin is to streams. To quantify this discharge, seepage measurements were made on all measurable streams in the basin during September and October of 1987 and 1988. These measurements did not include the Columbia and Willamette Rivers because their large discharge in relation to the small quantity of seepage made measurement impractical. The seepage measurements for the measurable streams are listed in table 3 (at back of report), and the location of the measurement sites are shown on plate 1.

In table 3, the discharge measurements for the major streams and their tributaries are listed, as well as seepage per stream mile. In addition, the average major stream and tributary discharges are listed, as well as average seepage per stream mile for 1987 and 1988. Positive values of seepage indicate that the stream has gained water from the ground-water system and negative values indicate that the stream has lost water to the aquifer system. Data listed in table 3 for the Sandy River may be questionable owing to the regulation of discharge on the Bull Run River. Releases from Roslyn Lake may have affected measurements both years.

For most streams in the basin, the 1987 streamflow measurements are probably the best estimate of ground-water leakage to the streams. The streamflow measurements show that water year 1987 had less precipitation than water year 1988 (fig. 3). Discharge measurements were generally lower in 1987 than in 1988. This sparse rainfall in 1987 was evident in the discharge measurements for the Bull Run River, where discharge was approximately 7 cubic feet per second compared with 160 cubic feet per second in 1988. The low flow in 1987 was due to the maximum drawdown that occurred in the Bull Run Reservoirs as a result of below average precipitation. Rainfall was 29.91 inches in 1987 and 31.63 inches in 1988 at Portland International Airport.

Most streams in the basin are gaining streams (table 3). East Fork Lewis River has the largest gain per stream mile, where, in its upper reaches, it gains nearly 10 cubic feet per second per stream mile. Other streams, like the Sandy River, Salmon Creek, and Johnson Creek, show gains of generally less than 5 cubic feet per second per stream mile.

The Sandy River is the only stream that has losses of greater than 1 cubic foot per second per stream mile. However, these measurements may not reflect the actual seepage owing to the release of water from the Bull Run River system.

Pumpage from Wells

Ground-water use in the Portland Basin fits into three general categories. These categories in order of decreasing quantity of water pumped are industrial, public supply, and irrigation.

In this study, an attempt was made to reconstruct historic pumpage as accurately as the data would allow. However, it was found that the data were insufficient to estimate the ground-water use in the basin during early years of development. Alternatively, pumpage was estimated for 1987 and 1988 because the data were readily available from most of the users. A complete and detailed discussion of the collection and estimates of pumpage for the basin can be found in Collins and Broad (1993). The distribution of total pumpage from all uses in 1988 is shown in figure 7.

Sites used only for domestic purposes were excluded because the total volume of ground water pumped from domestic wells in the basin is small. Although there were about 14,000 domestic wells in the basin, it is estimated that their combined pumpage

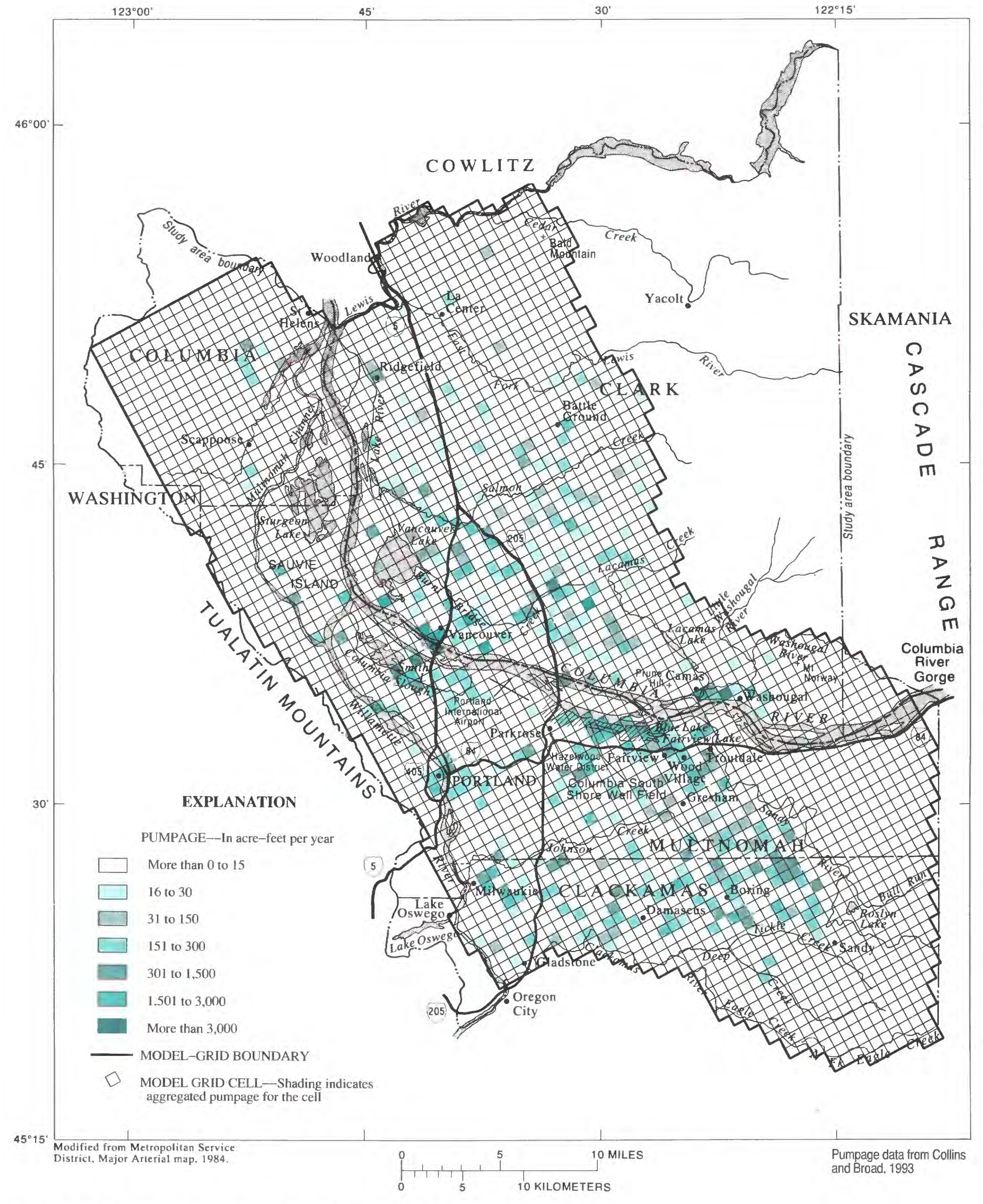


Figure 7. Total ground-water pumpage in the Portland Basin, 1988.

is less than 3 percent of the total ground water pumped.

Industrial and public-supply users generally have good to excellent records of pumpage and were interviewed to obtain this information. Where possible, flowmeter data were collected to verify the estimates given in the interviews.

Significant industrial use of ground water occurs in areas of Portland and Vancouver near the Willamette and Columbia Rivers, such as at the James River Corporation paper plant near Camas, Washington, and at Reynolds Metals Company in Troutdale, Oregon. Industrial ground-water use accounted for approximately 50 percent of the ground water pumped in the Portland Basin for 1987 and 1988 (table 2). Total industrial pumpage was about 63,400 acre-feet in 1987 and about 65,500 acre-feet in 1988 from approximately 93 wells. Many of these industrial wells are completed in the unconsolidated sedimentary aquifer adjacent to the Columbia River and can produce 4,000 to 6,000 gallons per minute with less than 20 feet of drawdown.

Public-supply use accounts for approximately 40 percent of the ground water pumped in the basin, and much of this water is used in Clark County, Washington. In 1987, pumpage for public supply in the basin was about 58,100 acre-feet, and in 1988 about 43,200 acre-feet was pumped from 154 wells. The 1987 estimate is significantly greater than the 1988 estimate because 1987 was a dry year in which the city of Portland was forced to use the supply wells along the south shore of the Columbia River.

Table 2. Ground-water pumpage in the Portland Basin, 1987 and 1988

[*, number of wells indicated for city of Vancouver is actually number of pumping stations. Each station may have multiple wells; PUD, Public Utility District]

	1987 (acre-feet)	1988 (acre-feet)	Percent of 1987–88 average	Number of total wells
		Type of Use		
Industrial	63,360	65,510	50	93
Public	58,090	43,200	40	154
Irrigation	14,360	12,000	10	252
Total (rounded)	135,800	120,700	100	499
		Major Public Supply Users		
City of Vancouver	22,890	23,900	36	9*
City of Portland	15,440	100	12	22
Clark County PUD	6,250	6,000	9	18

In average years, the city of Portland obtains all of its water from the Bull Run watershed. In such years, more than 50 percent of the ground water pumped from the basin for public supply is used in Clark County by the city of Vancouver and Clark County Public Utility District (PUD) (fig.7). The Portland well field was pumped for a 3-month period in 1987 from late September to early December, when the first significant rainfall occurred (fig. 3). During that period, Portland used more than 15,000 acre-feet of ground water. Although Portland normally does not use their well field, estimates made in 1987 show that the well field has the potential to withdraw a significant amount of water from the ground-water system.

Most of the ground water used in Clark County for public supply is pumped from near and east of Vancouver. Lesser amounts are used in the more rural parts of Clark County, although the Clark County PUD does provide public water to many rural communities. Water systems in several small towns in Clark County, including Ridgefield, La Center, Yacolt, Camas, and Washougal, obtain water from wells.

In Oregon, public-supply needs of most communities within the study area are served by the Portland Water Bureau. However, several small water districts in eastern Multnomah County and northern Clackamas County, as well as several cities, have their own well fields. Several water districts have been annexed by Portland. These water districts include Parkrose and Hazelwood water districts. Cities in Oregon with well fields include Troutdale, Fairview, Damascus, Happy Valley, and Milwaukie. In 1988, Milwaukie temporarily discontinued use of its wells owing to ground-water contamination in that area.

Irrigation use in the basin is relatively small owing to the abundant precipitation in the basin. In 1987, irrigation pumpage totaled approximately 14,360 acre-feet and in 1988 approximately 12,000 acre-feet from 252 wells. For the 1987–88 period, irrigation accounted for approximately 10 percent of the ground-water use in the basin (table 2). The most significant area of ground-water use for irrigation in the basin is in the Sandy-Boring area. This southeastern part of the basin has many large nursery farms. These nurseries grow in-ground and container plants. Container plants require large quantities of water, especially during the dry months of the year. The extensive use of ground water for irrigation on these farms has caused a significant local stress on the ground-water system.

Evapotranspiration

In many parts of the Western United States, evapotranspiration can be an important component of ground-water discharge, especially in desert climates where plants rely on shallow (less than 10 feet to water) ground water during much of the year. West of the Cascade Range in the Portland Basin, however, average annual temperatures are about 50 degrees Fahrenheit and average annual precipitation is about 41 inches.

In the Portland Basin, evapotranspiration is probably small during the winter, early spring, and late fall seasons owing to the relatively cool temperatures. However, in the summer evapotranspiration may be important primarily in areas where shallow ground water occurs, such as along the Columbia River flood plain. Areas in the basin with water levels less than 10 feet below land surface probably represent less than 5 percent of the total basin area.

Because evapotranspiration is not considered an important component of ground-water discharge in the basin, it was not studied in detail. However, evapotranspiration and other factors that could reduce the available water for ground-water recharge was accounted for in recharge calculations using the deep percolation model of Bauer and Vaccaro (1987).

Water-Level Fluctuations

Fluctuation of water levels in wells in the Portland Basin are caused by variations in recharge from precipitation, runoff to drywells, recharge from streams, and pumping of water from wells. A selected group of about 150 wells was measured on a bimonthly basis and all measurable located wells (approximately 800) were measured during synoptic water-level measurement runs. The bimonthly wells were measured to determine whether the ground-water system was in equilibrium; that is, whether there were any changes with respect to time other than those induced by natural causes such as annual and long-term variations in precipitation. Synoptic measurements were used to define flow directions in the ground-water system at a particular time and also to define areal rises or declines in water levels in each unit from 1988 to 1989.

Two types of wells, those with and those without long-term historical records, were measured on a bimonthly or more frequent basis. In many cases, wells that have a long historical record are part of an observation-well network, and are measured by the Oregon Water Resources Department or Washington Department of Ecology. Although only 26 in number, records of these wells are valuable in terms of identifying long-term trends in water levels. Hydrographs from most of the bimonthly and long-term observation wells for this study can be found in McCarthy and Anderson (1990).

Comparisons of several of the hydrographs for the 1987–90 period, such as those for wells 2S/2E-4DCC(Q), 1N/3E-31CDCD2(P), and 2N/1E-23 CBA1(M) (fig. 8), to the total monthly precipitation for Portland International Airport (fig. 3) show that water-level fluctuations were strongly related to variations in recharge from precipitation. Wells that are not influenced by pumping or by changes in streamflow generally had their highest water levels in February or March and lowest water levels from August through October.

Clackamas County, Oregon

Hydrographs of bimonthly measured wells in Clackamas County (fig. 8) show that most water levels fluctuated with precipitation; however, the slight increase in March water levels for wells 1S/2E-29BCA2(E) and 1S/2E-34CDB1(P) in the Milwaukie area of Clackamas County was probably related to a decrease in pumping by the city of Milwaukie during that period. Fluctuations in water level in well 2S/2E-4DCC(Q), 0.5 mile north of the town of Clackamas, appear to be directly related to the variability in precipitation throughout the year.

