SUMMARY OF THE SNAKE RIVER PLAIN REGIONAL AQUIFER-SYSTEM ANALYSIS IN IDAHO AND EASTERN OREGON

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1408-A

Summary of the Snake River Plain Regional Aquifer-System Analysis in Idaho and Eastern Oregon

By G.F. LINDHOLM

REGIONAL AQUIFER-SYSTEM ANALYSIS—SNAKE RIVER PLAIN, IDAHO

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1408-A

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FOREWORD

THE REGIONAL AQUIFER-SYSTEM ANALYSIS PROGRAM

The Regional Aquifer-System Analysis (RASA) Program was started in 1978 following a congressional mandate to develop quantitative appraisals of the major ground-water systems of the United States. The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which in aggregate underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and accordingly transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies, both to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities, and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number, and where the volume of interpretive material warrants, separate topical chapters that consider the principal elements of the investigation may be published. The series of RASA interpretive reports begins with Professional Paper 1400 and thereafter will continue in numerical sequence as the interpretive products of subsequent studies become available.

Gordon P. Eaton
Director

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Multiply	By	To obtain
acre	4,047	square meter
acre-foot (acre-ft)	1,233	cubic meter
cubic foot per second (ft^3/s)	.02832	cubic meter per second
foot per mile (ft/mi)	.1894	meter per kilometer
foot (ft)	.3048	meter
foot squared per day (ft^2/d)	.09290	meter squared per day
gallon per minute (gal/min)	.06309	liter per second
gallon per minute per foot [(gal/min)/ft)]	.2070	liter per second per meter
inch (in.)	25.4	millimeter
megawatthour (MWh)	3,600,000,000	joule
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

The conversion of degrees Celsius (°C) to degrees Fahrenheit (°F) is based on the equation °F = (1.8)(°C) + 32.

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum 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."

Abbreviated water-quality units:

µg/L	Micrograms per liter
µS/cm	Microsiemens per centimeter at 25 degrees Celsius
mg/L	Milligrams per liter

The concentration of ions, in milligrams per liter, may be converted to meq (milliequivalents per liter) by multiplying by the reciprocals of the combining weights of the appropriate ions.

SUMMARY OF THE SNAKE RIVER PLAIN REGIONAL AQUIFER-SYSTEM ANALYSIS IN IDAHO AND EASTERN OREGON

By G. F. LINDHOLM

ABSTRACT

Regional aquifers underlying the 15,600-square-mile Snake River Plain in southern Idaho and eastern Oregon were studied as part of the U.S. Geological Survey's Regional Aquifer-System Analysis program.

The largest and most productive aquifers in the Snake River Plain are composed of Quaternary basalt of the Snake River Group, which underlies most of the 10,800-square-mile eastern plain. Aquifer tests and simulation indicate that transmissivity of the upper 200 feet of the basalt aquifer in the eastern plain commonly ranges from about 100,000 to 1,000,000 feet squared per day. However, transmissivity of the total aquifer thickness may be as much as 10 million feet squared per day. Specific yield of the upper 200 feet of the aquifer ranges from about 0.01 to 0.20.

Average horizontal hydraulic conductivity of the upper 200 feet of the basalt aquifer ranges from less than 100 to 9,000 feet per day. Values may be one to several orders of magnitude higher in parts of individual flows, such as flow tops. Vertical hydraulic conductivity is probably several orders of magnitude lower than horizontal hydraulic conductivity and is generally related to the number of joints. Pillow lava in ancestral Snake River channels has the highest hydraulic conductivity of all rock types.

Hydraulic conductivity of the basalt decreases with depth because of secondary filling of voids with calcite and silica. An estimated 80 to 120 million acre-feet of water is believed to be stored in the upper 200 feet of the basalt aquifer in the eastern plain.

The most productive aquifers in the 4,800-square-mile western plain are alluvial sand and gravel in the Boise River valley. Although aquifer tests indicate that transmissivity of alluvium in the Boise River valley ranges from 5,000 to 160,000 feet squared per day, simulation suggests that average transmissivity of the upper 500 feet is generally less than 20,000 feet squared per day.

Vertically averaged horizontal hydraulic conductivity of the upper 500 feet of alluvium ranges from about 4 to 40 feet per day; higher values can be expected in individual sand and gravel zones. Vertical hydraulic conductivity is considerably lower because of the presence of clay layers.

Hydraulic heads measured in piezometers, interpreted from diagrams showing ground-water flow and equipotential lines and estimated by computer simulation, demonstrate that water movement is three dimensional through the rock framework. Natural recharge takes place along the margins of the plain where head decreases with depth; discharge takes place near some reaches of the Snake River and the Boise River where head increases with depth.

Geothermal water in rhyolitic rocks in the western plain and western part of the eastern plain has higher hydraulic head than the overlying cold water. Geothermal water, therefore, moves upward and merges into the cold-water system. Basin water-budget analyses indicate that the volume of geothermal water is small relative to the volume of cold water. Carbon-14 age determinations, which indicate that residence time of geothermal water is 17,700 to 20,300 years, plus or minus 4,000 years, imply slow movement of water through the geothermal system.

Along much of its length, the Snake River gains large quantities of ground water. On the eastern plain, the river gained about 1.9 million acre-feet of water between Blackfoot and Neeley, Idaho, in 1980. Between Milner and King Hill, Idaho, the river gained 4.7 million acre-feet, mostly as spring flow from the north side. Upstream from Blackfoot and in the vicinity of Lake Walcott, the river loses flow to ground water during parts or all of the year. On the western plain, river gains from ground water are small relative to those on the eastern plain; most are from seepage.

Streams in tributary drainage basins supply calcium/bicarbonate type and calcium/magnesium/bicarbonate type water to the plain. Water type is a reflection of the chemical composition of rocks in the drainage basin. Concentrations of dissolved solids are smallest, about 50 milligrams per liter, in streams such as the Boise River that drain areas of granitic rocks; concentrations are greatest, about 400 milligrams per liter, in streams such as the Owyhee and Raft Rivers that drain areas of sedimentary rocks.

Water chemistry reflects the interaction of surface water and ground water. The chemical composition of ground water in the plain is essentially the same as that in streamflow and ground-water discharge from tributary drainage basins. Tributary drainage basins supplied about 85 percent of the ground-water recharge in the eastern plain during 1980 and a nearly equivalent percentage of the solute load in ground water; human activities and dissolution of minerals supplied the other solutes. Dissolved-solids concentrations in ground water were generally less than 400 milligrams per liter.

Water from the lower geothermal system is chemically different from water from the upper cold-water system. Geothermal water typically has greater concentrations of sodium, bicarbonate, sulfate, chloride, fluoride, silica, arsenic, boron, and

lithium and smaller concentrations of calcium, magnesium, and hydrogen. Differences are attributed to ion exchange as geothermal water moves through the rock framework.

Irrigation, mostly on the Snake River Plain, accounted for about 96 percent of consumptive water use in Idaho during 1980. The use of surface water for irrigation for more than 100 years has caused major changes in the hydrologic system on the plain. Construction of dams, reservoirs, and diversions effected planned changes in the surface-water system but resulted in largely unplanned changes in the ground-water system. During those years of irrigation, annual recharge in the main part of the eastern plain increased to about 6.7 million acre-feet in 1980, or by about 70 percent. Most of the increase was from percolation of surface water diverted for irrigation. From preirrigation to 1952, ground-water storage increased about 24 million acre-feet, and storage decreased from 1952 to 1964 and from 1976 to 1980 because of below-normal precipitation and increased withdrawals of ground water for irrigation. Annual ground-water discharge increased to about 7.1 million acre-feet in 1980, or by about 80 percent since the start of irrigation. About 10 percent of the 1980 total discharge was ground-water pumpage.

About 3.1 million acres, or almost one-third of the plain, was irrigated during 1980: 2.0 million acres with surface water, 1.0 million acres with ground water, and 0.1 million acres with combined surface and ground water. About 8.9 million acre-feet of Snake River water was diverted for irrigation during 1980, and 2.3 million acre-feet of ground water was pumped from 5,300 wells. Most irrigation wells on the eastern plain are open to basalt. About two-thirds of them yield more than 1,500 gallons per minute with a reported maximum of 7,240 gallons per minute; drawdown is less than 20 feet in two-thirds of the wells. Most irrigation wells on the western plain are open to sedimentary rocks. About one-third of them yield more than 1,500 gallons per minute with a reported maximum of 3,850 gallons per minute; drawdown is less than 20 feet in about one-fifth of the wells.

The major instream use of water on the Snake River Plain is hydroelectric power generation. Fifty-two million acre-feet of water generated 2.6 million megawatthours of electricity during 1980.

Digital computer ground-water flow models of the eastern and western plain reasonably simulated regional changes in water levels and ground-water discharges from 1880 (preirrigation) to 1980. Model results support the concept of three-dimensional flow and the hypotheses of no underflow between the eastern and western plain.

Simulation of the regional aquifer system in the eastern plain indicates that if 1980 hydrologic conditions, including pumpage, were to remain the same for another 30 years, moderate declines in ground-water levels and decreases in spring discharges would continue. Increased ground-water pumpage to irrigate an additional 1 million acres could cause ground-water levels to decline a few tens of feet in the central part of the plain and could cause corresponding decreases in ground-water discharge. A combination of actions such as increased ground-water pumpage and decreased use of surface water for irrigation (resulting in reduced recharge) would accentuate the changes.

INTRODUCTION

The Snake River Plain (fig. 1) is a major geomorphic and geologic feature in southern Idaho. The surface of the plain, though flat relative to the mountains that surround it, is characterized by a variety of volcanic landforms—shield volcanoes, lava flows, cones, and fissures. Irrigated agriculture on the plain provides the economic base for southern Idaho. The Snake River is the main source of water for irrigation; however, since the late 1940's, the use of ground water for irrigation has increased steadily.

Underlying the plain is a regional aquifer system that was included in the U.S. Geological Survey's Regional Aquifer-System Analysis (RASA) program (see Foreword). Phase I of the Snake River Plain RASA began in fiscal year 1980 and was completed in fiscal year 1984. Phase II began in fiscal year 1985 and was completed in fiscal year 1989.

OBJECTIVES OF THE SNAKE RIVER PLAIN RASA

Specific objectives of Phase I of the Snake River Plain RASA were outlined by Lindholm (1981). The main objective was to gain a better understanding of the regional ground-water system. Major efforts were directed to (1) better define the geohydrologic framework, (2) determine historical and present (1980) water budgets, (3) describe ground-water chemistry and rock-water reactions, (4) determine

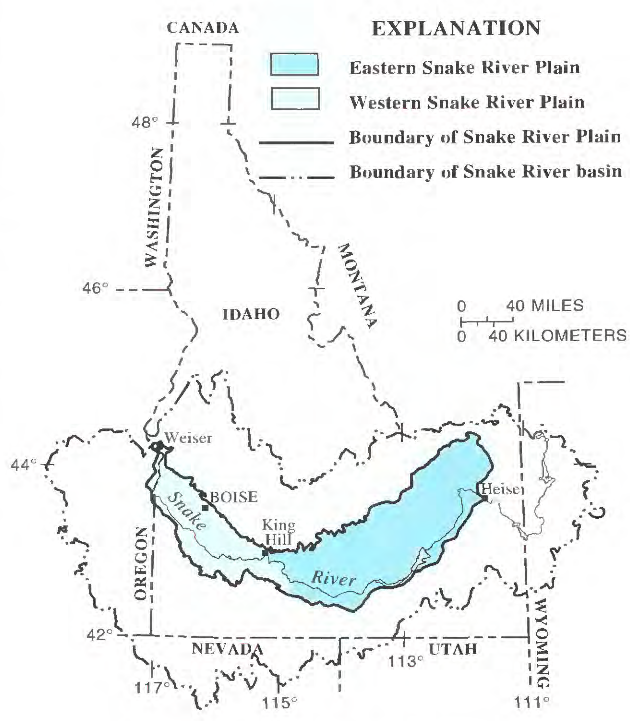


FIGURE 1.—Location of study area.

water use, and (5) develop digital models for analysis of ground-water flow systems in eastern and western parts of the plain.

To meet study objectives, existing geologic and hydrologic data were compiled and evaluated. Data needs were identified and additional data collected. Historical hydrologic data were compiled and analyzed to define hydrologic changes caused by more than 100 years of irrigation on the plain.

During Phase I, data deficiencies and parts of the regional system that presented major technical problems were identified. Those concerns were addressed during Phase II.

PURPOSE OF SUMMARY REPORT

The purpose of this report is to present an overall summary of the Snake River Plain regional aquifer system. Reports generated during Phase I of the Snake River Plain RASA, most of which address specific parts of the hydrologic system, are referenced frequently throughout this report. The following preliminary reports were generated early in Phase I and were published in various U.S. Geological Survey series:

Author	Short Title
Bigelow, B.B., and others (1987)	Water use for irrigation, 1980
Garabedian, S.P. (1986)	Application of parameter estimation technique to modeling the eastern plain
Kjelstrom, L.C. (1986)	Flow characteristics of the Snake River and water budget
Lindholm, G.F., and Goodell, S.A. (1986)	Irrigated acreage and other land uses, 1980
Lindholm, G.F., and others (1988)	Configuration of the water table, depth to water, water-level fluctuations, and water movement, 1980
Low, W.H. (1987)	Solutes in ground and surface water
Whitehead, R.L. (1986)	Geohydrologic frame work
Whitehead, R.L., and Lindholm, G.F. (1985)	Results of geohydrologic test drilling

Regional descriptions of the geology, hydrology, and geochemistry of the Snake River Plain aquifer system were completed during Phase I and are presented in Professional Paper 1408, which consists of seven chapters, as follows:

Chapter A (this report) is a summary of the aquifer system.

Chapter B (Whitehead, 1992) describes the geohydrologic framework, hydraulic properties of rocks composing the framework, and geologic controls on ground-water movement.

Chapter C (Kjelstrom, in press) describes streamflow gains and losses in the Snake River and ground-water budgets for the Snake River Plain.

Chapter D (Wood and Low, 1988) describes solute geochemistry of the cold-water and geothermal-water systems.

Chapter E (Goodell, 1988) describes water use.

Chapter F (Garabedian, in press) describes geohydrology and results of ground-water flow modeling of the eastern Snake River Plain.

Chapter G (Newton, 1991) describes geohydrology and results of ground-water flow modeling of the western Snake River Plain.

Many of the numerous geologic and hydrologic studies of the Snake River Plain or parts of the plain that preceded the RASA study are referenced in the above-listed reports.

PREVIOUS STUDIES

Numerous geologic and hydrologic studies of the Snake River Plain or parts of the plain preceded the RASA study. One of the first was a geologic reconnaissance by Hayden (1883). The first study to report in detail on ground water was that of Lindgren (1898). There followed reports on geology and water resources by Russell (1902, 1903a, 1903b); Stearns and others (1938) reported on the geology and ground-water resources of the eastern plain. More recently, Mundorff and others (1964) evaluated ground water for irrigation in the Snake River basin in Idaho and included a flow-net analysis of the Snake River Plain aquifer (eastern plain). The Snake River Plain aquifer was defined by Mundorff and others (1964, p. 142) as "the series of basalt flows and intercalated pyroclastic and sedimentary materials that underlie the Snake River Plain east of Bliss." As defined, the area south of the Snake River from Neeley to Salmon Falls Creek (pl. 1) was excluded; in this study, that area was included in the eastern plain.

Numerous geologic and hydrologic studies have been done by the U.S. Geological Survey at the Idaho National Engineering Laboratory (INEL) site on the eastern plain. A report by Robertson and others (1974) summarizes the geology, hydrology, and water chemistry at the site. Simulation studies of the regional aquifer system in the eastern plain include electric analog models by Skibitzke and da Costa (1962), Norvitch and others (1969), and Mantei (1974). The first digital ground-water flow model of the eastern plain was developed by deSonneville (1974) and modified by Newton (1978). Several subareas of the eastern plain and the Boise River valley in the western plain were modeled by the Idaho Department of Water Resources (IDWR) as part of local water-resource investigations.

Laird (1964) described the quality of surface water from drainage basins tributary to the plain. Several investigators have reported on water quality in the Snake River and on ground-water quality in different parts of the Snake River drainage basin. Only Mundorff and others (1964), Whitehead and Parliman (1979), and Yee and Souza (1987, p. 30–41) described ground-water quality in the entire plain. Norvitch and others (1969) and Dyer and Young (1971) described areal variations in ground-water quality in the eastern plain. More recently, Parliman (1982a, 1982b, 1983a, 1983b, 1986) evaluated ground-water quality and the suitability of water for various uses. A ground-water solute-transport model was developed by Robertson (1974, 1977) to predict the extent of waste plumes under the INEL site and later was evaluated by Lewis and Goldstein (1982). Robertson inferred that the chemical composition of ground water in the vicinity of INEL reflects the composition of rocks in drainage basins tributary to the plain more than the chemical composition of basalt underlying the site. Dion (1972) noted effects of land use on shallow ground-water quality in the Boise-Nampa area of the western plain. Young (1977, p. 25–29) described ground-water quality in the Mountain Home area and concluded that chemical similarities make it possible to identify probable recharge sources, some of which are mountainous areas that border the plain. A more complete listing and discussion of previous investigations is given in other chapters of this Professional Paper series.

