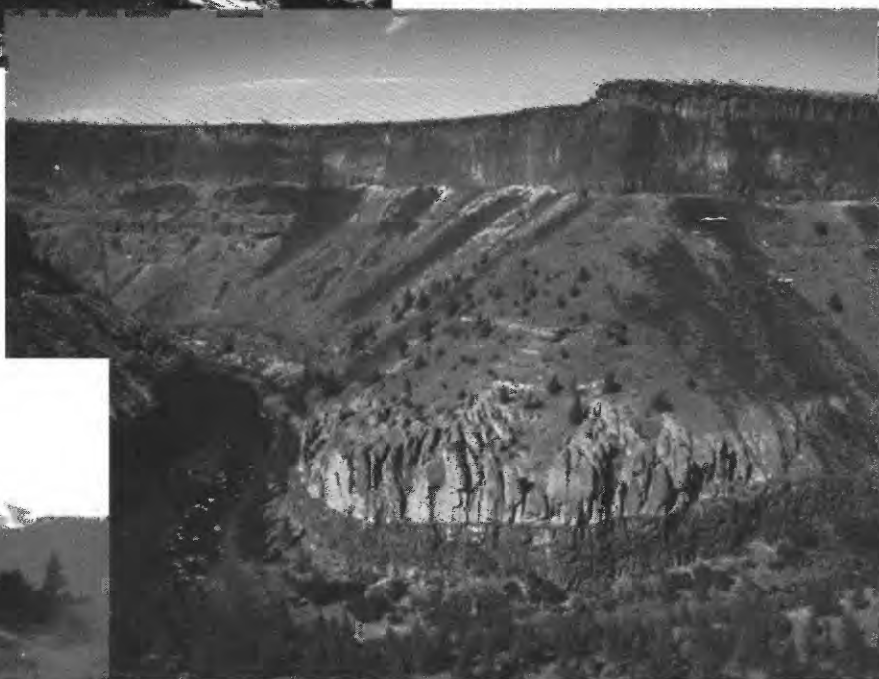


Chemical Study of Regional Ground-Water Flow and Ground-Water/Surface-Water Interaction in the Upper Deschutes Basin, Oregon



U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
Water-Resources Investigations
Report 97-4233



Prepared in cooperation with
OREGON WATER RESOURCES DEPARTMENT;
CITIES OF BEND, REDMOND, AND SISTERS;
DESCHUTES AND JEFFERSON COUNTIES;
THE CONFEDERATED TRIBES OF THE
WARM SPRINGS RESERVATION OF OREGON;
and U.S. ENVIRONMENTAL PROTECTION AGENCY

Cover photographs:

Top: Steelhead Falls on the Deschutes River near Crooked River Ranch, Oregon.

Middle: Crooked River Canyon at Crooked River Ranch, Oregon.

Bottom: North and Middle Sister with a wheel-line irrigation system in the foreground near Sisters, Oregon. (Photographs by Rodney R. Caldwell, U.S. Geological Survey.)

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By RODNEY R. CALDWELL

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Portland, Oregon
1998

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

U.S. GEOLOGICAL SURVEY
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
Length		
foot	0.3048	meter
mile	1.609	kilometer
Area		
square mile	2.590	square kilometer
Volume		
gallon	3.785	liter
acre-foot	1,233	cubic meter
Flow rate		
cubic foot per second	0.02832	cubic meter per second
inch per year	25.4	millimeter per year

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

$$^{\circ}\text{F}=1.8\text{ }^{\circ}\text{C}+32$$

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

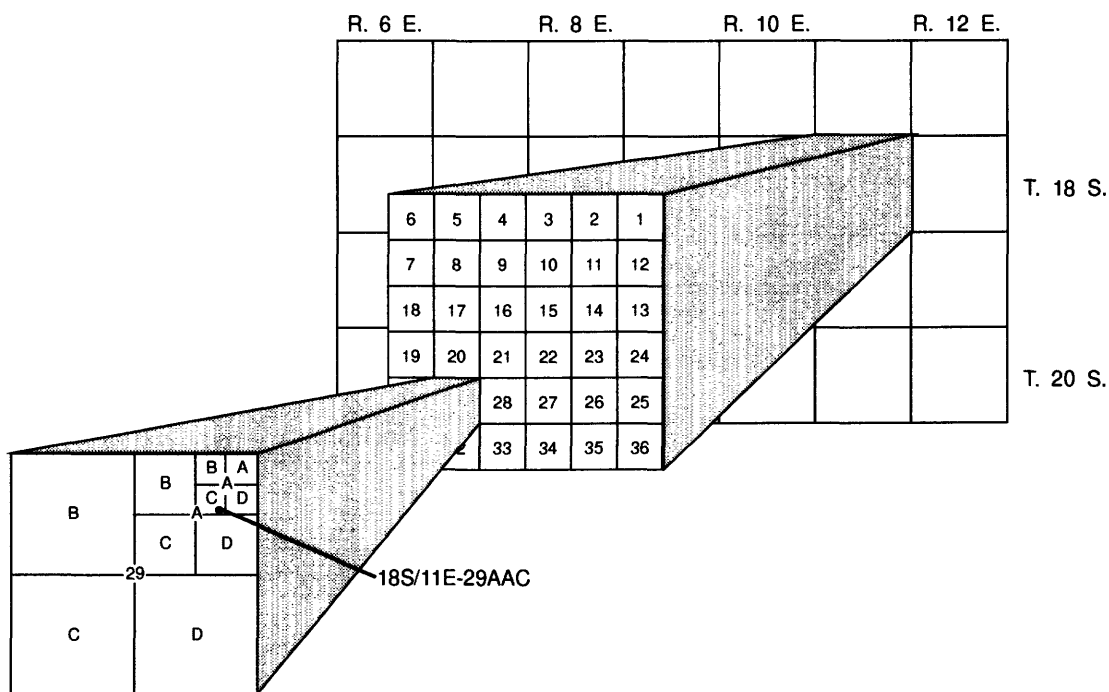
Altitude/Elevation, as used in this report, refers to distance above or below sea level.

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

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L). One mg/L equals 1,000 μg/L.

LOCATION SYSTEM

The system used for locating wells, springs, and surface-water sites in this report is based on the rectangular system for subdivision of public land. The State of Oregon is divided into townships of 36 square miles numbered according to their location relative to the east-west Willamette baseline and a north-south Willamette meridian. The position of a township is given by its north-south "Township" position relative to the baseline and its east-west "Range" position relative to the meridian. Each township is divided into 36 one-square-mile (640-acre) sections numbered from 1 to 36. For example, a well designated as 18S/11E-29AAC is located in Township 18 south, Range 11 east, section 29. The letters following the section number correspond to the location within the section; the first letter (A) identifies the quarter section (160 acres); the second letter (A) identifies the quarter-quarter section (40 acres); and the third letter (C) identifies the quarter-quarter-quarter section (10-acres). Therefore, well 29AAC is located in the SW quarter of the NE quarter of the NE quarter of section 29. When more than one designated well occurs in the quarter-quarter-quarter section, a serial number is included.



Each well is assigned a unique 8-digit identification number known as the log-id number. The first two digits of the log-id number indicate the county code from the Federal Information Processing Standards (FIPS) code file for the county in which the well exists. The FIPS codes for the counties in the study area are as follows: 13, Crook County; 17, Deschutes County; 31, Jefferson County; and 35, Klamath County. The last 6 digits of the number correspond to the State of Oregon well-log number (a unique number assigned by the Oregon Water Resources Department to the report filed by the well driller).

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ABSTRACT

Water-chemistry characteristics were used to assist in the understanding of regional ground-water flow and the interaction of ground water and surface water in the upper Deschutes Basin in central Oregon. Water samples were collected from sites along approximate ground-water flow paths inferred from water table maps to investigate chemical evolution and mixing, and at wells close to canals to investigate canal/ground-water interaction. Samples from 26 wells, 7 springs, and 5 surface-water sites were analyzed for common ions, nutrients, and stable isotopes. Selected samples were analyzed for tritium and carbon-14 to estimate residence times and relative ages. Historical water-chemistry data from more than 550 sites were retrieved from the Environmental Protection Agency's Storage and Retrieval data base (STORET) and the U.S. Geological Survey's National Water Inventory System data base to aid in the investigation.

Samples analyzed for this study were predominantly calcium-magnesium bicarbonate to mixed calcium-magnesium bicarbonate/sodium-potassium carbonate type waters with total dissolved solids concentrations ranging from 44 to 562 mg/L (milligrams per liter). Ground-water with the lowest total dissolved solids concentrations (44 to 60 mg/L) originated from Quaternary lavas in the regional ground-water recharge area on the eastern flank of the Cascade Range. Water from sites in the northern and eastern parts of the study area, which was withdrawn from the

Deschutes Formation and volcanic units of non-Cascade Range origin, had the highest total dissolved solids concentrations.

Specific conductance data from more than 550 ground-water sites (wells and springs) were examined. Most of the sites that had water with relatively low specific conductance values (less than 100 microsiemens per centimeter) are located in the western part of the study area, where most of the ground-water recharge occurs. Values increased to the east and northeast in the direction of ground-water flow. Specific conductance values were commonly greater than 250 microsiemens per centimeter in the eastern part of the study area, which is an area of low recharge, low permeability, and longer ground-water residence times.

Tritium values of samples from 14 ground-water sites ranged from less than 1 to 10.3 tritium units (TU). Samples with the highest tritium values (8.5 to 10.3 TU) were from sites in the regional recharge area on the eastern flank of the Cascade Range. Samples with tritium concentrations of less than 1 TU, indicative of water recharged prior to 1953, were from sites in or near a regional discharge area and in the eastern part of the study area.

Locally, wells and springs in close proximity had differing tritium values and ionic concentrations. This may have been due to local recharge from surface water, most notably from the numerous canals that traverse the area. Local recharge from irrigated lands and the mixing of waters of differing origins, residence times, or material

encountered along their flow paths may also contribute to the local variability of ground-water chemistry.

Water-level fluctuations resulting from canal leakage have been observed in several area wells. Samples from four canals and five wells adjacent to those canals were collected near the end of the summer irrigation season (September 1994) to examine possible ground-water chemistry effects resulting from canal leakage. The wells were sampled again (March 1995) prior to the operation of the canals for the season. Isotopic evidence indicates that canals (and possibly the Deschutes River from which these canals originate) are likely the predominant source of water in these wells. The deuterium and oxygen-18 composition of water from the canals and adjacent wells was tightly constrained within a range of 5 per mil δD (-95 to -100 per mil) and less than 1 per mil $\delta^{18}O$ (-12.56 to -13.32 per mil), respectively. Data from the study area as a whole show a much larger range of values. The canal water samples were nearly identical chemically, with total dissolved solids concentrations ranging from 51 to 52 mg/L. Total dissolved solids concentrations of the ground-water samples ranged from 93 to 307 mg/L. Water/rock interaction is a likely mechanism for the increased dissolved ion concentrations in the ground water relative to the canals. No significant chemical variation was observed in comparison of the ground-water samples collected in September 1994 and March 1995. However, multiple specific conductance measurements over a 1-year period (September 1994 to August 1995) indicated a temporal water-chemistry variation in two of the five wells.

INTRODUCTION

Background

The upper Deschutes Basin has had rapid population growth over the past few decades. Deschutes County, which includes most of the population within the upper Deschutes Basin, had a population increase of over 300 percent from 1970 to July 1, 1996 (esti-

mated) (S. Ordoz, Portland State University, Center for Population Research and Census, Portland, Oregon, written commun., 1997). This growth is expected to continue. Surface-water resources in the area have been closed by the State of Oregon to additional appropriation for many years. Virtually all new development in the region must rely on ground water as a source of water. To provide information on the ground-water resources of the upper Deschutes Basin, the U.S. Geological Survey (USGS) began a cooperative study in 1993 with the Oregon Water Resources Department (OWRD); the cities of Bend, Redmond, and Sisters; Deschutes and Jefferson counties; The Confederated Tribes of the Warm Springs Reservation of Oregon; and the U.S. Environmental Protection Agency. The objectives of this study were to provide a quantitative assessment of the regional ground-water system and to provide the understanding and analytical tools for State and local government agencies to make resource management decisions. This report is one in a series of reports that will present the results of the upper Deschutes Basin ground-water study.

Purpose and Scope

This report presents results of the water-chemistry component of the upper Deschutes Basin ground-water study. The primary objectives of this investigation were to (1) determine if the geochemical evidence supports a conceptual model of the ground-water flow system and (2) to use water-chemistry data to aid in the investigation of the interaction between water leakage from irrigation canals and water in nearby wells.

A preliminary conceptual model of the ground-water flow system, including areas of ground-water recharge and discharge and regional ground-water flow paths, was developed early in the project from the mapping of the water table, hydrogeologic mapping, surface-water gaging station data, seepage-run measurements, and precipitation data. Ground-water samples from sites along approximated flow paths were collected to determine if spatial trends in geochemical data are consistent with the conceptual ground-water flow model. The samples were analyzed for concentrations of major ions, nutrients, selected minor ions, total dissolved solids, stable isotopes of water, dissolved oxygen, pH, temperature, and specific conductance. Selected samples were analyzed for tritium, carbon-13 (^{13}C), and carbon-14 (^{14}C) to estimate

the ground-water age or residence time. Preexisting water-chemistry data from Federal and State agencies were compiled to aid in this investigation.

Water levels in several wells respond to the operation of the numerous irrigation canals that traverse the area. Irrigation canals and nearby wells of various depths were sampled to determine if a temporal variation in ground-water chemistry exists in response to canal operation. The samples were analyzed for selected inorganic ions, stable isotopes of water, and field parameters. The canals and adjacent wells were sampled in September 1994, near the end of the irrigation season, and the wells were again sampled in March 1995, preceding the summer operation of the canals.

Description of Study Area

The upper Deschutes Basin study area encompasses approximately 4,300 square miles of the Deschutes River drainage basin in central Oregon (fig. 1). The study area includes the major population centers in the basin, where ground-water development is most intense, and resource management questions are most urgent. The major communities include Bend, Redmond, Sisters, Madras, Prineville, and La Pine. The area is drained by the Deschutes River and its major tributaries the Crooked and Metolius Rivers. Elevation ranges from less than 1,300 feet near Madras in the north to more than 10,000 feet above sea level in the Cascade Range in the west. The study area boundaries were chosen to coincide as much as possible with natural hydrologic boundaries across which ground-water flow can be reasonably estimated or assumed to be negligible. The study area is bounded on the north by Jefferson Creek, the Metolius River, the Deschutes River, and Trout Creek; on the east by the generalized contact between the Deschutes Formation and the older, much less permeable John Day Formation; on the south by the drainage divide between the Deschutes Basin and the Fort Rock and Klamath Basins; and on the west by the Cascade Range crest.

Acknowledgments

The author wishes to acknowledge the private landowners, the U.S. Forest Service, and the water supply departments of the City of Bend, the City of Redmond, Deschutes Valley Water, Sunriver, Oregon Water Wonderland, and Black Butte Ranch, who

allowed access to their wells and springs for data collection. The author also acknowledges Rodney Weick and Greg Pettit of the Oregon Department of Environmental Quality, who supplied water-chemistry data for samples from the Deschutes River and ground-water sites in the La Pine and Prineville areas; Roger Prowell of the City of Bend Public Works Department for aid in the sample collection at one of the most remote sites sampled for this study; U.S. Geological Survey volunteers Esther Dixon and the Dr. Robert Sonnenburg family, who recorded several specific conductance measurements of samples from their wells; and Robert Caldwell, also a U.S. Geological Survey volunteer, who provided assistance with field work. Funding for this work was provided in part by the U.S. Environmental Protection Agency Regional Applied Research Effort.

HYDROGEOLOGIC SETTING

Aquifers within the upper Deschutes Basin are composed of a variety of volcanic rocks and sediments (pl. 1). Much of the area consists of late Miocene to Holocene lava flows, ignimbrites (ash-flow tuffs), and volcanoclastic sediments deposited in the Cascade Range and the adjacent sedimentary basin (Smith and others, 1987; Sherrod and Smith, 1989; Bishop and Smith, 1990; D.R. Sherrod and others, USGS, unpub. data, 1997). Eruptive centers within the basin supplied additional lavas, pyroclastic deposits, and sediments. The largest eruptive center is Newberry Volcano, which dominates the southeastern part of the study area. A substantial thickness of unconsolidated sediment of fluvial and lacustrine origin occurs within the subbasin surrounding La Pine. Oligocene to Miocene volcanic rocks of low permeability and limited potential as a source for ground water are exposed along the northeastern margin boundary and occur at depth in the eastern part of the area. These rocks are considered a low permeability boundary to the regional ground-water flow system.

Ground water occurs in most rocks of the basin, but fractured lava, interflow zones, and coarse-grained volcanoclastic sediments are particularly productive water bearing units (M.W. Gannett, USGS, oral commun., 1997). Individual lava flows or sedimentary layers rarely extend for more than a few miles in the subsurface. Therefore, ground water may flow through a variety of rock types along a particular flow path.

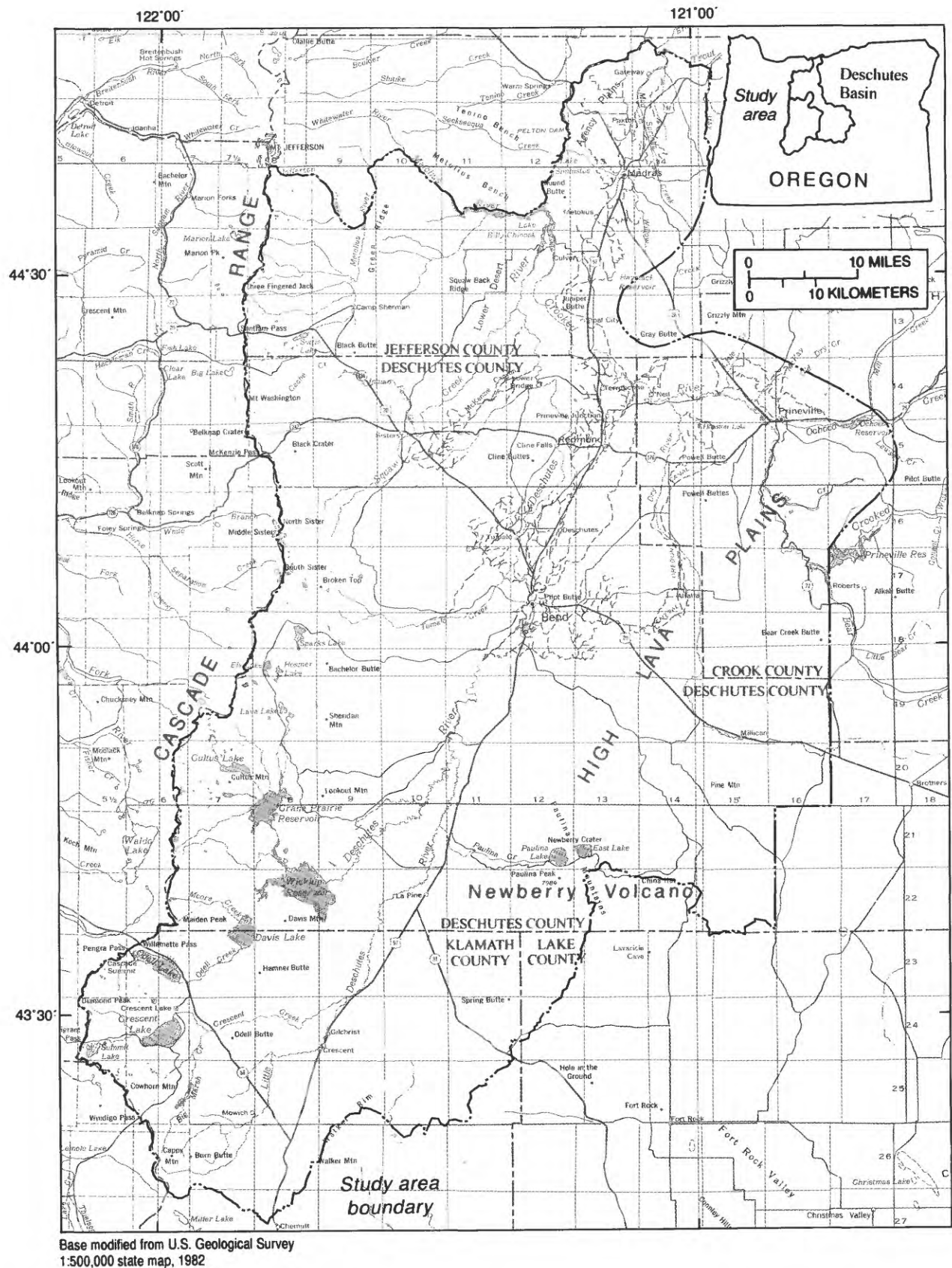


Figure 1. Location of the upper Deschutes Basin study area, Oregon.

Precipitation along the Cascade Range ranges from approximately 50 to 150 inches annually and is the primary source of recharge for the upper Deschutes Basin ground-water system (D.S. Morgan, USGS, unpub. data, 1997). Precipitation rates decrease markedly to less than 10 inches per year in the central and eastern parts of the study area. Ground-water recharge rates (estimated by using a daily moisture balance model [D.S. Morgan, unpub. data, 1997]) range from less than 1 inch per year in the central and eastern parts of the study area to approximately 20 to 100 inches per year in the Cascade Range (fig. 2). Secondary sources of recharge include leakage from lakes, streams, and irrigation canals, and on-farm irrigation losses. The total recharge in the basin is approximately 2.9 million acre-feet per year. The secondary sources of recharge are most important in the central and northern parts of the study area, where local recharge from precipitation is small to nonexistent. Nearly 330,000 acre-feet (44 percent) of the 750,000 acre-feet of water that is diverted into the canal systems during the irrigation season is lost due to leakage through unlined canal beds. Canal leakage and on-farm losses may account for nearly 13 percent (more than 370,000 acre-feet per year) of the total recharge per year.