Data for several of the observation wells in Clackamas County (fig. 9) indicate that long-term water-level declines are occurring in some areas. For example, wells 2S/2E-15BBB(D), 2S/3E-6BDB(F), 2S/3E-10BAC(C), and 2S/4E-5CBB(M) all had declines of 10 to 20 feet from 1960 to 1990. An abrupt decline of about 10 feet in well 2S/2E-15BBB(D) in 1976 may have been related to a change in use, nearby open-pit mining of aggregate, or both. The steady water-level decline in well 2S/3E-6BDB(F), west of

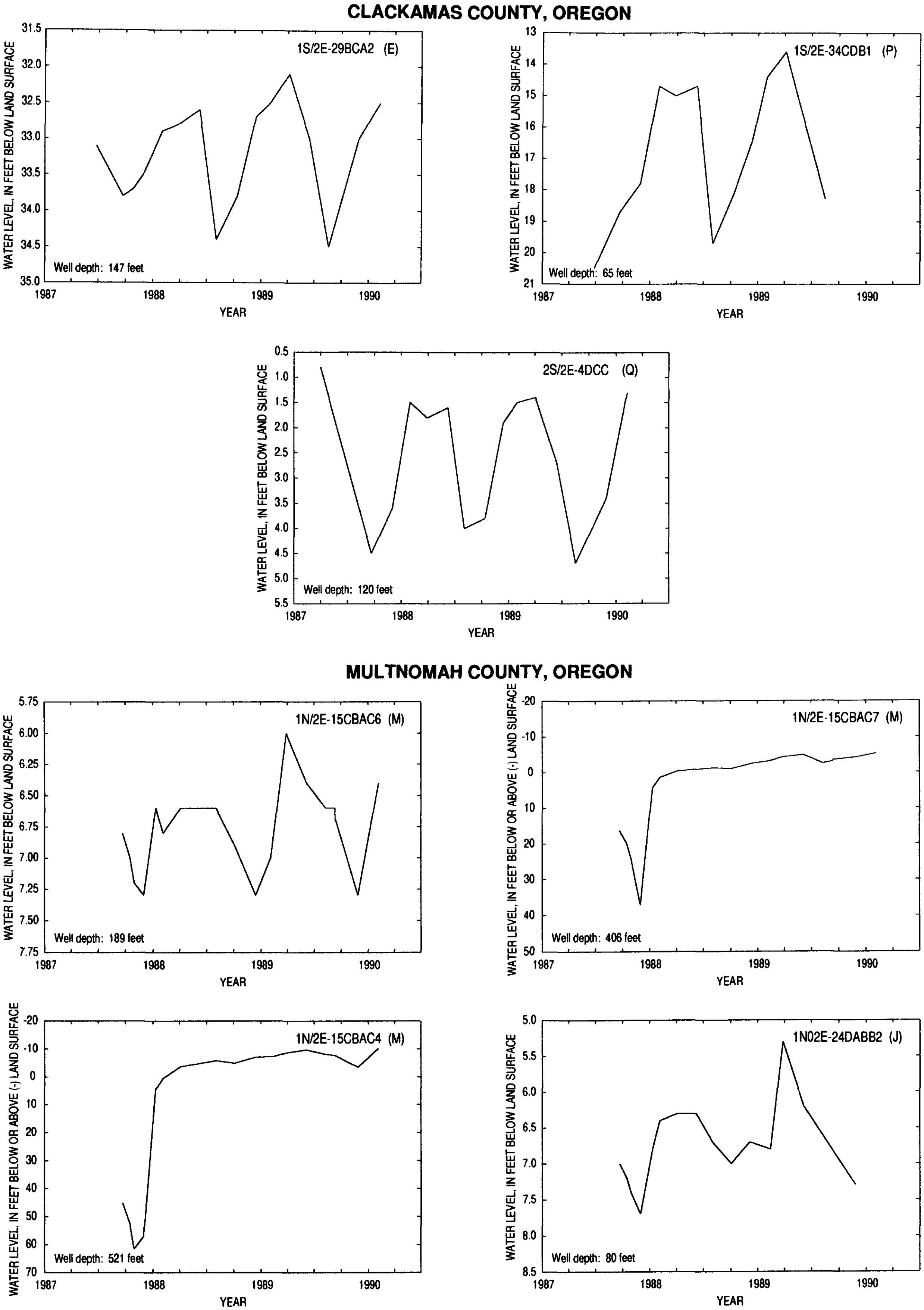


Figure 8. Selected water-level hydrographs 1987–90.

MULTNOMAH COUNTY, OREGON

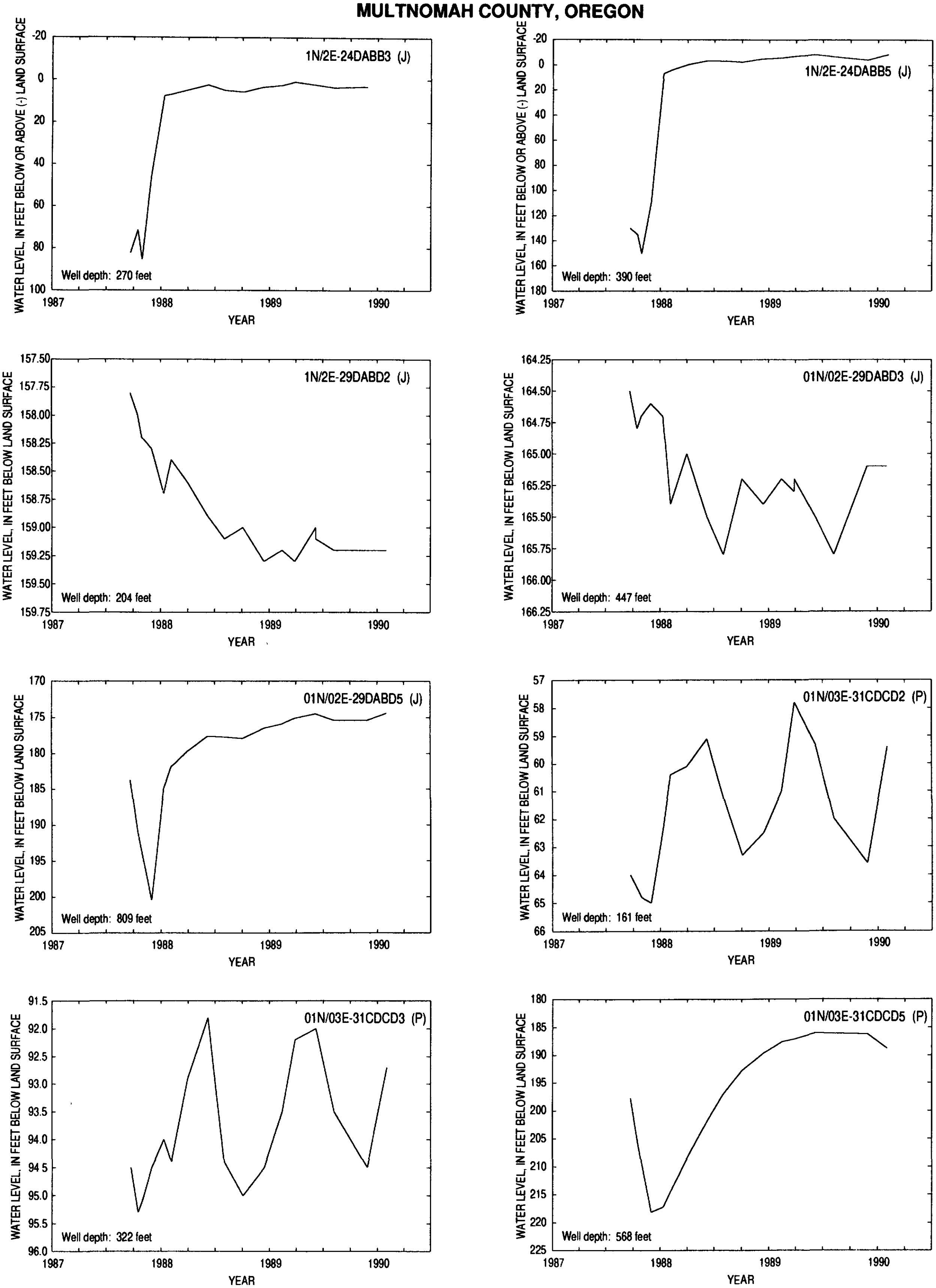


Figure 8. Selected water-level hydrographs 1987–90—Continued.

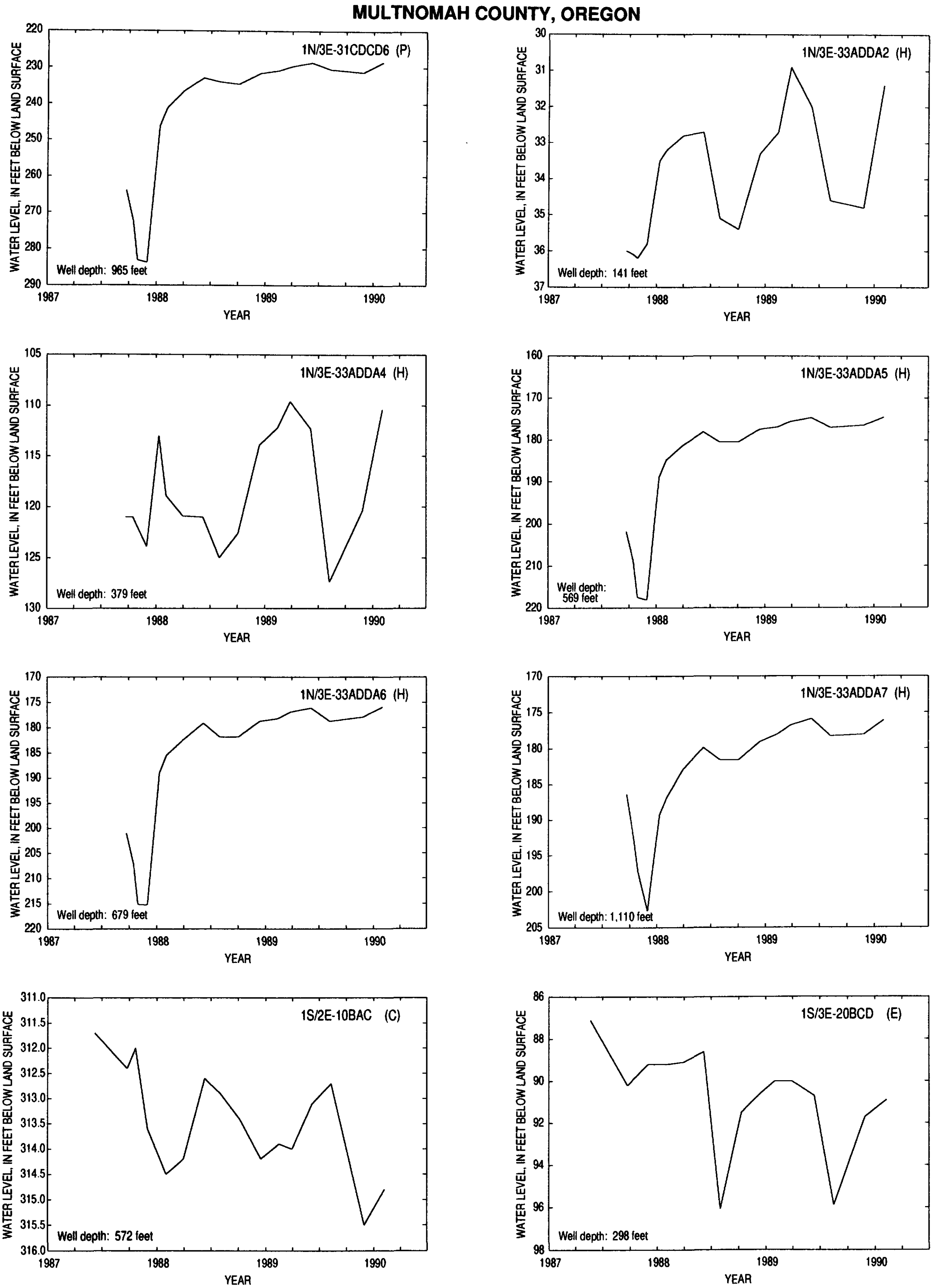


Figure 8. Selected water-level hydrographs 1987–90—Continued.

CLARK COUNTY, WASHINGTON

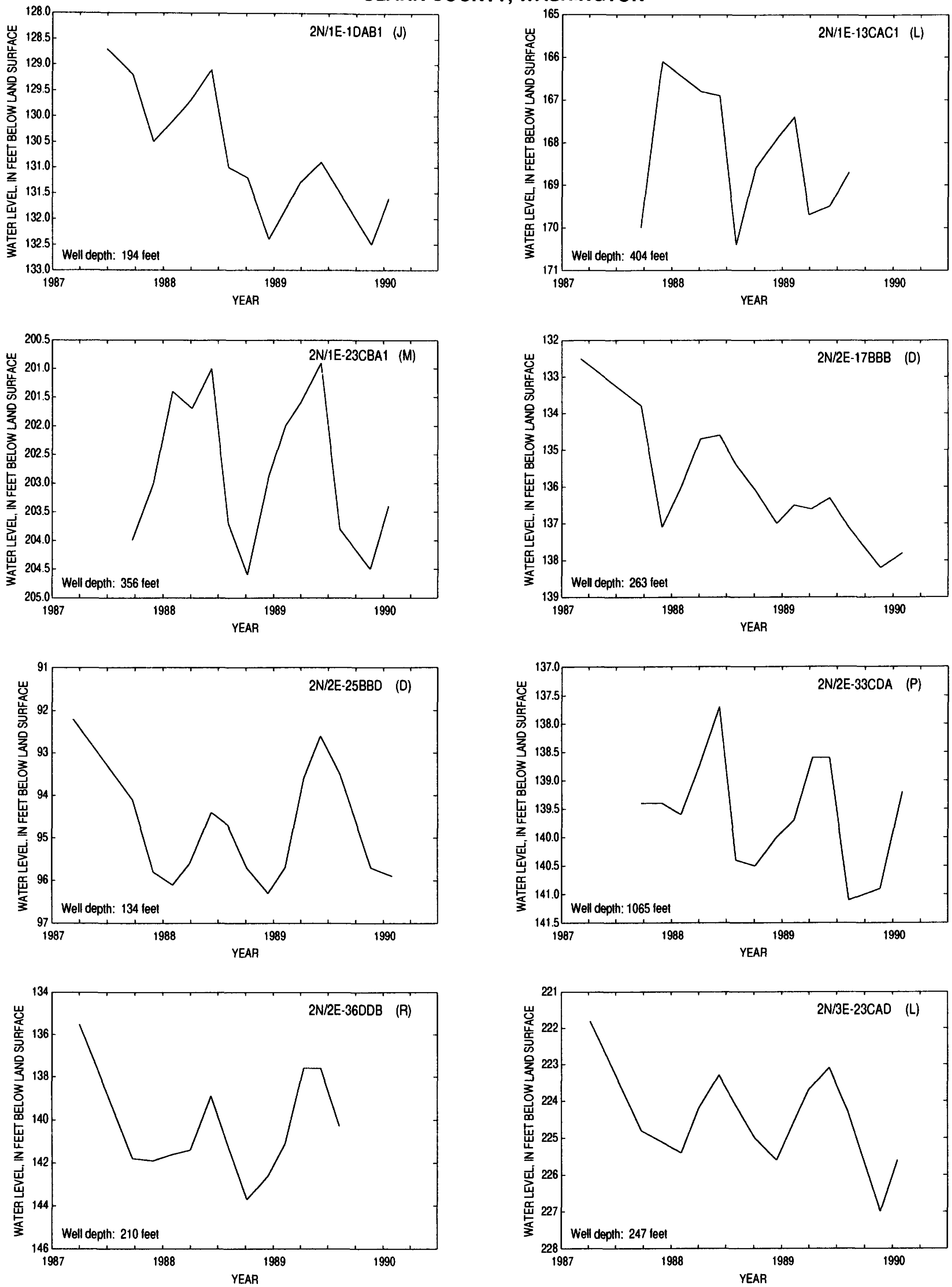


Figure 8. Selected water-level hydrographs 1987–90—Continued.