WELL- AND SITE-NUMBERING SYSTEM

The well-numbering system (fig. 2) used by the U.S. Geological Survey in Idaho indicates the location of wells within the official rectangular subdivision of the public lands, with reference to the Boise base line and Meridian. The first two segments of the number designate the township (north or south) and range (east or west). The third segment gives the section number; three letters, which indicate the ¼ section (160-acre tract), ¼-¼ section (40-acre tract), and ¼-¼-¼ section (10-acre tract); and serial number of the well within the tract, respectively. Quarter sections are lettered A, B, C, and D in counterclockwise order from the northeast quarter of each section. Within quarter sections, 40-acre and 10-acre tracts are lettered in the same manner. For example, well 8S-19E-5DAB1 is in the NW¼NE¼SE¼ sec. 5, T. 8 S., R. 19 E., and was the first well inventoried in that tract. Surface-water sites are assigned a six-digit downstream order number prefaced by the two-digit part number "13," which indicates that the site is in the Snake River basin; for example, 13037500 (Snake River near Heise).

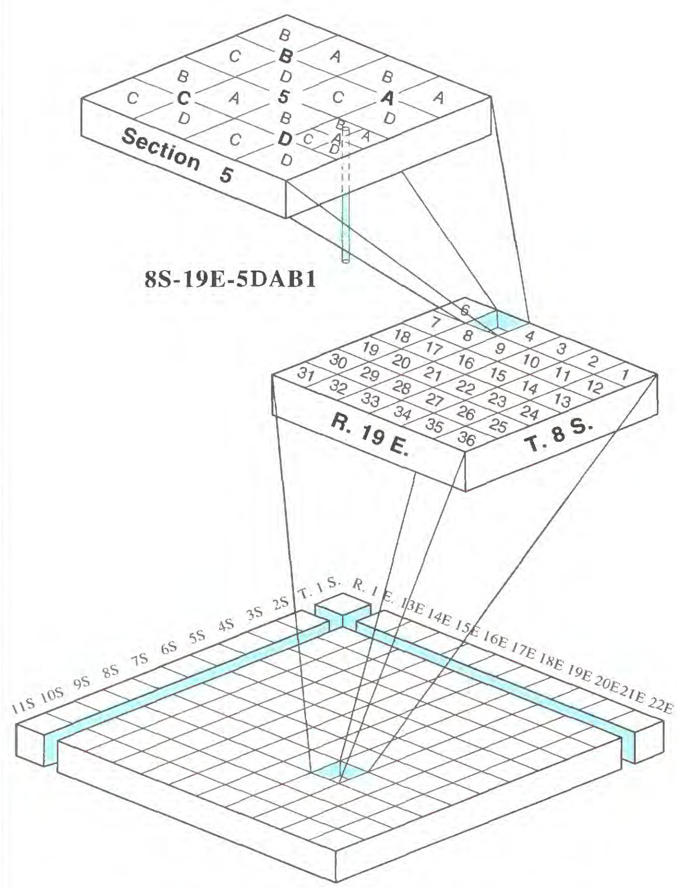


FIGURE 2.—Well- and site-numbering system.

DESCRIPTION OF STUDY AREA

The Snake River Plain contrasts sharply with its surroundings in physiography, climate, and geologic and hydrologic characteristics. Timbered mountains border much of the plain, especially on the north. Except where irrigated, sagebrush-covered rangeland with large areas of bare rock predominates. Irrigation is successful on the plain because of favorable climate, suitable topography, fertile soil, and an adequate water supply. The Snake River Plain is an agricultural area of national importance.

The Snake River Plain is an eastern extension of the Columbia Lava Plateau as defined by Fenneman (1931, p. 238–244). The plain is an area of about 15,600 mi^2 that extends for 350 mi in an arcuate path across southern Idaho into eastern Oregon (fig. 1). It ranges in width from 30 to 75 mi. The areal extent of the plain is defined on the basis of geology and topography, which are closely related. Although emphasis was on the Snake River Plain, the entire 69,200-mi^2 Snake River drainage basin upstream from Weiser, Idaho, was studied.

For purposes of study, the plain was divided into eastern and western parts on the basis of geologic and hydrologic differences. Most of the 10,800-mi^2 eastern plain is underlain by basalt, the 4,800-mi^2 western plain by sedimentary rocks. The dividing line between the eastern and western plain follows Salmon Falls Creek, the Snake River from the mouth of Salmon Falls Creek to King Hill, and a minor drainage divide to the northern boundary of the plain (pl. 1). Along the 40-mi reach of the Snake River from the mouth of Salmon Falls Creek to King Hill, the river follows the contact between basaltic and sedimentary rocks and gains large quantities of ground water, largely as spring flow.

PHYSIOGRAPHY

The Snake River Plain is a topographic depression. Although its surface is flat relative to the surrounding mountains, the plain rises gradually in altitude from about 2,100 ft above sea level at Weiser in the extreme western part of Idaho at the Oregon border to 6,000 ft in the extreme eastern part of Idaho near the Wyoming border (fig. 3). Mountains surrounding the plain are generally 5,000 to 12,000 ft above sea level. Highest average altitudes are in the Teton Range in Wyoming and the Lost River Range in Idaho. The transition from mountains to plain is abrupt in many places.

The surface of the plain is noted for its variety of volcanic landforms such as fissure flows, cinder cones, lava cones, pressure ridges, and shield volcanoes. Many of these features are aligned along volcanic rift zones that, in the eastern plain, are generally perpendicular to the long axis of the plain. Much of the eastern plain is mantled by loess of variable thickness. In several areas, sand dunes have accumulated.

The most prominent physiographic feature on the plain is the Snake River canyon. For about 40 mi, between Milner Dam and Buhl (pl. 1), the canyon is 350 to 3,500 ft wide, 50 to 550 ft deep, and walled on both sides by basalt. Downstream from Buhl, the canyon is generally wider and less incised, and canyon sides vary from almost vertical walls of basalt to highly dissected sedimentary rocks.

CLIMATE

The climate of the Snake River Plain is largely semiarid. Mean annual precipitation on much of the plain is 8 to 10 in. (fig. 4). On the extreme northeastern end, where land surface altitude exceeds 5,000 ft, precipitation exceeds 20 in/yr. Almost 40 percent of the annual precipitation on the western plain falls during the growing season, from April to September. July and August are typically the driest months, December and January the wettest (fig. 5). On the eastern plain, precipitation is more evenly distributed throughout the year than on the western plain; July and August are usually the driest months, May and June the wettest. In parts of the eastern plain, 50 to 60 percent of total annual precipitation falls during the growing season.

From November through March, snow may accumulate on the plain to depths ranging from several inches to several feet. Most snowmelt and runoff is from April through July. On parts of the eastern plain and on the western plain, snow accumulation is generally only a few inches. Snow depth is greatest at high altitudes in the northeastern part of the plain. Most snow melts and evaporates or infiltrates into the soil within a few days or weeks.

Mean annual air temperature is highest on the western plain. From 1951 to 1980, mean annual air temperature was 51.1°F (10.6°C) at Boise, where temperatures ranged from –23 to 111°F (–30.6 to 43.9°C). Temperatures are lower on the eastern plain because of higher altitudes. From 1951 to 1980, mean annual air temperature at Idaho Falls was 45.3°F (7.4°C) and temperatures ranged from –33 to 100°F (–36.1 to 37.8°C).

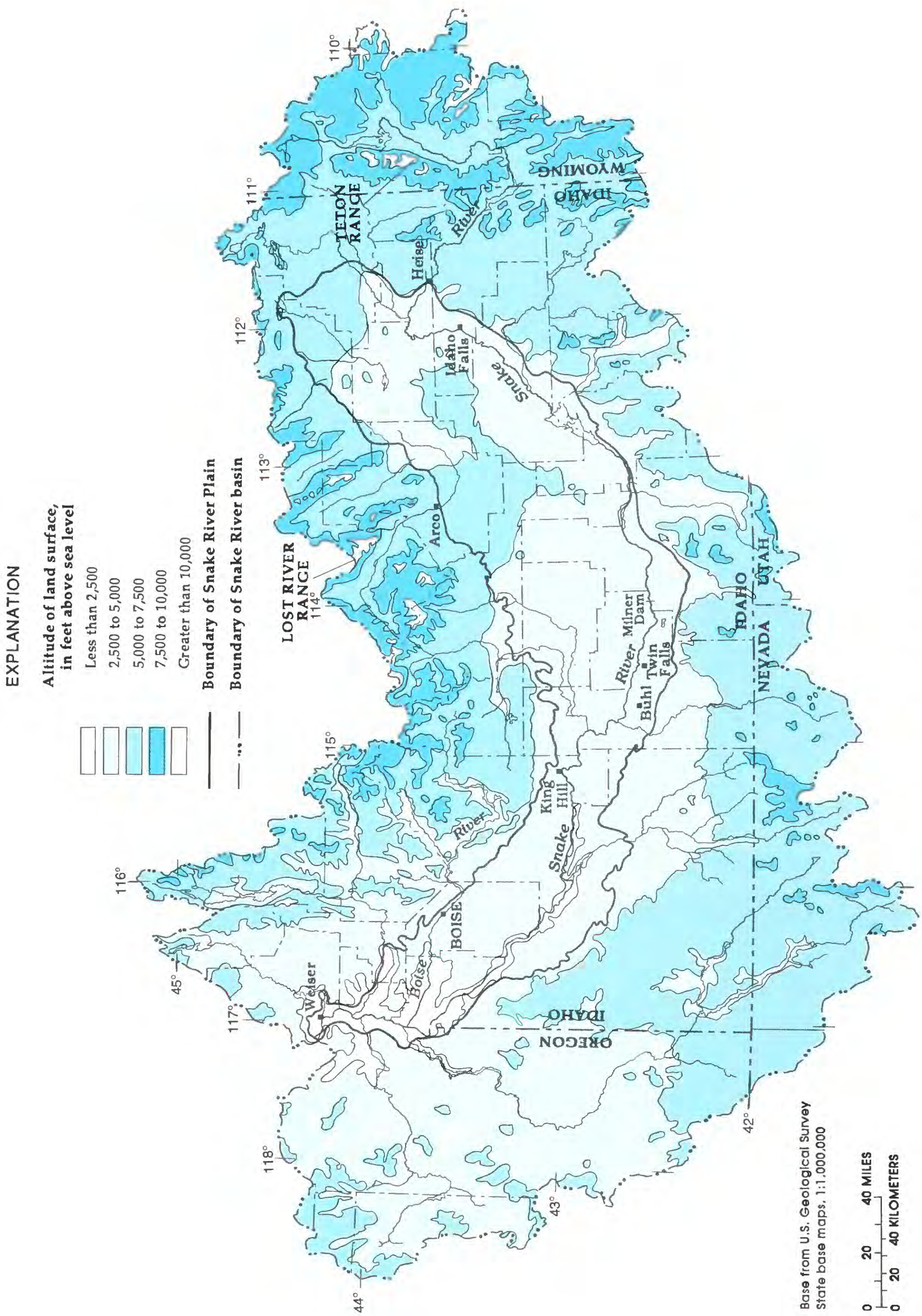


FIGURE 3.—Altitude of land surface.

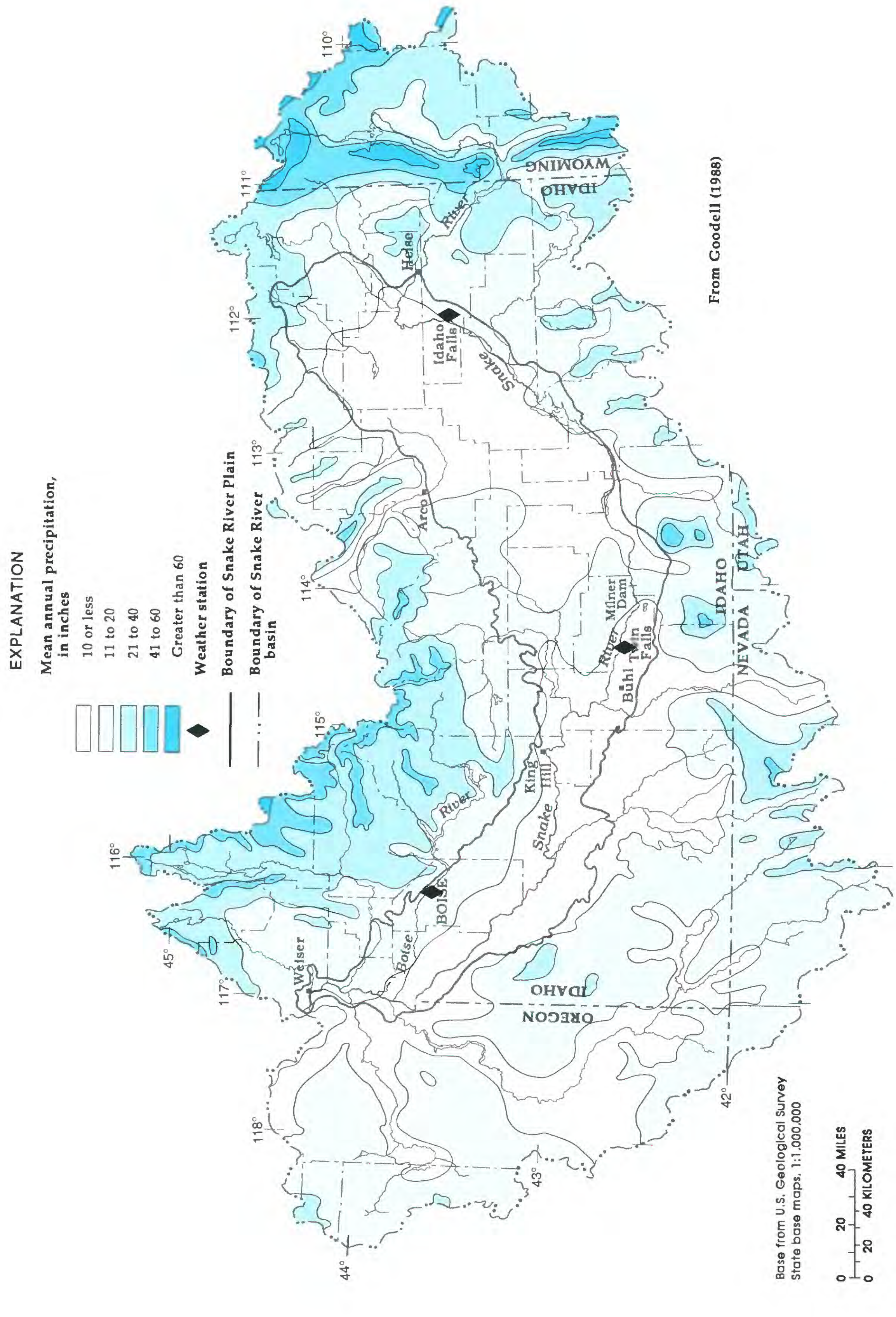


FIGURE 4.—Mean annual precipitation, 1931–52.

Mean monthly temperature varies as shown in figure 5; January is typically the coldest month and July the warmest. Average length of the growing season ranges from about 120 to 160 days; the last freeze is typically in May and the first freeze in September. Exceptions can be expected in the extreme northwestern and northeastern parts of the plain. Mean temperatures are lower in mountainous areas surrounding the plain.

HYDROLOGIC FEATURES

The headwater of the Snake River is a spring in the northwestern corner of Wyoming, near the southern boundary of Yellowstone National Park (pl. 1). The river drains an area of about 109,000 mi^2 upstream from its confluence with the Columbia River in Washington. Included in the 69,200-mi^2 Snake River drainage upstream from Weiser, Idaho, is the Snake River Plain. The Snake River flows onto the plain at Heise and parallels the plain's southern boundary across most of Idaho. In the 502-mi reach from Heise to Weiser, the river descends 2,930 ft, more than half of which is in the 90-mi reach from Milner Dam to King Hill (fig. 6 and pl. 1). About 370 ft of the drop is at Twin Falls and Shoshone Falls, about 4 mi and 6 mi northeast of the city of Twin Falls.