A generalized water-table map was generated for the upper Deschutes Basin ground-water study using water-level data from nearly 1,500 water wells (fig. 3). The water-table surface has a shape similar to that of the land-surface topography, but is much smoother. Generalized ground-water flow directions interpreted from the water-table surface are shown in figure 3. The horizontal head gradient is greatest in the Cascade Range and surrounding Newberry Volcano, and is much smaller north of Bend. The regional water-table surface is incised by the Crooked and Deschutes River Canyons a few miles upstream from Lake Billy Chinook, resulting in the occurrence of several springs that emanate from the canyon walls. Ground-water discharge accounts for more than an order of magnitude increase in flow in both the Deschutes and Crooked Rivers in the last few miles above Lake Billy Chinook (M. D. Clark, OWRD, unpub. data, 1992; K. Starnes, OWRD, unpub. data, 1994).

Downward head gradients are common throughout much of the study area (Gannett and Lite, 1996). Downward vertical head gradients occur in areas of ground-water recharge and downward flow. Such downward gradients occur throughout the western part of the study area in and adjacent to the Cascade Range,

and also in areas where irrigation canals are numerous, most notably in the area surrounding and north of Bend.

A generalized cross-section depicting a conceptual model of the hydrogeologic system is shown in figure 4. The location of the cross-section (A-A') is shown on figure 3. Figure 4 shows the relative magnitude of ground-water recharge from precipitation in the Cascade Range area and how it diminishes to the east. It also depicts the occurrence of localized recharge from canal leakage, and on-farm losses. Because most of the recharge occurs in the western part of the study area, and to a lesser extent in the southern part, most of the ground water in the system originates from those areas. Generalized ground-water flow lines in figure 4 represent the pathway a particle of water would travel as it moves through the aquifer system. The longer flow lines (regional ground-water flow lines) represent water from recharge at or near the ground-water divide discharging in the regional discharge area. The shorter flow lines (local ground-water flow lines) represent water from recharge closer to the regional discharge area. Generally, water from greater depths is older and from a more regional flow path, whereas water from shallower depths is from a more localized flow regime. Figure 4 also shows how waters of different origins may mix and how waters of different flow paths may converge in a discharge area. Finally, figure 4 depicts the common occurrence in the study area of water wells that tap only the upper part of the saturated zone.

STUDY DESIGN AND APPROACH

Methods

Field and Analytical

Samples for chemical analysis were collected according to standard USGS protocols and procedures as outlined by Claassen (1982), Friedman and Erdmann (1982), Horowitz and others (1994), Ward and Harr (1990), and Wells and others (1990). Field parameters (temperature, specific conductance, pH, and dissolved oxygen) were determined on site using a multiparameter water-quality logging system. Field alkalinities were determined on site in a mobile lab or at a nearby temporary lab using the incremental titration method. A 0.45 micrometer filter capsule was used

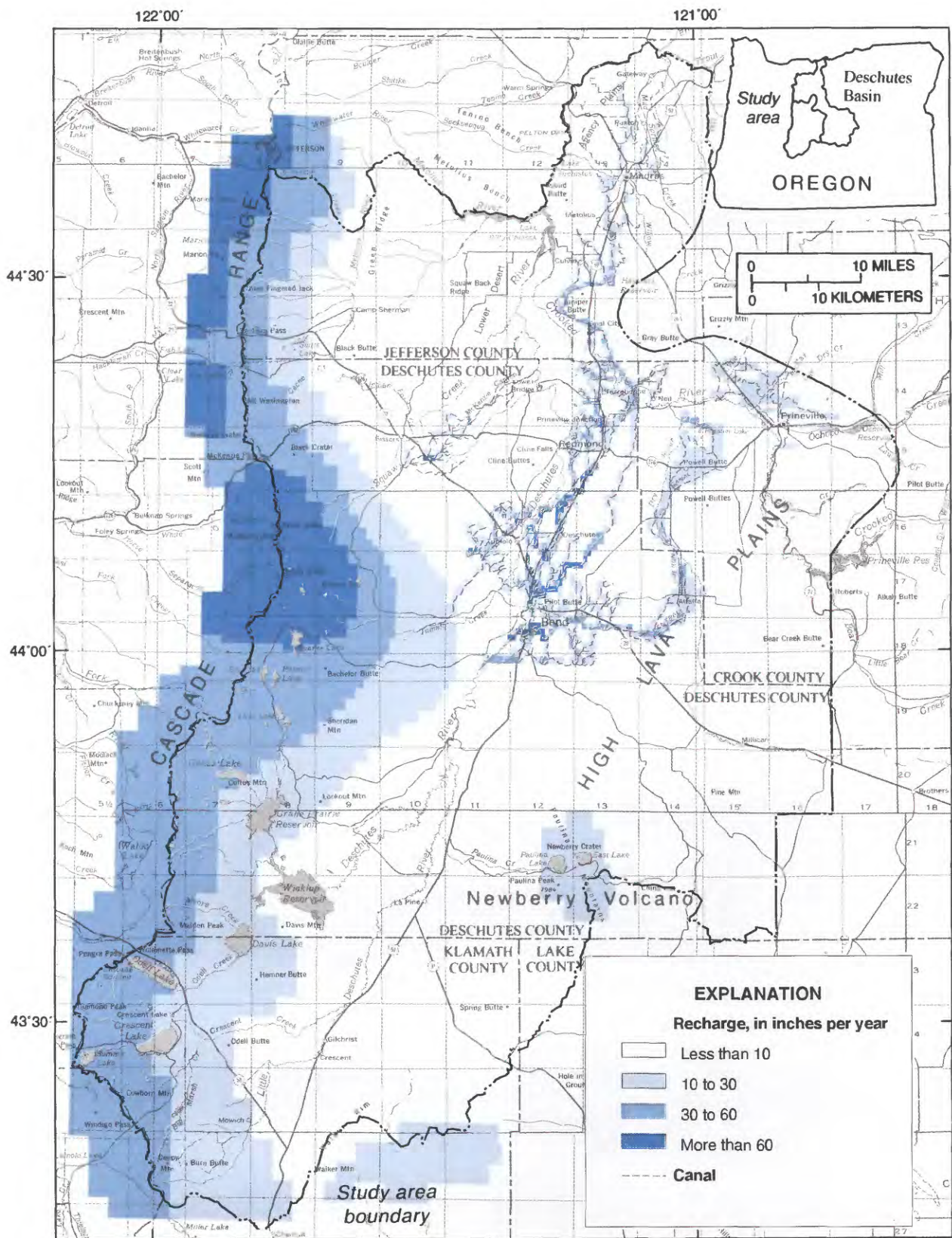


Figure 2. Estimated annual ground-water recharge rates in the upper Deschutes Basin, Oregon, 1993–95. (D.S. Morgan, unpub. data, 1997.)

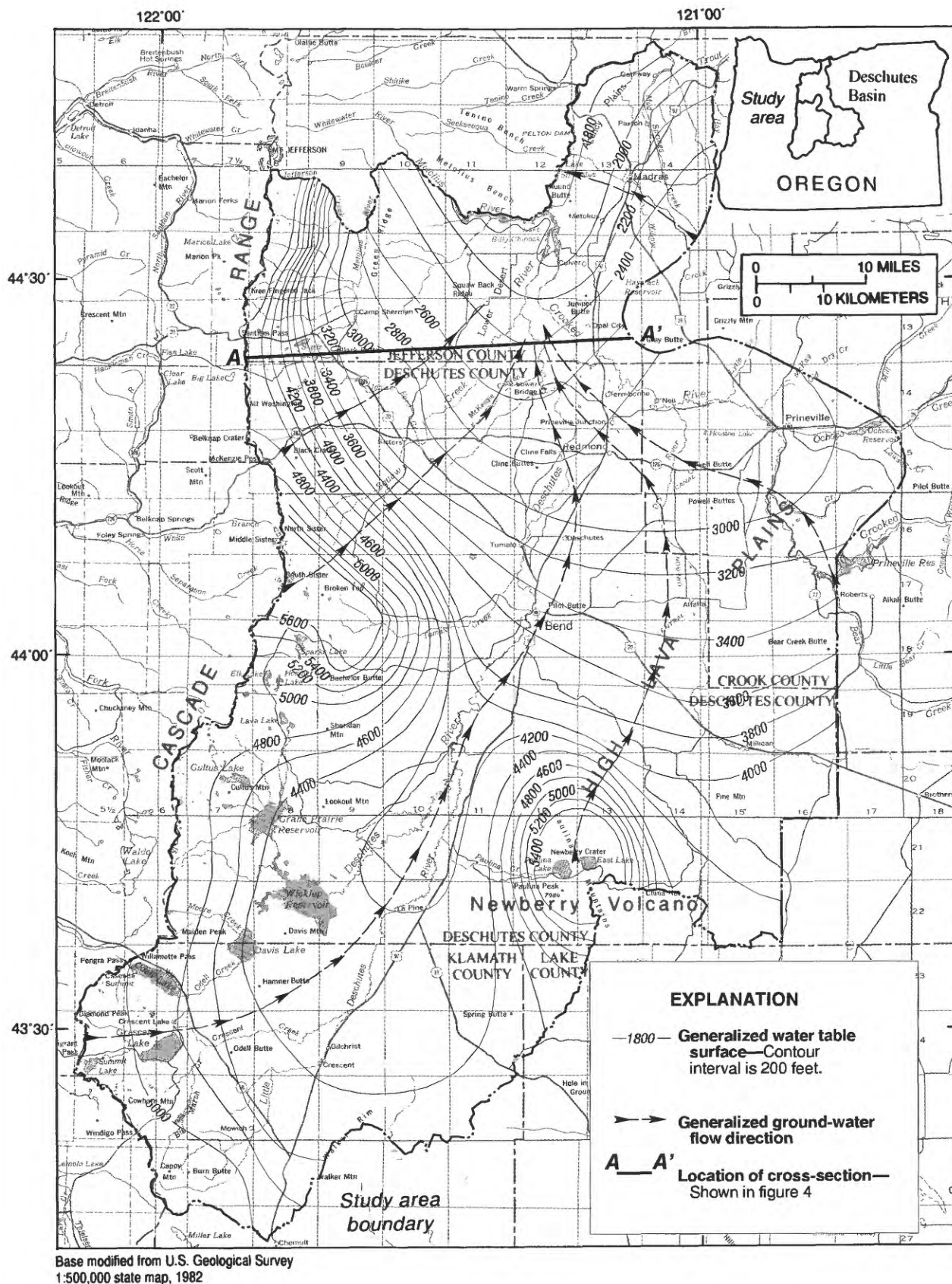


Figure 3. Generalized water table and ground-water flow directions of the upper Deschutes Basin, Oregon.

for in-line filtration. Samples were processed and preserved in the field within 1 hour of sampling.

The sampling equipment was precleaned in the office laboratory before going to the field according to standard protocol to minimize contamination. Native water was flushed through the sampling apparatus prior to sample collection in the field. The equipment was flushed with deionized water immediately after sampling.

Samples from wells were collected from discharge lines before passage through pressure tanks and water treatment equipment with the use of existing submersible or turbine pumps. The well samples were collected after the field parameters had stabilized and generally three times the volume of water stored in the well bore had been purged. Field parameters were recorded every 3 to 5 minutes with the multiparameter water-quality logging system transmitter inserted into a flow-through cell. The field parameters were considered stable if they met the following criteria in three successive measurements:

1. Temperature varied less than 0.2 degrees Celsius;
2. Specific conductance varied less than 5 percent ($5 \mu\text{S}/\text{cm}$ [microsiemens per cm] if less than $100 \mu\text{S}/\text{cm}$);
3. pH varied less than 0.1 pH unit; and
4. Dissolved oxygen varied less than 0.1 mg/L.

As the well was purged, the native water was discharged through the sampling apparatus. Samples were collected and filtered (when required) sequentially into the individual sample bottles through silicone tubing.

Canals, streams, and springs were assumed to be well-mixed relative to dissolved chemical constituents. Most of the canal and stream samples were collected with an isokinetic, depth integrated sampler according to the method of Ward and Harr (1990). Samples were collected into 3-liter polyethylene bottles and then transferred and filtered (when required) through silicone tubing into individual sample bottles by using a peristaltic pump. Samples were collected by using a peristaltic pump with the silicone tubing in the centroid of flow, or as grab samples with the bottle opening pointed upstream in the centroid of flow (according to the method of Wells and others [1990]) when velocities were too fast or depths too shallow for the isokinetic sampler. Springs were sampled at or near the main discharge point using a peristaltic pump with the silicone tubing submerged according to the method of Claassen (1982). Field parameters were determined by placing the multiparameter water-quality logging system trans-

mitter directly into the water body near the centroid of flow. Values were recorded until they stabilized.

Filtered samples were analyzed for concentrations of major ions, alkalinity, selected trace elements, and nutrients at the USGS National Water Quality Laboratory in Arvada, Colorado. Laboratory methods for the determination of the chemical constituents are presented by Fishman and Friedman (1989) and Fishman (1993). Calcium, magnesium, sodium, iron, manganese, and silica were analyzed by inductively coupled plasma atomic emission spectrometry. Potassium was analyzed by atomic absorption spectrometry. Chloride, bromide, nitrogen (ammonia, nitrite, and ammonia + organic, and nitrite + nitrate), phosphate, and orthophosphate were analyzed by colorimetry. Sulfate was analyzed by ion-exchange chromatography. Aluminum was analyzed by direct-current plasma atomic emission spectrometry. Fluoride was analyzed with an ion-selective electrode.

Selected samples were analyzed for the isotopic ratios of $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/\text{H}$ by mass spectrometry at a USGS National Research Program laboratory. Values are reported as delta (δ) D (deuterium, ^2H) and $\delta^{18}\text{O}$ in comparison to the standard reference composition of standard mean ocean water, where δ is expressed in units of per mil (o/oo, parts per thousand). Delta is defined as:

$$\delta \text{ in (o/oo)} = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 1,000 \quad (1)$$

where

$$R = \text{D/H or } ^{18}\text{O}/^{16}\text{O}.$$

The tritium (^3H) content of selected samples was analyzed at the USGS Isotope Tracers Laboratory in Menlo Park, California, and at the University of Miami Tritium Laboratory in Miami, Florida, by the electrolytic enrichment - liquid scintillation counting method. The tritium content is expressed in Tritium Units (TU), where one TU is defined as one atom of ^3H per 10^{18} atoms of H. One TU corresponds to 3.19 picocuries per liter (pCi/L) (International Atomic Energy Agency, 1981).

Radiocarbon measurements of selected samples were made at the National Science Foundation - University of Arizona Accelerator Mass Spectrometer laboratory. Carbon in the water was converted to CO_2 and reduced to graphite. The ratio of $^{14}\text{C}/^{13}\text{C}$ in the graphite was measured by accelerator mass spectrometry and used to calculate a radiocarbon age. The carbon-14

concentration was reported as percent modern carbon (pmc), relative to the National Institute of Standards and Technology oxalic acid standard, with a standard deviation of 0.4 to 0.6%. Conventional mass spectrometry was used to measure $\delta^{13}\text{C}$. Delta ^{13}C , referenced to the Pee Dee belemnite standard, is defined as:

$$\delta \text{ (o/oo)} = [(R_{\text{sample}} / R_{\text{standard}}) - 1] \times 1,000 \quad (2)$$

where

$$R = {}^{13}\text{C}/{}^{12}\text{C}.$$

Quality Assurance

Quality control samples were collected for both field and laboratory analysis at about 10 percent of the sites. Sequential replicate samples were collected to estimate the precision of analytical results due to combined sampling and analytical procedures. Field blanks were analyzed to estimate potential contamination of samples due to equipment-cleaning procedures, analyte carryover from previous sites, sampling and sample-processing procedures, and equipment handling and transport between sample collections. At least one quality control sample was collected during each sampling trip. Laboratory reruns of stable constituents were requested if questionable or inconsistent analytical results were received. Archival samples were collected and stored for analysis in the event that previous results were questionable.

Replicate samples were collected immediately after the environmental sample. The native water was briefly purged through the sampling apparatus between the collection of environmental and replicate samples. The filter used for the environmental samples was discarded and a new filter was used for the replicate sample.

Field blanks consisted of certified inorganic-free water supplied by the USGS Quality of Water Service Unit in Ocala, Florida. The inorganic-free water was pumped through the sampling apparatus after the environmental sample had been collected and the sampling equipment had been cleaned in the same manner used between environmental samples. The field blanks were collected according to the same procedures as the environmental samples.

The results of the replicate and the field-blank analyses were favorable. A review of the field blank results detected no significant contamination. The major ion and nutrient concentrations of the field

blanks were all less than 200 percent of the minimum reporting level (MRL) of the laboratory. The MRL is defined by the USGS National Water Quality Laboratory as the smallest measured concentration of a constituent that may be reliably reported using a given analytical method. Comparison of primary and replicate sample analyses generally indicated a high level of precision. The relative differences between the individual concentrations of the primary and replicate samples were nearly all less than 10 percent. Differences of greater than 10 percent were found only in constituents of low concentration (less than 10 times the MRL), and only one of those (from a site with a phosphorous concentration of 0.10 mg/L for the primary sample and 0.05 mg/L for the replicate sample) had a relative difference of greater than 100 percent of the MRL. The results of these analyses are stored in the USGS National Water Information System (NWIS) data base.

Selection and Description of Sample Sites

Samples from a total of 38 ground-water and surface-water sites were selected for chemical analysis for this investigation (pl. 1). A description of the wells sampled is reported in Appendix 1, the springs in Appendix 2, and the surface-water sites in Appendix 3. Construction information for the sampled wells was reported by Caldwell and Truini (1997). The sites sampled for water-chemistry analysis have been assigned unique identification numbers for reference. The unique identification numbers are included in Appendixes 1, 2, and 3 for the wells (an 8-digit log-id number, see page V for description), springs (S-1 to S-7), and the surface-water sites (SW-1 to SW-5).

Samples were collected from 29 sites to determine if geochemical trends were consistent with the conceptual model of the flow system inferred from water table maps. The samples were collected in the general downgradient direction of ground-water flow (approximate flow paths), but they were not collected along exact ground-water flow paths because (1) the locations of available sampling sites were restricted to preexisting wells and springs, (2) downward vertical head gradients occur throughout much of the study area, and wells commonly tap only the upper part of the saturated zone, resulting in limited or no access to the lower part of the flow system, and (3) some wells are open over a large interval, which may lead to the capture of water from different depth intervals when the well is pumped. Water samples from 13 wells and 5

springs were collected along 3 approximate flow paths originating near the communities of Sisters, La Pine, and Millican and ending just above Lake Billy Chinook in the regional discharge area. Samples were collected from six wells and Mud Springs Creek (which carries irrigation return flow and a ground-water component due to the springs that discharge to it) in the Madras-Gateway area. Two wells were sampled east of Opal Springs (a group of large springs that discharge to the Crooked River) to determine the geochemical characteristics of ground water flowing from the east towards the regional discharge area. Two springs and a well were sampled on the east flank of the Cascade Range to obtain analyses of regional recharge waters.

Samples from four canals and five wells near canals were collected to investigate ground-water/canal-water interactions. The water levels in these wells were measured every 3 months as part of the upper Deschutes Basin ground-water study observation well network. The water levels in these wells are affected by canal operation. The wells range in depth from 40 to 510 feet, with distances to the nearest canals or irrigation ditches ranging from 60 to 340 feet. Water-level fluctuations in these wells ranged from about 2 to more than 90 feet in response to canal operation.

CHEMICAL ANALYSIS OF REGIONAL GROUND-WATER FLOW

Most of the ground-water samples that have been collected in the upper Deschutes Basin (for this and previous studies) have similar chemical characteristics. Generally, calcium and magnesium are the dominant cations, bicarbonate is the dominant anion, and total dissolved solids (TDS) concentrations are low. However, some variation does exist in the proportions of major ions and in the TDS concentrations of ground water in the study area. This variation is expected because regional ground-water chemistry can be influenced by a variety of factors including the mineralogical properties of the aquifer materials and the time the water has been in contact with the materials. Sites that were sampled for previous studies and resampled for this study showed some temporal variability in the concentrations of individual constituents, but no long term trends are apparent from these data.

The chemical data for the samples collected for this investigation are presented in Appendixes 4, 5, and 6. Historical water-chemistry data are available from

previous investigations (Sceva, 1968a, 1968b; Oregon Department of Environmental Quality, unpub. data, 1974, 1978; USGS, unpub. data, 1978) for six of the sites sampled for this study (Appendix 7).

Relation of Water Chemistry to Ground-Water Flow

The amount of time water is in the ground, known as residence time, increases as the water flows through a ground-water system from a recharge area to a discharge area. The greater the residence time, the longer the water can react with the aquifer material and dissolve minerals and volcanic glass. Therefore, the concentrations of dissolved ions in ground water commonly increases along flow paths. Where mixing and dilution with newly recharged water occur, the opposite trend may be apparent. Both cases appear to be present in the study area.

To determine if geochemical trends were consistent with the conceptual model of the flow system, 29 sites were sampled in areas of recharge, discharge, and in transitional zones. Calculated TDS concentrations, available for 28 of the 29 ground-water sites sampled for this study, and generalized directions of ground-water flow are shown in figure 5. The TDS concentrations were lowest in the regional recharge area in the western part of the study area and generally increased towards parts of the basin where ground water discharges. The highest TDS values were found in the eastern and northeastern parts of the basin.