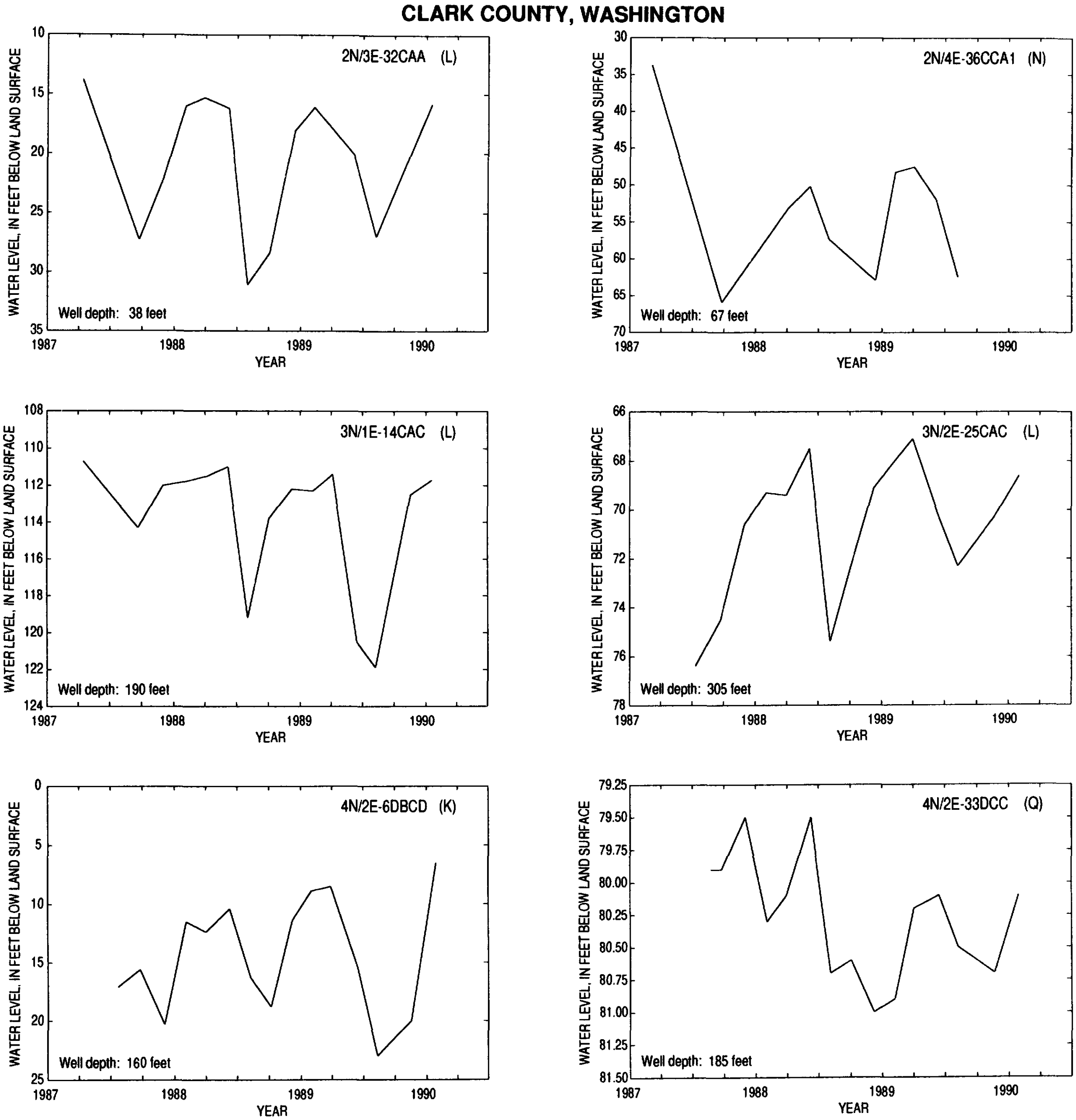


Figure 8. Selected water-level hydrographs 1987–90—Continued

Damascus, may be related to nearby pumping for irrigation or public-supply uses. The water level in a well 1.5 miles east of Damascus (2S/3E-10BAC(C)) also declined; however, the original reported water level in 1953 may not be accurate. The well was deepened in 1968 and water-level measurements made during this study were about 10 feet lower than the measurements made prior to 1968. This slight decline could also be attributed to increased use for public-supply and irrigation uses in recent years. The decline in well 2S/4E-5CBB(M), 1 mile east of Boring, can probably be attributed to the significantly increased use of ground water for irrigation of nursery plants in recent years in that area. From the mid-1960's to about 1980, water levels rose nearly 50 feet in well 2S/4E-4DDA(R). The cause of the water-level rises is unknown, but may be due to return flow from irrigation or a change in usage.

Multnomah County, Oregon

Water levels in many wells in eastern Multnomah County reflected the residual effects of pumping from the city of Portland well field in 1987. Piezometers, installed by the city of Portland throughout eastern Multnomah County, allowed measurement

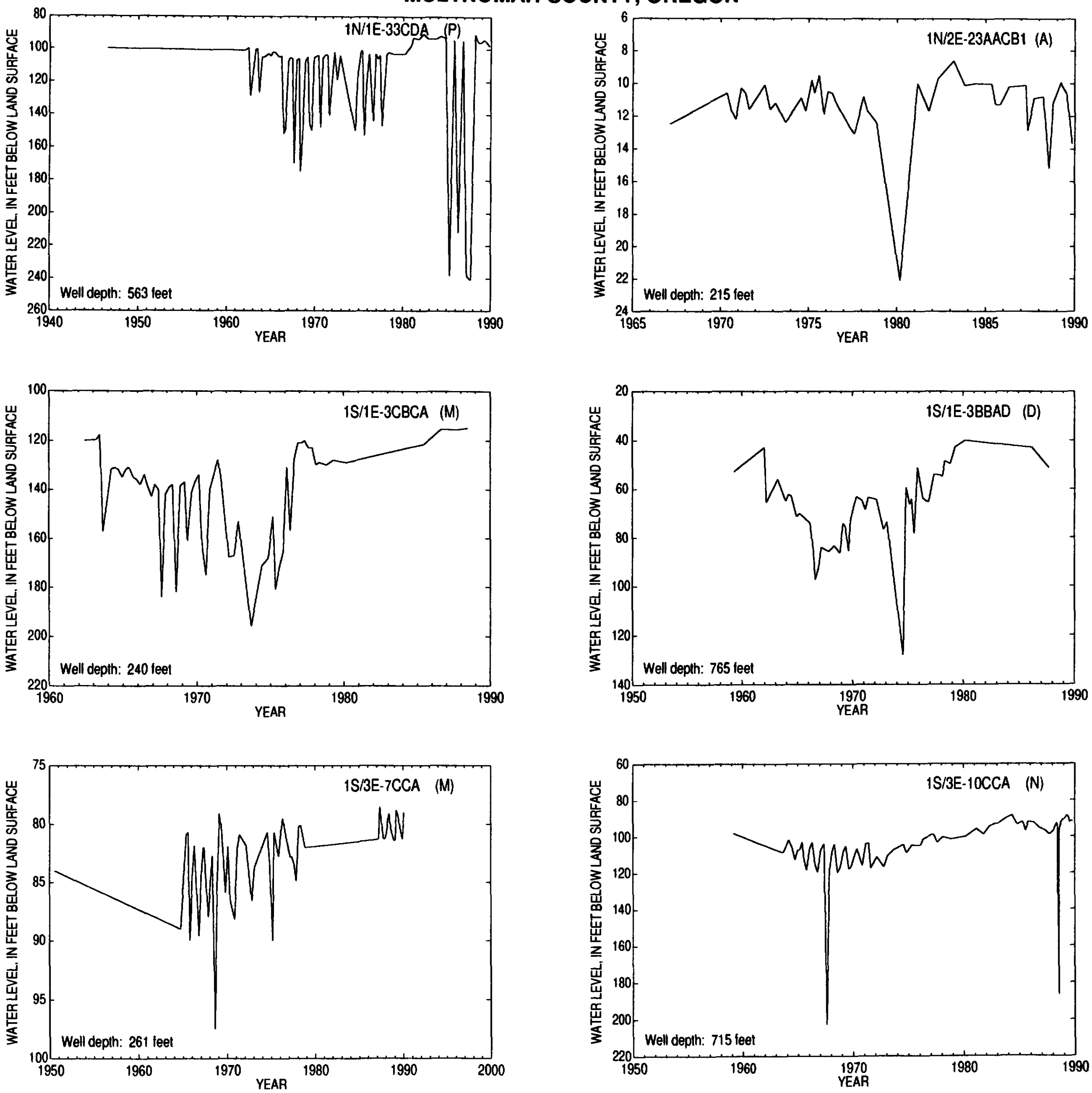


Figure 9. Selected long-term water-level hydrographs.

of water levels in multiple hydrogeologic units at one location. Bimonthly records from selected piezometers in five of these multiple piezometer sites are shown in figure 8.

Data from the piezometers 1.5 miles north of Rocky Butte (1N/2E-15BAC4,6,7(M)), in the western part of the Portland well field, allow comparison of water levels in the shallow unconsolidated sedimentary aquifer (15BAC6) with water levels in the deeper Troutdale sandstone aquifer (15BAC7) and in the deepest sand and gravel aquifer (15BAC4) during the 1987–90 pumping and recovery period of the well field. The deeper aquifers are separated from the unconsolidated sedimentary aquifer by confining unit 1. The fluctuation of water levels in the unconsolidated sedimentary aquifer is largely controlled by the Columbia River and variations in precipitation; water levels in the deeper aquifers are primarily controlled by pumping. The greatest impact of pumping on the deeper aquifers was evident in the sand and gravel aquifer, which subsequently recovered up to 70 feet, whereas recovery in the Troutdale sandstone aquifer was approximately 40 feet. The largest pumping rates during the 1987 pumping period were in the sand and gravel aquifer.

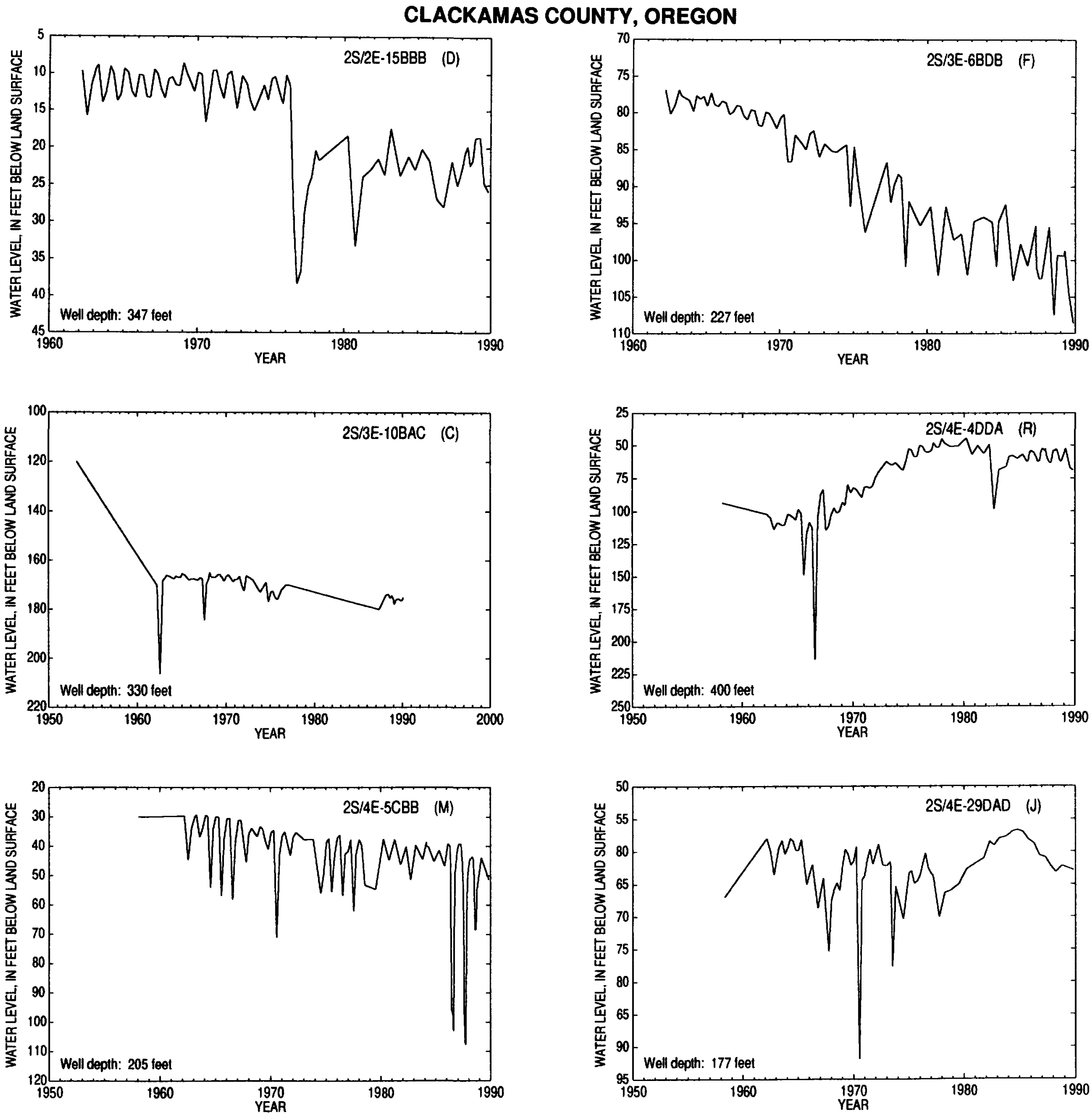


Figure 9. Selected long-term water-level hydrographs—Continued.