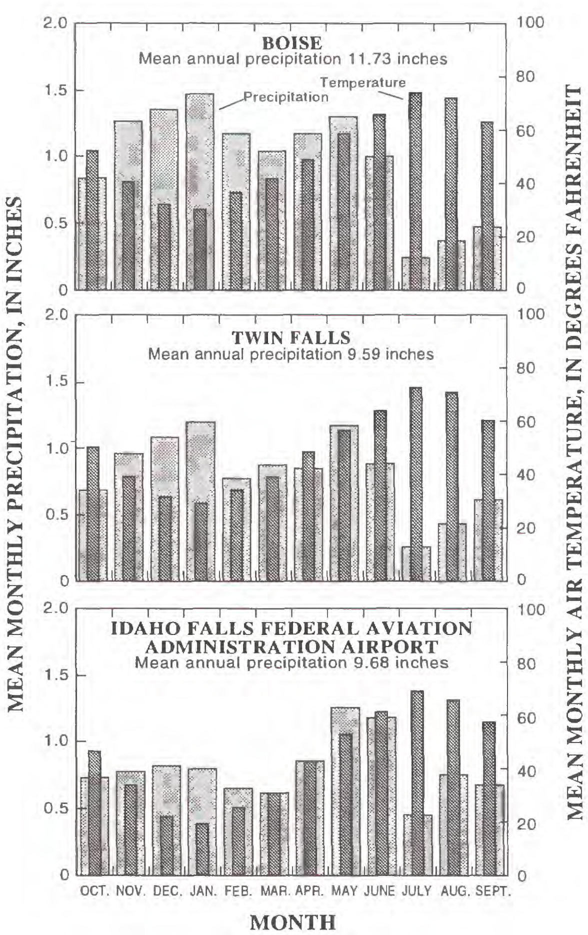


FIGURE 5.—Mean monthly precipitation and air temperature, 1951–80. Locations shown in figure 4.

Between Milner Dam and King Hill, numerous springs discharge to the Snake River from basalt that forms the north wall of the canyon. Included in that reach are 11 of the 65 first-magnitude springs in the United States (those springs with an average discharge of more than 100 ft^3/s; Meinzer, 1927, p. 42–51). The greatest concentration of springs, referred to as Thousand Springs, is near Hagerman. A second major group of springs discharges to the Snake River and its tributaries between Blackfoot and Neeley.

Six instream storage facilities on the Snake River upstream from Weiser, Idaho (pl. 1), have a combined total storage capacity of 4.3 million acre-ft. The largest, American Falls Reservoir, has a total storage capacity of 1.7 million acre-ft. Seventy-six reservoirs, each of which can store 10,000 or more acre-ft of water, are located on tributaries upstream from Weiser. Together, these reservoirs have 5.2 million acre-ft of storage capacity. The largest reservoir, Lake Owyhee on the Owyhee River, has a storage capacity of 1.1 million acre-ft. Twelve of the 75 other reservoirs can store a total of 3.3 million acre-ft of water. Forty of the remaining reservoirs have a storage capacity of less than 10,000 acre-ft.

Henrys Fork is the largest tributary of the Snake River in the eastern plain; Payette River is the largest tributary in the western plain (pl. 1). Streams in tributary drainage basins between Henrys Fork on the east and Big Wood River on the west do not discharge directly to the Snake River. Instead, after flowing onto the plain, their total flow evaporates or percolates to the ground-water system.

CULTURAL FEATURES AND ECONOMY

Prior to human settlement, the Snake River Plain was largely a sagebrush desert. Early emigrants followed the Oregon Trail across southern Idaho on their way to the Pacific Northwest and California. After the discovery of gold in the Boise River basin in 1862, permanent settlements were established.

Today, as in the past, large settlements are near the Snake and Boise Rivers. The Boise River flows through Boise, Idaho's largest city (pl. 1), which had a population of 102,451 in 1980. All major cities on the eastern plain—Idaho Falls, Pocatello, and Twin Falls—are near the Snake River and, in 1980, had populations of fewer than 50,000.

The economy of the Snake River Plain is largely dependent on irrigated agriculture, livestock production, food processing, and related activities. Idaho is most noted, perhaps, for leading the Nation in the production of potatoes, most of which are grown on the plain. Total cash receipts from farm marketing during 1980 exceeded $2 billion (Idaho Crop and Livestock Reporting Service, 1982, p. 14). A large part of the total was generated from agriculture on the Snake River Plain, which encompasses about 50 percent of the agricultural land in Idaho (Goodell, 1988, p. 8). Eighty-five percent of the State's irrigated land and 25 percent of the rangeland is on the Snake River Plain. Most areas irrigated with surface water are crisscrossed by networks of irrigation canals that distribute water. Aquaculture, primarily commercial trout production, uses large quantities of water discharged as spring flow. Ninety percent of the Nation's commercially produced trout are grown in Idaho (Klontz and King, 1975, p. 53).

The large quantity and rapid rate of Snake River flow makes hydroelectric power generation an important economic asset. About half of Idaho's hydroelectric power is generated on the Snake River and its tributaries upstream from Weiser (Goodell, 1988, p. 42).

The INEL near Idaho Falls, Idaho (pl. 1), is a major nonagricultural development on the plain that contributes millions of dollars to the State's economy. The 894-mi^2 site was established in 1949 as the National Reactor Testing Station. Of the 52 nuclear reactors constructed on the site, 13 are still operable and used primarily to test peaceful applications of atomic power. Total INEL costs during fiscal year 1978 were about $308 million; $167 million was for payroll (U.S. Department of Energy, written commun., 1979).

GEOLOGY

The surface geology of the Snake River Plain has been studied extensively and large-scale crustal features have been defined by researchers using a variety of geophysical techniques. However, the lithology and stratigraphy of the subsurface are, as yet, less adequately defined. Whitehead (1992)

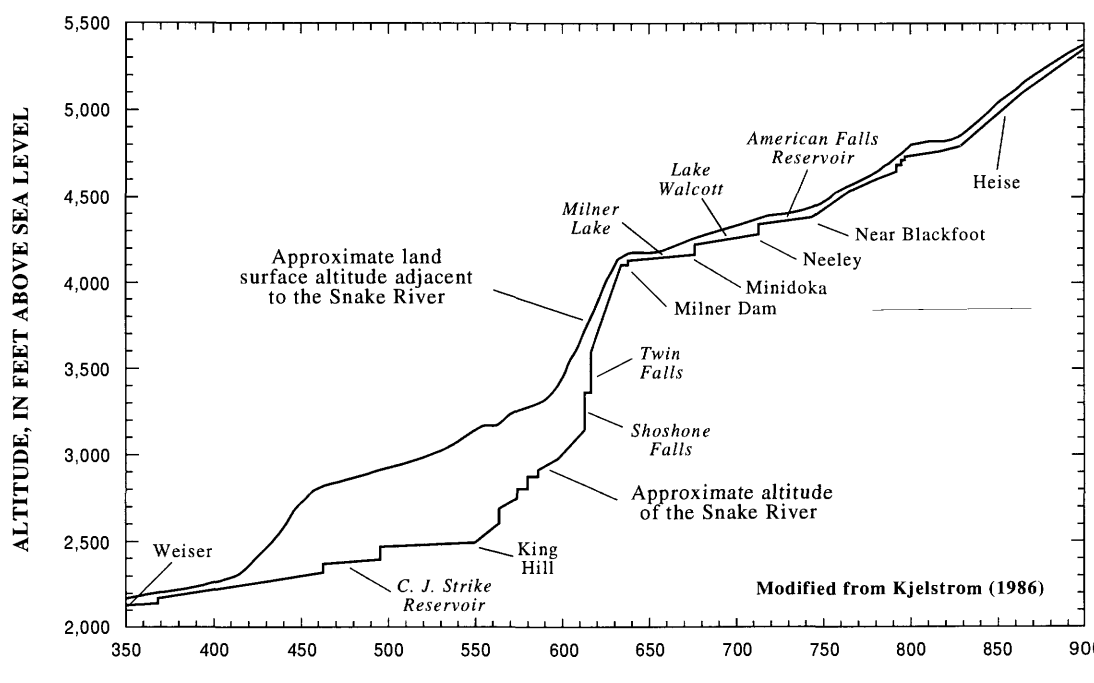


FIGURE 6.—Profile of Snake River.

described the regional subsurface geology of the Snake River drainage basin, with emphasis on the Snake River Plain, in Chapter B of this Professional Paper series, which is summarized in this section.

Although thousands of water wells have been drilled on the plain, only a few widely scattered drill holes entirely penetrate the major geologic units. Some effort has been made to define regional geologic controls on the occurrence and movement of ground water, but little has been done to define geologic controls on a local scale.

GEOLOGIC UNITS

A generalized diagram of the stratigraphic sequence of rock units (Whitehead, 1986) is shown in figure 7. The following is a brief discussion of rock units that comprise major aquifers in the Snake River drainage basin.

Pre-Tertiary sedimentary rocks in the eastern part of the basin (fig. 8) are generally a complex of shale, argillite, sandstone, and limestone. Because little is known about hydraulic properties of this complex, it is not discussed in this report. Cretaceous granitic rocks that comprise the Idaho batholith form the northern border of the western plain. Small outcrops of granite also are present south of the plain. Tertiary volcanic rocks east of the batholith range from rhyodacite to basalt.

The southwestern part of the Snake River drainage basin is a volcanic upland called the Owyhee Plateau, which is composed of Tertiary basalt and Quaternary-Tertiary silicic volcanic rocks. Similar rocks of equivalent age underlie basaltic and sedimentary rocks in much of the Snake River Plain. The oldest extrusive rocks that transmit moderate quantities of water are the Idavada Volcanics. Along the southwestern margin of the eastern plain and the margins of the western plain, the Idavada Volcanics constitutes an important geothermal aquifer system.

The Idavada Volcanics are largely welded ash flows but include some bedded vitric tuffs and lava flows (Malde and Powers, 1962, p. 1200). Wood and Low (1988, p. 7, table 1) listed the average chemical composition of 64 samples of rhyolite from the Idavada Volcanics. Samples averaged about 70 percent silica, 5 percent potassium, and less than 2 percent each of iron, magnesium, and calcium.

Tertiary basalt in the western part of the Snake River drainage basin is equivalent in age and chemical composition to the Columbia River Basalt Group that underlies the Columbia Lava Plateau in Washington, Oregon, and western Idaho. Columbia River Basalt was extruded from north- to northwest-trending fissures in the eastern part of the plateau (Camp and others, 1982, p. 55–75). Flows were voluminous and advanced as sheet floods over large areas. Thickness of individual flows ranges from a few feet to more than 300 ft and averages 100 to 130 ft (Swanson and Wright, 1978, p. 49); maximum total thickness may approach 15,000 ft (Reidel and others, 1982). Basalt of the Columbia River Basalt Group comprises major aquifers in Washington and Oregon. Only a few test holes on the western Snake River Plain penetrate the Columbia River Basalt Group (fig. 9); therefore, hydraulic properties of this rock unit within the study area are not well known.

Other, less extensive Tertiary basalt (Banbury Basalt) is interbedded with Quaternary-Tertiary sedimentary rocks of the Idaho Group in the western part of the Snake River drainage basin. Eastern extensions of Banbury Basalt crop out in the north wall of the Snake River canyon between Twin Falls and King Hill (Malde and Powers, 1972; Covington, 1976) and were identified in the subsurface east of the canyon (Whitehead and Lindholm, 1985, p. 17). Banbury Basalt typically is decomposed olivine basalt with plagioclase phenocrysts that weather to greenish-brown, sand-sized crystals (Wood and Low, 1988, p. 5). Wood and Low (1988, p. 7, table 1) listed the average chemical composition of 15 samples of Banbury Basalt. Samples averaged about 45 percent silica; 10 percent each of iron, magnesium, and calcium; and less than 1 percent potassium. A sample from a test hole in Gooding County (pl. 1) had vesicles filled with clay minerals (nontronite and montmorillonite) and calcite (Wood and Low, 1988, p. 5).

Quaternary-Tertiary sedimentary rocks of the Idaho Group are areally extensive in the western plain. Their composite thickness ranges from zero to as much as 5,000 ft near the Idaho-Oregon border. The Idaho Group is predominantly lacustrine clay and silt, though sand and gravel are common in the Glenns Ferry Formation, which is a complex of late Tertiary lacustrine, fluviatile, and flood-plain facies (Malde and Powers, 1962, p. 1206).

Quaternary-Tertiary basalt, mainly Quaternary basalt of the Snake River Group, is the predominant rock type in the eastern Snake River Plain. Quaternary basalt was extruded from a series of vents, most of which are aligned along northwest-trending volcanic rift zones (Kuntz and Dalrymple, 1979, p. 5). Intercalated with the basalt in the vicinity of the Snake River are fine-grained Tertiary sedimentary rocks of the Salt Lake and Starlight

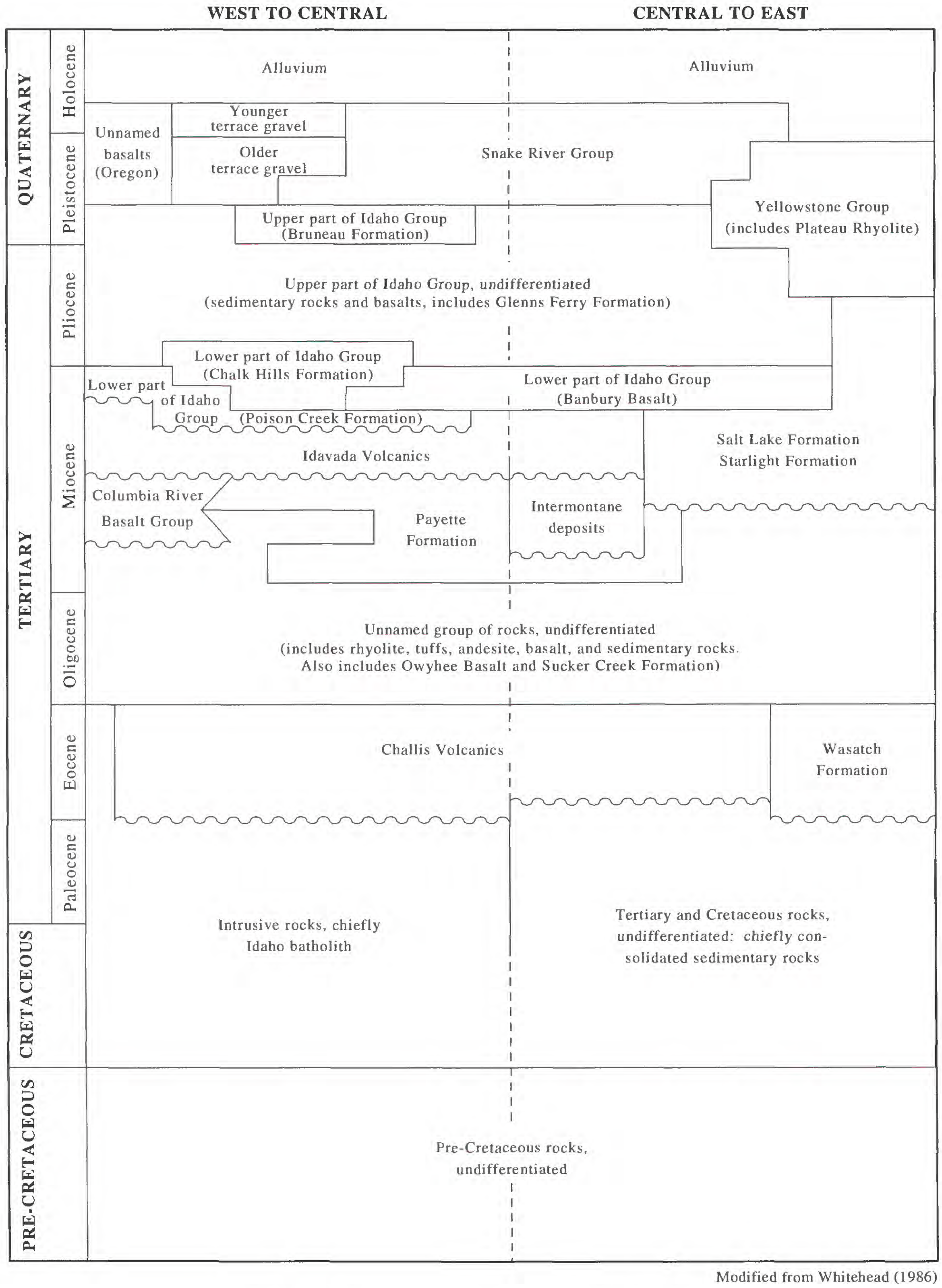


FIGURE 7.—Generalized stratigraphy of Snake River basin.