A similar trend of increasing TDS along flow paths can be seen in specific conductance data from this and other investigations. Specific conductance is a measure of the ability of a substance to conduct an electric current. Specific conductance increases with increased dissolved ion concentrations in water, and it can be used to examine geochemical trends or distributions in a regional ground-water flow system. Estimates of TDS can be made from specific conductance values with the use of a graph that compares specific conductance values with associated TDS concentrations (Hem, 1985). The relationship between TDS and specific conductance is approximately linear, but the slope of the line is different for waters of different chemical types. A linear regression analysis of specific conductance measurements and associated TDS concentrations of 141 analyses from 85 Deschutes Basin ground-water sites retrieved from the USGS NWIS data base was used to determine the local relationship

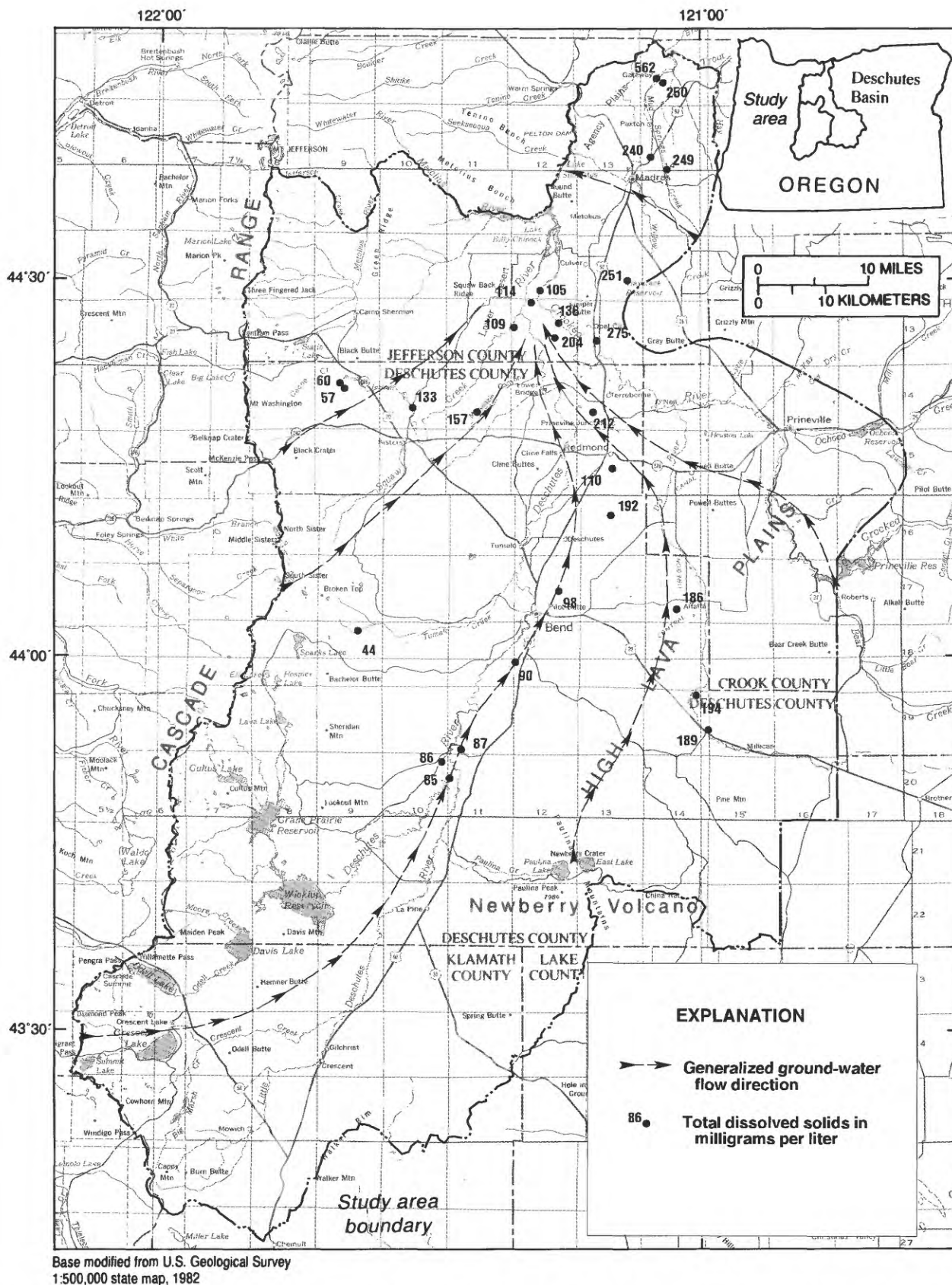


Figure 5. Total dissolved solids concentrations at ground-water sites and generalized ground-water flow directions in the upper Deschutes Basin, Oregon.

of specific conductance and TDS concentrations. The specific conductance and TDS of these samples were linearly related, with a correlation coefficient of 0.99. The regression equation is as follows:

$$TDS = (0.73 \times SC) + 12.93 \quad (3)$$

Equation (3) can be used with confidence to estimate TDS concentrations from specific conductance data in the study area. For example, a specific conductance value of 100 $\mu\text{S}/\text{cm}$ is roughly equivalent to 86 mg/L TDS.

More than 550 measurements of specific conductance, many more than the laboratory determinations of TDS concentrations, are available from this study, published reports (Sceva, 1968a, 1968b; Ingebritsen and others, 1988; Crumrine and Morgan, 1994; Morgan and others, 1997), and unpublished analyses from previous investigations (fig. 6). The unpublished specific conductance values were measured by the USGS, the U.S. Environmental Protection Agency (EPA), and the Oregon Department of Environmental Quality (ODEQ). The ODEQ (unpub. data, 1974, 1978) collected water-chemistry data at 22 of the ground-water sites sampled during the previous study by Sceva (1968a, 1968b). The USGS collected specific conductance data in 1978 from nearly 100 wells and springs during a regional ground-water study that was later discontinued (USGS, unpub. data, 1978). The ODEQ also collected specific conductance data in the Prineville area (ODEQ, unpub. data, 1993), and more recently in the La Pine area (ODEQ, unpub. data, 1995). Additional data were retrieved in January of 1995 from EPA's Storage and Retrieval data base (STORET). Analysis of specific conductance values from this and previous studies was limited to generalized interpretations, since variability exists between some of the historical data and data collected for this study. For example, six sites sampled during this study and during previous investigations (app. 7) show differences in specific conductance of as much as 20 percent.

The specific conductance values (fig. 6), which are more widely and densely distributed than the TDS data collected for this study, corroborate the trends observed with the TDS data (fig. 5). Most of the sites with specific conductance values of less than 100 $\mu\text{S}/\text{cm}$ are located in the western half of the study area. Specific conductance values increased to the east and northeast, where values were greater than 250 $\mu\text{S}/\text{cm}$.

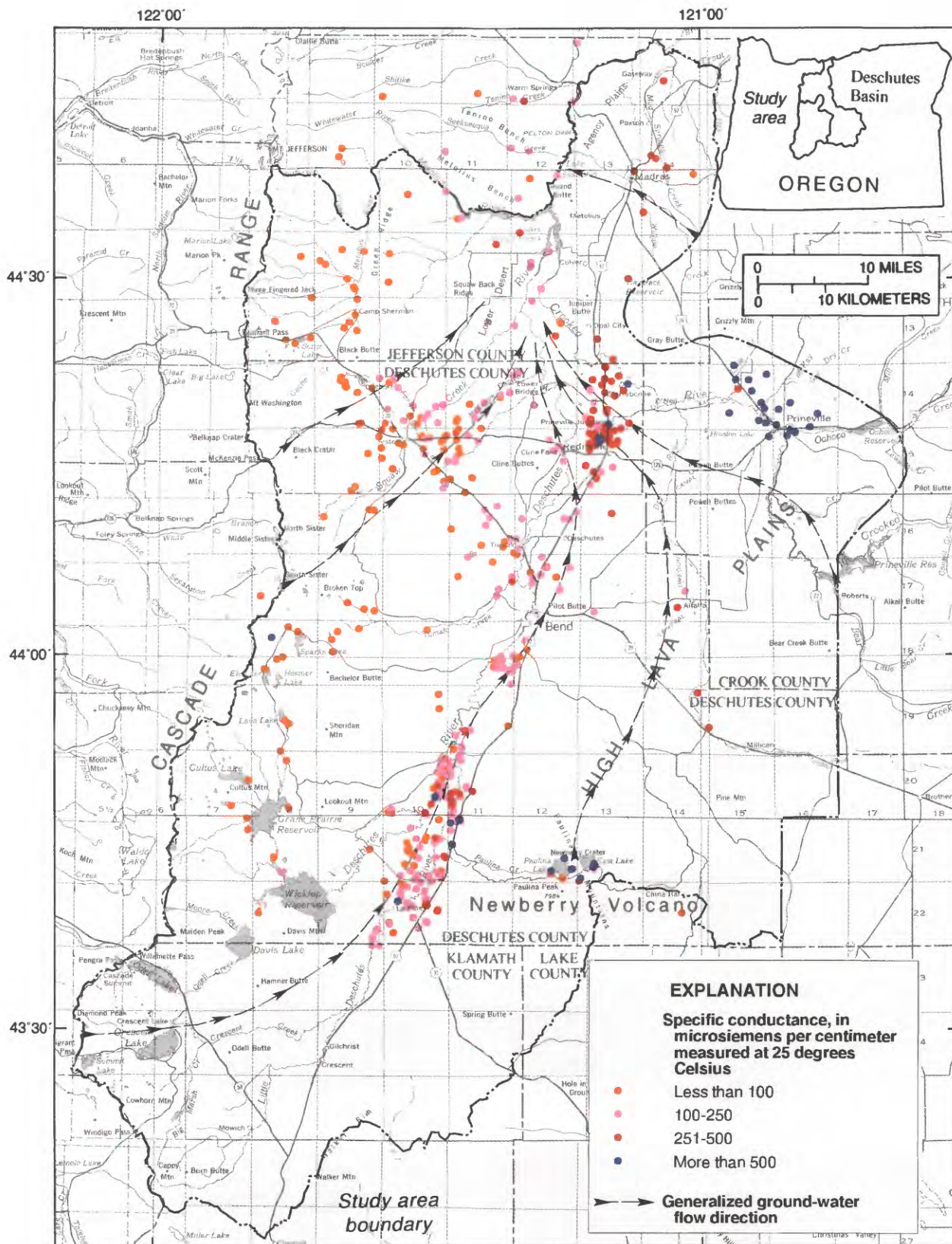
Anomalously high values ($>500 \mu\text{S}/\text{cm}$) were associated with (1) relatively deep (>100 feet) wells in the La Pine area, (2) wells in Quaternary alluvium near Prineville, and (3) geothermal waters in the Newberry Volcano area and the Cascade Range.

Sites sampled in the area of recharge on the eastern flank of the Cascades had relatively low ionic concentrations (figs. 5 and 6). The relatively low dissolved ion concentrations are likely the result of the high recharge rates and short residence times. The source of recharge near the eastern margin of the study area is in the east or southeast (Newberry Volcano area), as inferred from water-table mapping (fig. 3). Water from most of the sites sampled in the eastern part of the study area had specific conductance values of greater than 250 $\mu\text{S}/\text{cm}$ (fig. 5). The higher ion concentrations were likely the result of relatively low recharge rates, lower aquifer permeabilities, and longer ground-water residence times.

Most ground water originating from the east discharges in the vicinity of Lake Billy Chinook or just upstream (fig. 3). This conclusion is supported by relatively high specific conductance values ranging from 160 to 368 $\mu\text{S}/\text{cm}$ in spring water issuing from the east canyon wall to the Deschutes River in the vicinity of present-day Round Butte Dam (Bechtel Corp., 1958). These springs were sampled prior to the filling of Lake Billy Chinook. Ground water in the northeast near Madras is likely discharging downstream from Lake Billy Chinook.

Samples from sites in the regional discharge area had lower ion concentrations than some upgradient sites. A sample from Lower Opal Springs, a major regional discharge point on the Crooked River, had a relatively low dissolved ion concentration (TDS = 105 mg/L , specific conductance = 128 $\mu\text{S}/\text{cm}$). Upgradient sites to the south and east had higher dissolved ion concentrations, whereas upgradient sites to the west and southwest sampled in the area of dominant recharge on the east flank of the Cascades had lower dissolved ion concentrations. The relatively low dissolved ion concentrations at Lower Opal Springs and other discharge-area sites indicates a dominant component of water originating from the west or southwest.

The evaluation of water chemistry with respect to ground-water flow can be complicated by changes of water chemistry with depth. The specific conductance data indicate a variability of ion concentrations between ground-water sites within close proximity to one another, particularly near Redmond and in the La



Base modified from U.S. Geological Survey
1:500,000 state map, 1982

Figure 6. Specific conductance values at ground-water sites and generalized ground-water flow directions in the upper Deschutes Basin, Oregon.

Pine area (fig. 6). Poor quality water has been reported in deep wells in the La Pine area (Century West Engineering Corp., 1982). The relation of specific conductance values to several variables (well depth, well bottom elevation, depth to water, water-level elevation, depth to the open interval, and the elevation of the open interval) was analyzed to determine if the local variability of ion concentrations is primarily caused by differences in the vertical location sampled within the flow system. Specific conductance values from 66 wells with depths ranging from 59 to 1,058 feet in the central part of the study area were retrieved from the USGS NWIS data base. There were no strong correlations between specific conductance and the variables. Restricting the data to 23 sites from a smaller areal extent of 36-square-mile area (township 14 south, range 13 east) north of Redmond also resulted in weak correlations. Correlations were also weak for specific conductance data (ODEQ, upub. data, 1995) from more than 100 wells ranging in depth from 20 to 1,460 feet in the La Pine area. These data may be skewed because many wells that reportedly produce poor quality water are abandoned. The lack of strong correlations indicate that other factors, not solely the vertical location in the flow system, contribute to areal variations in dissolved ion concentrations.

The evaluation of ground-water chemistry can be further complicated by (1) the occurrence of waters from different origins, (2) mixing of waters from different origins, (3) local recharge, and (4) human-caused changes. Ground waters originating in different recharge areas within the flow system converge on the way to the regional discharge area (figs. 3 and 4). This phenomenon results in ground-water chemistry that may vary locally either by having distinct chemical characteristics of waters from different origins or from the mixing of various proportions of ground water from different origins. Ground water from the eastern part of the study area converges with waters from the west and south on the way to the regional discharge area near Lake Billy Chinook (fig. 3). The area of convergence likely extends from the vicinity of Redmond to the discharge area. This conclusion is consistent with the specific conductance values of samples from the suspected area of convergence, which vary from about 100 $\mu\text{S}/\text{cm}$ to over 500 $\mu\text{S}/\text{cm}$ (fig. 6). Local variations in ion concentrations may also be caused by local recharge sources, including leakage from the numerous canals that traverse the area, seepage from rivers and streams with stages above the local water table, and

excess irrigation water applied to crops. Local recharge is discussed in more detail in the Ground-Water/Surface-Water Interaction section of this report. Local variations in water chemistry may also be due to the input of constituents from human-caused sources such as waste disposal and land-use practices. The magnitude and distribution of human-caused sources were not specifically addressed by this project.

Relation of Water Chemistry to Geology

There is commonly a relation between the chemical characteristics of ground water and the mineralogical properties of the geologic material with which it has been in contact. The ratio of calcium to sodium in ground water from feldspar-rich rocks is generally related to the composition of the feldspar (Hem, 1985). The proportion of magnesium to other cations in ground water could be indicative of the relative abundance of ferromagnesian minerals present in the aquifer material (Hem, 1985). Alteration of rock material to clay or zeolites by weathering or hydrothermal processes reduces aquifer permeability. Reduced permeability increases residence time and allows for increased water-rock interaction. The interpretation of ground-water chemistry with respect to the aquifer mineralogy may be complicated by several processes and conditions, including the influence of interconnected aquifers of different composition, the mixing of unlike waters, biological influences, cation exchange, and adsorption (Hem, 1985). Water-chemistry data were evaluated to determine if geochemical characteristics could be ascribed to particular geologic units in the study area. The well driller's description of the water bearing zone and the geologic unit it represents for the water wells sampled for this study are listed in Appendix 1. Geologic units from which the springs issue are listed in Appendix 2. Plate 1 includes surficial geology, sample site locations, and diagrams that depict the major ion composition of the water samples. The diagrams are color-coded to indicate the geologic unit designation of the water bearing zone. The diagrams for surface-water sites are not shaded.

The geologic units within the upper Deschutes Basin consist mostly of lavas, tuffaceous material, and volcanoclastic sediments of Cascade Range origin. Water samples were collected from wells and springs that produce water from a variety of units. The majority of the samples were collected from Tertiary volcanic material, primarily of the Deschutes Formation (Plio-

cene and Miocene), which includes basalt and basaltic andesite lavas, dacitic and rhyodacitic ignimbrites, and volcanoclastic sediments (Smith and others, 1987; Sherrod and others, USGS, unpub. data, 1997). A sample was also collected from the John Day Formation (Miocene to Eocene), exposed in the eastern part of the study area, which consists chiefly of rhyolitic ash-flow tuff, basaltic to rhyolitic lava, tuffaceous sedimentary rocks, and vent deposits (Sherrod and others, USGS, unpub. data, 1997). Samples were collected in the northeastern part of the study area from the Prineville Basalt (Miocene). The Prineville Basalt has been included within the Columbia River Basalt Group (Swanson and others, 1979; Tolan and others, 1989), but some consider it to be a separate unit from the Columbia River Basalt Group (Hooper and others, 1993). Water samples were also collected from material of Quaternary age, including basalt from Newberry Volcano, basalt and basaltic andesite of Cascade Range origin, silicic ash-flow tuff, and unconsolidated sediments.

Several previous investigations included part of the study area or reported the water chemistry of samples from the same or similar geologic units in nearby areas. A study of the hydrothermal systems of the Cascade Range in north-central Oregon found that shallow nonthermal ground water is commonly mixed cation-bicarbonate water, with dissolved solids concentrations ranging from less than 100 mg/L in the Cascade Range to about 300 mg/L elsewhere in the study area (Ingebritsen and others, 1994). Most of the thermal waters were reported to be sodium chloride or sodium-calcium chloride waters with dissolved solids concentrations of up to 3,000 mg/L. A study of the water resources of the Warm Springs Reservation, which borders the study area to the north, found that water from the poorly permeable John Day and Clarno Formations is likely to have a greater proportion of sodium because of increased contact of sodium-bearing minerals (Robinson and Laenen, 1976). Ingebritsen and others (1994) also found that waters from sites in the northern part of the upper Deschutes Basin study area and on the Warm Springs Reservation are characterized by a predominance of sodium over other cations that may be a result of the dissolution of albite (a sodium feldspar).

Ground-water chemistry data are also presented in a report on the ground-water resources in the Prineville area (Robinson and Price, 1963). Several wells in the Prineville area are completed in an artesian (confined) aquifer of sand and gravel. Samples from the

artesian aquifer ranged from nearly equivalent proportions of calcium and sodium to waters with sodium as the slightly dominant cation. Robinson and Price reported a long-term decline in artesian pressure and a progressive increase in the mineral content of water in some artesian aquifer wells. Locally, the decline in artesian pressure may have caused an increase in the dissolved solids concentration of water in the artesian aquifer as a result of downward leakage of water from an overlying unconfined sedimentary aquifer with a higher dissolved solids concentration.

A report from a study in the La Pine area (Century West Engineering Corp., 1982) included water quality data collected to define baseline chemical water quality and to determine if shallow aquifer contamination was taking place. The study was authorized by ODEQ in an interagency agreement with Deschutes County, Oregon. Contamination of the shallow aquifer was observed in areas where on-site domestic waste disposal systems were used, with the major contaminant being nitrate nitrogen. More comprehensive analyses of water from 10 shallow (less than 40 feet deep) monitoring wells revealed total dissolved solids concentrations that ranged from 93 to 317 mg/L, with water from 9 of the wells having nearly equal amounts of sodium, calcium, and magnesium. Sodium was the dominant cation for one of the sites. Wells completed in deeper sedimentary deposits were reported to commonly produce poor quality water (higher dissolved solids content), whereas deep wells completed in basalt may produce water of good quality in the La Pine area.

Newcomb (1972) reported on a study of the quality of ground water in basalt of the Columbia River Basalt Group. The Prineville Basalt, located in the area of the current study, is arguably part of that group. Newcomb reported a generally uniform bicarbonate water having nearly equal amounts of calcium and sodium as the principal cations, with relatively high silica concentrations. The average dissolved solids content of over 500 chemical analyses was about 275 mg/L.

Samples from most of the sites sampled for the current study had similar relative proportions of major ions, but with variations in total concentrations as indicated by the water-chemistry diagrams (pl. 1). Although most of the waters sampled were chemically similar, water samples from wells completed in the John Day Formation, Prineville Basalt, and Deschutes Formation had the highest TDS concentrations (240 to 562 mg/L). The John Day Formation has relatively low

permeability due to the alteration of volcanic glass to clay and zeolite (Sherrod and others, USGS, unpub. data, 1997). Clay is also present in the Prineville Basalt as a result of the alteration of glass and olivine (Hooper and others, 1993). The Deschutes Formation wells with relatively high TDS concentrations are completed in sedimentary material and are located in the northeastern part of the study area. The high dissolved solids concentrations of the water samples from these sites may be a function of longer residence times resulting from low permeability, low recharge rates, and/or greater flow path lengths.

A sample from well 31000538 (12S/13E-26ABA), completed in the John Day Formation, had a relatively high sodium concentration and a comparably low magnesium concentration. Similar observations were made of samples collected in the John Day Formation on the Warm Springs Reservation (Robison and Laenen, 1976). Water samples collected from the John Day Formation for the Warm Springs study ranged from having sodium as the principal cation, to nearly equivalent calcium, sodium, and magnesium, to slightly calcium dominant. Owing to the variability in composition of the John Day Formation (basaltic to rhyolitic), a variability in the chemistry of ground water in contact with it is expected. However, of the samples collected for the Warm Springs study, waters with sodium as the principal cation only occurred in the John Day Formation. Samples from Prineville Basalt wells 31000231 (9S/14E-21CCC) and 31000373 (10S/14E-30DAD) had relatively high calcium concentrations (pl. 1), but were not as chemically distinct from the other sites as was the John Day Formation water (well 31000538).

Ground-water chemistry is influenced not only by the mineralogy of the water bearing unit of a well or spring, but also by the mineralogy of the material along a flow path. For example, water from a third Prineville Basalt well (31000221, 9S/14E-20CCA3) is chemically distinct from water from the other Prineville Basalt wells (31000231 and 31000373). Water from well 31000221 is chemically similar to that from the well completed in the John Day Formation (31000538), which had a relatively high sodium concentration. The John Day Formation crops out east and upgradient from well 31000221, suggesting that ground water flows from east to west in this area as depicted in figure 3. As another example, Deschutes Formation wells 31000396 (10S/14E-33CDD) and 31000164 (13S/13E-20DAC) in the northeastern part

of the study area had water with relatively high concentrations of calcium. They are chemically similar to wells (31000231 and 31000373) completed in Prineville Basalt and some wells completed in the John Day Formation from the Warm Springs study (Robison and Laenen, 1976). The John Day Formation is present upgradient from both wells and the Prineville Basalt is present upgradient from well 31000396 and may be present (but is not mapped) upgradient from well 31000164. Therefore, some wells (31000221, 31000396, and 31000164) may show the chemical signature of material encountered along their respective flow paths and not the water bearing unit of the wells.