At multiple piezometer site 1N/2E-24DABB2, 3,5 near the south shore of the Columbia River and near the center of the Portland well field (fig. 8), shallow water levels in the unconsolidated sedimentary aquifer (24DABB2) also fluctuate due to river stage and precipitation variations. The deeper piezometers (24DABB3,5) show recovery of more than 80 and more than 150 feet in the Troutdale sandstone and the sand and gravel aquifers, respectively, after the 1987 pumping.

At multiple piezometer site 1N/2E-29DABD2, 3,5, just southwest of Rocky Butte, declining shallow water levels may have been caused by local ground-water pumping for irrigation, but also could reflect a delayed leakage of water to the deeper hydrogeologic units following the pumping of the city of Portland well field. Water levels in well 29DABD5 show that recovery in the Troutdale sandstone aquifer was more than 25 feet at that location.

Hydrographs from multiple piezometer site 1N/3E-31CDCD2,3,5,6, south of the Portland well field, indicate that water levels in the shallow aquifers were relatively unaffected by pumping during 1987, but that the Troutdale sandstone and the sand and gravel aquifers had more than 30 and 50 feet of recovery, respectively. Similar effects were observed at another

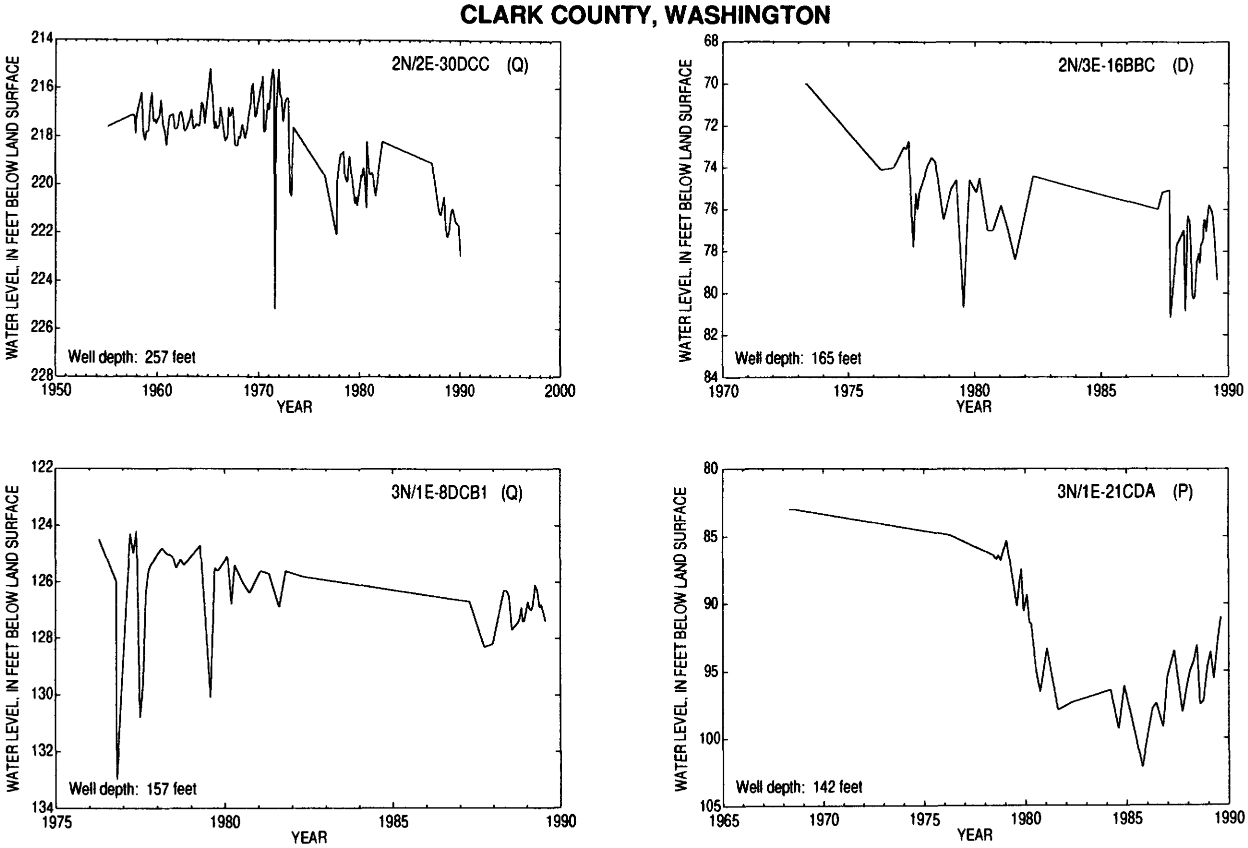


Figure 9. Selected long-term water-level hydrographs—Continued

multiple-piezometer site (1N/3E-33ADDA2,4,5,6,7) just north of Gresham.

The relation between stream and aquifer water levels is evident in data from a U.S. Geological Survey piezometer (1N/1E-2ADD2) just east of the Portland International Airport on the south shore of the Columbia River, data from the Columbia River gaging station at the Interstate Highway 5 bridge (2N/1E-34B, operated by the Corps of Engineers), and data from a staff gage monitored during this study on the Columbia River (1N/1E-3AAD) (fig. 10). The piezometer is 83 feet in depth, screened in the unconsolidated sedimentary aquifer, and located approximately 300 feet south of the Columbia River. The gaging station on the Columbia River is approximately 2 miles downstream from the piezometer and on the main channel of the Columbia River (north of Hayden Island), and the staff gage is approximately 1 mile downstream from the piezometer on the channel south of Hayden Island. The gaging station at Interstate Highway 5 provides a continuous record of minimum and maximum stage; however, the staff gage, located closer to the piezometer, provides the best data for determining the relative movement of water between the river and the aquifer. The staff gage typically was observed twice daily.

Water levels in the piezometer (1N/1E-2ADD2) and for the Columbia River gaging station at Interstate Highway 5 show that water-level changes in the river are transmitted relatively quickly to the aquifer (fig. 10). Maximum and minimum water levels in the piezometer indicated that there is an approximate 24-hour lag time between a change in river stage and a change in water level in the piezometer. A comparison of staff gage measurements and piezometer water levels indicate that, from day 2 to day 5 of the 2-week period shown, the hydraulic gradient was such that water moved from the aquifer to the river; however, during the rest of the period, water levels in the river and the aquifer were nearly equivalent. During periods of high river stage, there is a hydraulic gradient from the river to the shallow ground-water system.

In the southern part of Multnomah County, water levels in relatively deep wells did not appear to respond to pumping in the Portland well field. Water levels in wells 1S/2E-10BAC(C) at Kelly Butte and 1S/3E-20BCD(E), 3 miles southwest of Gresham, appear to fluctuate seasonally; however, the Kelly Butte well had its highest water levels approximately 3 to 4 months after most shallow wells in the area (fig. 8), probably due to its location and depth. The

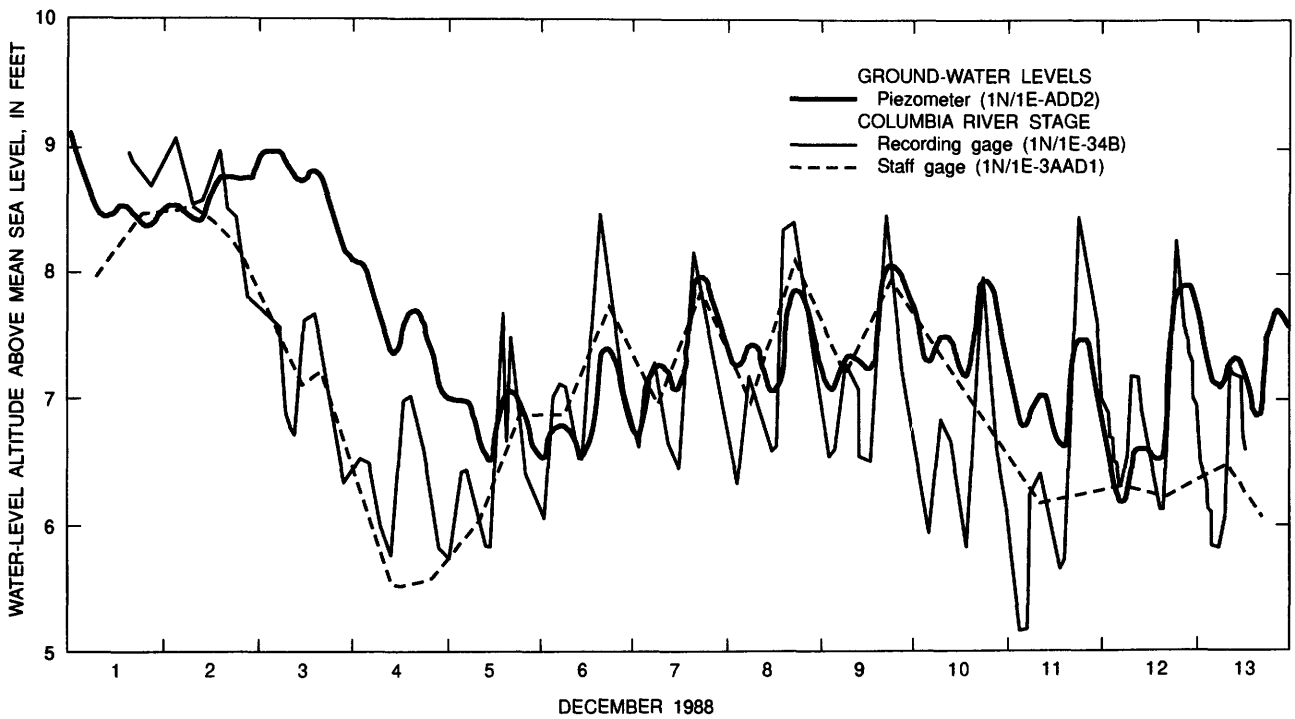


Figure 10. Relation of ground-water levels in a piezometer adjacent to the Columbia River with Columbia River stage at two different sites.

Kelly Butte well is completed in the Troutdale sandstone aquifer and the well southwest of Gresham is in the Troutdale gravel aquifer. Hydrographs from both wells show a decline in water levels from 1987 to 1990.

Long-term observation wells in Multnomah County in downtown Portland, Oregon, indicate that, in general, water levels have risen since the 1960's and early 1970's, when ground water may have been used more extensively for heating and cooling purposes. Water levels in wells 1N/1E-33CDA(P), 1S/1E-3CBCA(M), and 1S/1E-3BBAD(D) all show rises in static water level in the late 1970's and 1980's (fig. 9). These wells are all completed in the Columbia River basalts.

The long-term hydrograph for well 1N/2E-23AACB1(A) shows the impact of local pumping as well as fluctuations in the stage of the Columbia River (fig. 9). This well is completed in the Troutdale gravel aquifer and the Troutdale sandstone aquifer. The slight decline in water levels in that well in the late 1980's may be related to pumping in the Portland well field.

Hydrographs of two long-term observation wells in southern Multnomah County indicate that water levels have risen slightly in recent years in those areas. In both of these wells, the rises are probably related to reduced use of the wells. Well 1S/3E-7CCA(M) is northeast of Powell Butte and is completed in the Troutdale gravel aquifer. Well 1S/3E-10CCA(N) is located in Gresham.

Clark County, Washington

In Clark County, water levels in wells fluctuated about 4 to 15 feet from the spring-high measurements to the fall-low measurements for the 1987–90 period (fig. 8). Some of the larger fluctuations resulted from pumping in the observation well itself. Bimonthly water-level measurements in wells showed that seasonal fluctuations are typical, but some trends are evident in the hydrographs. In the Vancouver area, data from several wells (2N/1E-1DAB1(J), 2N/1E-13CAC1(L), 2N/2E-17BBB(D), 2N/2E-33CDA(P)) indicate that water levels declined during 1987–90. Hydrographs from other bimonthly observation wells (2N/1E-23CBA1(M), 2N/2E-25BBD(D), 2N/2E-36DDB(R)), however, indicate that in some areas water levels remained about the same throughout this study or rose slightly. Most of these wells are completed in the Troutdale gravel aquifer, with the exception of well 2N/2E-25BBD(D), which is completed in the unconsolidated sedimentary aquifer.