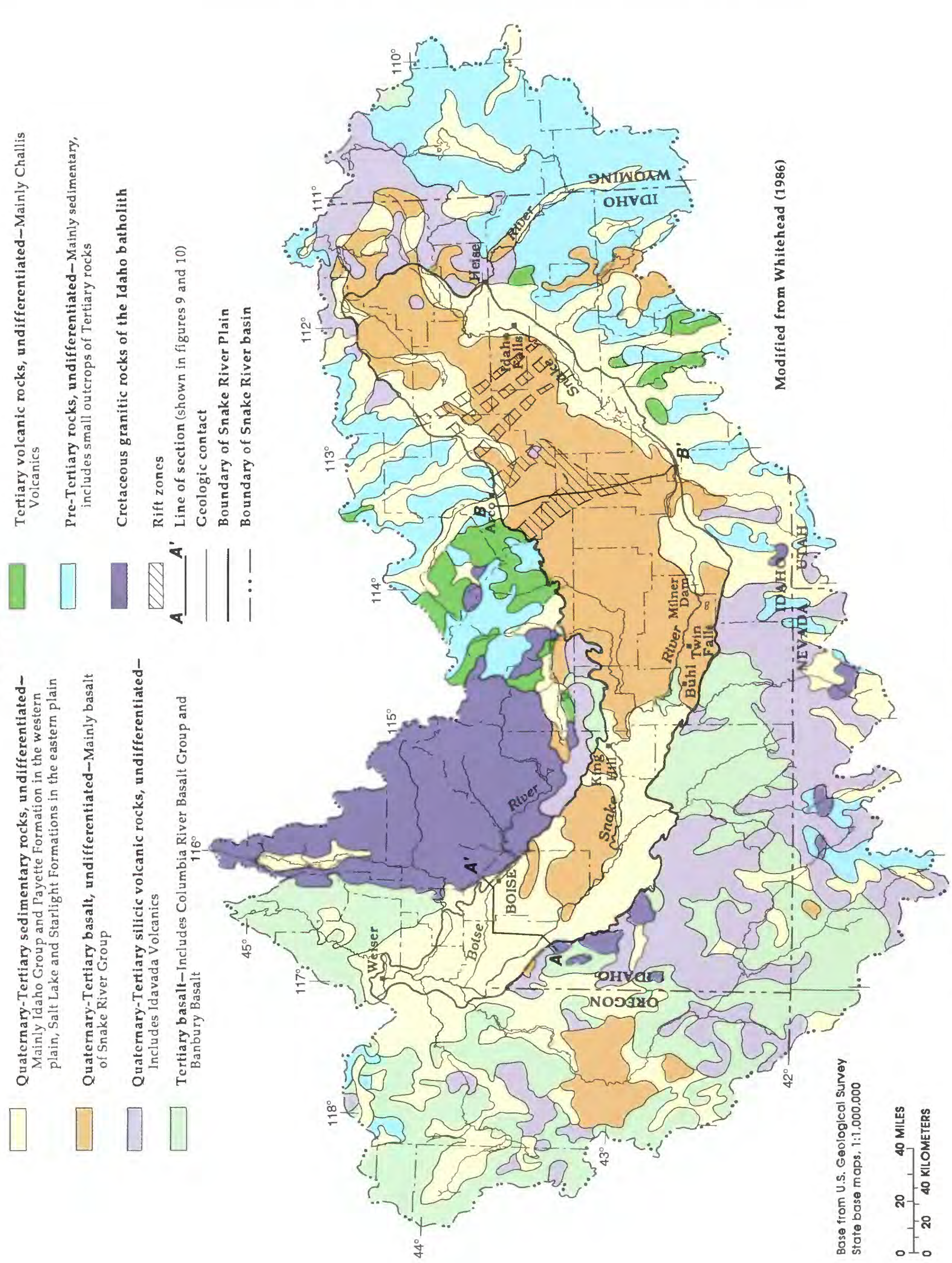


FIGURE 8.—Generalized geology of Snake River drainage basin upstream from Weiser, Idaho.

Formations (figs. 7 and 10) and, along the northwestern boundary of the plain, alluvium from adjacent mountains. Elsewhere on the plain, sediments were deposited by fluvial, lacustrine, and eolian processes. Little information is available on the distribution and mineralogic composition of sedimentary interbeds.

The total thickness of the Quaternary basalt sequence is known from only a few widely scattered drill holes. Therefore, electrical resistivity soundings were used to help estimate areal variations in thickness of Quaternary basalt and to define the base of the regional aquifer system. An electrical resistivity profile and a map of Quaternary basalt thickness (Whitehead, 1986) are shown in figure 11. Basalt is thickest near the center of the eastern plain and thins toward the margins, where it is intercalated with sedimentary rocks.

Layering is prominent in the thick sequence of lava flows that were erupted from numerous centers. The result is a complex overlapping and interlocking of flows (Nace and others, 1975, p. 15). Thickness of individual flows in the Snake River Group generally ranges from 10 to 50 ft and averages about 20

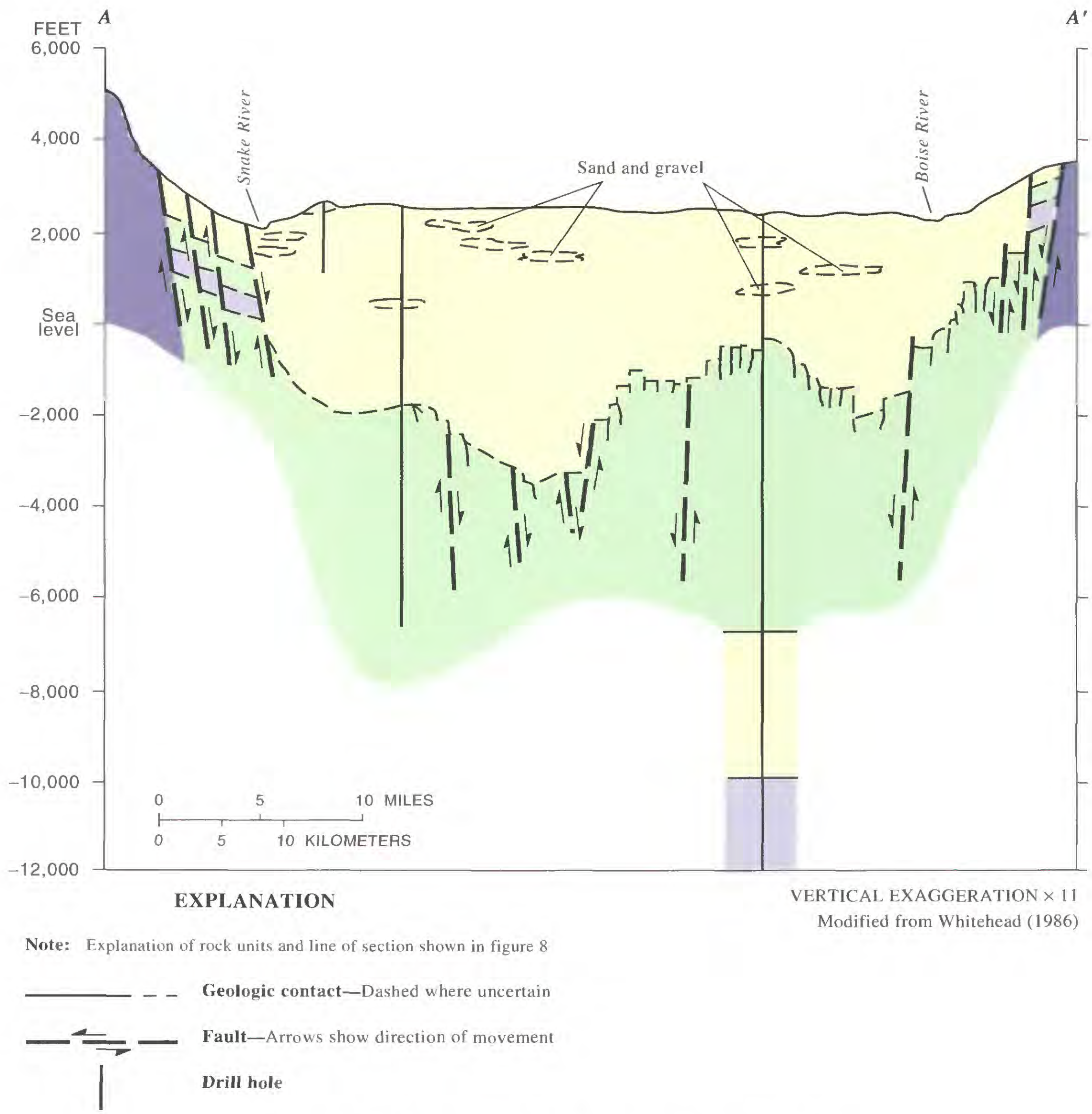


FIGURE 9.—Geologic section *A–A'*, western Snake River Plain.

to 25 ft (Mundorff and others, 1964, p. 143). Areal extent of flows is commonly 50 to 100 mi^2 (Nace and others, 1975, p. B15); individual flows are as much as 30 mi in length. A typical flow consists of (1) a basal layer of oxidized, fine-grained scoriaceous basalt (less than 3 ft thick), (2) a massive central layer of coarser-grained basalt of variable thickness, commonly from several feet to as much as 60 ft thick, and (3) a top layer of fine-grained, vertically and horizontally jointed, vesicular, clinkery basalt (less than 6 ft thick) (Kuntz and others, 1980, p. 11).

Basalt of the Snake River Group typically is fractured, and tension joints formed by cooling and contraction are characteristic. Joints in the massive central parts of flows are typically almost vertical; these form polygonal (commonly hexagonal) columns of basalt. Less regular fractures characterize leading edges of flows and collapse features. Joints, open fissures, and minor displacement faults are concen-

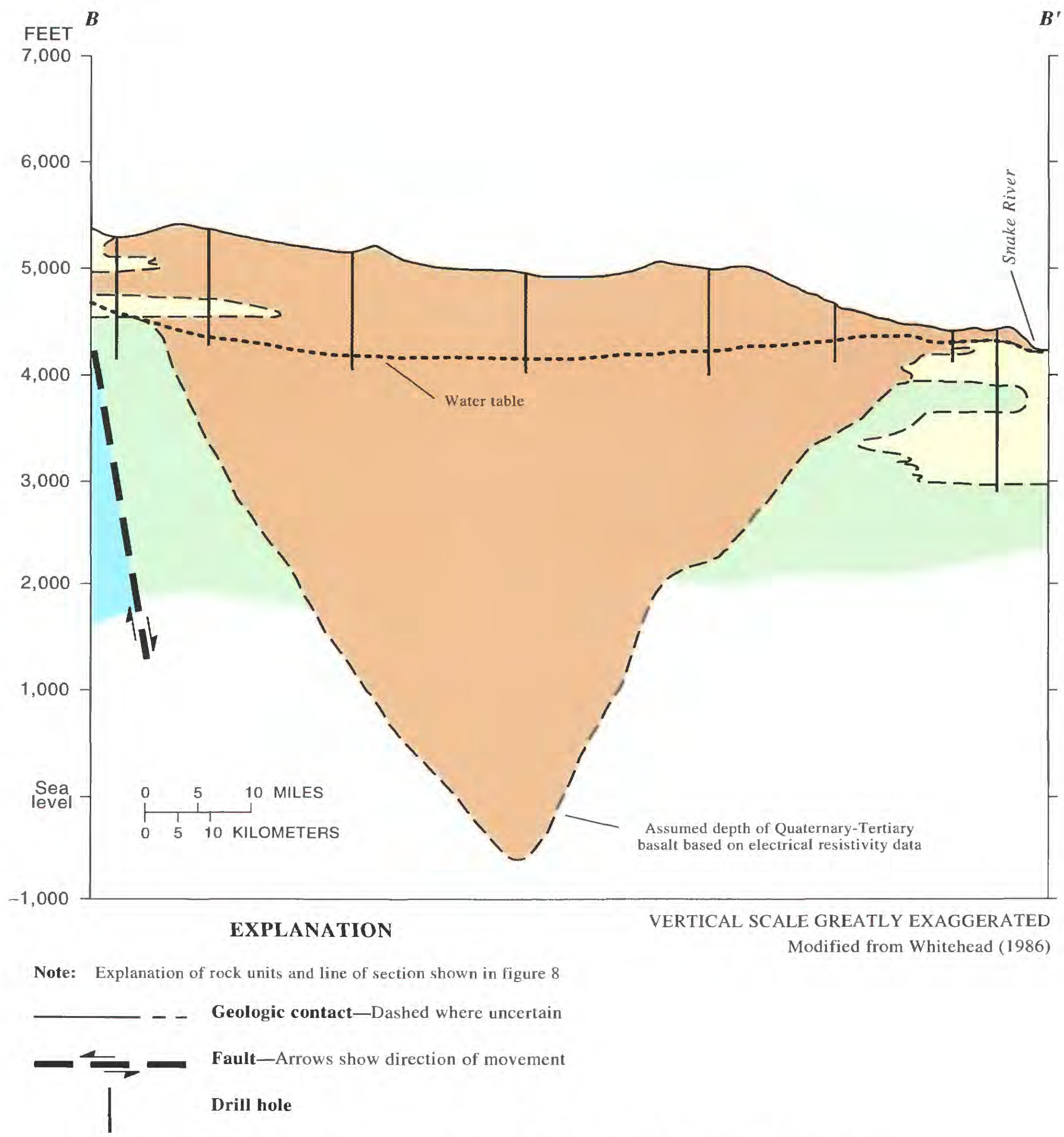


FIGURE 10.—Geologic section *B–B′*, eastern Snake River Plain.

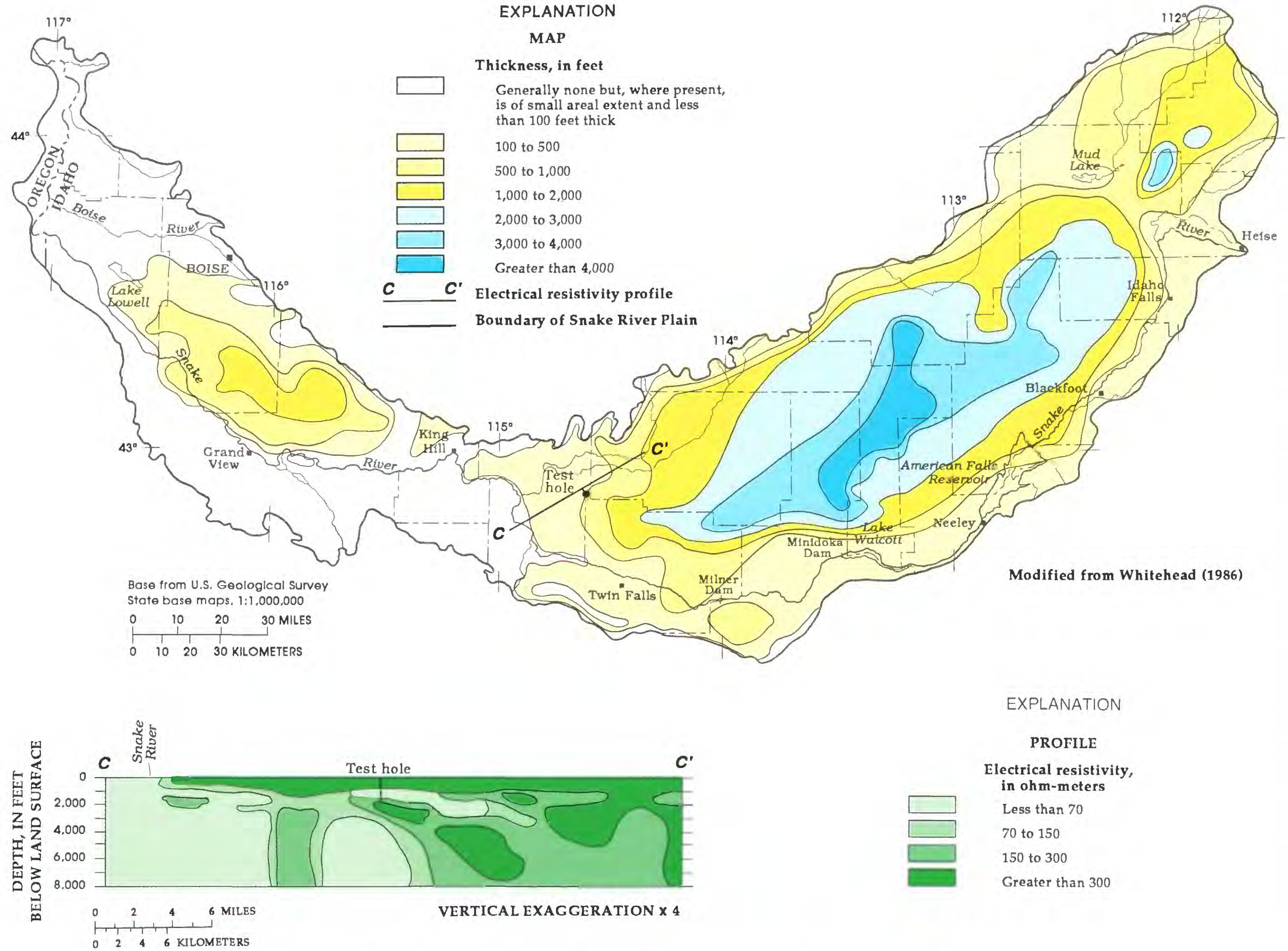


FIGURE 11.—Thickness of Quaternary-Tertiary basalt and electrical resistivity profile C–C'.

trated in rift zones. Depths of fractures visible at the surface are unknown, but the presence of cinder cones, lava cones, fissure flows, and other volcanic landforms along rift zones indicates that the fractures may be healed at depth by emplacement of magma subsequent to fracturing. Open fissures are common on pressure ridges formed by more recent lava flows.