Estimated Age of Ground Water

Ground-water age dating techniques were used to further investigate the validity of the conceptual model of the flow system. The age of ground water refers to the period of time that has elapsed since the water moved deep enough into the ground-water zone to be isolated from the earth's atmosphere (Freeze and Cherry, 1979). The age of ground water can be used to (1) recognize areas of recharge (relatively young waters) and discharge (relatively old waters), (2) define the direction of flow, and (3) determine the flow velocity in ground-water systems. The methods selected for the age dating of ground water in this study involved analysis of tritium and carbon-14, which are both radioactive isotopes. Samples were analyzed for tritium concentrations in an effort to determine if the waters were recharged to the system before or after thermonuclear testing, which began in the early 1950's. Carbon-14 is a common method for dating waters as old as 50,000 years (Drever, 1988). Samples were analyzed for carbon-14 in an attempt to obtain approximate ages. The use of either method can be complicated by the mixing of waters of different ages. The interpretation of carbon-14 in ground water can be further complicated by the addition or loss of carbon to or from the water (carbon-mass transfer) along a flow path.

Tritium

Tritium (^3H), is an isotope of hydrogen with an atomic weight of 3. Tritium decays by beta emission to form helium-3 and has a half-life of 12.43 years (International Atomic Energy Agency, 1981). Tritium is produced naturally by the interaction of cosmic rays with nitrogen and oxygen in the atmosphere. However,

tritium concentrations in precipitation began to increase in 1953 as a result of thermonuclear weapons testing (Plummer and others, 1993). Prior to weapons testing, the natural level in precipitation probably did not exceed 2 to 8 tritium units (TU) (1 TU = one tritium atom per 10^{18} hydrogen atoms) (Plummer and others, 1993). This number is uncertain, because there were few analyses made of precipitation prior to the weapons testing. During the 1960s, tritium concentrations in precipitation rose to over 1,000 TU. The tritium concentration in precipitation at Portland, Oregon, has been monitored by the USGS since 1961 (fig. 7). Figure 7 is an example of the characteristic variation of tritium concentrations with time showing a peak due to thermonuclear testing (nearly 4,000 TU in 1963). Recent concentrations are variable, but are less than 10 TU (fig. 7). Tritium values of study area precipitation may have differed from those of the Portland area, but they likely followed a similar trend.

Tritium data can be used to determine if a sample of water entered the ground-water system as recharge before 1953 or if the water has at least a component that entered the system after 1953. Assuming that precipitation with tritium concentrations of 8 TU or less recharged the ground-water system prior to 1953, those waters would have tritium concentrations of less than 1 TU in 1995 due to radioactive decay. Tritium concen-

trations greater than 1 TU indicate that some fraction of the sample consists of post-1953 waters.

Samples from 14 ground-water sites were selected for tritium analyses (fig. 8). The data are included in Appendixes 4 and 5. Samples having the highest tritium values (8.5 to 10.3 TU) came from the regional recharge area on the eastern flank of the Cascade Range (well 17001800 [14S/9E-16ADB], Paulina Springs [S-5], and Source Spring [S-6]). Because these sites are located in the area of regional recharge, the tritium concentrations of these sites are probably near that of present-day precipitation. A sample from well 31000164 (13S/13E-20DAC) in the northeastern part of the study area had a tritium value of 7.5 TU, which is near that of the sites in the recharge area. This well is located close to the North Unit Main Canal and a lateral diversion from it. The tritium concentration of this well may be a result of modern water recharged locally from canal leakage. Samples with tritium concentrations indicative of water recharged prior to 1953 (less than 1 TU) came from a relatively deep well (17001510, 14S/11E-28ADD) located east of the town of Sisters, wells in the eastern and northeastern parts of the study area (31000231, 9S/14E-21CCC; 31000538, 12S/13E-26ABA; and 17005752, 19S/14E-24DDA), and sites in the regional discharge area near Lake Billy Chinook (Lower Opal Springs [S-1] and well 31000090 [13S/12E-05ADC]).

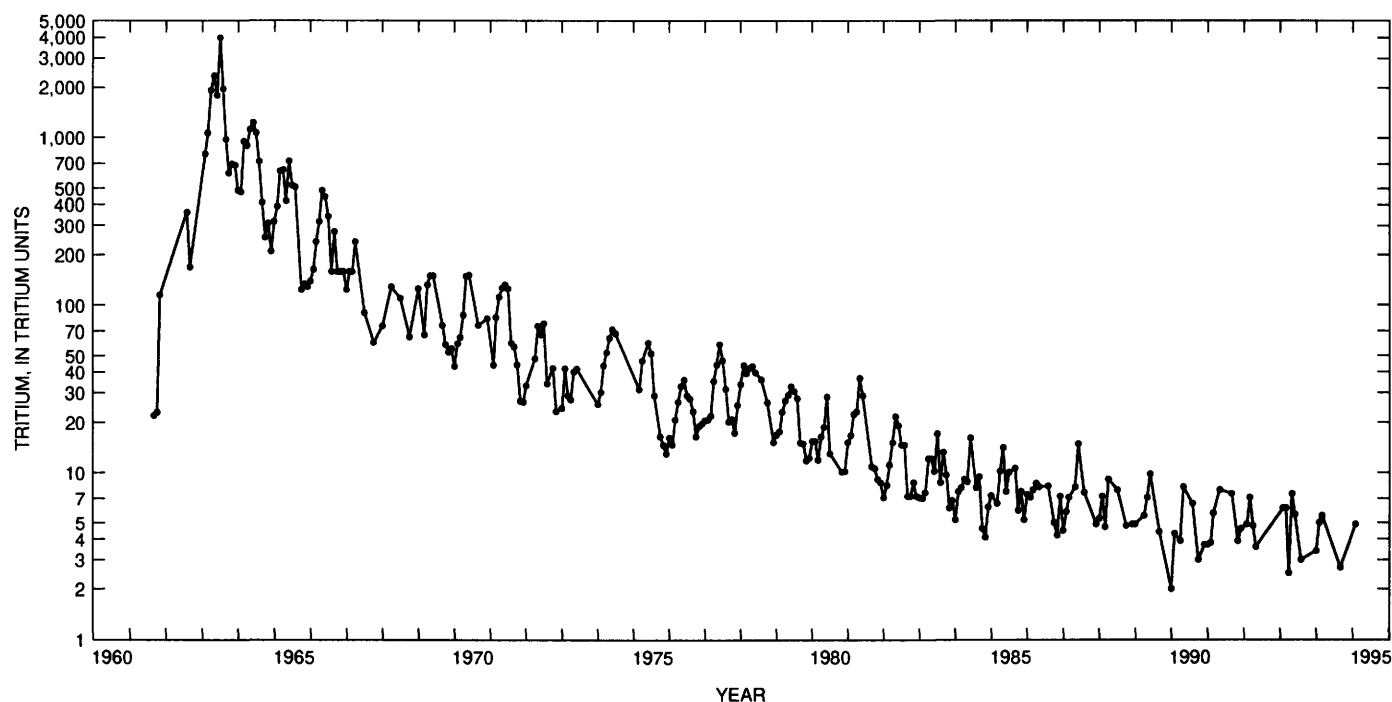


Figure 7. Tritium concentrations in precipitation at Portland, Oregon (U.S. Geological Survey, National Water Information System data base, 1996).

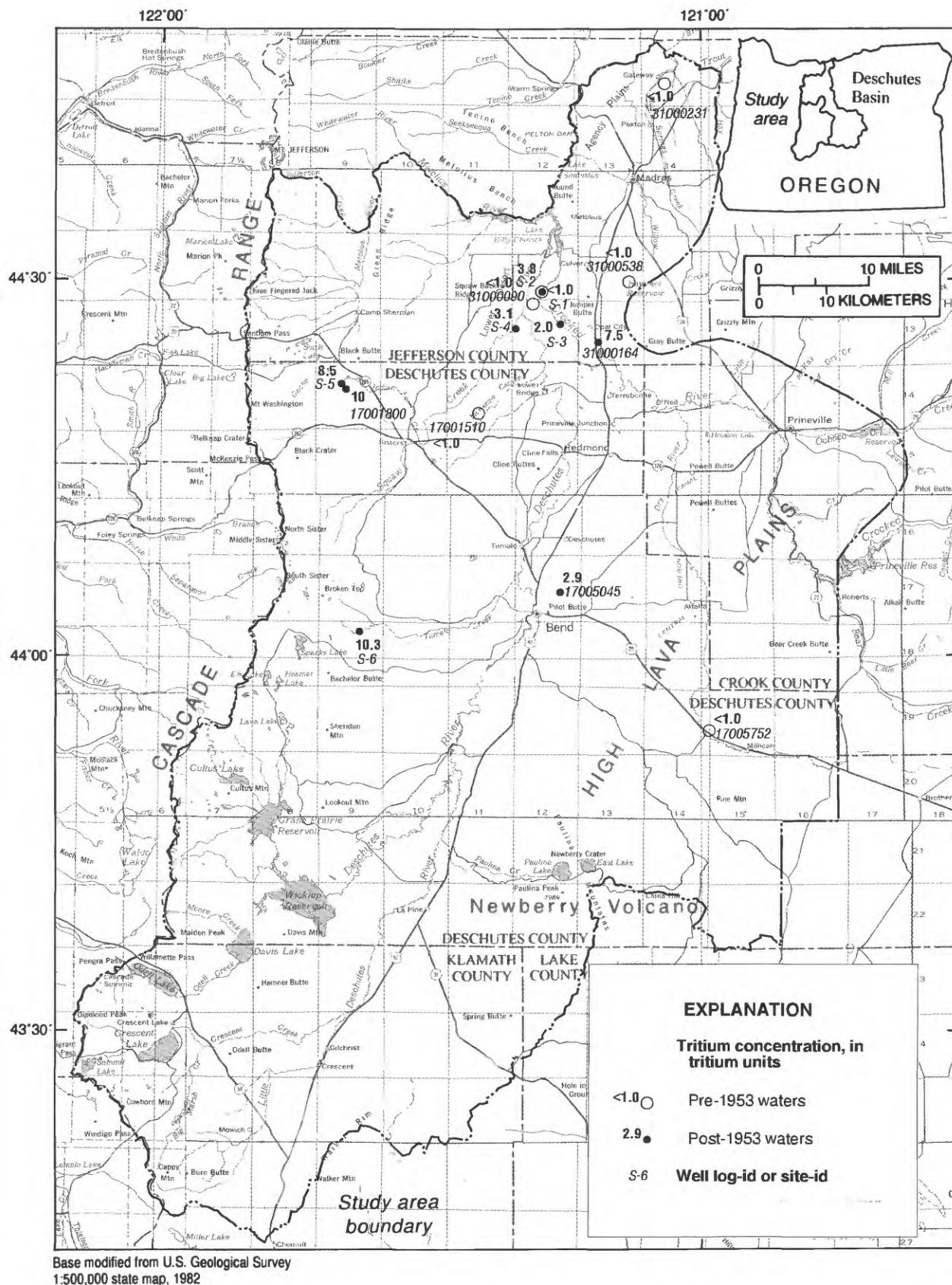


Figure 8. Tritium concentrations from ground-water sites in the upper Deschutes Basin, Oregon.

The differences in water chemistry and age that result from sampling different parts of the flow system or from the influence of local recharge may be apparent in water sampled in the ground-water discharge area. Figure 9 shows the tritium concentrations plotted against elevations of springs and the water bearing interval of a well in the regional ground-water discharge area near Lake Billy Chinook. Samples with tritium concentrations greater than 1 TU (post-1953 water) and samples with concentrations less than 1 TU (pre-1953 water) were collected from sites within close proximity in the ground-water discharge area, indicating that waters of different origins, or waters having traveled distinctly different flow paths, locally coexist in the area. Water from Lower Opal Springs (S-1) and well 31000090 (13S/12E-05ADC) produce water from nearly the same elevation and have tritium concentrations of less than 1 TU, indicating water that recharged the system prior to the early 1950's. Nearby Upper Opal Springs (S-2), Virgin River Springs (S-3), and Alder Springs (S-4), at higher elevations, have significantly higher tritium concentrations (fig. 9), indicating that a least a component of their flow is water having shorter residence times, different origins, or a local recharge source.

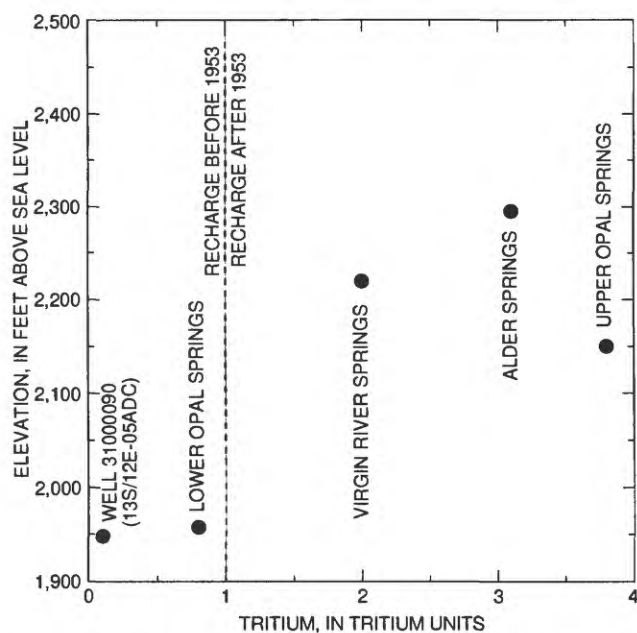


Figure 9. Tritium concentrations and the elevations of ground-water sites near Lake Billy Chinook, Oregon. (The elevation of well 31000090 represents the elevation of the open interval of the well. Tritium concentrations in precipitation began to increase in 1953 as a result of nuclear weapons testing [Plummer and others, 1993].)

Carbon-14

Carbon-14 (^{14}C) is formed in the atmosphere by the bombardment of nitrogen-14 (^{14}N) with cosmic rays. Carbon-14 decays to stable ^{14}N by the emission of a negative beta particle and has a half-life of 5,730 years (Faure, 1986). Like tritium, nuclear weapons testing produced large amounts of ^{14}C . The ^{14}C generated in the atmosphere is carried down to the earth's surface by precipitation and becomes incorporated into biomass or is transported into water bodies (Drever, 1988). The source of ^{14}C in ground water is primarily CO_2 gas in the soil zone (Domenico and Schwartz, 1990). When precipitation soaks into the ground as ground-water recharge and reaches the water table, it becomes isolated from the ^{14}C source. The ^{14}C concentration in ground water decreases with time as it undergoes radioactive decay. Therefore, the amount of ^{14}C found in ground water can be used to estimate the time elapsed since the water was recharged to the system.

Carbon-14 is reported as the ratio of ^{14}C in the sample to that of an international standard and is expressed as percent modern carbon (pmc) (Domenico and Schwartz, 1990). A value of 100 pmc or greater is considered to be modern. Ages are expressed in years before the present (BP), where 1950 is considered present or modern (Faure, 1986). If radioactive decay is the only cause for a decrease in ^{14}C , the age of ground water can be determined by the following equation:

$$\text{Age} = 5,730 / \ln(2) * \ln(A_0/A) \quad (4)$$

where

A is the ^{14}C concentration of the sample and

A_0 is the starting concentration in the ground water (Coplen, 1993).

Carbon-14 age determinations of ground water are most accurate when the mixing of waters of different ages and mass transfers of carbon are minimal. Unfortunately, both mechanisms appear to occur in the study area, resulting in suspect ground-water ages based on ^{14}C data. Carbon-14 undergoes radioactive decay and the ^{14}C concentration decreases exponentially with time. Therefore, the ^{14}C concentration of a sample composed of a mixture of waters of different ages does not yield a mean (average) age. Moreover, ground water may acquire inactive (no detectable ^{14}C) carbon along a flow path from the dissolution of carbonate minerals or from volcanic CO_2 gas emissions.

The addition of inactive carbon increases the dissolved inorganic carbon (DIC) concentration and decreases the percent modern carbon concentration of the water. Therefore, contributions of inactive carbon can skew the unadjusted ^{14}C date to indicate an age much older than that of the actual water sample.

Six sites were sampled for ^{14}C analyses; one site (well 17001800) is located in the area of regional recharge on the eastern flank of the Cascade Range, and five sites are at or near the regional discharge area near Lake Billy Chinook. Table 1 lists the DIC concentration, $\delta^{13}\text{C}$, ^{14}C concentration, unadjusted ^{14}C age, and tritium concentrations for the sites sampled for ^{14}C analysis. Dissolved inorganic carbon concentrations and $\delta^{13}\text{C}$ values were utilized to explore the magnitude and source of mass carbon transfers. Tritium and ^{14}C concentrations for individual sites were examined to determine if ground-water ages based on these two techniques were consistent. Unadjusted age dates are reported in table 1 as ages calculated from the ^{14}C concentrations with no correction for the addition or removal of inactive carbon.

The presence of at least a component of post-bomb (younger than the early 1950's) water is indi-

cated by the tritium concentrations from four out of six of the sites selected for carbon-14 analysis (table 1). Assuming natural tritium concentrations of 8 TU or less for pre-nuclear weapons testing recharge waters (prior to 1953), a water sample about 60 years old or older would have tritium concentrations less than the lowest detection limit (0.3 TU) used for this study. Samples from three sites (springs S-1, S-3, and S-4) had measurable tritium concentrations (0.8 to 3.1 TU), which is inconsistent with the unadjusted carbon-14 ages (ranging from 2,480 to 4,105 yr BP) derived from the measured modern carbon concentrations (ranging from 60.0 to 73.4 pmc). Even if the ^{14}C concentrations of these samples were not affected by carbon mass transfer, the unadjusted carbon-14 ages of these springs would represent a mixture of unknown proportions of post-bomb (post-1953) water and older (on the order of thousands of years old) water. Therefore, the unadjusted carbon-14 ages for these sites (springs S-1, S-3, and S-4) are suspect and were not reported in table 1. The tritium and ^{14}C concentrations of the remaining sites are consistent with, but are not restricted to, samples that do not contain mixed waters (table 1). The

Table 1. Data for ground-water sites selected for carbon-isotope analysis in the upper Deschutes Basin, Oregon
[per mil, per 1,000; BP, years before the present (1950); ^{13}C , carbon-13; ^{14}C , carbon-14; +/-, plus or minus; TU, tritium units]

Site- identification ¹ (Location)	Dissolved inorganic carbon (millimoles)	$\delta^{13}\text{C}$ (per mil)	^{14}C (percent modern carbon)	Unadjusted ^{14}C age ² (year BP)	Tritium (TU)
17001800 (14S/09E-16ADB)	0.49	-15.3	106.63 +/- .64	post-bomb	10.0
S-3 (Virgin River Spring)	1.5	-13.8	73.42 +/- .41	--	2.0
17001510 (14S/11E-28ADD)	1.8	-13.9	71.60 +/- .45	2,685 +/- 50	<.8
S-4 (Alder Springs)	1.1	-13.0	65.20 +/- .38	--	3.1
S-1 (Lower Opal Springs)	1.0	-12.7	60.00 +/- .48	--	.8
31000090 (13S/12E-05ADC)	1.2	-12.2	55.69 +/- .39	4,700 +/- 55	<.3

¹See plate 1 for location.

²The unadjusted ages represent maximum possible ages and have not been corrected for carbon mass transfer and the mixing of ground-waters along a flow path. The actual ages are probably younger. The unadjusted ^{14}C ages inconsistent with the tritium data were not reported (--).

tritium value (10 TU) and ^{14}C concentration (> 100 pmc) of well 17001800, located in the recharge area, support a modern (post-bomb) age for the sample. The tritium concentrations of two of the wells (31000090 and 17001510) are below the laboratory detection limits and have unadjusted carbon-14 ages (4,700 and 2,685 yr BP, respectively) consistent with water recharged prior to the testing of nuclear weapons.

The DIC concentrations of recharge area waters and of waters collected downgradient were investigated to determine if mass transfers of carbon occur in the system (table 1). Data from Ingebritsen and others (1988) and from this study were used to calculate the DIC concentrations of recharge waters from nine sites on the eastern flank of the Cascades. The DIC concentrations were calculated with the use of the WATEQ4F program (Ball and Nordstrom, 1992) using pH and alkalinity values. The DIC concentrations of the nine sites ranged from 0.27 to 0.79 millimoles (mmoles) with a mean of 0.49 mmoles. A 0.5 mmoles DIC concentration for the recharge waters was assumed for mass transfer analyses for this study. A recharge area spring reported in Ingebritsen and others (1988) had an anomalously high DIC concentration (1.8 mmoles) and was excluded from this analyses. Volcanic CO_2 may be responsible for the higher concentration at the site, as evidenced by a high sulfate concentration.

The DIC concentrations of samples collected for this study near the discharge area ranged from 1.0 to 1.8 mmoles. Therefore, waters sampled at or near the discharge area could have gained 2 to 3.6 times their original DIC concentration as they moved along their respective flow paths. Because a quaternary volcanic arc is in the study area, a possible source for the DIC increase from sites on the eastern flank of the Cascade Range to sites in the central basin may be the input of volcanic CO_2 . The dissolution of carbonate minerals is another possible source of carbon to the ground-water system. Although carbonate minerals are not prevalent in the region, secondary calcite has been found in cuttings from drill holes in the Newberry Caldera, Oregon, and in the Oregon Cascades (Gannett and Bargar, 1981; Keith and others, 1986). The addition of dissolved inactive carbon from volcanic CO_2 or the dissolution of carbonate minerals would result in erroneous unadjusted ^{14}C ages that are older than the actual age of the water.