Water levels in wells farther east of Vancouver (2N/3E-23CAD(L), 2N/3E-32CAA(L), 2N/4E-

36CAA1(N)) indicate seasonal fluctuations, but no significant water-level changes (fig. 8). Water levels in wells (3N/1E-14CAC(L), 3N/2E-25CAC(L), 4N/2E-6DBCD(K), and 4N/2E-33DCC(Q)) show seasonal fluctuations with minor short-term trends.

Hydrographs of wells with continuous long-term records for Clark County are shown in figure 9. The most complete record is for well 2N/2E-30DCC(Q), which is located east of Vancouver and is completed in the Troutdale gravel aquifer. Water levels in the well remained relatively stable from about 1954 to about 1972; thereafter, water levels began to decline. Recent water-level measurements are approximately 4 feet lower than in the 1950's and 1960's. Similar long-term trends are evident in hydrographs for long-term observation wells 2N/3E-16BBC(D), 3N/1E-8DCB1(Q), and 3N/1E-21CDA(P) in Clark County. These wells also are completed in the Troutdale gravel aquifer. The declines probably were due to pumping from public-supply wells.

Areal Water-Level Changes

The changes in water levels from spring 1988 to spring 1989 were used to determine where significant water-level changes in the ground-water system were occurring during the short term, and where long-term changes might be occurring. In a few areas, long-term changes were verified with long-term hydrographs. In other areas, continued water-level monitoring will be necessary to determine whether long-term trends are occurring. Changes in ground-water levels from spring 1988 to spring 1989 for the four major sedimentary aquifers for which observation wells exist are shown on plate 7. Precipitation records from Portland International Airport show that, for the 6-month and 1-year period prior to the spring 1988 ground-water-level measurements, precipitation was less than for the same periods prior to the spring 1989 ground-water-level measurements (fig. 11). Precipitation for both premeasurement periods also was below the long-term (1951–81) normal (National Climatic Data Center, 1989).

Large withdrawals of water from the aquifer system in the Portland Basin caused water levels to decline between spring 1988 and spring 1989. These declines represent changes during a 1-year period and do not necessarily indicate that long-term water-level declines are occurring.

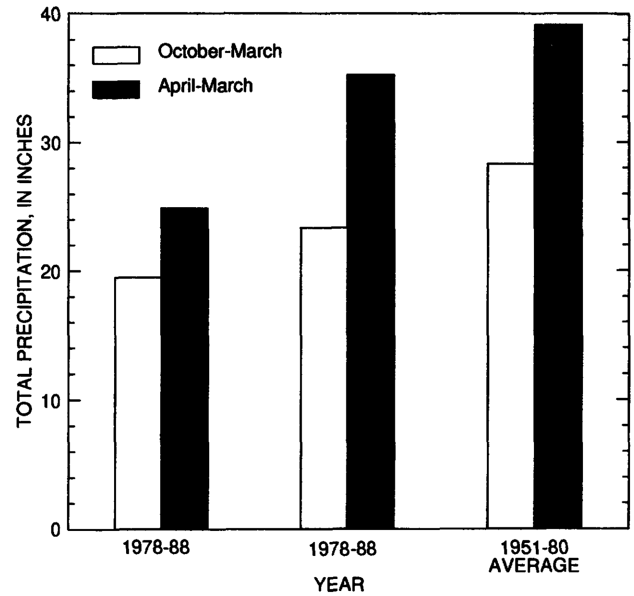


Figure 11. The relation of precipitation at Portland International Airport, prior to spring 1988 and spring 1989 synoptic water-level measurements, with the long-term average.

In eastern Multnomah County, Oregon, water levels in the sand and gravel aquifer rose as much as 10 feet during the 1-year period. This overall increase in water levels was the result of delayed recovery from pumping in the Portland well field during September and December 1987. During that period, the city of Portland pumped more than 7,600 acre-feet of water from the sand and gravel aquifer (Glicker, 1989).

In the sand and gravel aquifer in the Mount Norway area of Clark County, Washington, just south of the Washougal River, the most significant change, a decline in one area of more than 15 feet, probably was due to local pumping conditions.

Water levels in the Troutdale sandstone aquifer show rises near the Columbia River, with a significant rise of more than 20 feet just south of the Portland well field (pl. 7). This increase in water level can be attributed to the delayed recovery in the aquifer from pumping by the city of Portland in late 1987, when more than 1,300 acre-feet of water was pumped from the Troutdale sandstone aquifer. In addition, a large stress on the underlying sand and gravel aquifer probably increased leakage downward from the Troutdale sandstone aquifer. As a result, a significant recovery from the 1987 pumping period is evident from the water-level-change data in the area near the well field.

Water-level declines occurred in the Troutdale sandstone aquifer in the Sandy-Boring area during the spring 1988 to spring 1989 period (pl. 7). These de-clines were generally less than 4 feet; however, one area near Boring had a decline of nearly 7 feet. These declines may have been due to the extensive use of ground water for irrigation of nursery stock. Also, an important factor is the proximity of these wells to deeply cut canyons at Tickle Creek, Noyer Creek, and Deep Creek, which truncate this aquifer and form boundaries to the ground-water system. These boundaries increase the effects of pumping and changes in recharge on the aquifer system. Farther west, near Damascus, data from one well indicate a change of more than 5 feet.

With the exception of two small areas, water levels in the Troutdale sandstone aquifer in Clark County, Washington, generally rose from spring 1988 to spring 1989. This aquifer is not heavily used in Clark County.

The Troutdale gravel aquifer has the best areal coverage of data to evaluate water-level changes for the 1988 to 1989 period. In Oregon, water levels in the Troutdale gravel aquifer in the Sandy-Boring area have declined by the same magnitude as the water levels in the Troutdale sandstone aquifer (pl. 7). However, in the gravel aquifer, the declines occur over a larger area, including the Damascus area. The declines in that area also appear to be long-term declines on the basis of data from well 2S/3E-6BDB (fig. 9). During a 30-year period, 1960–90, water levels in that well declined steadily more than 20 feet (fig. 9).

Water-level declines also have occurred in the Troutdale gravel aquifer on the east side of the Willamette River, east of downtown Portland. The reason for these declines is unknown; however, the aquifer is used for industry in that area. In the Milwaukie area, significant water-level rises occurred between spring 1988 and spring 1989 because the city of Milwaukie shut down its well field in January 1989. Prior to the shutdown, Milwaukie had been pumping approximately 3,000 acre-feet per year. As a result, following the shutdown, water levels rose more than 20 feet over several square miles (pl. 7). Throughout the rest of the Oregon part of the basin, water levels have risen, possibly in response to increased precipitation.

In Clark County, some widespread declines are evident in the Troutdale gravel aquifer for the 1988 to 1989 period (pl. 7). The largest area of decline is in the southwestern part of the county in the Vancouver-Orchards-Battle Ground area, where ground water is used for public supply. Vancouver and the Clark County PUD pumped an average of more than 29,000 acre-feet per year for 1987 and 1988, primarily from the Troutdale gravel aquifer and the unconsolidated gravel aquifer. A few long-term hydrographs available in this large area of decline indicate that some long-term water-level declines may have occurred. The most complete hydrograph record for this area, from well 2N/2E-30DCC, shows water levels somewhat stable from the middle 1950's through about 1970 and then declining approximately 6 feet between 1970 and 1990 (fig. 9).

The area between the East Fork Lewis River and Salmon Creek, southeast of Ridgefield (pl. 7), is another area of widespread water-level decline in Clark County. The cause of those declines is unknown, but may be due to increased ground-water use in that area.

Water levels in the unconsolidated sedimentary aquifer in the Portland Basin closely follow seasonal trends in precipitation. However, water levels declined locally in this aquifer for the spring 1988 to spring 1989 period. In Oregon, there are only a few isolated areas of decline (pl. 7), while in Clark County a large area of decline north and east of Vancouver is shown on plate 7. This area corresponds to the large area of decline in Clark County in the Troutdale gravel aquifer and is probably related to the large amounts of water withdrawn from that area for public supply.

SUMMARY AND CONCLUSIONS

The Portland Basin is a structural basin filled with lacustrine and fluvial sediments. Although the bedrock, or older rocks, in the basin contain usable quantities of water, the basin-fill sediments are the primary source of ground water. Eight major hydrogeologic units have been mapped in the basin. From youngest to oldest, they are (1) unconsolidated sedimentary aquifer, (2) Troutdale gravel aquifer, (3) confining unit 1, (4) Troutdale sandstone aquifer, (5) confining unit 2, (6) sand and gravel aquifer, (7) older rocks, and (8) undifferentiated fine-grained sediments. This last unit occurs in areas of the basin where the Troutdale sandstone aquifer and the sand and gravel aquifer are not present or there is insufficient information to differentiate these aquifers.

Hydraulic-conductivity data from aquifer tests and single-well tests were used to estimate the water-bearing characteristics of each hydrogeologic unit. Hydraulic-conductivity estimates indicate that confining unit 1, confining unit 2, and the older rocks have median hydraulic-conductivity values of 4, 1, and 0.3 feet per day, respectively. The aquifers have relatively higher median hydraulic conductivities, ranging from about 7 to more than 200 feet per day. The most widely used aquifer in the basin is the Troutdale gravel aquifer, but the highest capacity wells are completed in the unconsolidated sedimentary aquifer adjacent to the Columbia River.

Recharge to the ground-water system in the Portland Basin is from infiltration of precipitation, runoff to drywells, and discharge to on-site waste-disposal systems. Estimates of recharge indicate that in some urban areas, such as eastern Multnomah County, the most significant recharge is from the drywells and on-site waste-disposal systems, which may account for more than 40 inches per year of recharge. In rural parts of the study area, however, infiltration of precipitation and leakage from streams are the most significant components of recharge. Total ground-water recharge for the basin is estimated to be about 1,150,000 acre-feet per year, an average rate of 22 inches per year. Of this quantity, precipitation accounts for about 21 inches per year.

Ground water generally moves from upland areas, such as the Tualatin Mountains, Boring Hills, or the western Cascade Range, toward major discharge points in the basin, such as the Columbia, Willamette, Lewis, and Clackamas Rivers. Upland areas have strong downward components of ground-water flow and are classified as recharge areas; lowland areas generally have strong upward components of ground-water flow and are classified as discharge areas. In the Portland Basin, these discharge areas are generally limited to narrow zones along the major streams. In some areas, geologic structure and erosional features influence ground-water flow directions.

Discharge of ground water from the aquifer system in the Portland Basin is primarily to springs and streams, and by pumping from wells. Forty-two springs were measured during this study to quantify spring discharge from the aquifer system and for comparison with historical measurements to determine if significant changes in discharge had occurred. The largest springs are along the Columbia and Willamette Rivers. Crystal Springs, in southeast Portland and adjacent to the Willamette River, have a total discharge of 5,300 gallons per minute. Ellsworth Springs, east of Vancouver and adjacent to the Columbia River, have a total discharge of nearly 2,800 gallons per minute. In Clark County, Washington, total spring discharge between Vancouver and Prune Hill has decreased to 42 percent of the discharge measured in 1949. For springs in the Oregon part of the study area, limited historical data and measurements during this study indicate that only two springs had significantly decreased discharge (35 and 60 percent of the discharge measured in 1957).

The largest component of ground-water discharge in the Portland Basin is to streams. Most streams in the basin are gaining streams. The stream with the largest gain per stream mile (excluding the Columbia and Willamette Rivers) is the East Fork Lewis River, which gains nearly 10 cubic feet per second per stream mile. Other streams, like the Sandy River, Salmon Creek, and Johnson Creek, generally have gains less than 5 cubic feet per second per stream mile.

Total ground-water pumpage in the Portland Basin was more than 120,000 acre-feet in 1988. Fifty percent of the ground water used in the Portland Basin is used for industrial purposes, 40 percent for public supply, and 10 percent for irrigation purposes. More than 50 percent of the water pumped for public supply is used in Clark County, Washington.

Water-level data in the basin indicate that declines are occurring in some areas. A comparison of 1988 water levels for the Troutdale gravel aquifer with those mapped by Mundorff in 1949 shows that 10 or more feet of decline has occurred in southern Clark County, probably as a result of development of ground-water resources in that area. A comparison of spring 1988 and spring 1989 water levels in the Portland Basin indicates that water-level changes are mappable in several areas.

SUGGESTIONS FOR FUTURE STUDIES

Ground water in the Portland Basin remains the abundant resource that earlier workers reported. Future demands on the aquifer system and the increased concern regarding ground-water contamination, however, will require a better evaluation and quantification of the aquifer system than is presented in this report.

The work done in this study has allowed the identification of several types of data that will be required for future ground-water studies. Development and improvement of ground-water flow models for the aquifer system in the basin will require temporal and spatial water-level and pumpage data. A summary of data needs follows:

(1) A long-term observation-well network could be established and maintained to provide data for future studies. This network could document changes in water levels with respect to time. Short-term water-level data collected during this study indicate that water levels may be declining in large areas of southern Clark County, Washington, and in Clackamas County, Oregon. Wells in the network could be selected with regard to areal distribution, appropriate well construction, historic record, and representation of all aquifers.
(2) Synoptic water-level measurements, similar to those made in this study, could be made to document changes in the ground-water flow directions.
(3) Pumpage data, especially for public-supply and industrial users, could be collected so that yearly ground-water use estimates could be facilitated.

The following changes will likely affect the Portland Basin aquifer system in the next 20 years: (1) population growth will result in increased ground-water withdrawals, possibly lowering ground-water levels; (2) population growth also will result in an increased percentage of impervious surfaces in urban areas, possibly reducing ground-water recharge; and (3) installation of municipal sewers in the mid-Multnomah County area may cause measurable declines in water levels in wells in that area. Observation of the aquifer system (including measurement of water levels, monitoring ground-water use, and recording land-use changes) during these changes to the recharge and discharge components of the system will provide additional data to improve the understanding of the aquifer system.