Voids in basalt differ greatly in shape, size, and degree of interconnection. Large-scale features include lava tubes "from pencil size to tunnels 15 ft or more in diameter and a few yards to some miles in length" (Nace and others, 1975, p. B17). Vesicles (voids formed during rock solidification by the escape of entrapped gas) may be minute to about 1 in. in diameter and, if elongate, several inches to 1 ft in length. The volume of voids attributed to vesicles may exceed 25 percent of total rock volume; 10 to 20 percent is common in the upper parts of flows. Laboratory tests on cores of basalt of the Snake River Group at the INEL site indicate that total porosity ranges from about 6 to 37 percent, and effective porosity, the percentage of rock volume that is interconnected voids, ranges from 4 to 22 percent (Johnson, 1965, p. 59–61). Effective porosity is greatly enhanced by fracturing.

Zones of blocky, rubbly basalt near tops of flows and pillow lava typically have the highest porosity and permeability. Pillow lava was deposited in water that ponded behind basalt dams in ancestral valleys of the Snake River. Pillow lava in the north wall of the Snake River canyon between the mouth of Salmon Falls Creek and King Hill (pl. 1) was first described by Russell (1902, p. 113–117). The north canyon wall between Milner and King Hill was mapped as part of the RASA study by Covington and Weaver (1990a–d, 1991) to determine geologic controls on springs. They determined that the largest springs in the Milner-to-King Hill reach issue from pillow lava.

As part of the RASA study, a 1,123-ft-deep test hole was drilled about 21 mi northwest of Twin Falls and 12 mi northeast of Thousand Springs and the Snake River (pl. 1) to help verify geologic interpretations made from geophysical data. Test drilling results and increase in hydraulic head with depth were summarized by Whitehead and Lindholm (1985) and are shown diagrammatically in figure 12. On the basis of test hole core analyses and reported information, Wood and Low (1988, p. 7) concluded that "the mineral and chemical composition of basalt in the Snake River Group is uniform, even though the color, rock density, and other properties of the rock vary significantly." Basalt of the Snake River Group is typically 40 to 60 percent calcic plagioclase (usually labradorite), 20 to 50 percent pyroxene, and 5 to 10 percent olivine. Wood and Low (1988, p. 7, table 1) listed the average chemical composition of 152 basalt samples from the Snake River Group in southern Idaho. The basalt is chemically similar to Banbury Basalt.

The youngest rock unit of regional hydrologic significance on the western and eastern plain consists of Quaternary clay, silt, sand, and gravel in the vicinity of modern stream courses. Alluvium is thickest (several hundred feet) and the percentage of sand and gravel largest in the Boise River valley. Gravel-capped terraces in the Boise River valley are as much as 150 ft above the present flood plain.

STRUCTURE

The western Snake River Plain is bounded by northwest-trending, high-angle normal faults (fig. 9) that were first described by Russell (1902, p. 47, 48). Malde (1959, p. 272) speculated that, given the gravity, seismic, and geologic data, aggregate vertical displacement along the faults is as much as 9,000 ft. Tertiary volcanic rocks along the southwestern margin of the western plain are extensively faulted. Wood and Anderson (1981, p. 14) described deep-seated faulting in the central part of the western plain and along the margins.

The structure of the eastern Snake River Plain is less well defined. Geophysical data indicate that southwest-trending faults along the northwestern margin may have an aggregate throw of as much as 13,000 ft (Sparlin and others, 1982, p. 2619–2633). No major faults along the southeastern margin of the eastern plain have been defined. Rift zones on the plain trend northwestward and are aligned with normal faults in the Basin and Range physiographic province, which bounds the eastern plain. Evidence that basin-and-range structures might extend under the plain generally is masked by the cover of Quaternary basalt and unconsolidated sedimentary rocks.

Regional geologic structure related to Quaternary volcanism is only generally defined, and complex local structure related to lava extrusion, cooling, and subsequent tectonic activities has been described in only a few places. Structures along volcanic rift zones on the eastern plain were described by Kuntz and Dalrymple (1979, p. 25) and include open fissures, faults, and grabens. Although several rift zones have been mapped on the basis of surface expression, it is probable that additional rift zones or offsets of rift zones with no surface expression may be present in the subsurface.

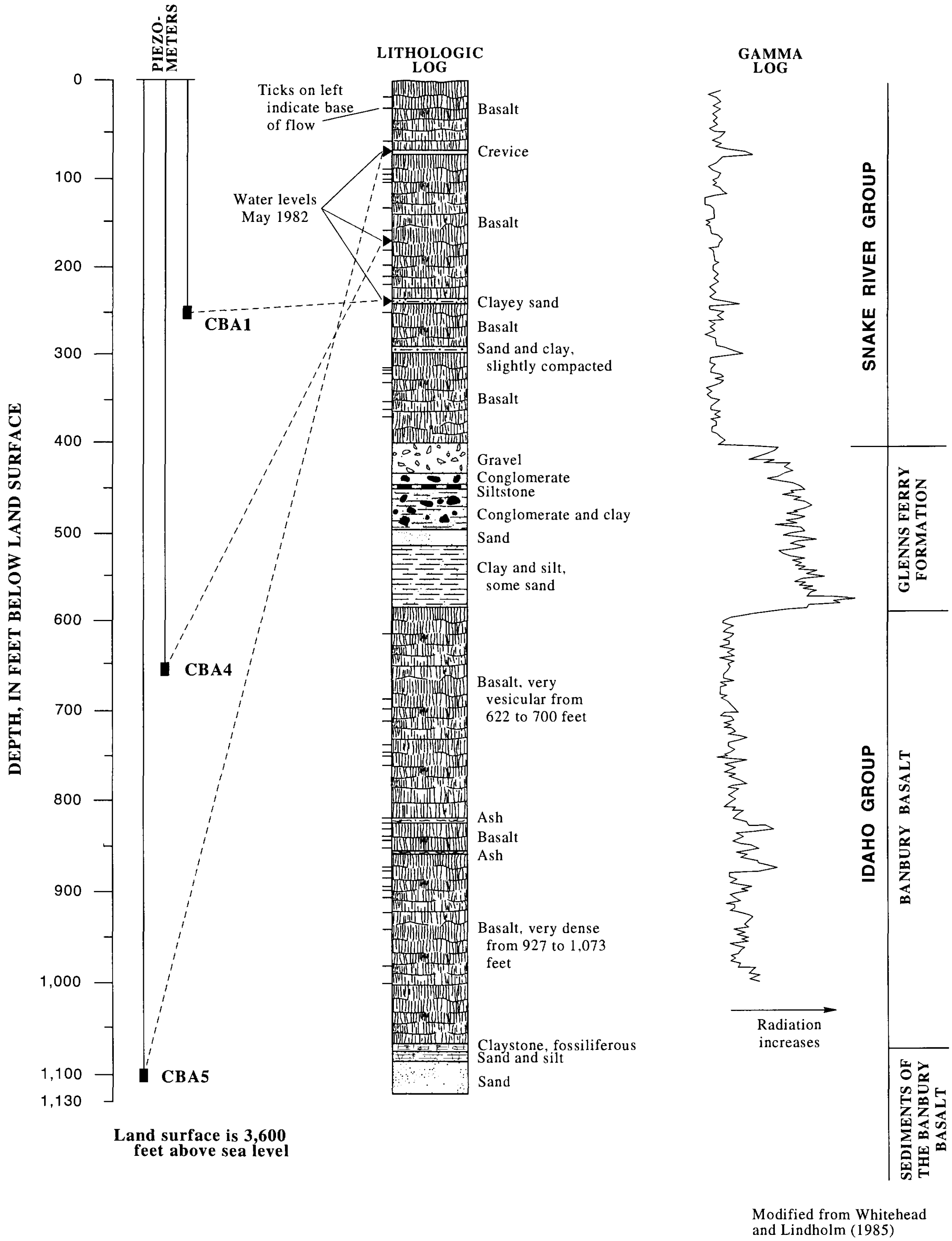


FIGURE 12.—Lithologic and gamma ray logs of test hole 7S-15E-12CBA1, 4, and 5, and increases in hydraulic head with depth, May 1982.

GEOHYDROLOGY

Rocks underlying the Snake River Plain have differing hydraulic properties that control the occurrence, storage, and movement of water. The degree of weathering, amount of primary and secondary porosity, permeability, and degree of fracturing affect infiltration of water through the unsaturated zone and movement in the saturated zone.

The geohydrology of the Snake River Plain is described in Chapters B, F, and G of this Professional Paper series (Garabedian, in press; Newton, 1991; Whitehead, 1992) and is summarized here. The RASA study emphasized the determination of hydraulic properties of rocks underlying the Snake River Plain, which, together with climate and development of water resources, control recharge to, discharge from, and movement within the regional aquifer system.

HYDRAULIC PROPERTIES

Transmissivity, storage coefficient, and specific yield of rocks underlying the Snake River Plain vary greatly. Variability is greatest in fractured volcanic rocks. Because some hydraulic properties are difficult to quantify, they were estimated by indirect methods and should be considered only as reasonable approximations of what actual values might be. Transmissivity was estimated from aquifer-test data, specific-capacity data, flow-net analyses, and ground-water flow models. Storage coefficient and specific capacity were estimated from aquifer tests.

Aquifer tests have been done at 44 sites on the Snake River Plain. Most tests were of partially penetrating wells and results vary greatly. Test results are grouped for eastern and western parts of the plain.

Results of aquifer tests on the eastern Snake River Plain (Mundorff and others, 1964, p. 147, 153–155; Haskett and Hampton, 1979, p. 26, 29; and unpubl. data, on file in the Boise office of the U.S. Geological Survey) are summarized in table 1; test sites are shown on plate 1. Many of the tests were done during the 1950's by the U.S. Geological Survey for the U.S. Bureau of Reclamation.

Estimates of transmissivity of fractured volcanic rocks depend on the number and permeability of interflow zones and the number and size of fractures penetrated. Many of the wells tested on the eastern plain penetrate less than 100 ft and most penetrate less than 200 ft of the several hundred- to several thousand-foot-thick aquifer. Aquifer-test data indicate that transmissivity of the upper 100 to 200 ft of the predominantly basalt aquifer ranges from less than 10,000 to 2,400,000 ft^2/d. Values generally are lower near the northwestern boundary of the plain where sedimentary rocks are present. Higher values are from wells completed in thick sections of permeable basalt. Transmissivity of basalt of the Snake River Group in Butte County (pl. 1) varies by more than a hundredfold (Garabedian, in press). Total transmissivity of the basalt aquifer in the eastern plain has not been determined by aquifer tests.

Specific yield is also variable, as might be expected for fractured rocks. Aquifer-test data indicate that specific yield of the basalt aquifer ranges from about 0.01 to 0.20, or within the range characteristic of unconfined aquifers.

Larry Mann (U.S. Geological Survey, oral commun., 1986) reanalyzed a number of aquifer tests done on the INEL site in the eastern plain. Use of delayed-yield curves in the analysis resulted in generally lower transmissivity values than previously reported. Several of the tests were in areas where sediments made up a major part of the tested interval.

Results of aquifer tests in the western Snake River Plain are given in table 2; test sites are shown on plate 1. All wells tested are totally, or in part, completed in alluvial sand and gravel aquifers in the Boise River valley. Transmissivity, as reported by Nace and others (1957, p. 55, table 17), ranges from about 5,000 to 230,000 ft^2/d. Test results indicate that specific yield of unconfined aquifers in the alluvium ranges from about 0.001 to 0.20 and storage coefficient of shallow, confined aquifers ranges from 0.00007 to 0.001.

Because aquifer tests have been done in only a few places, more readily available specific-capacity data were used to estimate transmissivity. Whitehead (1992) summarized reported specific-capacity data for the Snake River Plain and used mean specific-capacity data for wells in each county to estimate transmissivity (Theis and others, 1963, p. 331). Mean specific capacity and estimated transmissivity are generally high in the eastern plain, where most wells are completed in highly permeable basalt of the Snake River Group; they are lower in the western plain, where many wells are completed in fine-grained sedimentary rocks of the Idaho Group. Some values of transmissivity estimated from specific-capacity data approximate values estimated from aquifer tests; many estimated values are as much as an order of magnitude lower and are suspect.

TABLE 1.—*Aquifer-test data, eastern Snake River Plain*

[Well locations on plate 1; ft, foot; gal/min, gallon per minute; ft^2/d, foot squared per day; ft/d, foot per day; Qb, Quaternary basalt; Qb/Qs, Quaternary basalt and sedimentary rocks; —, no data available. Modified from Haskett and Hampton (1979, p. 26, 29); Mundorff and others (1964, p. 146, 147, 153–155); and unpublished data on file in the Boise office of the U.S. Geological Survey]

County	No.	Well location	Aquifer	Saturated thickness of aquifer tested (ft)	Pumping rate (gal/min)	Duration of test (hour)	Drawdown in pumping well (ft)	Specific capacity [(gal/min)/ft]	Transmissivity (x 1,000 ft^2/d)	Average horizontal hydraulic conductivity (ft/d) (rounded)	Specific yield/ storage coefficient
Bingham	1	3N-32E-13BB2	Qb	110	1,020	47	0.2	5,100	920	8,400	—
Blaine	2	8S-26E-3DCC2	Qb	387	4,050	19	22	180	640	1,700	—
Bonneville	3	3N-37E-12BD2	Qb	441	4,040	18	2.5	1,600	1,000	2,300	—
	4	1N-36E-1CC1	Qb	67	2,480	7	.5	5,000	2,000	30,000	0.08
Butte	5	6N-31E-13AC1	Qb	157	1,240	24	11.5	110	94–130	600–830	0.01
		6N-31E-13AC2	Qb	133	1,220	24	21.3	57	106	800	0.03
	6	6N-31E-14AB1	Qb	139	1,735	16	12.3	140	44	320	—
		6N-31E-14AB2	Qb	259	1,820	16	17.9	100	91	350	—
	7	5N-31E-10CD1	Qb/Qs	177	—	—	—	—	76	430	—
	8	4N-26E-32CB1	Qb	55	610	18	24	25	98	1,800	0.02
	9	4N-30E-7AD1	Qb	367	420	24	5	84	230	630	—
	10	4N-30E-30AA1	Qb	172	1,400	12	.5	2,800	200	1,200	—
		4N-30E-30AA2	Qb	180	2,160	46	15.2	140	65–150	360–830	—
		4N-30E-30AD1	Qb	163	2,610	48	1.3	2,000	500–580	3,100–3,600	—
	11	3N-29E-12DD1	Qb	97	663	7	7.2	92	410	4,200	—
	12	3N-29E-14AC1	Qb	144	3,740	48	3.3	1,100	1,900	13,000	0.02
		3N-29E-14AD2	Qb	141	4,350	48	2.0	2,200	2,400	17,000	0.06
	13	3N-29E-24AD1	Qb	153	2,500	24	3.2	780	440	2,900	0.06
	14	3N-30E-34BA1	Qb/Qs	196	375	4	21.1	18	16	82	—
	15	2N-29E-1DB1	Qb/Qs	209	235	3	15.6	15	21	100	—
	16	2N-30E-1BD1	Qb	747	550	16	.6	920	390	520	—