The amount of inactive carbon added along a flow path can sometimes be estimated with the use of $\delta^{13}\text{C}$ values (table 1). In a study of springs and spring-fed creeks in the southern Cascade range of

Oregon and California, Rose and Davisson (1996) identified the values of three isotopic carbon end members for the mixing of waters with carbon obtained from atmospheric, magmatic (volcanic), or biogenic soil sources: (1) DIC in equilibrium with biogenic soil CO_2 ($\delta^{13}\text{C}$ near -18 per mil and $^{14}\text{C} \geq 100$ pmc); (2) DIC in equilibrium with atmospheric CO_2 ($\delta^{13}\text{C}$ near 0 per mil and $^{14}\text{C} \geq 100$ pmc); and (3) DIC in equilibrium with volcanic CO_2 ($^{14}\text{C} = 0$ pmc). The $\delta^{13}\text{C}$ values of DIC of volcanic origin are more widespread, but closer to 0 per mil. Rose and Davisson (1996) reported $\delta^{13}\text{C}$ values of -11.7 to -5.7 per mil for Cascade volcanic center springs with negligible ^{14}C activity. Also, Rose and Davisson (1996) determined that low temperature (10°C) isotopic equilibration with CO_2 gas from the Lassen geothermal system in California could yield $\delta^{13}\text{C}$ values as enriched as 0 per mil. Carbonate minerals have ^{14}C concentrations near 0 pmc (Mook, 1976). Craig (1953) reported a range of $\delta^{13}\text{C}$ values of -14 to +10 per mil for freshwater carbonates. Therefore, water that has a component of volcanic CO_2 or that has dissolved carbonate minerals along a flow path would be enriched in ^{13}C and have lower ^{14}C concentrations (shifted towards 0 pmc) relative to recharge waters in equilibrium with biogenic soil CO_2 .

The $\delta^{13}\text{C}$ values of samples collected for this study range from -12.2 to -15.3 per mil, with concentrations ranging from 56 to 107 pmc (table 1). The ^{14}C concentration (107 pmc) of a sample from well 17001800 (14S/9E-16ADB), located in the recharge area, is consistent with relatively recent water, and the $\delta^{13}\text{C}$ value (-15.3 per mil) is relatively close to the assumed value of CO_2 gas in equilibrium with biogenic soil (-18 per mil). The remaining sites sampled downgradient from the recharge area have lower ^{14}C concentrations (55.7 to 73.4 pmc) and enriched $\delta^{13}\text{C}$ values (-12.2 to -13.8). These values are consistent with waters that have acquired volcanic CO_2 (or dissolved carbonate minerals) with ^{14}C concentrations near 0 pmc along their flow paths, which results in unadjusted ^{14}C ages for these samples that are older than the actual age of the ground water.

GROUND-WATER/SURFACE-WATER INTERACTION

Ground-water/surface-water interaction is of regional significance in the upper Deschutes Basin ground-water system. Rivers and streams lose and gain water to and from the ground-water system within the

study area. Canal leakage is a significant source of local recharge in the more arid areas where recharge from precipitation is minimal. Water chemistry was used to help understand the ground-water/surface-water interaction that takes place.

Ground-Water Discharge to Surface Water

Ground-water discharge is responsible for a component of the streamflow in reaches of many area rivers and streams. Streamflow in the lower reaches of the Deschutes and Crooked Rivers above Lake Billy Chinook is dominated by ground-water discharge from April through November (M.W. Gannett, USGS., oral commun., 1997). Streamflow in the Metolius River and the lower reaches of Squaw Creek are dominated by ground-water discharge throughout the year. If ground water discharging to a stream has chemical characteristics distinct from the stream, then the chemistry of the stream water should change with the addition of the ground water. Specific conductance (ODEQ, unpub. data, 1996) and streamflow measurements (OWRD, unpub. data, 1994, 1995; Hubbard and others, 1996) of the Deschutes River show changes in water chemistry and increases in streamflow resulting from ground-water discharge to the river.

OWRD staff measured Deschutes River streamflow during May 1994 (OWRD, unpub. data, 1994) to quantify natural gains and losses in the river between a stream-gaging station at Bend (near river mile 164) and a stream-gaging station directly upstream from Lake Billy Chinook (near river mile 120). The river mile locations are shown in figure 10 and the flow rates are shown in figure 11. Flow rates were relatively consistent from river mile 164 to river mile 138, with values ranging from 35.5 ft³/s (cubic feet per second) to 45.1 ft³/s (fig. 11). In contrast, the streamflow in the Deschutes River increased by more than 430 ft³/s from river mile 138 to the stream-gaging station near river mile 120 (fig. 11). Squaw Creek (river mile 123), which gains nearly 100 ft³/s from ground-water discharge within 1 mile of the creek's confluence with the Deschutes River (OWRD, unpub. data, 1992), is responsible for most of the Deschutes River streamflow gain (126 ft³/s) between river mile 123.3 and the stream-gaging station near river mile 120. Contributions to streamflow in the Deschutes River from other tributaries (Tumalo and Deep Canyon Creeks) are relatively insignificant. Therefore, ground-water discharge is primarily responsible for the greater than 10-fold increase

in Deschutes River streamflow from river mile 138 to the stream-gaging station near river mile 120 (fig. 11).

Ground-water inflow markedly affects the water chemistry of the Deschutes River. Specific conductance data were collected by the ODEQ during August 1995 at several sites along the Deschutes River and its tributaries (ODEQ, unpub. data, 1996). Mean August 1995 streamflow measurements (OWRD, written commun., 1996; Hubbard and others, 1996) from three stream-gaging stations are shown in figure 11 to depict the relative change in streamflow from May 1994. The mean August 1995 flow rates are comparable to those from the May 1994 seepage run. Specific conductance measurements made in August 1995 at 11 sites, from just downstream of Wickiup Reservoir (fig. 1) (near river mile 226) to river mile 138 (fig. 10) ranged from 50 to 67 μ S/cm. The concentration of dissolved constituents increased by more than two-fold downstream from river mile 138 as a result of ground-water discharge. The specific conductance values markedly increased from 64 to 119 μ S/cm from river mile 138 to river mile 134 (fig. 11) where ground water discharges to the river. The specific conductance of Squaw Creek was 146 μ S/cm and a measurement of the Deschutes River just downstream from the mouth of Squaw Creek (near river mile 123) was 136 μ S/cm.

Streamflow (OWRD, unpub. data, 1994), Deschutes River specific conductance (ODEQ, unpub. data, 1996), and area ground-water specific conductance data collected during this and previous studies (Sceva, 1968a, 1968b; ODEQ, unpub. data, 1974, 1978; USGS, unpub. data, 1978; Ingebritsen and others, 1988) were used to determine the origins of the ground-water discharge to the Deschutes River. These determinations are based on the assumptions that (1) the rate of ground-water discharge determined from the May 1994 discharge data (OWRD, unpub. data, 1994) was similar to the ground-water discharge that occurred during August 1995, when the ODEQ collected Deschutes River specific conductance data, and (2) ground-water discharge is responsible for the change in specific conductance observed in the river.

Streamflow and specific conductance measurements from river mile 138 to 134 increased from 35.5 ft³/s to 46 ft³/s and 64 μ S/cm to 119 μ S/cm, respectively. A mean specific conductance value of 305 μ S/cm for the ground-water discharge to the river (10.5 ft³/s) would account for the resultant specific conductance (119 μ S/cm) at river mile 134. This value (305 μ S/cm) is consistent with the range of specific conductance values (commonly ranging from

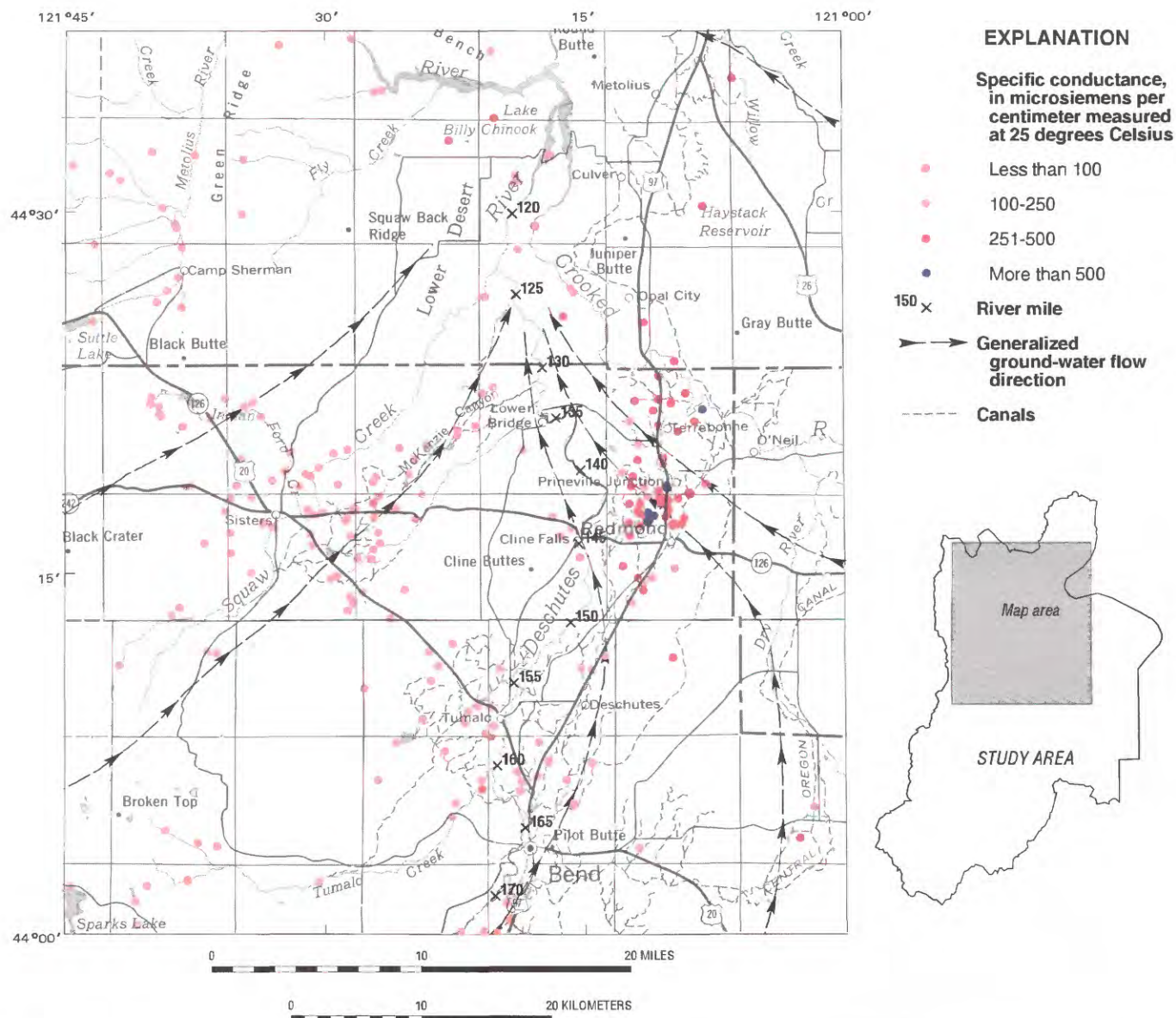


Figure 10. River mile locations of the Deschutes River, specific conductance values at ground-water sites, and generalized ground-water flow directions in the central part of the upper Deschutes Basin, Oregon.

251 $\mu\text{S}/\text{cm}$ to 500 $\mu\text{S}/\text{cm}$) found in nearby wells and springs to the east and southeast (fig. 10) of this reach of the Deschutes River. Streamflow and specific conductance measurements from river mile 134 to 123 increased from 46 ft^3/s to 442 ft^3/s and 119 $\mu\text{S}/\text{cm}$ to 136 $\mu\text{S}/\text{cm}$, respectively. Ground-water discharge of 396 ft^3/s with a mean specific conductance value of 138 $\mu\text{S}/\text{cm}$, including contributions from Squaw Creek, would account for the 136 $\mu\text{S}/\text{cm}$ value at river mile 123. This is consistent with the range of specific conductance values (commonly 100 $\mu\text{S}/\text{cm}$ to 250 $\mu\text{S}/\text{cm}$) found in nearby wells and springs to the west and south of this reach (fig. 10). Therefore, the initial

gains in the Deschutes River flow (river mile 138 to 134) are probably due to ground water flowing from the southeast or east, whereas the most significant gains (river mile 134 to 123) are dominated by the discharge of ground water with lower dissolved solids concentrations flowing from the south or west (fig. 10).

Local Ground-Water Recharge from Surface Water

Streams and unlined canals are sources of local recharge in the Deschutes Basin. Recharge from the

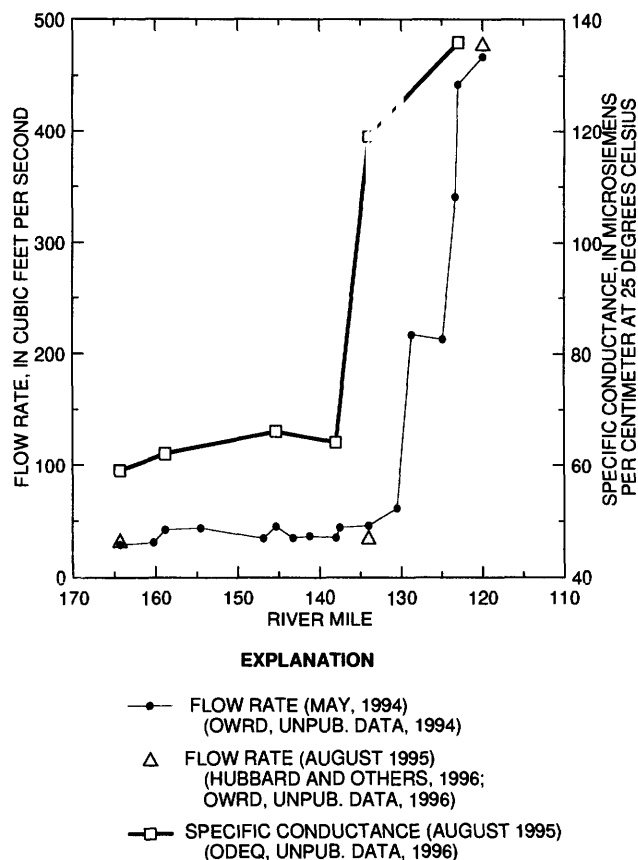


Figure 11. Flow rate and specific conductance measurements for the Deschutes River from Bend (river mile 164.3) to near Lake Billy Chinook (river mile 120), Oregon.

Deschutes River and canals is reflected in the hydraulic head in underlying aquifers (fig. 12). The Deschutes River loses on average about 100 ft³/s from Benham Falls to Bend (Gannett and others, 1996). Average canal losses for irrigation districts in the study area range from 0.4 to 2.6 cubic feet of water per square foot of canal bottom per day (ft³/ft²/day), the average for the study area is 0.9 ft³/ft²/day (D.S. Morgan, USGS, written commun., September 1997). Field studies on segments of some study area canals show leakage rates up to 4.20 ft³/ft²/day (Bureau of Reclamation, 1991).

Chemical variability in ground water may result from the occurrence of local recharge from surface-water sources. Samples of the Deschutes River (upstream from significant contributions of ground-water discharge) and canals in the central part of the study area collected for this and previous studies (ODEQ, unpub. data, 1995; USGS, unpub. data, 1978) had a mean specific conductance value of about 65 µS/cm (equivalent to about 50 mg/L TDS). Ground water in the study area generally has conduc-

tance values greater than 100 µS/cm (greater than 85 mg/L TDS) (fig. 10). The variability of dissolved ion concentrations in ground water in the Bend-Redmond area illustrated in figure 10 may be due to the mixing of various proportions of low ionic-concentration local recharge waters (canals and the Deschutes River) with higher ionic-concentration water from regional flows.

Water-level changes in response to streamflow from the Deschutes River and canals have been observed in several wells of varying depth throughout much of the area. Hydrographs of water-level data from wells equipped with continuous water-level recorders and wells measured quarterly, Deschutes River flow rates at the Benham Falls stream-gaging station, and Central Oregon Canal flow rates are shown in figure 12. The locations of the sites in figure 12 are included in figure 13. The water-level in well 17005741 (19S/11E-16ACC) near Benham Falls on the Deschutes River responds to Deschutes River stage measured at the Benham Falls gage (fig. 12A).

Area canals commonly operate during the irrigation season from April through the beginning of October, and are also filled periodically on a short term basis at other times to enable the filling of stock ponds and other storage facilities. Central Oregon Canal flow during 1994 and 1995 is shown in figure 12B to illustrate the periodicity of canal operation. The wells whose hydrographs are shown in figure 12B respond to canal leakage. The greatest water level response to canal operation is seen in well 17004844 (17S/12E-08ABD), which has over 90 feet of seasonal water-level variation. Construction information for the wells represented in figure 12 is presented in a report by Caldwell and Truini (1997).

Water-chemistry samples were collected to further explore the canal/ground-water interaction mechanisms. Water from four canals and five wells adjacent to those canals (17002498, 17004320, 17004413, 17004844, and 17005180; see fig. 12B for hydrograph; see fig. 13 for locations) were sampled to determine if the chemistry of water in these wells varies with canal operation. The wells and nearby canals were sampled in September 1994, near the end of the summer irrigation season. The wells were again sampled in March 1995 before the canals started to flow for the summer. Descriptions of the sites are given in Appendixes 1 and 3. The diagrams representing the water chemistry of the canals and the March 1995 analyses of the wells are shown on plate 1. The chemical analyses are included

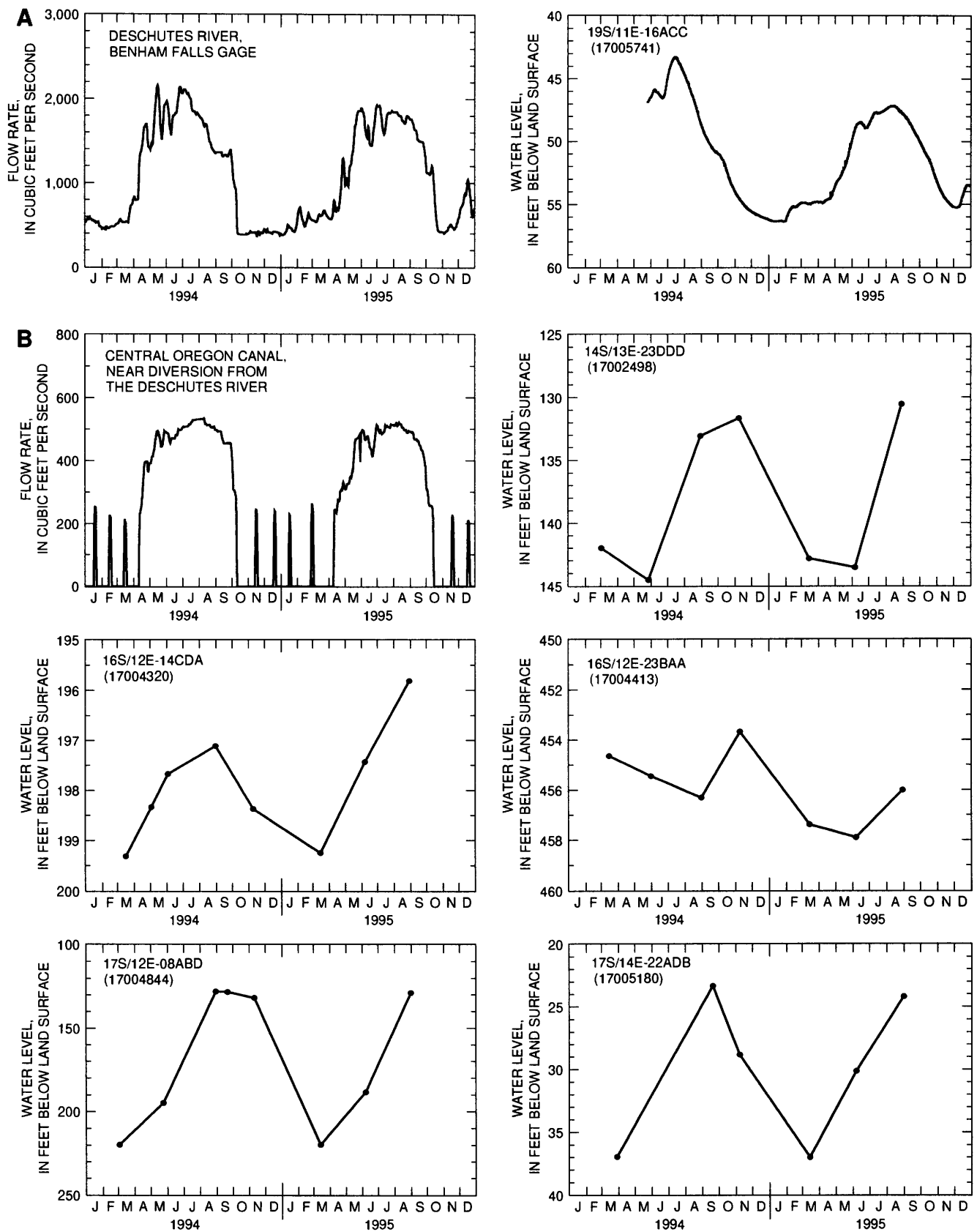


Figure 12. (A) Deschutes River flow rate (Oregon Water Resources Department, unpub. data, 1997) and a hydrograph of a nearby well, (B) Central Oregon Canal flow rate (Oregon Water Resources Department, unpub. data, 1997) and hydrographs of wells that respond to canal operation.