SELECTED REFERENCES

Arvid Grant and Associates, 1974, An engineering study of the Ellsworth Springs: Vancouver, Washington, 25 p. [available from the city of Vancouver, Washington].

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.

Broad, T.M., and Collins, C.A., 1996, Estimated water use and general hydrologic conditions for Oregon, 1985 and 1990: U.S. Geological Survey Water-Resources Investigations Report 96–4080.

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., 2 pls.

Buchanan, T.J., and Somers, W.P., 1984, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8, 65 p.

Collins, C.A., and Broad, T.M., 1993, Estimated average annual ground-water pumpage in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 91–4018, 26 p., 4 pls.

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: Oregon Water Resources Department Ground Water Report 3, 79 p., 1 pl.

Glicker, J., 1989, Results of monitoring Portland's well field: Portland, Oregon, Internal city of Portland Report, 27 p.

Griffin, W.C., Watkins, F.A., Jr., and Swenson, H.A., 1956, Water resources of the Portland, Oregon and Vancouver, Washington area: U.S. Geological Survey Circular 372, 45 p., 2 pls., 25 figs.

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., 6 pls.

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., 2 pls.

Laenen, Antonius, 1980, Storm runoff as related to urbanization in the Portland, Oregon—Vancouver, Washington area: U.S. Geological Survey Water-Resources Investigations Report 80–689, 71 p.

Leonard, A.R., and Collins, C.A., 1983, Ground water in the northern part of Clackamas County, Oregon: Oregon Water Resources Department Ground Water Report no. 29, 85 p., 2 pls.

Madin, I.P., 1989, Evaluating earthquake hazards in the Portland, Oregon, metropolitan area—Mapping potentially hazardous soils: Oregon Department of Geology and Mineral Industries, Oregon Geology, v. 51., no. 5, September 1989, p. 106–110

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.

McFarland, W.D., Luzier, J.E., and Willis, R.F., 1982, Well field hydrogeology and simulation modeling, Portland, Oregon: EOS, Transactions, American Geophysical Union Abstracts, v. 63, no. 45, p. 933.

Metropolitan Services District, 1984, Major arterial map, Portland, Oregon.

Morgan, D.S., and McFarland, W.D., 1994, Simulation analysis of the ground-water flow system in the Portland Basin, Oregon and Washington: U.S. Geological Survey Open-File Report 94–505, 85 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., 3 pls.

National Climatic Data Center, 1987, Climatological data for Oregon, monthly reports: Asheville, North Carolina.

———1988, Climatological data for Oregon, monthly reports: Asheville, North Carolina.

———1989, Climatological data for Oregon, monthly reports: Asheville, North Carolina.

Orzol, L.L., and McGrath, T.M., 1992, Modifications of the U.S. Geological Survey modular, finite-difference, ground-water flow model to read and write a geographic information system files: U.S. Geological Survey Open-File Report 92–50, 202 p.

Phillips, W.M., 1987a, Geologic map of the Mount St. Helens Quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open-File Report 87–4, 59 p., 1 pl.

———1987b, Geologic map of the Vancouver Quadrangle, Washington and Oregon: Washington Division of Geology and Earth Resources Open-File Report 87–10, 32 p., 1 pl.

Robison and Noble Incorporated, 1985, City of Vancouver—Ellsworth Springs rotary test drilling, well 2N/2E-33CCC, May 1985: Tacoma, Washington, 10 p. [available from the city of Vancouver, Washington].

———1990, City of Vancouver—Construction of station 7, well 2, June 1990: Tacoma, Washington, 9 p. [available from city of Vancouver, Washington].

Snyder, D.T., Morgan, D.S., McGrath, T.M., 1994, Estimates of recharge from infiltration of precipitation, on-site sewage disposal systems, and drywells in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 92–4010, 34 p.

Swanson, R.D., McFarland, W.D., Gonthier, J.B., Wilkinson, J.W., 1993, A description of hydrogeologic units in the Portland Basin, Oregon and Washington: U.S. Geological Survey Water-Resources Investigations Report 90–4196, 62 p.

Trimble, D.E., 1963, Geology of Portland, Oregon and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p., 1 pl.

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

Vorhis, R.C., 1979, Transmissivity from pumped-well data: National Water Well Association Well Log, v. 10, no. 11, p. 50–52.

Wantz, J.W., Feris, C.M., and Larsen, N.S., 1983. Fifteen year average precipitation patterns as revealed by the Portland, Oregon Mesoscale Precipitation Network: Data on file in the Weather Office of the Bonneville Power Administration, Portland, Oregon.

Williams, T.A., and Williamson, A.K., 1989, Estimating water-table altitudes for regional ground-water flow modeling, U. S. Gulf Coast: National Water Well Association Groundwater Journal, v. 27, no. 3, p. 333–340.

Willis, R.F., 1977, Ground water exploratory program: Portland, Oregon, Bureau of Water Works, 284 p., 17 pls.

———1978, Pilot well study: Portland, Oregon, Bureau of Water Works, 150 p., 23 pls.

TABLE 3

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988

ID: Unique identification number for stream reach.

Stream description: Description of the stream measurement site. AVE, Avenue; CR, Creek; HWY, Highway; RR, Railroad; TRIB, tributary; E.F., East Fork; BLVD, Boulevard; NE, northeast; NW, northwest; SE, southeast; MT, Mount; USGS, U.S. Geological Survey.

Location: Township, Range, and Section number for the stream measurement site.

River mile: The distance in miles, measured upstream, from the mouth to the measurement site.

Q: Discharge in cubic feet per second at the measurement site.

Trib Q: Discharge in cubic feet per second of a tributary entering the stream of interest.

Seepage: Calculated seepage in cubic feet per second per stream miles between stream measurement sites (corrected for tributary inflow). Negative value indicates a loss of water to the aquifer.

Avg Q: Average discharge (1987–88) in cubic feet per second at a measurement site.

Avg trib: Average discharge (1987–88) in cubic feet per second of a tributary entering the stream of interest.

Avg seepage: Average calculated seepage (in cubic feet per second) per stream mile based on Avg Q at stream measurement sites (corrected for Avg trib discharge).

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
						Washington								
1	BURNT BRIDGE CREEK AT 112TH AVE.	2N/2E-16DBA	8.9	9/15/87	1.46	--	0.54	10/ 7/88	1.39	--	0.51	1.43	--	0.53
2	BURNT BRIDGE CREEK AT BURBON ROAD	2N/2E-20DAC	7.4	9/15/87	2.98	--	1.01	10/ 7/88	2.82	--	.95	2.90	--	.98
3	BURNT BRIDGE CREEK AT EVERGREEN STREET	2N/1E-24DDC	5.0	9/15/87	3.01	--	.01	10/ 7/88	3.67	--	.35	3.34	--	.18
4	BURNT BRIDGE CREEK AT ST. JOHNS BLVD	2N/1E-24BBC	3.6	9/15/87	3.62	--	.44	10/ 7/88	3.62	--	-.04	3.62	--	.20
5	BURNT BRIDGE CREEK AT LEVERICH PARK	2N/1E- 14CCA	2.2	9/15/87	3.60	--	-.01	10/ 6/88	4.55	--	.66	4.08	--	.33
6	COLD CANYON CR AT HAZEL DELL DR. BY BURNT BRIDGE CR	2N/1E-15ABD	1.2	9/15/87	--	0.56	--	10/ 6/88	--	0.45	--	--	0.51	--
7	BURNT BRIDGE CREEK	2N/1E-15BAD	1.0	9/15/87	4.14	--	-.02	10/ 6/88	4.61	--	-.33	4.38	--	-.18
8	CEDAR CREEK AT ROAD 16 NEAR YACOLT	5N/3E-35CBB	15.0	9/17/87	2.32	--	--	10/ 4/88	2.63	--	--	2.48	--	--
9	CEDAR CREEK TRIBUTARY AT ROTSDY ROAD	5N/3E-27DAA	13.9	9/17/87	--	.04	--	10/ 4/88	--	.10	--	--	.07	--
10	CEDAR CREEK TRIBUTARY	5N/3E-34ABA	13.2	9/17/87	--	.02	--	--/--/--	--	--	--	--	.01	--
11	CEDAR CREEK TRIBUTARY	5N/3E-27BAD	11.5	9/17/87	--	.05	--	10/ 4/88	--	.10	--	--	.03	--
12	CEDAR CREEK TRIBUTARY	5N/3E-28DAD	--	9/17/87	--	--	--	--/--/--	--	--	--	--	--	--
13	CEDAR CREEK AT AMBOY	5N/3E-21BBA	11.1	9/17/87	4.08	--	.42	10/ 4/88	3.87	--	.27	3.98	--	.36
14	CHELATCHIE CREEK AT AMBOY NEAR CEDAR CREEK	5N/3E-16CDC	11.0	9/17/87	--	3.49	--	10/ 4/88	--	3.65	--	--	3.57	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
15	CEDAR CREEK TRIBUTARY	5N/3E-16CAB	--	9/17/87	--	0.02	--	--/-- /--	--	--	--	--	0.01	--
16	BITTER CREEK AT MUNCH ROAD NEAR CEDAR CREEK	5N/3E-20ABB	10.3	9/17/87	--	.10	--	10/ 4/88	--	0.10	--	--	.10	--
17	CEDAR CREEK TRIBUTARY	5N/3E-17ADB	10.1	9/17/87	--	.05	--	10/ 4/88	--	.05	--	--	.05	--
18	BRUSH CREEK NEAR CEDAR CREEK	5N/3E-08CCA	9.2	9/17/87	--	.16	--	10/ 4/88	--	.28	--	--	.22	--
19	JOHN CREEK AT COUNTY ROAD 16 NEAR CEDAR CREEK	5N/2E-12DAC	7.6	9/17/87	--	.21	--	10/ 4/88	--	.23	--	--	.22	--
20	CEDAR CREEK ABOVE USGS STREAM-GAGING STATION 14221500	5N/2E-11CAA	6.1	9/15/87	12.80	--	.94	10/ 4/88	8.16	--	--	10.48	--	0.47
21	CEDAR CREEK TRIBUTARY	5N/2E-11CAA	--	9/15/87	--	.20	--	10/ 5/88	--	.10	--	--	.15	--
22	CEDAR CREEK TRIBUTARY AT ROAD 16 AND EMERICK	5N/2E-10DDB	5.3	9/15/87	--	.16	--	10/ 5/88	--	.20	--	--	.18	--
23	CEDAR CREEK TRIBUTARY	5N/2E-10CDB	4.8	9/15/87	--	.48	--	10/ 5/88	--	.53	--	--	.51	--
24	PUP CREEK AT SPURREL ROAD NEAR CEDAR CREEK	5N/2E-03DCC	4.2	9/15/87	--	1.26	--	10/ 5/88	--	1.11	--	--	1.19	--
25	CEDAR CREEK TRIBUTARY	5N/2E-10CBB	--	9/17/87	--	.01	--	--/--/--	--	--	--	--	--	--
26	CEDAR CREEK TRIBUTARY	5N/2E-09CBA	--	9/17/87	--	.01	--	--/--/--	--	--	--	--	--	
27	CEDAR CREEK AT GRIST MILL	5N/2E-05DCD	2.4	9/ 5/87	17.70	--	.75	10/ 5/88	13.60	--	.95	15.65	--	.85
28	CEDAR CREEK TRIBUTARY	5N/2E-08CAA	--	9/17/87	--	.05	--	--/--/--	--	--	--	--	--	--
29	CEDAR CREEK TRIBUTARY	5N/2E-07DDB	1.4	9/17/87	--	.02	--	--/--/--	--	--	--	--	.01	--
30	CEDAR CREEK TRIBUTARY	5N/2E-07CDA	.6	9/17/87	--	.03	--	--/--/--	--	--	--	--	.02	--
31	CEDAR CREEK AT CONFLUENCE	5N/1E-12AAD	.1	9/15/87	17.90	--	.04	10/25/88	12.70	--	-.39	15.30	--	-.17
32	EAST FORK LEWIS RIVER ABOVE MOULTIN FALLS	4N/4E-20BCD	27.2	10/29/87	19.50	--	--	10/11/88	27.50	--	--	23.50	--	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
33	BIG TREE CREEK NEAR EAST FORK LEWIS RIVER	4N/3E-13BDB	24.5	10/29/87	--	3.00	--	10/11/88	--	3.38	--	--	3.19	--
34	EAST FORK LEWIS RIVER AT MOULTIN FALLS	4N/3E-13BDC	24.5	10/29/87	34.07	--	4.29	10/11/88	45.40	--	5.38	39.74	--	4.83
35	EAST FORK LEWIS RIVER TRIBUTARY	4N/3E-15BBB	22.1	10/28/87	--	.04	--	--/--/--	--	--	--	--	.02	--
36	EAST FORK LEWIS RIVER TRIBUTARY	4N/3E-09CCD	21.1	10/29/87	--	.02	--	--/--/--	--	--	--	--	.01	--
37	EAST FORK LEWIS RIVER STREAM-GAGING STATION 142225.00	4N/3E-17ABC	20.4	10/29/87	32.80	--	-0.32	10/11/88	43.80	--	-.39	38.30	--	-.36
38	BASKET CR AT BASKET CR ROAD NEAR EAST FORK LEWIS RIVER	4N/3E-17ACD	--	10/28/87	--	--	--	--/--/--	--	--	--	--	--	--
39	BASKET CR AT CON-FLUENCENEAR EAST FORK LEWIS RIVER	4N/3E-17ABC	--	10/29/87	--	.25	--	10/11/88	--	0.38	--	--	.32	--
40	EAST FORK LEWIS RIVER TRIBUTARY	4N/3E-18ACB	19.3	10/27/87	--	.01	--	10/11/88	--	.10	--	--	.06	--
41	EAST FORK LEWIS RIVER TRIBUTARY	4N/2E-24ABB	18.0	10/27/87	--	.12	--	10/11/88	--	.10	--	--	.11	--
42	EAST FORK LEWIS RIVER AT LEWISVILLE PARK	4N/2E-23BCB	14.4	10/27/87	35.02	--	.31	10/12/88	43.70	--	-.11	39.36	--	.10
43	EAST FORK LEWIS RIVER AT DAYBREAK PARK	4N/2E-20CAD	10.6	10/27/87	35.33	--	.08	10/12/88	47.80	--	1.08	41.57	--	.58
44	MILL CREEK NEAR EAST FORK LEWIS RIVER	4N/2E-19DCC	7.7	10/27/87	--	.05	--	10/12/88	--	.15	--	--	.10	--
45	EAST FORK LEWIS RIVER TRIBUTARY	4N/2E-20CDC	8.0	10/28/87	--	.12	--	10/12/88	--	.52	--	--	.32	--
45	EAST FORK LEWIS RIVER TRIBUTARY	4N/2E-20CDC	8.0	10/28/87	--	.12	--	10/12/88	--	.52	--	--	.32	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
46	EAST FORK LEWIS RIVER TRIBUTARY	4N/2E-20CAB	9.8	9/11/87	--	0.57	--	10/12/88	--	0.46	--	--	0.52	--
47	EAST FORK LEWIS RIVER TRIBUTARY	4N/1E-13DBC	9.8	10/27/87	--	.10	--	10/12/88	--	.15	--	--	.13	--
48	EAST FORK LEWIS RIVER ABOVE MASON CREEK	4N/1E-14AAD	6.5	10/28/87	40.18	--	0.98	10/12/88	58.10	--	2.20	49.14	--	1.59
49	EAST FORK LEWIS RIVER TRIBUTARY	4E/1E-14AAC	--	10/26/87	--	.10	--	10/12/88	--	.05	--	--	.08	--
50	MASON CREEK AT J.A. MORRE ROAD BY EAST LEWIS RIVER	4E/1E-13ADB	--	10/26/87	--	--	--	--/--/--	--	--	--	--	--	--
51	MASON CR AT CON-FLUENCE NEAR E.F. LEWIS RIVER	4N/1E-14AAA	5.7	10/26/87	--	1.17	--	10/12/88	--	1.45	--	--	1.31	--
52	EAST FORK LEWIS RIVER TRIBUTARY	4N/1E-11DAC	5.4	10/27/87	--	.10	--	10/12/88	--	.14	--	--	.13	--
53	EAST FORK LEWIS RIVER TRIBUTARY	4N/1E-11ACD	--	10/27/87	--	.01		--/--/--	--	--	--	--	--	--
54	EAST FORK LEWIS RIVER ABOVE LOCKWOOD CREEK	4N/1E-11ACC	4.9	10/27/87	56.32	--	9.2	10/12/88	65.00	--	3.29	60.66	--	6.25
55	LOCKWOOD CR NEAR EAST FORK LEWIS RIVER	4N/1E-01CCA	4.4	10/27/87	--	.77	--	10/12/88	--	1.07	--	--	.92	--
56	BREZEE CREEK NEAR EAST FORK LEWIS RIVER	4N/1E-03ADB	3.2	10/26/87	--	.32	--	10/12/88	--	.68	--	--	.50	--
57	EAST FORK LEWIS RIVER TRIBUTARY	5N/1E-33CBB	--	10/26/87	--	.05	--	10/11/88	--	.10	--	--	.08	--
58	MCCORMICK CR NEAR EAST FORK LEWIS RIVER	4N/1E-04DCC	2.5	10/26/87	--	.03	--	10/11/88	--	.16	--	--	.10	--
59	JENNY CREEK NEAR EAST FORK LEWIS RIVER	5N/1E-33CBA	1.4	10/26/87	--	.32	--	10/11/88	--	.29	--	--	.31	--
60	JENNY CREEK TRIBUTARY NEAR E.F. LEWIS RIVER	5N/1E-33CBB	--	10/26/87	--	.04	--	--/--/--	--	--	--	--	.02	--
61	FIFTH PLAIN CREEK NE 212TH AVE.	3N/3E-20DDD	5.3	9/17/87	.04	--	.03	10/13/88	.09	--	.08	.07	--	.06