TABLE 1.—*Aquifer-test data, eastern Snake River Plain—Continued.*

County	No.	Well location	Aquifer	Saturated thickness of aquifer tested (ft)	Pumping rate (gal/min)	Duration of test (hour)	Drawdown in pumping well (ft)	Specific capacity [(gal/min)/ft]	Transmissivity (x 1,000 ft²/d)	Average horizontal hydraulic conductivity (ft/d) (rounded)	Specific yield/ storage coefficient
Cassia	17	10S-21E-34DD1	Qb	44	1,510	25	1.8	840	840	19,000	0.22
Fremont	18	7N-39E-16DBB4	Qb	447	6,450	24	3.7	1,700	4,800	11,000	—
Gooding	19	8S-15E-33CC1	Qb	36	1,490	4	—	—	1,300	36,000	0.04
Jefferson	20	8N-34E-11DC1	Qb	31	5,450	74	2.9	1,900	1,100	35,000	0.04–0.07
	21	7N-34E-24AA1	Qb	94	7,160	74	2.9	2,500	560–660	6,000–7,000	0.02–0.19
	22	6N-32E-22CC1	Qb	109	615	22	53	12	4.0	37	—
	23	6N-35E-26CC1	Qb	63	2,560	80	—	—	480–710	7,600–11,000	0.0008–0.07
Jerome	24	7S-19E-19AA1	Qb	54	1,630	8	.8	2,000	1,200	22,000	—
	25	8S-19E-5AD1	Qb	72	1,330	8	15.1	88	670	9,300	—
	26	9S-19E-25BB1	Qb	106	2,230	8	1.5	1,500	370	3,500	—
	27	10S-21E-26AAA2	Qb	452	700	—	95.5	7	110	240	—
Lincoln	28	5S-17E-26AC1	Qb	74	2,030	24	1.5	1,400	580	7,800	0.0002
	29	6S-18E-7BC1	Qb	67	1,820	8	4	460	460	6,900	—
Madison	30	6N-38E-25ACB1	Qb	667	4,960	48	3.8	1,300	2,100	3,100	—
	31	7N-38E-23DB1	Qb	196	1,820	3	4.2	430	1,600	8,200	0.00002
Minidoka	32	8S-24E-8AD2	Qb	80	3,400	4	4.9	690	1,200	15,000	0.01

TABLE 2.—*Aquifer-test data, western Snake River Plain*

[Well locations on plate 1; ft, foot; gal/min, gallon per minute; ft^2/d, foot squared per day; *, confined aquifer; **, confined and unconfined aquifers; Qs, Quaternary sedimentary rocks; Qb/Qs, Quaternary basalt and sedimentary rocks; —, no data available; ***, test data affected by induced recharge from nearby canals. Modified from Nace and others (1957, p. 55, table 17; p. 57, table 19; p. 59, table 20)]

County	No.	Well location	Aquifer	Well depth (ft)	Pumping rate (gal/min)	Draw-down in pumping well (ft)	Specific capacity [(gal/min)/ft]	Trans-missivity (x 1,000 ft^2/d)	Specific yield/ storage coefficient
Ada	33	4N-1W-13DC1	Qs	375	—	—	—	7	—
		4N-1W-13DC2	Qs	412	660	—	—	16	0.001
	34	3N-1E-5AB1*	Qs	124	125	40.0	3	5	.001
		3N-1E-5AB1**	Qs	124	600	—	—	25	.006
	35	3N-1E-36AD2	Qs	310	980	14.8	66	36	.00007
	36	3N-2E-25BB1	Qb/Qs	44	1,380	27.6	50	17	.43***
Canyon	37	5N-4W-28CC1	Qs	80	1,030	22.9	45	43	.025
	38	4N-3W-25DA1	Qs	80	1,550	31.0	50	28	.004
	39	3N-3W-3BB1	Qs	71	2,110	16.1	131	130	.23
	40	3N-3W-11DA1	Qs	90	2,175	25.6	85	160	.006
	41	3N-2W-8CC1	Qs	130	1,480	37.9	39	18	.0006
	42	3N-2W-9DD4	Qs	404	1,830	61.0	30	37	.0001
	43	3N-1W-7BB1	Qs	116	1,060	20.4	52	22	.003
	44	2N-1W-7BC4	Qb/Qs	103	2,900	19.3	150	230	.004

If flow to a well is assumed to be horizontal, a first approximation of average horizontal hydraulic conductivity (table 1) can be made by dividing transmissivity by depth of penetration of the well below the water table. The wide range of conductivity values for the eastern plain might have been anticipated considering the nonhomogeneity of basalt aquifers. Extremely high values might reflect a predominance of extensively fractured rubble basalt or pillow lava or penetration of a lava tube. Low values might indicate a more massive basalt or the presence of sediments in the tested interval. With few exceptions, aquifer tests in Butte County indicate that average horizontal hydraulic conductivity of basalt of the Snake River Group at the INEL site ranges from about 100 to 4,000 ft/d. Robertson (1977, p. 25) reported that typical horizontal hydraulic conductivity of basalt at the INEL site ranges from 1 to 7,000 ft/d. Garabedian (in press) estimated values of similar range based on a simulation of flow in the eastern Snake River Plain.

Hydraulic conductivity of basalt in the eastern plain decreases with depth. Robertson and others (1974, p. 12, 148) noted that the upper 500 ft is probably the most permeable part of the aquifer. Data from a 10,000-ft test hole at the INEL site verifies initial observations (Mann, 1986, p. 6–14). Mann (1986, p. 21) noted that the hydraulic conductivity of rocks below 1,500 ft is two to five orders of magnitude less than that of basaltic rocks in the upper 200 to 800 ft. Whitehead and Lindholm (1985) noted a decrease in hydraulic conductivity with depth in the test hole in the west-ern part of the eastern plain. Much of the decrease is due to secondary filling of voids with calcite, silica, and clay minerals (Wood and Low, 1988, p. 5–13).

As might be expected in a layered basalt aquifer in which horizontal hydraulic conductivity varies greatly, vertical hydraulic conductivity also varies greatly. The top part of an individual basalt flow may have extremely high horizontal and vertical hydraulic conductivity, and the massive central part of the same flow may have extremely low conductivities. If the basalt is fractured, vertical hydraulic conductivity may be much higher. Because of the irregularity and unpredictability of fractures in basalt, site-specific estimates of vertical hydraulic conductivity of basalt of the Snake River Group are uncertain.

Vertical hydraulic conductivity of sedimentary interbeds at one location on the INEL site ranges from 1×10^{-1} to 1×10^{-5} ft/d (Robertson, 1977, p. 26). Because values for vertical hydraulic conductivity of basalt are generally much higher than those of sedimentary interbeds reported by Robertson, fine-grained sedimentary interbeds are a major control on the vertical movement of water.

GROUND-WATER FLOW SYSTEMS

Shallow ground water moves approximately at right angles to the water-table contours, as shown in figure 13. The map is based on March 1980 water levels measured in wells completed in the upper part of the regional aquifer system (Lindholm and others, 1988).

In the eastern plain, most ground water follows long southwest-trending flow lines. The hydraulic gradient of the water table ranges from about 3 to 100 ft/mi and averages about 12 ft/mi (Lindholm and others, 1988). Gradients are smallest in the central part of the plain, which is underlain by a thick section of transmissive basalt. Under almost half of the eastern plain, the water-table gradient is less than 5 ft/mi. Gradients are steep in the extreme northeastern part of the plain and along the northwestern boundary. In Gooding and Jerome Counties (southwestern end of the eastern plain), the steep gradient is due largely to thinning of the basalt aquifer, as indicated by geophysics (Whitehead, 1986) and test drilling (Whitehead and Lindholm, 1985, p. 17). Gradients are steepest in the immediate vicinity of the Snake River canyon.

Closely spaced contours with steep gradients (25 to 30 ft/mi) cross the eastern plain in north-northwesterly directions and are coincident with or near marked transmissivity changes. The band of steep gradient in the vicinity of Mud Lake approximately coincides with an area where transmissive basalt interfingers with less transmissive sedimentary rocks. Steep gradients in the vicinity of the Great Rift are immediately upgradient from and generally parallel to a band of decreased transmissivity attributed to rifting. Fractures and possibly subsequent healing of fractures in the rift zone might impede horizontal water movement.

In areas of recharge, water moves vertically downward, as shown by decreasing hydraulic head with depth in piezometers at 7N-39E-16DBB (fig. 14). Natural recharge is greatest along the margins of the eastern plain; artificial recharge takes place in surface-water-irrigated areas (fig. 15).

Where fine-grained sedimentary rocks are interbedded with basalt above the regional water table, vertical water movement is impeded and perched aquifers may form. Water from perched aquifers slowly leaks to the regional aquifer system, discharges to rivers, and is pumped for local supply.

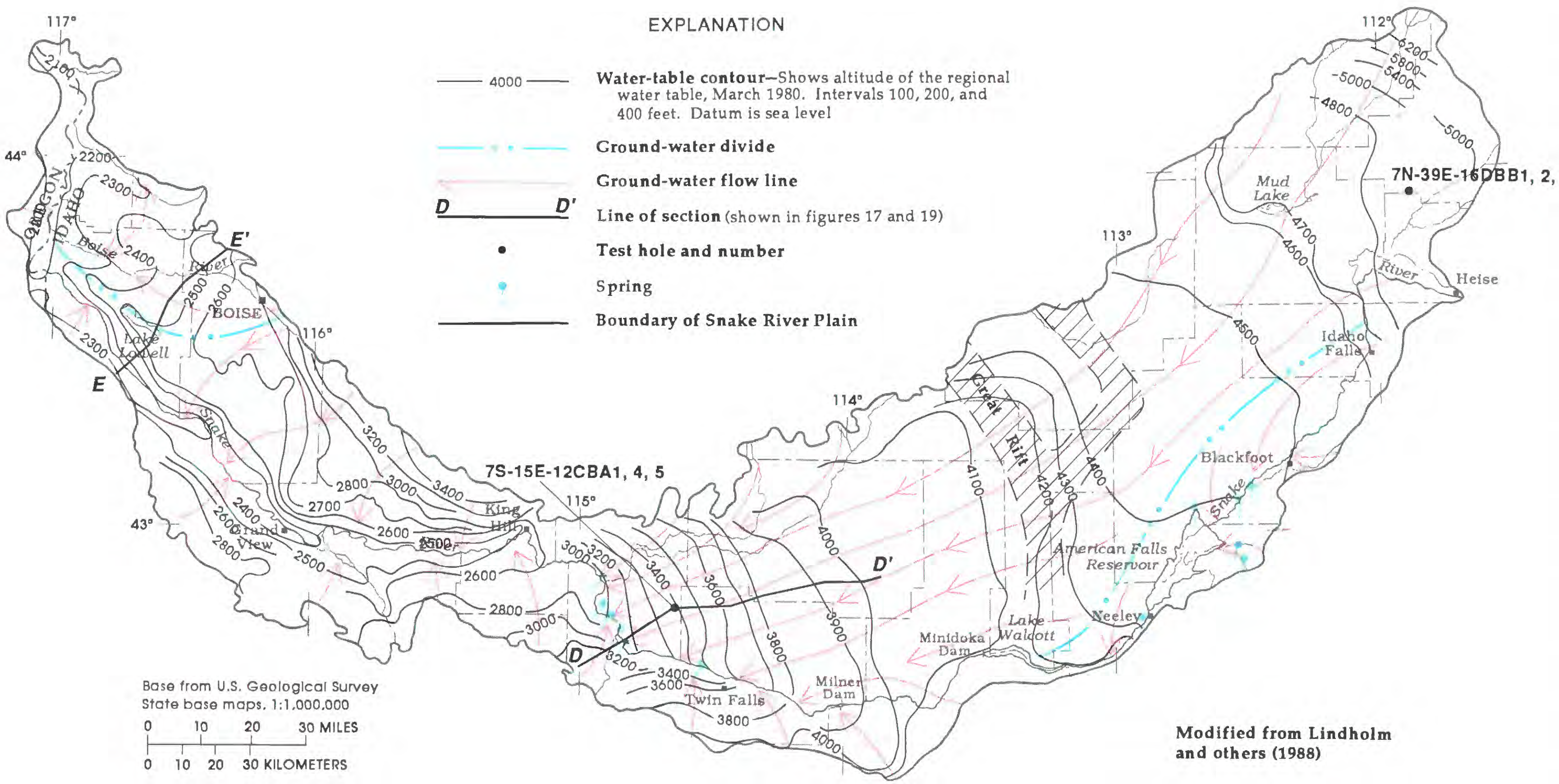


FIGURE 13.—Configuration of water table and general direction of horizontal ground-water movement in upper part of regional aquifer system, March 1980.

Ground-water movement is mainly horizontal in the central part of the eastern plain where hydraulic head is constant to depths of 600 ft below the water table.

Between Milner Dam and King Hill (pl. 1 and fig. 6), the Snake River is entrenched as much as 700 ft and ground water from the eastern plain is discharged in a spectacular manner. Numerous springs of greatly varying size, spacing, and altitude issue from the north wall of the canyon. Some spring vents are as much as 200 ft above river level; others discharge directly into the river. Most, including Thousand Springs, are in the 44-mi reach from Twin Falls to Bliss. Stearns and others (1938, p. 59) first noted and Covington and Weaver (1990a–d, 1991) most recently verified that the largest springs issue from pillow lava in the Snake River Group. The modern Snake River transects ancestral canyons where highly porous and permeable pillow lava is exposed. Many springs in the reach from Twin Falls to Bliss issue at the contact between basalt of the Snake River Group and underlying sedimentary and basaltic rocks of the Idaho Group. In many places, points of emergence are covered by basalt talus that, in places, extends several hundred feet above the present canyon floor.

In areas of discharge, such as between Milner Dam and King Hill, ground water moves vertically upward as well as horizontally. Hydraulic head increases with depth in piezometers in the test hole (7S-15E-12CBA) near Thousand Springs (figs. 12, 13, and 16). Head in the test hole increases about 150 ft with an 850-ft increase in depth. The need to determine hydraulic head in this discharge area was first expressed by Russell (1902, p. 181), who proposed a test hole 700 to 1,000 ft deep. The flow section in figure 17 shows that water moves to the Snake River vertically as well as horizontally from both sides of the river. Further evidence of upward water movement is provided by sand boils (springs) in the Snake River, such as Blue Heart Springs, 2 to 3 mi south of Thousand Springs (pl. 1).

Geothermal water is discharged from flowing wells and springs in the Banbury Hot Springs area,

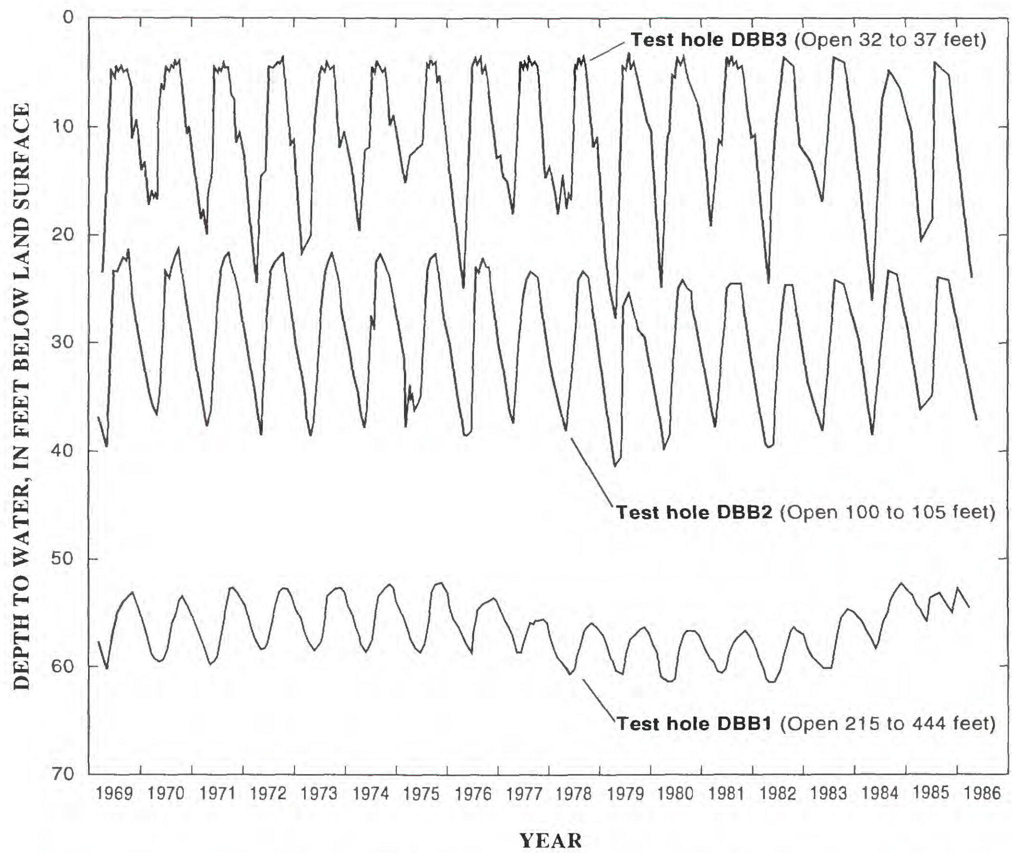


FIGURE 14.—Decreases in hydraulic head with depth in a recharge area (piezometers 7N-39E-16DBB1, 2, and 3). Location shown in figure 13.