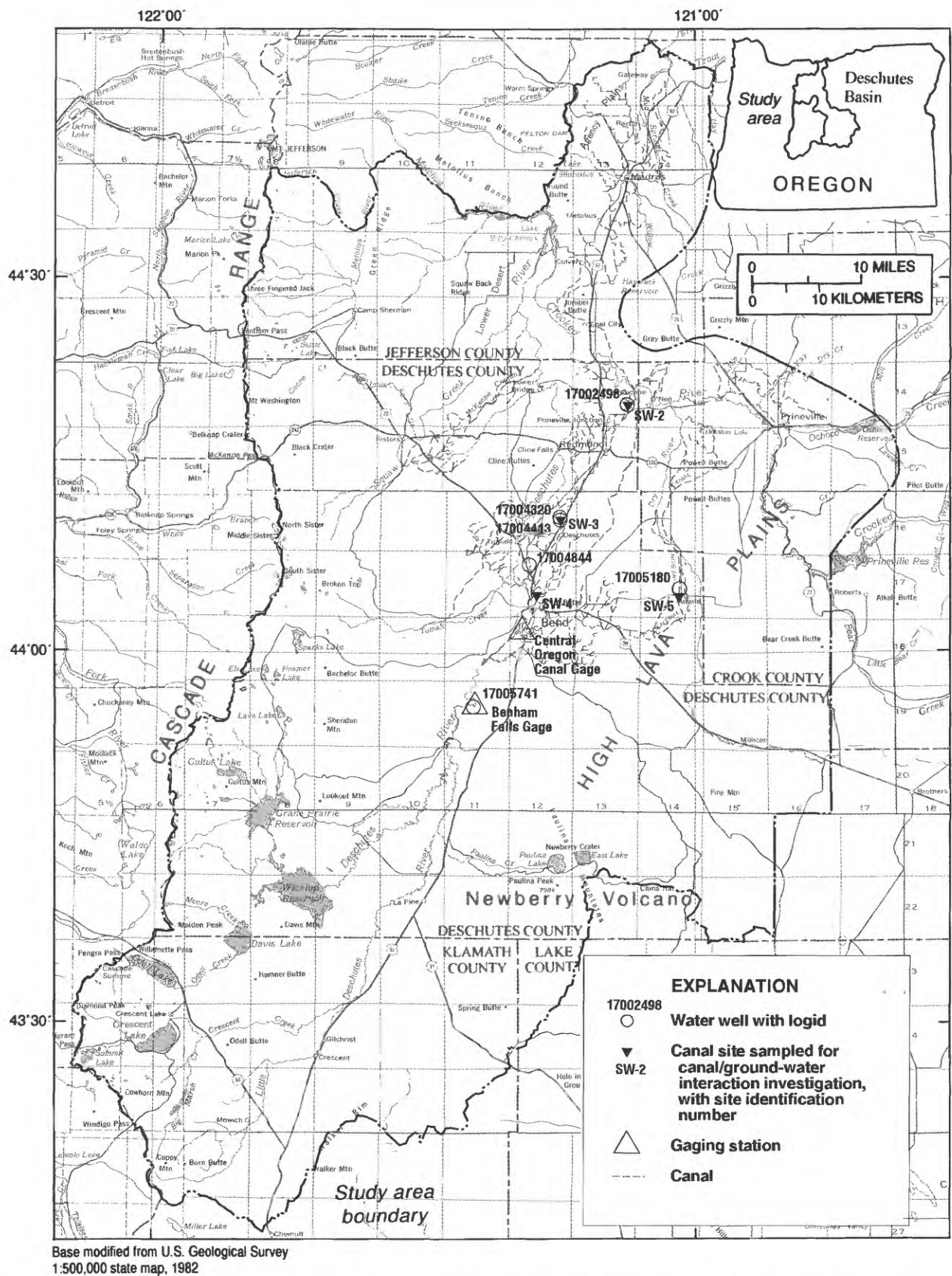


Figure 13. Location of wells and stream-gaging stations with hydrographs shown in figure 12 and sites sampled to investigate canal/ground-water interaction in the upper Deschutes Basin, Oregon.

in Appendixes 4 and 6. Chemically, the canal water samples were nearly identical to one another, with TDS concentrations ranging from 51 to 52 mg/L. The ground-water samples had similar molar proportions as the canal water samples, but were distinct from the canal water, with approximately two to six times the TDS concentration.

Although the water levels in the wells responded to canal operation, no substantial chemical differences were observed between the September 1994 and March 1995 well-water samples from any given well (Appendix 4). In contrast, field measurements of specific conductance from September 1994 to August 1995 indicate that temporal variability in water chemistry may exist in some of the wells (fig. 14).

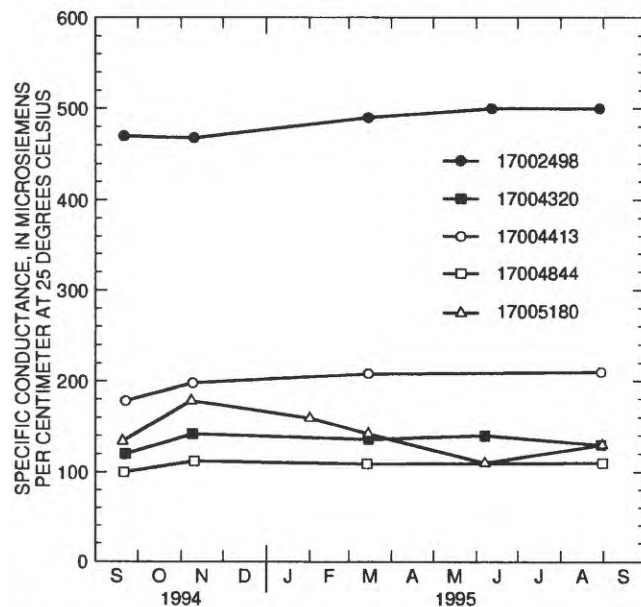


Figure 14. Specific conductance values of water from wells near canals in the upper Deschutes Basin, Oregon. (Specific conductance was measured in the field from September 1994 to August 1995.)

The largest variation was measured in well 17005180 (17S/14E-22ADB), a shallow well (40 feet deep) that nearly goes dry in the spring before the canals are in operation for the irrigation season. The specific conductance values in this well ranged from 110 to 178 $\mu\text{S}/\text{cm}$. The highest value occurred in November 1994 (after the irrigation season) and the lowest value occurred in June 1995 (during the irrigation season). This timing does not correlate with the timing of the measured high (September 1994) and low (March 1995) water levels in this well (fig. 12B). Given that (1) canal leakage is responsible for the temporal water level fluctuations, and (2) the lowest specific

conductance value is the result of the arrival of the greatest proportion of low TDS concentration ground water resulting from canal leakage, there is a delay between the time when the pressure response is observed in the water levels and the time when the greatest proportion of local recharge from canal leakage reaches the well. The specific conductance values measured by USGS personnel in the other four wells varied by less than 20 percent (fig. 14). Volunteers collected additional specific conductance data at two of the sites on a more frequent basis during the spring and summer of 1995. Water from well 17002498 (14S/13E-23DDD) showed little variation in specific conductance, with values ranging from 470 to 510 $\mu\text{S}/\text{cm}$. This is similar to the range measured by USGS personnel from September 1994 to August 1995 (468 to 500 $\mu\text{S}/\text{cm}$) (fig. 14). However, well 17004844 (17S/12E-08ABD), previously mentioned as having seasonal water-level variations of more than 90 feet, had reported values ranging from 50 to 130 $\mu\text{S}/\text{cm}$. The measurements by USGS personnel from September 1994 to August 1995 ranged from 100 to 112 $\mu\text{S}/\text{cm}$ for this well. The specific conductance data, especially in the cases of wells 17005180 (USGS measurements) and 17004844 (volunteer measurements), suggests that (1) a temporal variation in ground-water chemistry in response to canal leakage may exist and (2) the timing of the water-chemistry sampling (September 1994 and March 1995) failed to reveal this variation.

Stable-isotope data were examined to further explore the possibility that canals are a local source of recharge for some area wells. The most abundant stable isotopes of water are the ^{16}O and ^{18}O isotopes of oxygen and the ^1H and ^2H (deuterium, D) isotopes of hydrogen (Drever, 1988). Values of δD and $\delta^{18}\text{O}$ (to a lesser degree) are generally unaffected by reaction with aquifer materials at low temperatures (Drever, 1988), making them useful in the determination of ground-water sources. Craig (1961) found that the δD and $\delta^{18}\text{O}$ values of precipitation and fresh waters from around the world plotted close to a straight line (the global meteoric water line) defined as $\delta\text{D} = 8\delta^{18}\text{O} + 10$. Coplen (1993) discusses the following mechanisms that can cause the isotopic composition of a water sample to differ from that of the local meteoric water: (1) Recharge to the system during a different geologic age with different climatic conditions, (2) evaporation before being recharged to the system (Evaporation is a nonequilibrium process that enriches D and ^{18}O in the water such that the $\delta\text{D}/\delta^{18}\text{O}$ is less than 8 [that of the

meteoric water line] and is usually between 3 and 6), (3) water-rock interaction at high temperatures, which can result in an increase the ^{18}O content of the water, and (4) silicate hydrolysis, a common diagenetic reaction, which results in a decrease in the content of ^{18}O the water, while possibly increasing the D content.

Deschutes Basin surface-water and ground-water isotope data from this study, as well as historical data (Ingebritsen and others, 1988; Crumrine and Morgan, 1994; Morgan and others, 1997) are shown in figure 15. Anomalous enriched isotope values for East Lake (δD ranging between -75.8 and -79.2, $\delta^{18}\text{O}$ values ranging between -7.7 and -8.5) in the Newberry Volcano area (Crumrine and Morgan, 1994; Morgan and others, 1997) were omitted from the graph to show the remaining data in greater detail. The Newberry

Volcano area data in figure 15 includes measurements from 25 sites, 16 of which have multiple measurements over a 4-year period, with a maximum δD variation of 7 per mil and a maximum $\delta^{18}\text{O}$ variation of less than 1 per mil at individual sites. Both the September 1994 and March 1995 isotope data for the five wells sampled for the canal/ground-water interaction part of this study are shown (fig. 15). The global meteoric water line of Craig (1961) closely approximates the linear trend of the data (fig. 15).

The isotopic similarity of water from canals and the adjacent wells (17002498, 17004320, 17004413, 17004844, and 17005180) indicates that the canals (and possibly the Deschutes River) are probably major local recharge sources for these wells (fig. 15). The isotopic compositions of water from canals and nearby

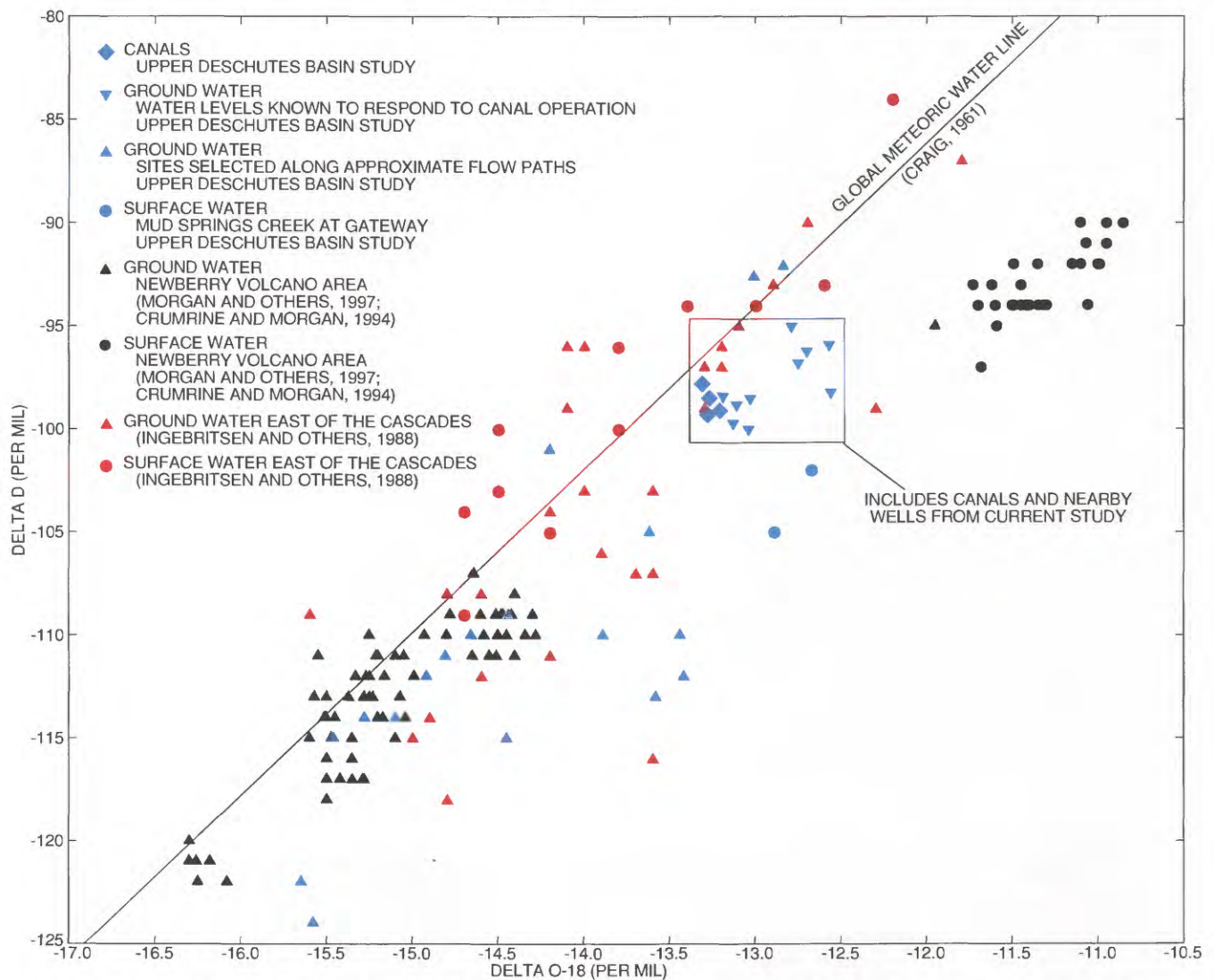


Figure 15. Delta deuterium and delta oxygen-18 of ground-water and surface-water sites in the upper Deschutes Basin, Oregon.

wells were tightly constrained and unique from most of the other waters, with a range of less than 5 per mil δD (-95 to -100 per mil) and a less than 1 per mil $\delta^{18}O$ (-12.56 to -13.32 per mil) (fig. 15). Data for the study area in general show a much larger range of values. Ground-water samples from other sites are composed of water from different sources and are conceivably dominated by waters of a more regional flow path.

The wells sampled for the canal/ground-water interaction part of this study (referred to here as the canal study wells) have isotopic signatures characteristic of a canal source, but also have increased (2- to 6-fold) TDS concentrations relative to the canals. Possible conditions that may account for the increased TDS concentrations include (1) mixing of local canal recharge with higher TDS concentration ground water not of a canal source (referred to here as regional ground water), (2) recharge of irrigated canal water that has undergone evaporation prior to recharge (on-farm losses), and (3) dissolution of aquifer material (minerals and glass) as the ground water traveled from the canal to the well. Conditions (1) and (2) are likely to occur in the study area, but the isotopic data indicate that they are not the dominant contributors to the increased TDS concentrations in the canal study wells.

If the composition of regional ground water is isotopically distinct from that of canal water, a mixture of water of canal origin and regional ground water would have an isotopic composition shifted away from that of the canal water. The magnitude of this shift would depend on the isotopic composition and proportion of regional ground water in the sample. A slight shift is seen (less than 1 per mil $\delta^{18}O$ and less than 5 per mil δD) in comparison of the samples from canals and the canal study wells. For regional ground water to be responsible for the increased TDS concentrations found in the canal study wells, while still maintaining only the slight isotopic shift seen in the data, the regional ground water would either have an isotopic composition similar to that of the canal water, or have relatively high concentrations of dissolved solids so the presence of only a small proportion could be responsible for the TDS increase.

Irrigated canal water would have to undergo extensive evaporation (approximately 50 to 80 percent) prior to recharge in order for it to be the source of the increased TDS concentrations found in the canal-study wells. Gilath and Gonfiantini (1983) calculated the isotopic composition of an evaporating water body under various humidity conditions. Gilath and Gonfiantini

found significant isotopic shifts (greater than +30 per mil δD , greater than 4 per mil $\delta^{18}O$) from that of the original water to that of the residual water after about 50 percent of the volume had been lost to evaporation. This is inconsistent with the observed δD and $\delta^{18}O$ shifts (less than 5 and less than 1 per mil, respectively) between the canals and the canal-study wells.

The most likely dominant mechanism for the relative increase in TDS concentrations from that of the canals to that of the canal study wells is water-rock interaction. This scenario is consistent with the isotopic data. Although the wells are in close proximity to canals, the actual recharge could be from a canal, multiple canals or the Deschutes River at a greater distance away. This would allow sufficient residence time for mineral and glass dissolution which would elevate the TDS concentrations with little impact on the isotopic composition of the ground-water.

A conceptual model (fig. 16) is proposed to explain the relation between the chemical data and the water-level responses due to canal leakage. Figure 16A represents conditions prior to the operation of canals for the irrigation season and figure 16B represents conditions after the canal is flowing. Leakage from the canals may produce a mounding of the water table, which then creates a pressure response that is transmitted quickly to nearby wells (fig. 16B). The mounding produces a rapid rise in the water-level (h_2 , fig. 16B) in a nearby well, but the ground water travels more slowly, dissolves minerals and volcanic glass as it interacts with aquifer material, and conceivably becomes mixed with other waters of local or regional origin. The proportion of ground water originating from a more regional source (Cascade Range precipitation is the predominant source of recharge in the study area) would be small relative to the locally derived water or would be limited to having an isotopic signature similar to that of the canal water. Therefore, a well adjacent to a canal may produce water that (1) leaked from the nearby canal, but in the past (after the original pressure response reached the well), (2) originated from a canal or the Deschutes River at a greater distance, (3) originated as canal water that was applied as irrigation and did not undergo extensive evaporation prior to reaching the water table, (4) has a component of water that originated from a regional recharge source that is small in proportion or has an isotopic signature similar to that of the canal water, or (5) is a combination of any of these conditions.

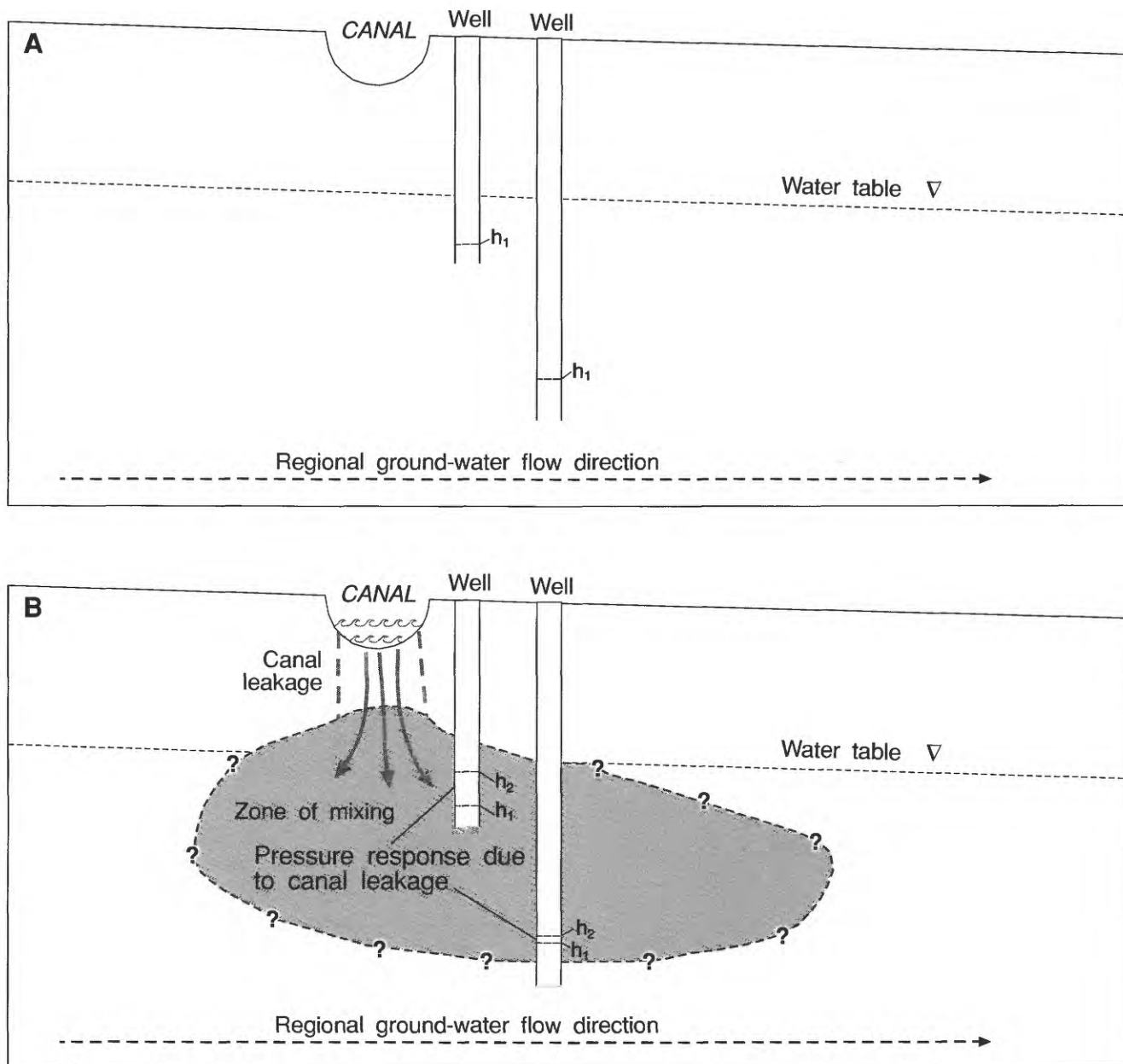


Figure 16. Conceptual model of the localized effect of canal leakage on the ground-water system. (A) Water levels (h_1) in wells near to a canal prior to canal operation. (B) Conditions as the canal is flowing, with the pressure response due to canal leakage resulting in higher water levels (h_2) in nearby wells.

SUMMARY AND CONCLUSIONS

Water-chemistry data support the conceptual model of the regional ground-water flow system developed during the present upper Deschutes Basin ground-water study. The TDS concentrations and specific conductance values from ground-water sites generally increase in the inferred direction of ground-water flow. Most of the sites having water with low TDS concentrations and specific conductance values

are located in the western part of the study area. Ground-water with the highest tritium values (8.5 to 10.3 TU [tritium unit]), interpreted as modern, also came from the western part of the study area. The western part of the study area, particularly the Cascade Range, is identified as the predominant area of recharge. Ground water in the vicinity of the regional discharge area near Lake Billy Chinook and from sites in the eastern part of the study area had values of less than 1 TU, indicative of water recharged

to the system before the early 1950's. Most of the sites having water with high TDS concentrations and specific conductance values occur in the eastern part of the study area, which is consistent with the low recharge rates, low permeability, and longer residence times. There are variations in TDS concentrations, specific conductance values, and tritium concentrations in wells and springs in close proximity to each other. Factors that contribute to the local chemical variability include (1) local recharge from surface water (most notably from the numerous canals that traverse the area), (2) local recharge from irrigated lands, and (3) and the presence and mixing of waters of different origins with varying residence times and aquifer material encountered along their flow paths.