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
62	FIFTH PLAIN CREEK AT NE DAVIS ROAD	3N/3E-32CBD	3.3	9/17/87	0.19	--	0.08	10/12/88	0.26	--	0.09	0.23	--	0.08
63	SHANGHAI CREEK AT 222ND AVE. NEAR FIFTH PLAIN CREEK	2N/3E-04BAA	2.6	9/17/87	.36	--	--	10/13/88	.56	--	--	.46	--	--
64	SHANGHAI CREEK AT NE 212 AVE.NEAR FIFTH PLAIN CREEK	2N/3E-05ADD	1.8	9/17/87	.26	--	-.13	10/12/88	.60	--	.05	.43	--	-.04
65	SHANGHAI CREEK AT FIFTH PLAIN CREEK	2N/3E-06BAA	2.3	9/17/87	--	0.46	--	10/13/88	--	0.54	--	--	0.50	--
66	FIFTH PLAIN CREEK AT WARD ROAD	2N/3E-06BBA	1.9	9/17/87	.57	--	-.06	10/13/88	.76	--	-.03	.67	--	-.04
67	CHINA DITCH AT WARD ROAD NEAR FIFTH PLAIN CREEK	2N/3E-06BBB	1.8	9/17/87	--	.24	--	10/12/88	--	.15	--	--	.20	--
68	FIFTH PLAIN CREEK AT HWY 500	2N/3E-07CBA	.2	9/18/87	3.22	--	1.42	10/12/88	3.10	--	1.29	3.16	--	1.35
69	GEE CREEK AT PARK	4N/1E-33AAA	9.4	9/11/87	.04	--	.01	10/ 6/88	.12	--	.04	.08	--	.03
70	GEE CREEK AT NW ROYLE ROAD	4N/1E-29DAB	8.0	9/11/87	.29	--	.18	10/ 6/88	.43	--	.22	.36	--	.20
71	GEE CREEK TRIBUTARY	4N/1E-19DAB	6.2	9/11/87	--	.15	--	10/ 5/88	--	.10	--	--	.13	--
72	GEE CREEK AT HWY 501	4N/1E-19DBA	6.2	9/11/87	.26	--	-.10	--/ --/--	--	--	--	.26	--	-.10
73	GEE CREEK AT ABRAMS PARK	4N/1E-19BDB	5.7	9/11/87	.51	--	.50	10/ 5/88	.78	--	.11	.65	--	.31
74	ACAMAS CREEK AT CAMP BONNEVILLE	2N/3E-03AAC	14.7	9/18/87	2.56	--	--	9/21/88	3.71	--	--	3.14	--	--
75	MATNEY CREEK AT NE 68TH STREET NEAR LACAMAS CREEK	2N/3E-09ACD	12.5	9/18/87	--	.37	--	9/21/88	--	1.06	--	--	.72	--
76	LACAMAS CREEK AT NE 217TH AVE.	2N/3E-09BCD	12.0	9/18/87	2.65	--	-.10	9/21/88	6.32	--	.57	4.49	--	.23
77	LACAMAS CREEK AT HWY 500	2N/3E-07CAA	9.9	9/18/87	2.61	--	-.02	9/21/88	6.54	--	.10	4.58	--	.04

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
78	SPRING BRANCH OFF NE 182ND AVE. NEAR LACAMAS CREEK	2N/3E-19ABD	7.1	9/21/87	--	2.11	--	9/21/88	--	1.94	--	--	2.03	--
79	LACAMAS CREEK AT LACAMAS PARK	2N/3E-20DDA	5.5	9/21/87	9.02	--	0.98	9/22/88	12.30	--	0.87	10.66	--	0.92
80	LITTLE WASHOUGAL RIVER AT SE BLAIR ROAD	2N/3E-25ADB	3.3	9/21/87	5.90	--	--	9/16/88	8.49	--	--	7.20	--	--
81	LITTLE WASHOUGAL RIVER AT BLAIR (GAGE SITE)	2N/4E-31DBA	1.1	9/21/87	5.77	--	-.06	9/16/88	7.98	--	-.23	6.88	--	-.15
82	ROCK CREEK ABOVE SALMON CREEK GAGING STATION	3N/3E-04BDD	20.2	9/16/87	--	.21	--	9/29/88	--	.59	--	--	.40	--
83	SALMON CREEK NEAR VENERSBERG	3N/3E-04CAA	20.1	9/ 9/87	1.92	--	--	9/29/88	3.91	--	--	2.92	--	--
84	SALMON CREEK AT 182ND AVE.	3N/3E-07ABC	17.5	9/ 9/87	2.09	--	.07	9/29/88	4.04	--	.05	3.07	--	.06
85	SALMON CREEK AT 167TH AVE.	3N/2E-12AAC	16.6	9/ 9/87	1.80	--	-.32	9/29/88	4.27	--	.26	3.04	--	-.03
86	MORGAN CREEK AT NE 167TH AVE. NEAR SALMON CREEK	3N/2E-12DCA	15.9	9/30/87	--	0.97	--	9/29/88	--	1.64	--	--	1.31	--
87	SALMON CREEK AT HWY 503	3N/2E-15DBC	3.2	9/ 9/87	2.34	--	-.13	9/29/88	7.20	--	.38	4.77	--	.12
88	WEAVER CREEK NEAR HWY 503 NEAR SALMON CREEK	3N/2E-15DBB	13.2	9/ 9/87	--	1.81	--	9/29/88	--	1.43	--	--	1.62	--
89	SALMON CREEK TRIBU-TARYAT END OF 112TH AVE.	3N/2E-15CBD	12.7	9/10/87	--	.45	--	9/29/88	--	.52	--	--	.49	--
90	SALMON CREEK AT 112TH AVE.	3N/2E-15CCC	12.6	9/10/87	4.83	--	.38	9/29/88	9.13	--	-.03	6.98	--	.17
91	SALMON CREEK TRIBU-TARY AT 112TH AVE.	3N/2E-15CCC	9.9	9/10/87	--	.41	--	9/29/88	--	.36	--	--	.78	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
						Washington—Continued								
92	SALMON CREEK TRIBUTARY AT 159TH STREET	3N/2E-20ABA	--	9/10/87	--	0.34	--	9/30/88	--	0.44	--	--	0.39	--
93	CURTIN CREEK AT 139TH STREET NEAR SALMON CREEK	3N/2E-29BAA	--	9/16/87	--	2.89	--	9/30/88	--	3.43	--	--	3.16	--
94	SALMON CREEK AT 72ND AVE.	3N/2E-20CBB	9.8	9/16/87	13.40	--	1.76	9/30/88	13.20	--	-0.06	13.30	--	0.71
95	MILL CREEK AT SALMON CR ROAD NEAR SALMON CREEK	3N/1E-24ACD	7.8	9/ 9/87	--	.58	--	9/30/88	--	.64	--	--	.61	--
97	SALMON CREEK TRIBUTARY AT 119TH STREET	3N/1E-25CCC	5.9	9/ 9/87	--	1.12	--	9/30/88	--	.80	--	--	.96	--
98	SALMON CREEK AT HWY 99	3N/1E-26DCC	5.5	9/ 9/87	12.40	--	-1.31	9/30/88	19.50	--	1.29	15.95	--	-.01
99	SALMON CREEK TRIBUTARY 200 FEET EAST OF I-5	3N/1E-35BAD	5.1	9/ 9/87	--	.37	--	9/30/88	--	.38	--	--	.38	--
100	SALMON CREEK TRIBUTARY AT 117TH AND HWY 99	3N/1E-35BAC	5.0	9/17/87	--	1.37	--	9/30/88	--	1.00	--	--	1.19	--
101	SALMON CREEK BELOW KLINELINE POND	3N/1E-27DDD	4.6	9/15/87	17.50	--	3.73	9/30/88	19.60	--	-1.42	18.55	--	1.14
102	SALMON CREEK TRIBUTARY BELOW POWER-LINES	3N/1E-27DDC	--	9/ 9/87	--	.53	--	10/ 3/88	--	.18	--	--	.36	--
103	COUGAR CANYON CR AT 19TH STREET NEAR SALMON CREEK	3N/1E-28DDD	3.1	9/10/87	--	1.25	--	10/ 3/88	--	.77	--	--	1.01	--
104	SALMON CREEK ABOVE 36TH AVE.	3N/1E-28BBD	2.2	9/ 9/87	17.40	--	-.78	9/30/88	23.40	--	1.19	20.40	--	.20
105	WHIPPLE CREEK AT UNION ROAD	3N/1E-23BAB	6.1	9/10/87	.01	--	--	--/--/--	--	--	--	.01	--	--
106	WHIPPLE CREEK AT 11TH AVE.	3N/1E-22BCB	4.7	9/10/87	.42	--	.29	10/ 6/88	.42	--	--	.42	--	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Washington—Continued													
107	WHIPPLE CREEK TRIBUTARY AT 149TH STREET	3N/1E-21DBA	3.0	9/10/87	--	0.19	--	10/ 6/88	--	0.22	--	--	0.21	--
108	PACKARD CREEK AT 179TH STREET NEAR WHIPPLE CREEK	3N/1E-08DCC	2.5	9/10/87	--	.17	--	10/ 6/88	--	.16	--	--	.17	--
109	WHIPPLE CREEK AT 179TH STREET	3N/1E-08CDC	2.5	9/10/87	1.89	--	0.50	10/ 6/88	2.65	--	0.84	2.27	--	0.67
110	WHIPPLE CREEK TRIBUTARY AT END OF 189TH STREET	3N/1E-07DAB	1.6	9/16/87	--	.20	--	10/ 6/88	--	.18	--	--	.19	--
	Oregon													
401	BEAVER CREEK AT COCHRAN ROAD	1S/3E-01CBD	2.8	9/28/87	.12	--	--	9/15/88	.04	--	--	.08	--	.01
402	KELLY CR AT MT. HOOD COMMUNITY COLLEGE NEAR BEAVER CREEK	1S/3E-02ADD	2.6	9/28/87	--	.33	--	9/12/88	--	.64	--	--	.49	--
403	BEAVER CREEK AT TROUTDALE ROAD	1N/3E-36CAC	1.7	9/28/87	1.00	--	.50	9/12/88	1.44	--	.69	1.22	--	.60
404	BEAVER CREEK AT COLUMBIA ROAD, TROUTDALE	1N/3E-25DBC	.3	9/28/87	.71	--	-.21	9/12/88	.91	--	-.38	.81	--	-.30
409	MT. SCOTT CREEK AT MT. SCOTT CR ROAD.	1S/2E-35BDB	4.9	10/20/87	.04	--	--	9/13/88	--	--	--	.02	--	--
410	MT. SCOTT CREEK AT SUNNYSIDE	2S/2E-03AAB	3.9	10/20/87	.07	--	.03	9/13/88	.02	--	.02	.04	--	.02
411	MT. SCOTT CREEK AT SE 97TH	2S/2E-04ADB	2.8	10/20/87	.06	--	-.01	9/13/88	.04	--	.02	.05	--	.01
412	MT. SCOTT CREEK BEHIND COSTCO	2S/2E-04BCB	1.9	10/20/87	.23	--	.19	9/13/88	.15	--	.12	.19	--	.16
413	PHILLIPS CREEK BEHIND COSTCO NEAR MT. SCOTT CREEK	2S/2E-04BCB	1.9	10/20/87	--	.27	--	9/13/88	--	.10	--	--	.19	--