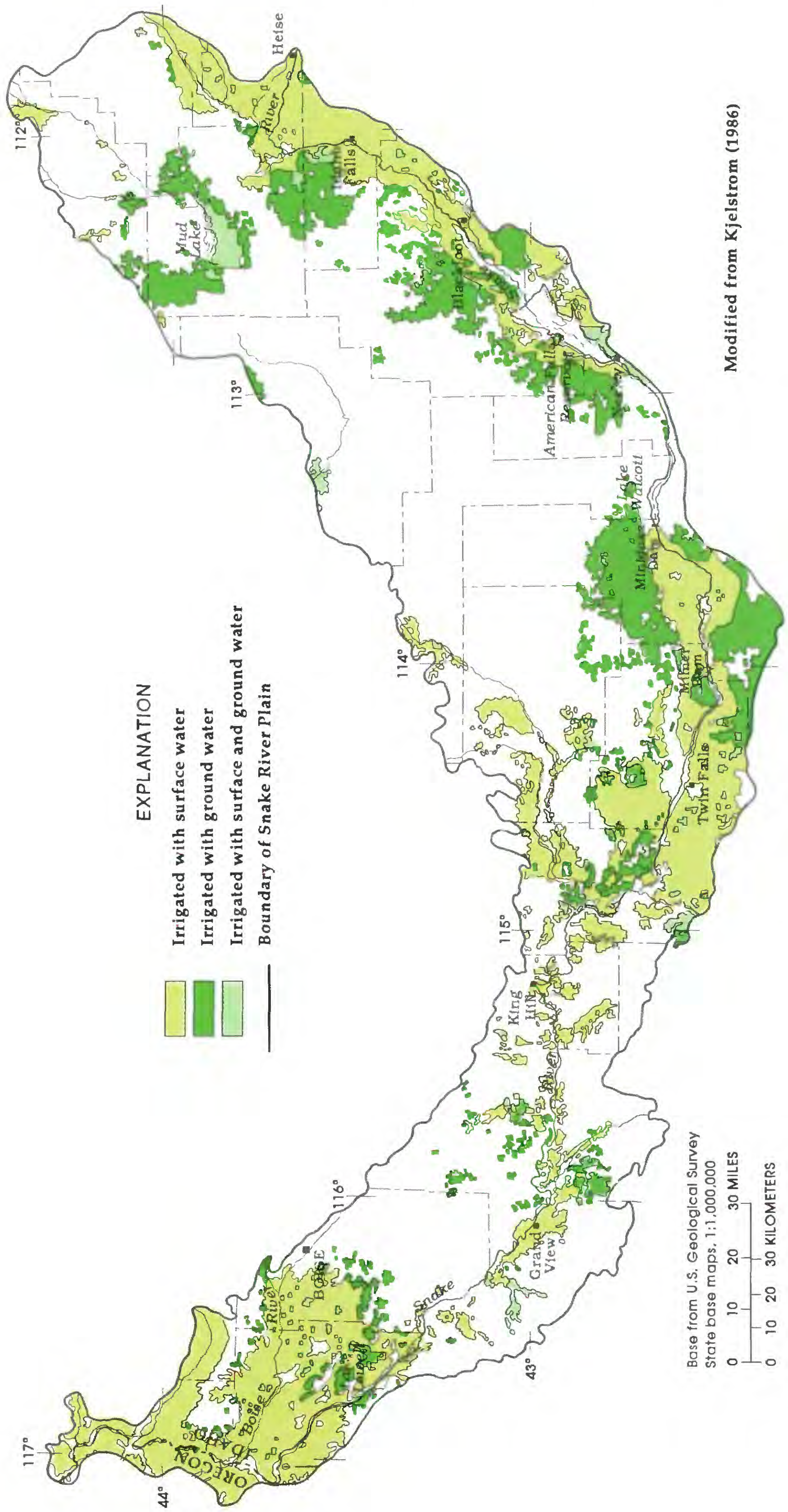


FIGURE 15.—Irrigated acreage, 1980.

4 to 5 mi south of Thousand Springs (pl. 1). Lewis and Young (1982, p. 8) speculated that geothermal water moves upward by convection, probably along faults. Because the Snake River between the mouth of Salmon Falls Creek and King Hill is a regional ground-water sink (fig. 17), the assumption was made that little or no water moves as underflow between the eastern and western plain.

Sedimentary interbeds have a significant effect on ground-water movement in a discharge area such as Thousand Springs, as shown in figure 18. The low vertical hydraulic conductivity of sedimentary interbeds impedes vertical water movement, as shown by close vertical spacing of equipotential lines within the interbeds. The wide horizontal spacing of equipotential lines within the interflow zones reflects the relative ease of horizontal water movement through interflow zones.

Springs between Blackfoot and Neeley issue from basalt and sand and gravel at, or a few tens of feet above, the level of the Snake River. As shown in figure 13, a ground-water divide separates flow north of the Snake River into two main components. Southeast of the divide, from about Idaho Falls to Neeley, water moves to the Snake River along short flow lines. North of the divide, a larger component of flow discharges to the Snake River between Milner and King Hill.

Shallow ground-water movement in the western Snake River Plain is to the Snake River and its tributaries (fig. 13). In contrast with the eastern plain, there are few springs and most discharge is seepage through sedimentary rocks.

In the Boise River valley, upward water movement is well defined (fig. 19) and many wells flow above land surface. Water with temperatures higher than 20°C was obtained from several wells in the central part of the western plain (Parliman, 1982a, p. 137, 141, 145) and indicates upward movement of deep geothermal water. Mitchell (1981, p. 73–77)

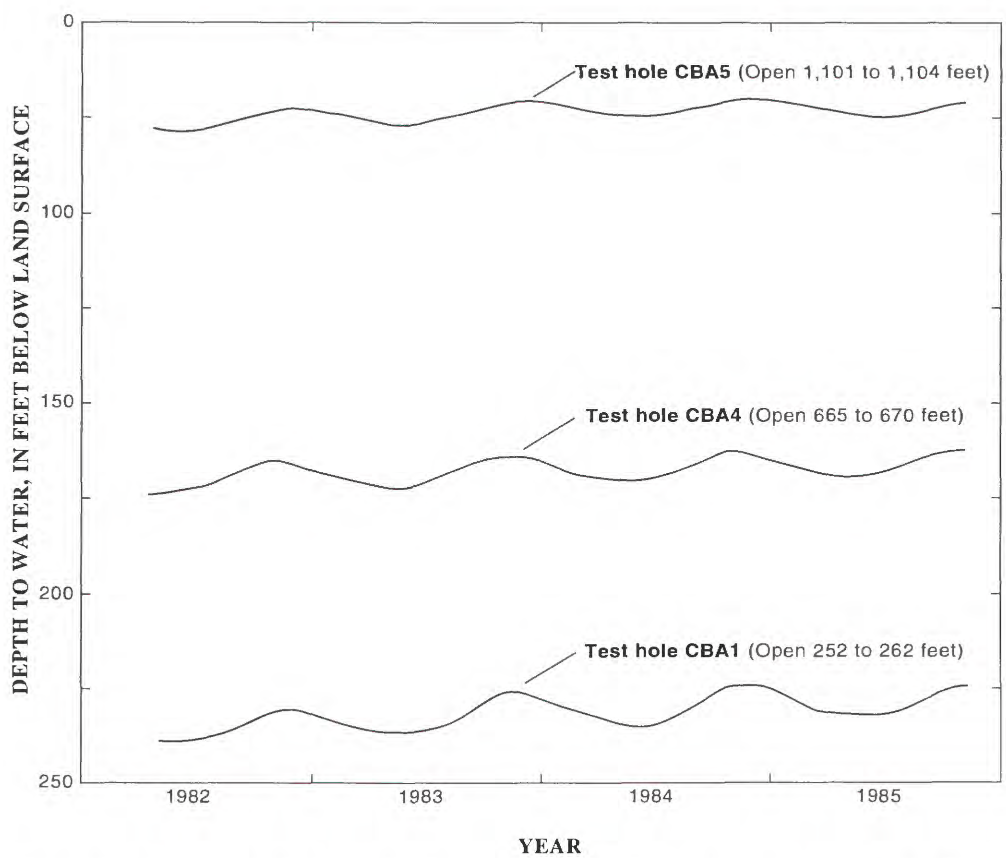


FIGURE 16.—Increases in hydraulic head with depth in a discharge area (piezometers 7S-15E-12CBA1, 4, and 5). Location shown in figure 13.

concluded that geothermal water in the Nampa-Caldwell area may be migrating upward along faults or joints.

Along the southwestern and northeastern boundaries of the western plain, geothermal water has high hydraulic head. South of the Snake River, in the Grand View area (pl. 1), Young and Lewis (1982, p. J13, J14, table 5) measured heads that were 100 to 150 ft above land surface in several wells. Hydraulic head as high as 240 ft above land surface has been reported. In the Grand View area, some wells flow 1,000 to 3,000 gal/min (Young and others, 1979, p. 6, 7, table 1).

SOLUTE GEOCHEMISTRY

Solute geochemistry in cold (water temperature 26°C and less) and geothermal (water temperature greater than 26°C) ground-water systems in the Snake River Plain and plausible geochemical reactions in each system are described in Chapter D of this Professional Paper series (Wood and Low, 1988) and are summarized in this section.

Ground water in the Snake River drainage basin is largely of meteoric origin. Areal variations in the chemistry of ground water reflect (1) chemistry of recharge water, (2) composition of the rock frame-

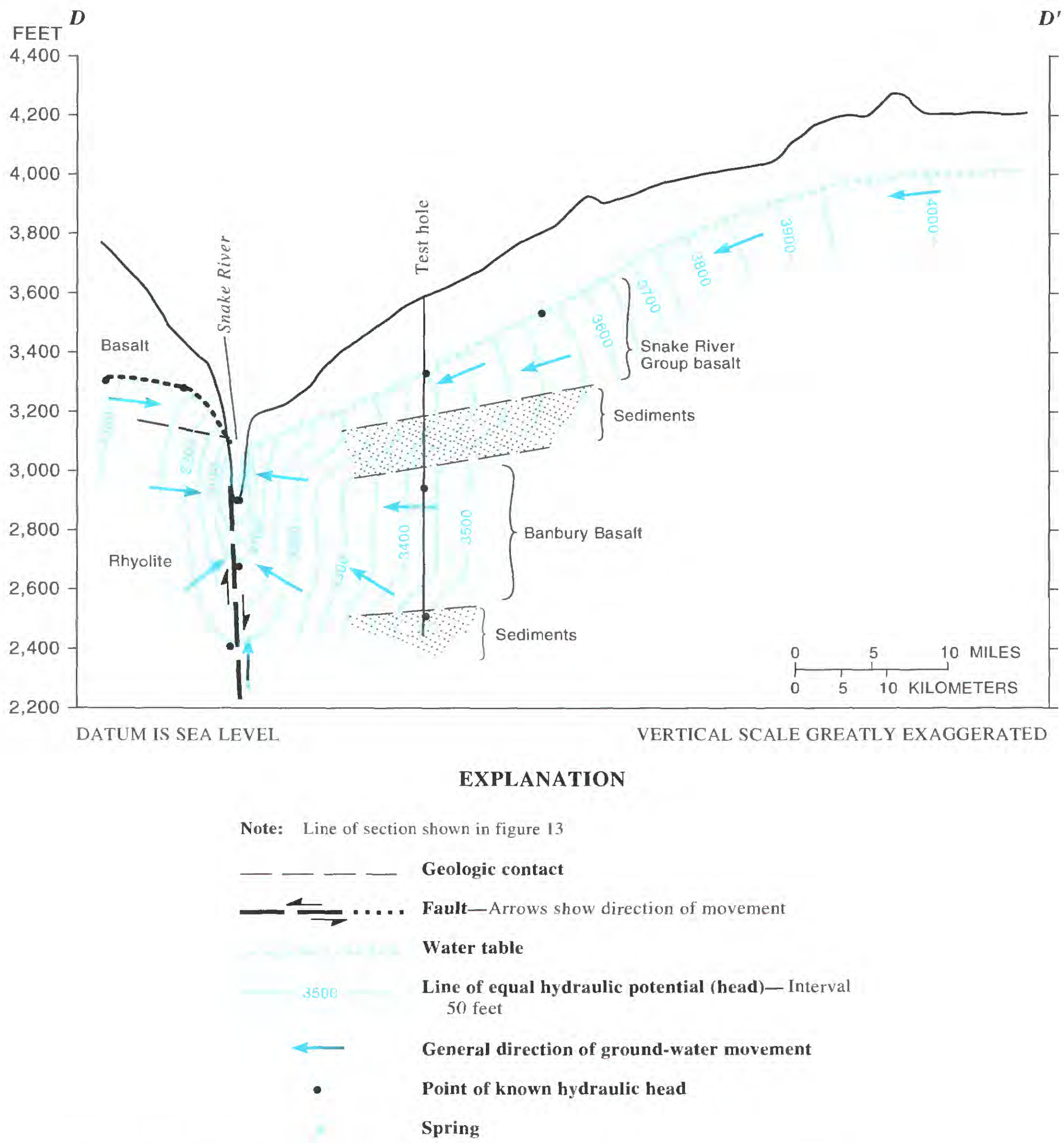


FIGURE 17.—Directions of ground-water movement to Snake River near Thousand Springs.

work, (3) position of water in the regional flow system, and (4) human activities. As water moves through the regional flow system, it reacts chemically with the rock framework. Natural reactions may be affected and new reactions can be introduced by human activities.

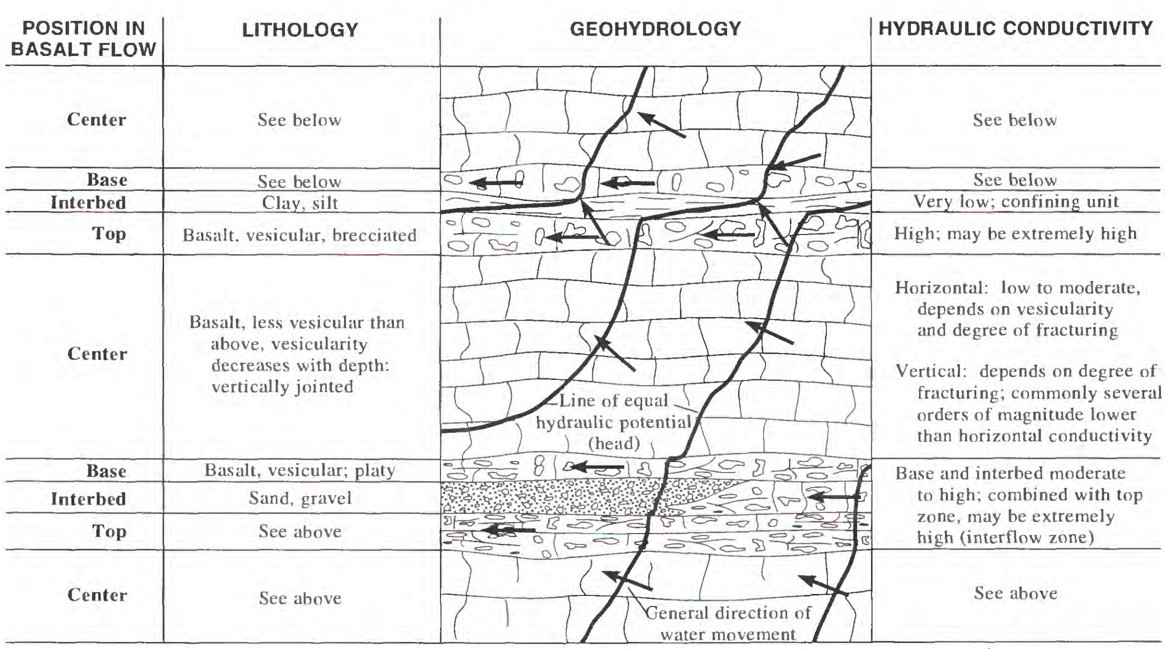
UPPER COLD-WATER SYSTEM

Solutes in surface water available to the Snake River Plain reflect the chemical composition of rocks in tributary drainage basins. Low (1987) summarized the chemical composition of water from 26 tributary drainage basins. Water from most basins is calcium/bicarbonate type or calcium/magnesium/bicarbonate type. Notable exceptions are sodium/bicarbonate and sodium/calcium/bicarbonate water from Falls, Owyhee, and Malheur Rivers (pl. 1), which drain areas of silicic volcanic rocks. Dissolved-solids concentrations in water from tributary drainage basins differ according to the predominant rock type in each basin. Concentrations are smallest, about 50 mg/L, in streams such as the Boise River that drain areas of granitic rocks; concentrations are greatest, about 400 mg/L, in streams such as the Owyhee and Raft Rivers that drain areas of fine-grained sedimentary rocks.