Interpretation of the carbon-14 (^{14}C) data proved to be problematic and less conclusive. Unadjusted ages ranged from modern to 4,700 years before present. Samples yielding premodern ages (pre-1950) had increased dissolved inorganic carbon (DIC) concentrations relative to recharge area waters. A likely source of the increased DIC concentrations is the addition of inactive carbon from volcanic CO_2 , which results in unreliable and unreasonably old age estimates. The actual ages of the samples are probably younger than the unadjusted ^{14}C ages. However, the unadjusted ^{14}C ages can be used as a maximum age constraint for ground-water flow model calibration.

Most of the ground-water samples had comparable proportions of major ions. Samples from wells completed in the John Day Formation and the Prineville Basalt, or from flow paths that may have been in contact with these units, were among the highest in TDS concentrations and were somewhat distinct from the rest of the waters sampled. The high TDS concentrations may be a function of low permeability, low recharge rates, and (or) longer flow paths, resulting in longer residence times. Ground water that probably interacted with John Day Formation materials had relatively high sodium concentrations in comparison to water samples from other water-bearing units. Similar observations have been made of water from John Day Formation wells in the Warm Springs Reservation to the north of the study area. Relatively high calcium concentrations were found in study area waters that likely had interacted with Prineville Basalt. The interpretations made in this investigation concerning water

chemistry in relation to geology should be viewed as preliminary because the sample set was small. Even with a larger aqueous sample set, the degree of certainty to which water can be characterized to be of a particular geologic unit is limited owing to (1) the similar geochemical compositions of the many of the geologic units in the study area, (2) the variability in chemical composition within some of the geologic units, and (3) the fact that ground water is commonly in contact with multiple geologic units as it travels along a flow path.

Samples from canals and nearby wells were collected to evaluate whether canal leakage affects ground-water chemistry in addition to ground-water levels. The isotopic composition of water from the canals and adjacent wells was tightly constrained, whereas data from the study area as a whole show a much larger range of values. The similarity in the isotopic composition of water from canals and nearby wells suggests that canal leakage is a significant source of recharge to the wells. Canal-water samples were nearly identical chemically. Ground-water samples, although isotopically similar to canal water, had greater TDS concentrations than the canals. The increased dissolved ion concentrations suggests that there has been sufficient time for water/rock interaction (mineral and glass dissolution). Although the wells are in close proximity to canals, the actual water sampled could have originated from canals or the Deschutes River (from which these canals originate) at a greater distance away. This greater distance would increase the ground-water/aquifer interaction time, and allow for increased dissolution of minerals and glass. No significant seasonal variability of ground-water chemistry was observed between samples collected in September 1994 and March 1995; however, miscellaneous field specific conductance measurements from two of the wells suggest that a seasonal variability in water chemistry exists that was not detected by the September 1994 and March 1995 sampling efforts because of the lack of interim water-chemistry samples. Future investigations would benefit from more frequent collection of water-chemistry samples or field measurements of specific conductance, possibly on a weekly basis, to aid in the quantification of chemical variations in ground water attributable to canal operation.

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APPENDIXES

APPENDIX 1. DESCRIPTION OF WELLS SELECTED FOR WATER-CHEMISTRY ANALYSES IN THE UPPER DESCHUTES BASIN, OREGON

[ft. feet; D; measured by driller; *, measured immediately before water-chemistry sampling]

Log-id ¹	Location	Elevation (ft)	Well depth (ft)	Open interval (ft)	Water level (ft)	Water level date	Driller's description of water-bearing zone	Geologic unit
31000221	09S/14E-20CAA3	1,796	40	29-40	5.69* 4.41*	09-21-94 03-13-95	Broken pink rock	Tertiary basalt (Prineville Basalt)
31000231	09S/14E-21CCC	1,956	232	197-232	70 (D)	06-22-74	Broken gray lava	Tertiary basalt (Prineville Basalt)
31000373	10S/14E-30DAD	2,372	640	520-600	318 (D)	04-20-78	Hard gray basalt, brown clay	Tertiary basalt (Prineville Basalt)
31000396	10S/14E-33CDD	2,480	260	126-260	190 (D) 174.45	02-08-79 06-28-94	Sandstone, gravel and coarse sand	Tertiary sediment of the Deschutes Formation
31000538	12S/13E-26ABA	2,955	850	18.5-850	375 (D)	06-27-74	Green and brown rock, gray clay, green and gray clay conglomerate, green and brown rock, brown rock and gray clay, basalt and gray clay, brown and green rock and gray clay	Tertiary John Day Forma- tion—composed chiefly of rhyolitic ash-flow tuff, lava flows, and vent deposits.
31000090	13S/12E-05ADC	2,778	870	830-870	739 (D)	02-26-92	Black basalt, brown sandstone conglomerate	Tertiary basalt (Opal Springs Member) and sediment of the Deschutes Formation
31000829	13S/12E-22DAA	2,801	570	530-570	477 (D)	09-21-93	Sandstone, black lava	Tertiary sediment and basalt of the Deschutes Formation
31000164	13S/13E-20DAC	2,865	540	500-540	397 (D) 398.22	08-27-93 01-11-94	Light brown sandstone	Tertiary sediment of the Deschutes Formation
17001800	14S/09E-16ADB	3,355	370	324-370	265 (D)	04-26-91	Red cinder conglomerate, black sand, gravel, boulder	Quaternary basalt or basaltic andesite and Quaternary sediment
17000867	14S/10E-27BBB	3,230	423	358-423	242.3 (D)	04-16-91	Cinder and pumice, medium black basalt	Tertiary basalt
17001510	14S/11E-28ADD	3,105	663	643-663	575 (D)	09-30-92	Reddish brown conglomerate	Tertiary basalt of the Deschutes Formation
17002498	14S/13E-23DDD	2,943	175	150-175	130.65* 142.86*	09-21-95 03-15-95	Black sand, brown soft fine sandstone, coarse sand, brown sandstone	Tertiary sediment of the Deschutes Formation
17000053	14S/13E-29BDD	2,860	233	213-233	174 (D) 176.01	05-16-90 08-18-93	Brown broken basalt, gray cindery rubble	Tertiary basalt of Tethrow Buttes, Deschutes Formation
17003951	15S/13E-22CBA2	3,053	801	515-537	310 (D)	01-30-87	Brown sand and gravels	Tertiary sediment, basalt, and cinders of the Deschutes Formation
				595-635	328.95	09-09-94	Brown sandstone, black sand and small gravels	

APPENDIX 1. DESCRIPTION OF WELLS SELECTED FOR WATER CHEMISTRY ANALYSES IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Log-id ¹	Location	Elevation (ft)	Well depth (ft)	Open interval (ft)	Water level (ft)	Water level date	Driller's description of water-bearing zone	Geologic unit
17003951 (continued)	15S/13E-22CBA2	3,053	801	650–690			Brown sand, coarse gravel, red sand and coarse gravels, broken rock, red cinders	Tertiary sediment, basalt, and cinders of the Deschutes Formation
				757–777			Black broken rock, red cindered lava, black lava	
17004320	16S/12E-14CDA	3,185	235	790–800			Broken black pin-hole lava, hard, black basalt	
				19–235	197.57* 199.25*	09–22–94 03–15–95	Coarse black sand	Tertiary sediment of the Deschutes Formation
17004413	16S/12E-23BAA	3,193	510	490–510	455.00* 457.38*	09–22–94 03–15–95	Very hard black basalts	Tertiary basalt of the Deschutes Formation
17004655	16S/13E-16ADB	3,163	465	19–465	435 (D) 425.81	07–05–78 03–01–79	Black sandstone conglomerate, black sand	Tertiary sediment of the Deschutes Formation
17004844	17S/12E-08ABD	3,428	240	134–240	128.42* 219.82*	09–21–94 03–14–95	Fine gravel, pumice, soft pink rock containing pumice	Quaternary silicic ash-flow tuff
17005045	17S/12E-23BBC	3,462	1,057	837–877	702 (D) 717.87	02–16–77 05–31–95	Broken reddish basalt, hard gray basalt, broken gray basalt	Tertiary basalt
				893–1,057			Porous broken gray basalt, hard gray basalt, broken gray basalt, reddish soft basalt, broken basalt, porous round basalt	
17005180	17S/14E-22ADB	3,357	40	19–40	23.33* 37.00*	09–20–94 03–15–95	Broken gray basalt with yellow-gray clay seams	Quaternary basalt of the Newberry Volcano
17005203	17S/14E-27CCB	3,370	730	689–730	650 (D)	10–23–80	Sandstone, brown sandstone	Tertiary sediment of the Deschutes Formation
17000876	18S/12E-19CCB2	3,915	500	440–460	418 (D)	04–30–91	Gray basalt, gray broken basalt	Tertiary basalt
17005749	19S/11E-32CCA	4,160	266	254–266	6.5 (D)	05–12–67	Sand and gravel	Quaternary sediment
17005750	19S/14E-02DAA1	3,579	931	19.5–931	850 (D)	12–20–86	Red cinder gravels	Tertiary basalt/andesitic basalt
17005752	19S/14E-24DDA	4,262	1,260	19–1,260	1,181 (D)	12–08–81	Deteriorated lava	Tertiary basalt/andesitic basalt
17006340	20S/11E-18BCD	4,170	87	65–85	3 (D)	10–22–74	Small gravel, black sand	Quaternary sediment

¹Site-identification number. See plate 1 for sample site location.

APPENDIX 2. DESCRIPTION OF SPRINGS SELECTED FOR WATER-CHEMISTRY ANALYSES IN THE UPPER DESCHUTES BASIN, OREGON

[ft³/s, cubic feet per second]

Site ID ¹	Site name (location)	Latitude	Longitude	Elevation (feet)	Geologic unit	Remarks
S-1	Lower Opal Springs (12S/12E-33ACA1)	442928	1211749	1,958	Tertiary basalt (Opal Springs Member) of the Deschutes Formation	Source of Deschutes Valley Water public supply, sampled at improved orifice, estimated average flow rate equals 240 ft ³ /s (Deschutes Valley Water, oral commun., 1996)
S-2	Upper Opal Springs (12S/12E-33ACA2)	442927	1211746	2,150	Tertiary basaltic andesite of the Deschutes Formation	Sampled at improved orifice, estimated flow rate equals 2 to 3 ft ³ /s (1-9-95)
S-3	Virgin River Spring (13S/12E-14BAD)	442652	1211545	2,220	Near the contact of Quaternary intercanon basalt flows of the Crooked River Canyon and Tertiary basalt (Opal Springs Member) of the Deschutes Formation	Sampled at improved orifice, largest of several springs issuing from a 6 foot diameter cavern, flow rate equals 20 ft ³ /s as of 8-20-25 (Stearns, 1931)
S-4	Alder Springs (13S/12E-18CAC)	442630	1212044	2,295	Tertiary porphyritic basaltic andesite of the Deschutes Formation	Sampled at stream origin supplied by springs, estimated flow rate equals 4 to 5 ft ³ /s (1-18-95)
S-5	Paulina Springs (14S/09E-09CDB)	442203	1214003	3,358	Quaternary basaltic andesite	Sampled at stream origin supplied by springs, flow rate equals 6.17 ft ³ /s (7-12-95 (Oregon Water Resources Department, oral commun., 1996)
S-6	Source Spring (18S/09E-03DCD)	440216	1213754	6,325	Quaternary basaltic andesite	Sampled at stream 300 feet downstream from origin, estimated average annual flow rate equals 19 to 21 ft ³ /s (City of Bend Public Works, oral commun., 1996)
S-7	Spring River Springs (20S/10E-01CDD)	435151	1212835	4,175	Quaternary basaltic andesite	Sampled at stream origin supplied by springs, estimated flow rate equals 1 ft ³ /s (2-15-95)

¹Site-identification number. See plate 1 for sample site location.

APPENDIX 3. DESCRIPTION OF SURFACE-WATER SITES SELECTED FOR WATER-CHEMISTRY ANALYSES IN THE UPPER DESCHUTES BASIN, OREGON

[ft³/s, cubic feet per second]

Site ID ¹	Site name	Location	Latitude	Longitude	Elevation (feet)	Flow Rate
SW-1	Mud Springs Creek at Gateway	09S/14E-20BDA	444632	1210451	1,780	2.8 ft ³ /s (9-19-94) 4.3 ft ³ /s (3-13-95)
SW-2	Pilot Butte Canal, J-lateral at 33rd Avenue Bridge	14S/13E-23DDD2	442008	1210738	2,941	26 ft ³ /s (9-19-94)
SW-3	Pilot Butte Canal at Gift Road Bridge	16S/12E-14CDD	441053	1211509	3,193	² 408 ft ³ /s (9-20-94)
SW-4	North Canal at gage 0.5 miles from Deschutes River	17S/12E-21CDC	440448	1211746	3,555	411 ft ³ /s (9-20-94)
SW-5	Central Oregon Canal at Alfalfa Market Road Bridge	17S/14E-22DDC	440441	1210152	3,360	205 ft ³ /s (9-24-94)

¹Site-identification number. See plate 1 for sample site location.

²Flow rate measured at Young Road bridge, 1 mile downstream from sampling site.

APPENDIX 4. WATER-CHEMISTRY DATA FOR SELECTED WELLS IN THE UPPER DESCHUTES BASIN, OREGON

[Site locations are shown on plate 1; well information is listed in appendix 1; Log-id number, unique identification number; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; lab, laboratory; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; per mil, per 1,000; delta deuterium, (δD); delta oxygen-18, (δ¹⁸O); PCi/L, picocuries per liter; <, less than]

Log-id number	Location	Station number	Date	Temperature, water (°C)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH whole water, field (standard units)
31000221	09S/14E-20CAA3	444622121045201	09-21-94	14.5	729	751	2.4	7.4
31000221	09S/14E-20CAA3	444622121045201	03-13-95	12.0	833	866	2.3	7.6
31000231	09S/14E-21CCC	444602121040701	02-13-95	15.0	365	364	--	8.1
31000373	10S/14E-30DAD	444006121053101	02-13-95	20.0	330	330	--	8.2
31000396	10S/14E-33CDD	443906121034401	02-13-95	15.5	338	335	--	8.0
31000538	12S/13E-26ABA	443016121080601	03-14-95	21.0	394	398	4.7	7.9
31000090	13S/12E-05ADC	442829121184801	01-18-95	12.0	144	153	7.6	8.3
31000829	13S/12E-22DAA	442542121161201	02-14-95	13.5	310	313	8.5	8.1
31000164	13S/13E-20DAC	442526121113101	03-14-95	16.0	409	416	9.7	7.8
17001800	14S/09E-16ADB	442137121393201	01-1,1-95	4.5	63	60	11.8	7.7
17000867	14S/10E-27BBB	442004121315601	01-10-95	11.0	159	169	9.2	8.1
17001510	14S/11E-28ADD	441945121244801	01-10-95	11.0	199	219	--	7.8
17002498	14S/13E-23DDD	442009121073901	09-21-94	13.0	470	494	12.3	7.6
17002498	14S/13E-23DDD	442009121073901	03-15-95	13.5	490	476	10.0	7.7
17000053	14S/13E-29BDD	441945121115401	02-14-95	17.5	316	313	8.5	8.1
17003951	15S/13E-22CBA2	441515121094602	02-14-95	11.5	127	141	10.7	8.2
17004320	16S/12E-14CDA	441106121151301	09-22-94	13.5	120	129	9.2	7.4
17004320	16S/12E-14CDA	441106121151301	03-15-95	13.5	136	137	9.1	7.4
17004413	16S/12E-23BAA	441053121151101	09-22-94	14.0	178	195	9.2	7.8
17004413	16S/12E-23BAA	441053121151101	03-15-95	14.0	208	207	9.5	7.9
17004655	16S/13E-16ADB	441131121095501	01-09-95	11.0	328	319	--	8.1
17004844	17S/12E-08ABD	440715121183701	09-21-94	14.0	100	109	9.5	6.9
17004844	17S/12E-08ABD	440715121183701	03-14-95	11.5	109	115	7.6	7.6
17005045	17S/12E-23BBC	440529121154101	06-20-95	11.5	115	121	9.1	8.1
17005180	17S/14E-22ADB	440518121014801	09-20-94	12.5	134	145	7.1	7.4
17005180	17S/14E-22ADB	440518121014801	03-15-95	12.5	143	145	8.0	8.0
17005203	17S/14E-27CCB	440401121023701	02-16-95	19.0	256	265	8.8	8.1
17000876	18S/12E-19CCB2	435949121202701	02-14-95	11.5	99	104	8.8	8.0
17005749	19S/11E-32CCA	435251121262801	02-15-95	8.0	108	111	6.7	8.3
17005750	19S/14E-02DAA1	435709121002801	02-16-95	23.0	261	268	9.1	8.0
17005752	19S/14E-24DDA	435423120591001	02-16-95	21.0	250	259	8.3	7.9
17006340	20S/11E-18BCD	435032121274001	02-15-95	7.5	105	110	.1	8.5

APPENDIX 4. WATER-CHEMISTRY DATA FOR SELECTED WELLS IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Hardness, total (mg/L as CaCO ₃)	Nitrogen, ammonia filtered (mg/L as N)	Nitrogen, nitrite filtered (mg/L as N)	Nitrogen, ammonia + organic filtered (mg/L as N)	Nitrogen, NO ₂ + NO ₃ filtered (mg/L as N)	Phosphorus, filtered (mg/L as P)	Phosphorus, ortho filtered (mg/L as P)	Calcium, filtered (mg/L as Ca)
300	309	120	<.010	<.01	<.2	4.8	0.29	0.28	29
343	345	150	<.015	<.01	<.2	4.8	.24	.24	35
120	124	120	<.015	<.01	<.2	3.0	<.01	.01	32
130	134	95	<.015	.05	<.2	2.0	<.01	<.01	25
120	124	100	<.015	<.01	<.2	2.6	<.01	.01	27
173	175	12	<.015	<.01	<.2	1.6	.05	.05	4.9
71	74	48	<.015	<.01	<.2	.30	.06	.07	8.2
132	132	95	<.015	<.01	<.2	2.1	.10	.11	15
169	172	170	<.015	<.01	<.2	4.1	.08	.06	41
28	28	18	<.015	<.01	<.2	.06	.06	.07	3.9
--	84	67	<.015	<.01	<.2	.51	.04	.05	14
--	107	87	<.015	<.01	<.2	.69	.05	.06	15
247	248	180	<.010	<.01	.2	1.2	.13	.13	31
240	243	180	<.015	<.01	<.2	.94	.12	.13	29
138	139	98	<.015	<.01	<.2	1.5	.04	.05	16
65	67	41	<.015	<.01	<.2	.26	.09	.09	6.7
61	62	46	<.010	<.01	<.2	.64	.08	.08	9.2
63	66	46	<.015	<.01	<.2	.44	.10	.09	9.2
92	94	65	<.010	<.01	<.2	.96	.13	.13	13
96	98	69	--	--	--	--	--	--	14
--	151	130	<.015	<.01	<.2	1.5	.07	.07	21
51	52	36	<.010	<.01	<.2	.41	.08	.08	5.8
51	52	38	<.015	<.01	<.2	.53	.10	.05	6.1
57	59	37	.02	<.01	<.2	.25	.09	.09	5.9
67	70	41	<.010	<.01	<.2	.40	.18	.19	9.0
65	68	41	<.015	<.01	<.2	.47	.17	.15	9.1
114	116	84	<.015	<.01	<.2	1.2	.08	.08	14
51	51	32	<.015	<.01	<.2	.10	.10	.09	4.8
51	52	30	<.015	<.01	<.2	.08	.18	.17	5.6
115	117	75	<.015	<.01	<.2	.85	.02	.02	12
117	115	69	<.015	<.01	<.2	.79	.03	.02	11
50	49	22	.630	<.01	.7	<.05	.34	.32	4.4

APPENDIX 4. WATER-CHEMISTRY DATA FOR SELECTED WELLS IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Log-id number	Date	Magnesium, filtered (mg/L as Mg)	Sodium, filtered (mg/L as Na)	Sodium percent	Sodium adsorption ratio	Potassium, filtered (mg/L as K)	Chloride, filtered (mg/L as Cl)	Sulfate, filtered (mg/L as SO ₄)	Fluoride, filtered (mg/L as F)	Silica, filtered (mg/L as SiO ₂)
31000221	09-21-94	12	120	67	5	4.9	20	44	0.3	58
31000221	03-13-95	15	140	66	5	7.1	26	56	1.1	54
31000231	02-13-95	10	24	29	.9	3.9	17	18	.7	59
31000373	02-13-95	8.0	26	35	1	8.0	9.7	11	.4	65
31000396	02-13-95	8.6	26	34	1	5.6	11	16	.5	71
31000538	03-14-95	.06	87	94	11	.30	9.0	11	.8	27
31000090	01-18-95	6.8	12	34	.8	2.6	2.6	2.0	.1	35
31000829	02-14-95	14	25	35	1	6.3	8.2	8.0	.2	39
31000164	03-14-95	16	21	21	.7	3.6	5.9	20	.2	48
17001800	01-11-95	1.9	5.3	38	.6	1.0	.9	1.0	<.1	26
17000867	01-10-95	7.8	8.5	21	.5	3.1	1.4	.40	<.1	52
17001510	01-10-95	12	13	24	.6	3.0	2.9	1.7	.2	50
17002498	09-21-94	26	36	29	1	3.7	2.8	12	.4	42
17002498	03-15-95	25	36	30	1	4.3	1.9	10	.4	41
17000053	02-14-95	14	25	34	1	4.6	5.9	10	.2	47
17003951	02-14-95	5.9	13	39	.9	2.1	2.1	1.2	.2	38
17004320	09-22-94	5.5	8.7	28	.6	1.6	1.6	1.2	.2	45
17004320	03-15-95	5.6	9.2	29	.6	2.2	1.2	.80	.2	43
17004413	09-22-94	7.8	16	34	.9	1.7	1.9	2.2	<.1	48
17004413	03-15-95	8.2	16	33	.8	2.1	1.8	2.6	.3	47
17004655	01-09-95	18	20	25	.8	3.6	5.4	6.1	<.1	36
17004844	09-21-94	5.2	7.6	30	.6	1.5	1.5	1.5	.1	39
17004844	03-14-95	5.5	7.8	30	.6	2.0	1.7	1.6	.2	35
17005045	06-20-95	5.3	10	36	.7	1.8	1.8	.90	.2	36
17005180	09-20-94	4.6	14	41	.9	1.5	1.4	1.0	.2	41
17005180	03-15-95	4.5	13	39	.9	2.0	1.6	1.6	.2	39
17005203	02-16-95	12	21	34	1	3.6	5.9	6.5	.2	49
17000876	02-14-95	4.8	8.2	35	.6	1.4	1.4	.30	.1	38
17005749	02-15-95	3.9	11	43	.9	1.5	2.9	.40	.1	30
17005750	02-16-95	11	24	39	1	4.8	7.1	7.6	.2	54
17005752	02-16-95	10	24	41	1	4.9	6.8	5.5	.2	53
17006340	02-15-95	2.6	13	55	1	.80	2.6	.70	.1	29