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Oregon—Continued													
414	MT. SCOTT CREEK TRIB. AT RR AND HARMONY ROAD	2S/2E-05BBB	1.0	10/20/87	--	0.70	--	--/--/--	--	0.70	--	--	0.35	--
415	MT. SCOTT CREEK AT RUSK ROAD	2S/2E-06AAD	.7	10/20/87	1.37	--	0.14	9/13/88	2.05	--	1.50	1.71	--	0.82
416	MT. SCOTT CREEK NEAR KELLOGG CR	2S/2E-06CAB	--	10/20/87	1.96	--	.84	9/13/88	1.91	--	-.20	1.94	--	.32
421	ROCK CREEK AT TROGE ROAD	1S/3E-31DAD	3.2	10/20/87	--	--	--	9/13/88	.05	--	--	.03	--	--
422	ROCK CREEK AT SUNNYSIDE ROAD	2S/3E-06BCA	1.8	10/20/87	.10	--	.07	9/13/88	.20	--	.11	.15	--	.09
423	ROCK CREEK AT HWY 224	2S/2E-12DBB	.3	10/20/87	.53	--	.29	9/13/88	.58	--	.25	.56	--	.27
428	RICHARDSON CREEK AT ROYER ROAD	2S/3E-09ACB	2.4	10/20/87	--	--	--	9/15/88	.02	--	--	.01	--	--
429	RICHARDSON CREEK AT HWY 224	2S/3E-17BCD	.5	10/21/87	.27	---	.14	9/15/88	.25	--	.12	.26	--	.13
434	KELLOGG CREEK AT WEBSTER ROAD	2S/2E-08DCC	4.1	10/19/87	.04	--	--	9/15/88	--	--	--	.02	--	--
435	KELLOGG CREEK AT THEISEN ROAD	2S/2E-08BBC	3.0	10/19/87	.22	--	.16	9/15/88	.13	--	.12	.18	--	.15
436	KELLOGG CREEK AT RUSK ROAD	2S/2E-06DAC	2.4	10/19/87	1.80	--	2.63	9/15/88	1.89	--	2.93	1.85	--	2.78
437	KELLOGG CREEK AT OATFIELD ROAD	2S/1E-36CDD	.9	10/19/87	3.54	--	1.16	9/14/88	3.70	--	1.21	3.62	--	1.18
438	TRIBUTARY TO KELLOGG CREEK	2S/1E-01BAB	--	10/19/87	--	.01	--	9/16/88	--	--	--	--	--	--
439	TRIBUTARY TO KELLOGG CREEK AT MCLOUGHLIN BLVD	2S/1E-01BAB	.8	10/19/87	--	.15	--	9/16/88	--	.15	--	--	.15	--
444	TICKLE CREEK AT HWY 211	2S/4E-24BAB	6.6	10/21/87	.11	--	--	9/14/88	.05	--	--	.08	--	--
445	TICKLE CREEK TRIBUTARY AT MEING PARK	2S/4E-13DBB	6.0	10/21/87	--	.02	--	9/14/88	--	.03	--	--	.03	--
446	TICKLE CREEK AT 362ND	2S/4E-15ADA	5.0	10/21/87	.19	--	.04	9/14/88	.40	--	.20	.30	--	.12

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Oregon—Continued													
447	TICKLE CREEK AT COLORADO ROAD	2S/4E-09CCC	2.6	10/21/87	0.93	--	0.31	9/14/88	1.18	--	0.33	1.06	--	0.32
448	TICKLE CREEK TRIBUTARY AT COLORADO ROAD	2S/4E-09CCC	--	10/21/87	--	0.05	--	9/14/88	--	0.15	--	--	0.10	--
449	TICKLE CREEK TRIBUTARY AT DEEP CR ROAD	2S/4E-07DCA	2.6	10/21/87	--	.08	--	9/14/88	--	.05	--	--	.07	--
450	TICKLE CREEK AT DEEP CR ROAD	2S/4E-07DCC	1.0	10/21/87	2.50	--	.90	9/14/88	2.39	--	.63	2.45	--	.76
455	DEEP CREEK AT CRANE ROAD	2S/4E-34DBD	10.1	10/22/87	.41	--	--	9/14/88	.39	--	--	.40	--	--
456	DEEP CREEK TRIBUTARY AT CRANE ROAD	2S/4E-34DCA	--	10/22/87	--	.03	--	9/14/88	--	.02	--	--	.03	--
457	DEEP CREEK TRIBUTARY NEAR HWY 211	2S/4E-28ABB	8.2	10/22/87	--	.25	--	9/14/88	--	.13	--	--	.19	--
458	DEEP CREEK AT HWY 211	2S/4E-28DAD	6.9	10/21/87	1.16	--	.25	9/14/88	1.02	--	.25	1.09	--	.36
459	DEEP CREEK AT HOIST ROAD	2S/4E-18CCA	4.0	10/21/87	1.16	--	--	9/14/88	1.22	--	.07	1.19	--	.03
460	DEEP CREEK AT AEMISEGGER ROAD	2S/3E-13CCA	2.8	10/21/87	4.42	--	2.72	9/14/88	4.07	--	2.38	4.25	--	2.55
461	DEEP CREEK TRIBUTARY AT AEMISEGGER ROAD	2S/3E-13AAC	2.0	10/21/87	--	.05	--	9/14/88	--	.05	--	--	.05	--
462	NORTH FORK DEEP CREEK AT CONFLUENCE NEAR DEEP CREEK	2S/3E-14CBD	1.4	10/21/87	--	1.43	--	9/15/88	--	.78	--	--	1.11	--
463	NOYER CREEK AT DEEP CR ROAD NEAR DEEP CREEK	2S/3E-15DAB	.8	10/22/87	--	.02	--	9/15/88	--	.03	--	--	.03	--
464	DEEP CREEK AT HWY 224	2S/3E-15DBD	.7	10/21/87	5.76	--	-.08	9/15/88	5.28	--	.17	5.52	--	.04
469	JOHNSON CREEK AT PALMBLAD ROAD	1S/3E-23ABC	16.8	9/30/87	.22	--	--	9/12/88	.08	--	--	.15	--	--
470	JOHNSON CREEK AT WALTERS ROAD	1S/3E-09DAD	14.2	9/30/87	.70	--	.30	9/12/88	.42	--	.13	.56	--	.16
471	JOHNSON CREEK AT SE 190TH AVE	1S/3E-17BAA	12.2	9/29/87	.67	--	-.02	9/12/88	.47	--	.03	.57	--	.01S

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Oregon—Continued													
472	JOHNSON CREEK AT GAGING STATION NEAR FOSTER ROAD	1S/2E-13CDA	9.8	9/29/87	0.76	--	0.04	9/12/88	0.64	--	0.07	0.70	--	0.05
473	JOHNSON CREEK AT SE 112TH & BROOKSIDE	1S/2E-22BAD	7.4	9/29/87	.77	--	--	9/12/88	.74	--	.04	.76	--	.03
474	JOHNSON CREEK AT 82ND AVE	1S/2E-21CCB	5.4	9/29/87	.74	--	-.02	9/12/88	.92	--	.09	.83	--	.04
475	JOHNSON CREEK AT SE 45TH AND JOHNSON CREEK BLVD.	1S/2E-19CCD	2.9	--/--/--	--	--	--	9/13/88	1.35	--	.17	1.35	--	.21
476	ERROL HEIGHTS SPRING, JOHNSON CREEK TRIB.	1S/2E-19CCC	2.8	--/--/--	--	--	--	9/ 9/88	--	0.39	--	--	0.39	--
477	STORM SEWER TRIBUTARY TO JOHNSON CREEK	1S/2E-19CCC	2.8	--/--/--	--	--	--	9/ 9/88	--	.90	--	--	.90	--
478	JOHNSON CREEK AT TIDEMAR JOHNSON PARK	1S/1E-24DDC	2.4	9/29/87	3.51	--	--	9/13/88	3.45	--	1.62	3.48	--	1.68
479	JOHNSON CREEK ABOVE CRYSTAL SPRINGS CREEK	1S/1E-26AAA	1.2	--/--/--	--	--	--	9/13/88	2.91	--	-.45	2.91	--	-.48
480	CRYSTAL SPRINGS CR AT SHERRETT STREET BY JOHNSON CREEK	1S/1E-26AA	1.2	9/29/87	--	13.30	--	9/13/88	--	10.50	--	--	11.90	--
481	SPRING CREEK AT MILWAU-KIE JUNIOR HIGH SCHOOL	1S/1E-36BBB	1.2	--/--/--	--	--	--	9/13/88	--	1.20	--	--	1.20	--
482	JOHNSON CREEK AT SE RIVER ROAD	1S/1E-35AAB	.2	9/29/87	23.10	--	--	9/13/88	17.70	--	3.09	20.40	--	4.39
483	SANDY RIVER NEAR SANDY	2S/5E-07DDD	24.1	9/24/87	218.00	--	--	9/22/88	219.00	--	--	218.50	--	--
484	CEDAR CREEK AT FISH HATCHERY NEAR SANDY RIVER	2S/4E-12DCA	21.6	10/ 7/87	--	4.50	--	9/22/88	--	3.55	--	--	4.03	--
485	BULL RUN RIVER ABOVE SANDY RIVER AT DODGE PARK	1S/5E-31BBC	18.2	9/24/87	--	7.19	--	9/22/88	--	160.00	--	--	83.60	--
486	SANDY RIVER AT GAGING STATION NEAR BULL RUN	1S/5E-30CCD	18.0	9/24/87	257.00	--	4.48	9/22/88	370	--	-2.06	313.50	--	1.21

Table 3. Seepage measurements for streams in the Portland Basin, 1987 and 1988—Continued

ID	Stream description	Location	River mile	Date	Q	Trib Q	Seepage	Date	Q	Trib Q	Seepage	Avg Q	Avg trib	Avg seepage
	Oregon—Continued													
487	WALKER CREEK AT CONFLUENCE NEAR SANDY RIVER	1S/5E-30CAC	17.8	9/24/87	--	2.21	--	9/22/88	--	3.03	--	--	2.62	--
488	RIGHT BANK TRIBUTARY BELOW WALKER CR BY SANDY RIVER	1S/5E-30BCC	17.5	9/24/87	--	.20	--	9/22/88	--	--	--	--	--	--
489	RIGHT BANK TRIBUTARY—SEVERAL SPRINGS BY SANDY RIVER	1S/4E-25ADC	17.2	9/24/87	--	2.00	--	9/22/88	--	1.12	--	--	1.66	--
490	RIGHT BANK TRIBUTARY STREAM OFF CLIFF BY SANDY RIVER	1S/4E-24CDC	16.3	9/24/87	--	.37	--	9/22/88	--	.27	--	--	.32	--
491	RIGHT BANK TRIBUTARY IN FLOW NEAR SANDY RIVER	1S/4E-23DAB	15.5	9/24/87	--	.10	--	9/22/88	--	.35	--	--	.23	--
492	LEFT BANK TRIBUTARIES IN FLOW NEAR SANDY RIVER	1S/4E-23DBB	15.3	9/24/87	--	.20	--	9/22/88	--	.22	--	--	.21	--
493	SANDY RIVER AT OXBOW PARK	1S/4E-14BBA	13.3	9/24/87	274.00	--	2.54	9/23/88	294.00	--	-17.23	284.00	--	-7.35
494	TROUT CREEK AT GORDON CREEK ROAD NEAR SANDY RIVER	1S/4E-14DBA	13.3	9/28/87	--	3.83	--	9/23/88	--	4.35	--	--	4.09	--
495	GORDON CREEK AT GORDON CREEK ROAD NEAR SANDY RIVER	1S/4E-11DCA	12.8	9/28/87	--	8.83	--	9/23/88	--	11.70	--	--	10.27	--
496	SANDY RIVER AT STARK STREET	1S/4E-06ABC	5.7	9/24/87	250.00	--	-4.82	9/23/88	317.00	--	.91	283.50	--	-1.96
497	SANDY RIVER AT TROUTDALE	1N/3E-25DAC	2.9	9/24/87	259.00	--	3.21	9/23/88	318.00	--	.36	288.50	--	1.79