APPENDIX 4. WATER-CHEMISTRY DATA FOR SELECTED WELLS IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Iron, filtered (µg/L as Fe)	Manganese, filtered (µg/L as Mn)	Aluminum, filtered (µg/L as Al)	Bromide, filtered (mg/L as Br)	Solids, sum of constituents, filtered (mg/L)	Solids, residue at 180°C, filtered (mg/L)	δD (per mil)	δ ¹⁸ O (per mil)	Tritium, total (PCI/L)	Tritium, 2 sigma total (PCI/L)
<3	<1	<10	0.18	490	503	-112.0	-13.42	--	--
4	<1	<10	.22	562	558	-110.0	-13.44	--	--
4	1	<10	.19	250	248	-113.0	-13.58	<2.5	1.9
85	3	<10	.11	240	236	--	-14.44	--	--
<3	<1	<10	.15	249	244	--	-14.11	--	--
9	<1	<10	.11	251	255	-115.0	-14.45	.4	.4
210	15	<10	.03	114	126	-112.0	-14.92	<1.0	1.0
14	5	10	.08	204	186	--	-14.06	--	--
16	6	10	.07	275	273	-105.0	-13.62	24.0	1.6
<3	<1	20	<.01	58	54	-92.6	-13.01	32.0	3.2
4	<1	<10	.02	133	124	--	--	--	--
97	18	20	.03	157	148	-110.0	-13.89	<2.5	1.9
4	<1	<10	.02	307	300	-95.9	-12.57	--	--
<3	<1	<10	.02	296	290	-98.2	-12.56	--	--
5	<1	<10	.06	212	202	--	-14.10	--	--
<3	<1	<10	.02	110	96	-115.0	-15.46	--	--
9	<1	<10	<.01	113	108	-98.8	-13.11	--	--
<3	<1	<10	.01	111	107	-98.4	-13.19	--	--
11	1	10	<.01	151	125	-98.5	-13.03	--	--
4	<1	<10	.02	151	144	-99.7	-13.13	--	--
<3	<1	<10	.09	192	182	--	--	--	--
6	<1	<10	<.01	95	94	-95.0	-12.79	--	--
16	4	30	<.01	93	90	-100.0	-13.04	--	--
5	<1	<10	.01	98	98	-110.0	-14.66	9.3	2.6
4	<1	<10	<.01	115	112	-96.2	-12.70	--	--
<3	<1	<10	<.01	113	111	-96.8	-12.75	--	--
5	<1	<10	.05	186	174	--	-14.77	--	--
3	<1	<10	<.01	90	82	--	-14.57	--	--
9	<1	<10	.02	87	80	--	-14.56	--	--
<3	<1	10	.06	194	184	-124.0	-15.58	--	--
3	<1	10	.06	189	176	-122.0	-15.65	<2.5	1.9
150	47	10	.01	85	70	--	-14.52	--	--

APPENDIX 5. WATER-CHEMISTRY DATA FOR SELECTED SPRINGS IN THE UPPER DESCHUTES BASIN, OREGON

[Site locations are shown on plate 1; site information is listed in appendix 2; Site ID, site identification; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; lab, laboratory; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; per mil, per 1,000; δD, delta deuterium; δ¹⁸O, delta oxygen-18; PCi/L, picocuries per liter; <, less than]

Site ID	Location	Station number	Date	Temperature, water (°C)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH whole water, field (standard units)
S-1	12S/12E-33ACA1 (Lower Opal Springs)	442928121174901	01-09-95	12.0	128	129	9.9	8.1
S-2	12S/12E-33ACA2 (Upper Opal Springs)	442927121174601	01-09-95	15.5	191	--	9.2	8.2
S-3	13S/12E-14BAD (Virgin River Springs)	442652121154501	01-18-95	14.0	178	189	8.4	8.0
S-4	13S/12E-18CAC (Alder Springs)	442630121204401	01-19-95	10.5	125	136	9.0	8.0
S-5	14S/09E-09CDB (Paulina Springs)	442203121400301	01-11-95	4.5	62	60	11.2	7.2
S-6	18S/09E-03DCD (Source Springs)	440216121375401	01-17-95	3.0	34	37	9.9	7.5
S-7	20S/10E-01CDD (Spring River Springs)	435151121283501	02-15-95	7.5	98	101	8.0	8.3

Site ID	Magnesium, filtered (mg/L as Mg)	Sodium, filtered (mg/L as Na)	Sodium percent	Sodium adsorption ratio	Potassium, filtered (mg/L as K)	Chloride, filtered (mg/L as Cl)	Sulfate, filtered (mg/L as SO ₄)	Fluoride, filtered (mg/L as F)	Silica, filtered (mg/L as SiO ₂)
S-1	5.8	12	39	0.8	2.1	1.6	0.90	0.1	38
S-2	--	--	--	--	--	--	--	--	--
S-3	8.4	16	36	.9	2.7	3.3	3.7	.1	40
S-4	6.1	11	34	.7	2.2	1.9	1.4	<.1	39
S-5	2.0	4.3	31	.4	1.0	.5	.30	<.1	29
S-6	.97	2.5	31	.3	1.2	.3	.50	<.1	27
S-7	3.6	9.5	41	.8	1.3	2.4	.40	.1	34

APPENDIX 5. WATER-CHEMISTRY DATA FOR SELECTED SPRINGS IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Hardness, total (mg/L as CaCO ₃)	Nitrogen, ammonia filtered (mg/L as N)	Nitrogen, nitrite filtered (mg/L as N)	Nitrogen, ammonia + organic filtered (mg/L as N)	Nitrogen, NO ₂ + NO ₃ filtered (mg/L as N)	Phosphorus, filtered (mg/L as P)	Phosphorus, ortho filtered (mg/L as P)	Calcium, filtered (mg/L as Ca)
--	63	39	<0.015	<0.01	<0.2	0.21	0.07	0.08	6.0
--	--	--	--	--	--	--	--	--	--
87	88	58	<.015	<.01	<.2	.53	.06	.08	9.2
64	65	43	<.015	<.01	<.2	.27	.07	.08	7.3
29	29	20	<.015	<.01	<.2	.06	.06	.07	4.7
15	18	10	<.015	<.01	<.2	<.05	.05	.05	2.6
48	47	28	<.015	<.01	<.2	.06	.12	.12	5.1

Iron, filtered (µg/L as Fe)	Manganese, filtered (µg/L as Mn)	Aluminum, filtered (µg/L as Al)	Bromide, filtered (mg/L as Br)	Solids, sum of constituents, filtered (mg/L)	Solids, residue at 180 °C, filtered (mg/L)	δD (per mil)	δ ¹⁸ O (per mil)	Tritium, total (PCI/L)	Tritium, 2 sigma total (PCI/L)
3	<1	<10	0.01	105	96	-114.0	-15.28	2.7	0.6
--	--	--	--	--	--	--	--	12.0	2.6
<3	<1	<10	.03	138	128	-114.0	-15.10	6.3	.6
<3	<1	<10	.02	109	96	-111.0	-14.81	10.0	1.0
<3	<1	50	<.01	60	50	-92.1	-12.84	27.0	3.2
3	<1	<10	<.01	44	50	-101.0	-14.20	33.0	3.2
<3	<1	<10	.01	86	80	-109.0	-14.44	--	--

APPENDIX 6. WATER-CHEMISTRY DATA FOR SELECTED SURFACE-WATER SITES IN THE UPPER DESCHUTES BASIN, OREGON

[Site locations are shown on plate 1, site information is listed in appendix 3; Site ID, site identification; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; lab, laboratory; --, no data; mg/L, milligrams per liter; µg/L, micrograms per liter; per mil, per 1,000; δD, delta deuterium; δ¹⁸O, delta oxygen-18; <, less than]

Site ID	Location	Station number	Date	Temperature, water (°C)	Specific conductance, field (µS/cm)	Specific conductance, lab (µS/cm)	Oxygen, dissolved (mg/L)	pH whole water, field (standard units)
SW-1	09S/14E-20BDA (Mud Springs Creek)	444632121045101	09-19-94	15.5	494	501	8.8	8.2
SW-1	09S/14E-20BDA (Mud Springs Creek)	444632121045101	03-13-95	13.5	480	492	10.4	8.7
SW-2	14S/13E-23DDD2 (Pilot Butte Canal, J-Lat),	442008121073801	09-19-94	17.5	61	67	9.0	8.7
SW-3	16S/12E-14CDD (Pilot Butte Canal)	441053121150901	09-20-94	13.0	60	67	9.2	7.6
SW-3	16S/12E-14CDD (Pilot Butte Canal)	441053121150901	06-20-95	14.0	58	--	9.0	8.0
SW-4	17S/12E-21CDC (North Canal)	440448121174601	09-20-94	14.0	59	66	9.6	8.0
SW-5	17S/14E-22DDC (Central Oregon Canal)	440441121015201	09-20-94	14.0	60	66	9.6	8.2

Site ID	Date	Magnesium, filtered (mg/L as Mg)	Sodium, filtered (mg/L as Na)	Sodium percent	Sodium adsorption ratio	Potassium, filtered (mg/L as K)	Chloride, filtered (mg/L as Cl)	Sulfate, filtered (mg/L as SO ₄)	Fluoride, filtered (mg/L as F)	Silica, filtered (mg/L as SiO ₂)
SW-1	09-19-94	15	55	45	2	3.7	11	25	0.5	46
SW-1	03-13-95	15	49	41	2	4.6	11	24	.5	49
SW-2	09-19-94	2.4	5.8	37	.6	1.0	1.0	.3	<.1	17
SW-3	09-20-94	2.3	5.7	37	.6	1.0	.9	.4	<.1	18
SW-3	06-20-95	--	--	--	--	--	--	--	--	--
SW-4	09-20-94	2.3	5.6	37	.6	1.0	.9	.4	<.1	19
SW-5	09-20-94	2.3	5.6	37	.6	1.1	1.0	.4	<.1	18

APPENDIX 6. WATER-CHEMISTRY DATA FOR SELECTED SURFACE-WATER SITES IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Alkalinity, field (mg/L as CaCO ₃)	Alkalinity, lab (mg/L as CaCO ₃)	Hardness, total (mg/L as CaCO ₃)	Nitrogen, ammonia filtered (mg/L as N)	Nitrogen, nitrite filtered (mg/L as N)	Nitrogen, ammonia + organic filtered (mg/L as N)	Nitrogen, NO ₂ + NO ₃ filtered (mg/L as N)	Phosphorus, filtered (mg/L as P)	Phosphorus, ortho filtered (mg/L as P)	Calcium, filtered (mg/L as Ca)
207	211	140	0.02	0.02	<0.2	4.7	0.15	0.15	32
203	200	150	.02	.01	<.2	4.8	.15	.16	34
31	33	20	.02	<.01	<.2	<.05	.06	.06	4.1
32	33	20	<.01	<.01	<.2	<.05	.05	.05	4.1
--	--	--	--	-	--	--	--	--	--
31	32	19	.01	<.01	<.2	<.05	.06	.06	3.9
31	32	19	.01	<.01	<.2	<.05	.12	.05	4.0

Iron, filtered (µg/L as Fe)	Manganese, filtered (µg/L as Mn)	Aluminum, filtered (µg/L as Al)	Bromide, filtered (mg/L as Br)	Solids, sum of constituents, filtered (mg/L)	Solids, residue at 180°C, filtered (mg/L)	δD (per mil)	δ ¹⁸ O (per mil)
28	4	<10	0.06	334	331	-102.0	-12.67
15	11	--	.08	331	324	-105.0	-12.89
78	3	<10	<.01	51	51	-99.1	-13.21
77	3	<10	<.01	52	54	-99.3	-13.28
--	--	--	--	--	--	-99.4	-13.32
90	7	<10	<.01	52	47	-98.5	-13.27
68	2	<10	<.01	51	52	-97.8	-13.31

APPENDIX 7. HISTORICAL WATER-CHEMISTRY DATA FOR GROUND-WATER SITES IN THE UPPER DESCHUTES BASIN, OREGON

[°C, degrees Celsius; µS/cm, microsiemens per centimeter at 25 degrees Celsius; ID, identification; lab, laboratory; --, no data; mg/L, milligrams per liter]

Site ID ¹	Location	Date	Temperature, water (°C)	Specific conductance, field (µS/cm)	pH, whole water, lab (standard units)	Alkalinity, field (mg/L as CaCO ₃)	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Potassium, dissolved (mg/L as K)
S-1	12S/12E-33ACA1 Lower Opal Springs	08-16-66	14	124	8.2	55	9.6	11	11	1.9
S-1	12S/12E-33ACA1 Lower Opal Springs	11-14-66	13	126	8.2	62	7.2	10	11	2.0
S-1	12S/12E-33ACA1 Lower Opal Springs	12-74	--	152	7.9	60	--	--	10.3	1.9
S-1	12S/12E-33ACA1 Lower Opal Springs	2-77	--	128	8.0	57	--	--	8.5	1.4
S-1	12S/12E-33ACA1 Lower Opal Springs	01-09-95	12	128	7.9	263	6.0	5.8	12	2.1
S-3	13S/12E-14BAD Virgin River Spring	11-15-66	15	182	8.0	86	13	14	17	3.1
S-3	13S/12E-14BAD Virgin River Spring	12-74	--	211	7.9	79	--	--	13.2	2.5
S-3	13S/12E-14BAD Virgin River Spring	2-77	--	185	7.9	77	--	--	12.7	1.9
S-3	13S/12E-14BAD Virgin River Spring	01-18-95	14	178	7.8	87	9.2	8.4	16	2.7
S-5	14S/09E-09CDB Paulina Spring	11-16-66	6	56	7.4	29	5.2	6.4	4.1	1.4
S-5	14S/09E-09CDB Paulina Spring	01-11-95	4.5	62	7.1	29	4.7	2.0	4.3	1.0
17005045	17S/12E-23BBC	09-01-78	12.0	128	--	60	6.7	5.9	12	1.8
17005045	17S/12E-23BBC	06-20-95	11.5	115	7.9	57	5.9	5.3	10	1.8
17005749	19S/11E-32CCA	08-23-78	8.5	104	7.6	49	5.5	3.9	11	1.9
17005749	19S/11E-32CCA	02-15-95	8.0	108	7.9	51	5.6	3.9	11	1.5
S-7	20S/10E-01CDD Spring River Springs	08-22-78	7.0	107	5.8	47	5.3	3.6	10	1.5
S-7	20S/10E-01CDD Spring River Springs	02-15-95	7.5	98	7.8	48	5.1	3.6	9.5	1.3

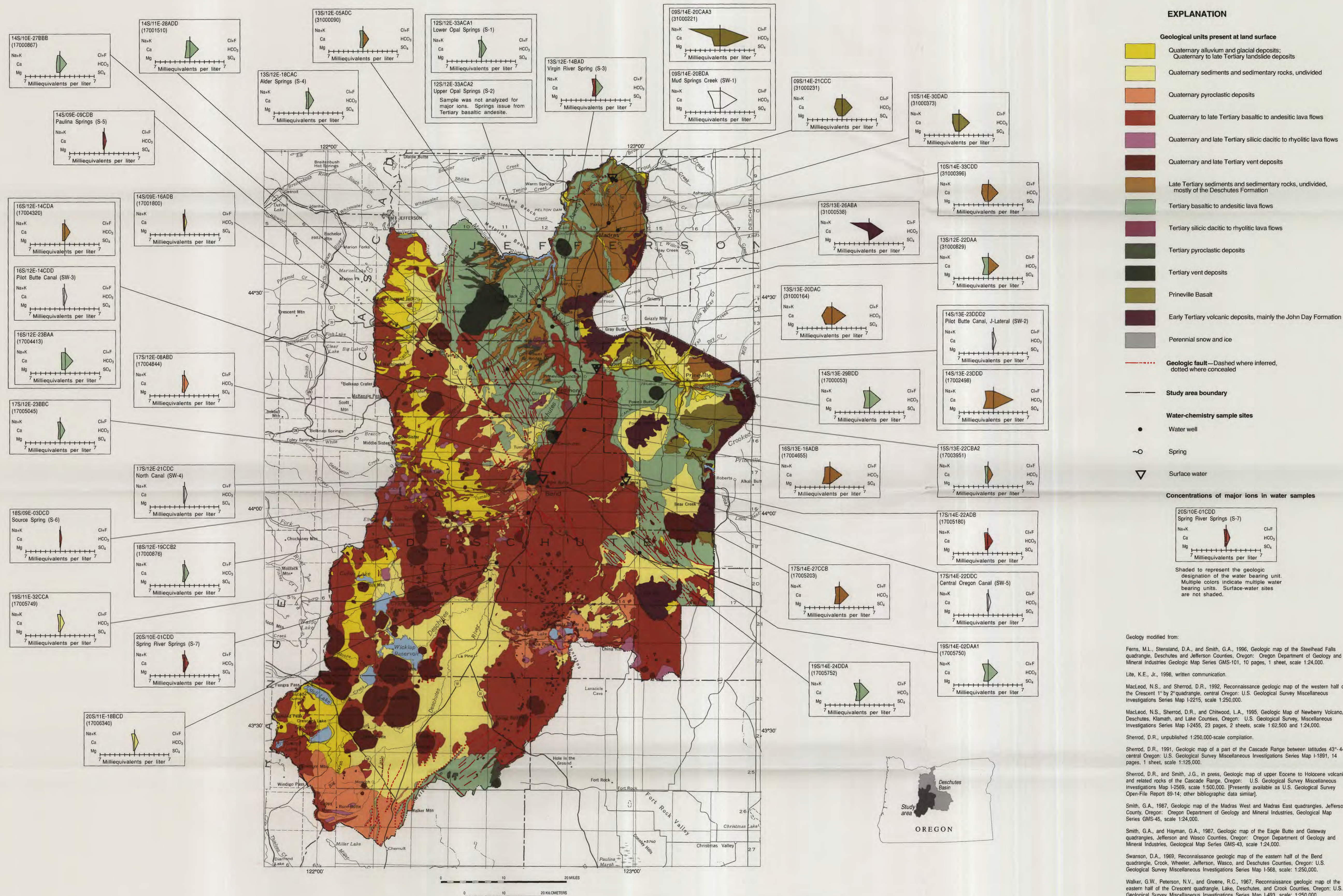
APPENDIX 7. HISTORICAL WATER-CHEMISTRY DATA FOR GROUND-WATER SITES IN THE UPPER DESCHUTES BASIN, OREGON—Continued

Site ID ¹	Date	Chloride, dissolved (mg/L as Cl)	Nitrogen, Nitrite dissolved (mg/L as N)	Nitrogen, NO ₃ + NO ₂ dissolved (mg/L as N)	Phosphorous, dissolved (mg/L as P)	Sulfate, dissolved (mg/L as SO ₄)	Fluoride, dissolved (mg/L as F)	Silica, dissolved (mg/L as SiO ₂)	Solids, total dissolved, (mg/L)	Laboratory ³
S-1	08-16-66	2.0	--	0.08	0.28	1.0	0.2	36	80	FWPCA
S-1	11-14-66	2.0	<0.001	.20	.30	2.0	--	38	97	FWPCA
S-1	12-74	2.0	--	.20	.3	1.2	--	--	121	ODEQ
S-1	2-77	1.4	--	.20	.31	1.2	--	--	99	ODEQ
S-1	01-09-95	1.6	<.01	.21	.07	.90	.10	38	105	USGS
S-3	11-15-66	3.0	<0.001	.50	.30	4.0	--	43	132	FWPCA
S-3	12-74	2.9	--	.47	.2	1.3	--	--	154	ODEQ
S-3	2-77	2.7	--	.49	.25	3.8	--	--	135	ODEQ
S-3	01-18-95	3.3	<.01	.53	.06	3.7	.10	40	138	USGS
S-5	11-16-66	1.0	<0.001	.05	.30	.0	--	30	56	FWPCA
S-5	01-11-95	.5	<.01	.06	.06	.30	<.10	29	60	USGS
17005045	09-01-78	1.9	--	.45	.10	1.4	.20	36	104	USGS
17005045	06-20-95	1.8	<.01	.25	.09	.90	.20	36	98	USGS
17005749	08-23-78	3.1	.01	.12	.18	1.2	.10	31	88	USGS
17005749	02-15-95	2.9	<.01	.08	.18	.40	.10	30	87	USGS
S-7	08-22-78	3.0	<.01	.09	.74	1.4	.10	34	88	USGS
S-7	02-15-95	2.4	<.01	.06	.12	.40	.10	34	86	USGS

¹ See plate 1 for sample site locations. Site-id = well log-id.

² Laboratory value.

³ FWPCA—Federal Water Pollution Control Administration, Northwest Region, Pacific Northwest Water Laboratory; ODEQ—Oregon Department of Environmental Quality; USGS—U.S. Geological Survey.



GENERALIZED SURFICIAL GEOLOGY, LOCATION OF WATER-CHEMISTRY DATA COLLECTION SITES, AND DIAGRAMS OF MAJOR-ION WATER CHEMISTRY IN THE UPPER DESCHUTES BASIN, OREGON

By
Rodney R. Caldwell

1998

Base modified from U.S. Geological Survey 1:500,000 state base map, 1982 with digital data from U.S. Bureau of the Census, TIGER/Line® 1990 and U.S. Geological Survey Digital Line Graphs published at 1:100,000

Publication projection is Lambert Conformal Conic. Standard parallels 43°00' and 45°30', central meridian -120°30'.