Dissolved-solids concentrations in ground water from 1,123 wells completed in the upper part of the regional aquifer system and in springs range from 60 to 5,740 mg/L with a median of 293 mg/L (Low, 1987). Concentrations are smallest in the eastern plain where basalt is at or near land surface (fig. 20). Concentrations on both the eastern and western plain are greatest in water from sedimentary rocks and are coincident with intensively irrigated areas, generally near the Snake River. The effect of irrigation on dissolved-solids concentrations in ground water has not been determined. Concentrations of dissolved chloride in ground water from 1,649 wells and springs range from less than 0.1 to 2,380 mg/L with a median of 16 mg/L (Low, 1987). The greatest chloride concentrations in ground water are generally in the same areas as high dissolved-solids concentrations.

Low (1987) concluded that all surface water and most ground water in the Snake River Plain is generally suitable for most uses.

Availability of geologic and hydrologic data and the regional nature of the ground-water flow system made the eastern Snake River Plain well suited for geochemical study. Because almost all surface water used for irrigation originates outside the plain and, in 1980, accounted for about 65 percent of total recharge, solutes in water from tributary drainage basins must be known to evaluate solutes in the ground-water system. Wood and Low (1988, p. 15–18) showed that solute concentrations in water from tributary drainage basins and the Snake River



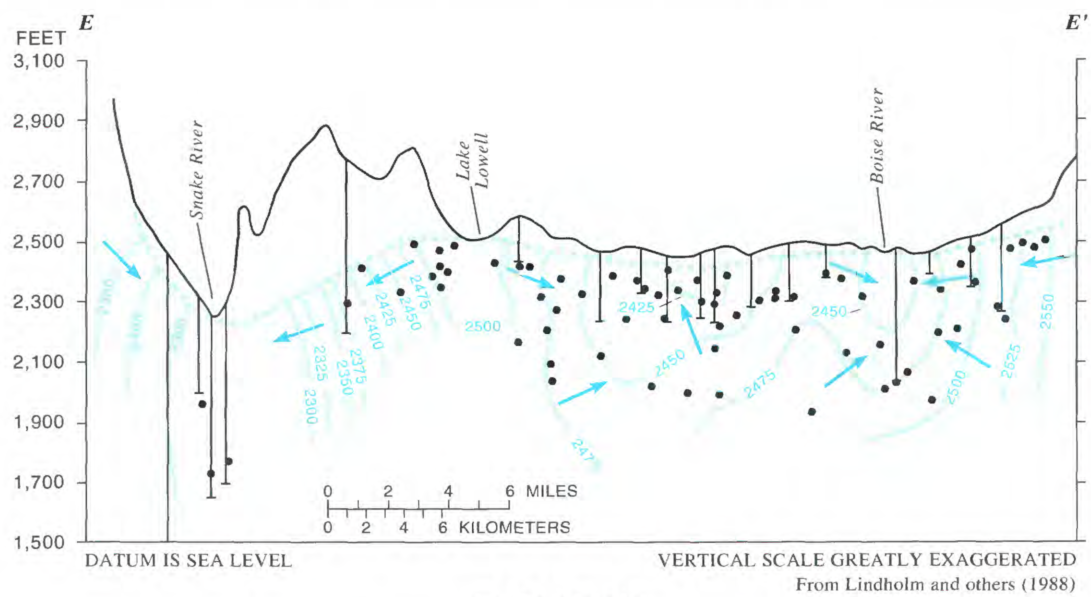
Modified from Lindholm and Vacarro (1988)

FIGURE 18.—Effect of sedimentary interbeds on ground-water movement.

are similar to those in the upper part of the regional aquifer system. Calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), potassium (K^{+}), bicarbonate (HCO_3^{-}), sulfate (SO_4^{2-}), chloride (Cl^{-}), and silica (SiO_2) constitute more than 95 percent of the total solutes in the cold (less than 26°C) ground-water system.

To determine whether solutes originate in or are removed from the regional aquifer system in the eastern plain, Wood and Low (1988, p. 16–18 and table 7) computed an average annual balance between solute input and output. They estimated that about 20 percent of the total solute load is from dissolution of rocks comprising the aquifer and from human activities. They also noted that the percentage of calcium entering the aquifer system exceeds the amount leaving. Geologic evidence for calcium loss is provided by calcite precipitates on rock surfaces, in sedimentary interbeds, and as vesicle fillings in basalt. Dissolution of minerals in the rock framework added calcium, magnesium, sodium, bicarbonate, sulfate, chloride, silica, and hydrogen ions (Wood and Low, 1988, p. 19). Wood and Low (1988, p. 24) concluded that geochemical reactions are important controls on solute concentrations in ground water and that the eastern plain aquifer system is both a source and a sink for solutes.

Determination of a solute balance and weathering reactions in the upper cold-water system is more difficult in the western plain than in the eastern plain. In the western plain, the rock framework is more heterogeneous, surface water used for irrigation differs more in solute composition, ground water moves more slowly through the sedimentary rocks, and ground-water discharge is less well defined than in the eastern plain. Although Wood and Low (1988, p. 24–25) were unable to prove that solute concentrations in the western plain were at steady state, by assuming so, they made several observations consistent with observations for the eastern plain. Precipitation of caliche and chalcedony or quartz is predictable, and the solute load that is attributable to water-rock reactions and human activities is similar to that in the eastern plain.



EXPLANATION

Note: Line of section shown in figure 13

Water table

Line of equal hydraulic potential (head)—Intervals 25 and 100 feet

General direction of ground-water movement

Well

Point of known hydraulic head—Projected where no well shown

FIGURE 19.—Directions of ground-water movement, western Snake River Plain.

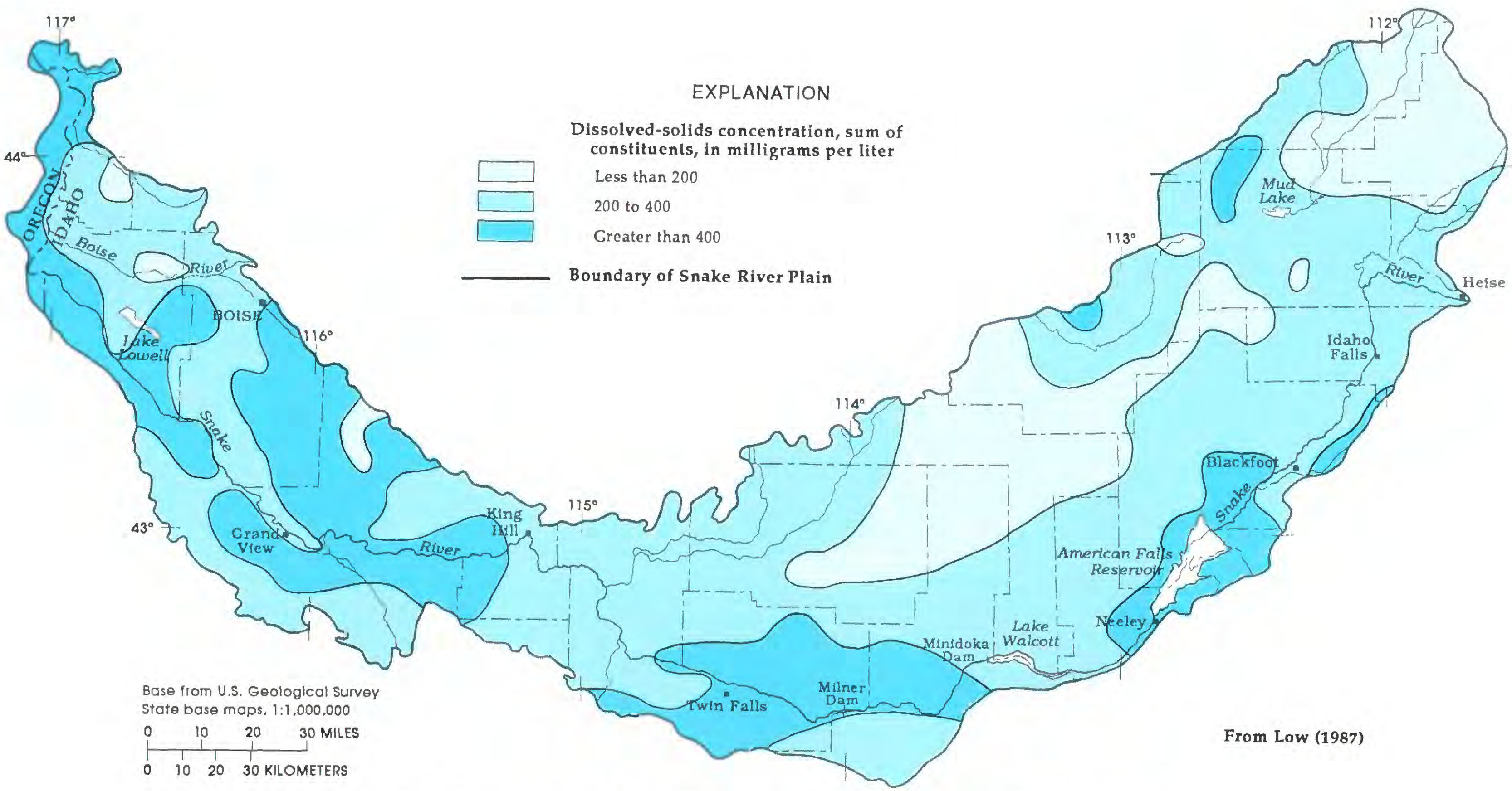


FIGURE 20.—Areal distribution of dissolved solids in upper part of regional aquifer system.

LOWER GEOTHERMAL-WATER SYSTEM

Wood and Low (1988, p. 31–38) proposed a series of dissolution reactions for the lower geothermal-water system that underlies the cold-water system in and adjacent to the Snake River Plain, particularly the western plain. The proposed reactions are supported by thermodynamic saturation indices and isotope and mass-balance calculations.

Young and Whitehead (1975, p. 8) presented a conceptual hydrogeologic model of the geothermal system in the Bruneau–Grand View area (pl. 1) of the western Snake River Plain. Their model, modified by Wood and Low (1988, p. 33), shows (fig. 21) that water in the upper cold-water system is in sedimentary and basaltic rocks (Idaho and Snake River Groups); water in the geothermal system is largely in rhyolitic rocks (Idavada Volcanics). Most recharge to the geothermal system is from precipitation on uplands adjacent to the plain. Movement of geothermal water is enhanced where the rhyolitic rocks are fractured, such as near margins of the plain.

Solute concentrations in geothermal water are similar over a large area. Typically, concentrations of sodium, bicarbonate, sulfate, chloride, fluoride, silica, arsenic, boron, and lithium are greater in geothermal water than in the upper cold-water system, and concentrations of calcium, magnesium, and hydrogen are smaller (Wood and Low, 1988, p. 32). Wood and Low (1988, p. 34) also proposed an ion exchange model on the basis of data from the Banbury Hot Springs and Bruneau–Grand View areas (Lewis and Young, 1982; Young and Lewis, 1982) to account for measured changes in ion concentrations as water moves through the geothermal system. Calcium and magnesium in water are exchanged for sodium in the rock framework and pH is increased as water moves into the confined geothermal system. Pyrite is oxidized by the addition of iron and sulfate to solution. As water temperature increases, clays and zeolites provide additional ion exchange capacity. Wood and Low (1988, p. 39) stated that throughout the basin, 43 of 76 reservoir water temperatures based on calculations using the silica-quartz geothermometer were greater than 90°C, and the maximum was 172°C.

The high pH of geothermal water, commonly 8 to 9.5 (Wood and Low, 1988, p. 34, table 23A), probably is caused by removal of H^+ ions during the conversion of carbonate minerals to bicarbonate. As temperature and pH increase, silica concentration increases owing to dissolution of plagioclase feldspars, quartz, and chalcedony.

As in the upper cold-water system, sulfur isotopes indicate that sulfate in geothermal water is from the dissolution of anhydrite or oxidation of pyrite. In both systems, 80 to 85 percent of sulfate ions are from the dissolution of anhydrite, which is present in sedimentary interbeds.

Carbon-14 dating was used to estimate residence time and the rate at which water moves through the geothermal system. Estimated residence times of water that traveled 25 and 35 mi downgradient from points of recharge were 18,000 and 17,700 ±4,000 years, respectively. Water that moved along an 85-mi flowpath had an apparent age of 20,300 ±4,000 years (Wood and Low, 1988, p. 42–43). Long residence time supports the concept of slow recharge and small volume of water moving slowly through the geothermal system in contrast to a much larger volume moving rapidly through the upper cold-water system.

WATER USE

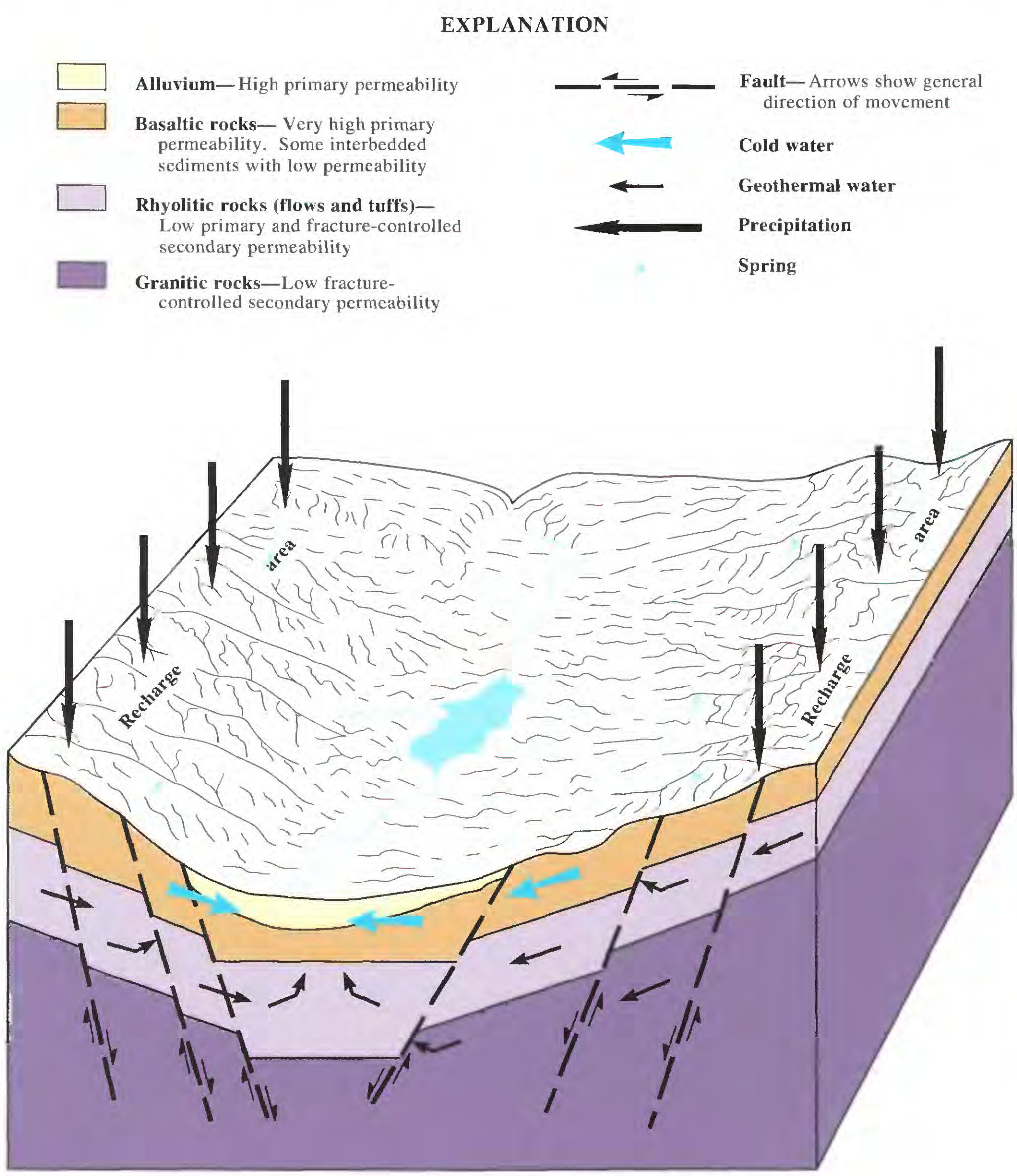
Idaho's economy is based largely on irrigated agriculture and ancillary activities. Since settlement of the Snake River Plain during the early 1800's, irrigation on the plain has far exceeded any other consumptive use of water. According to Solley and others (1983), about 96 percent of consumptive water use in Idaho during 1980 was for irrigation, 3 percent was for self-supplied industries, and 1 percent was for public water supplies. Eighty-five percent of Idaho's irrigated acreage is on the Snake River Plain, where probably an equivalent percentage of Idaho's farm marketing receipts—more than $2 billion during 1980—was generated. Water use on the Snake River Plain is described in Chapter E of this Professional Paper series (Goodell, 1988) and is summarized in this section.

The highest consumptive water-use rates on the plain are in the central and western parts; the lowest are in the extreme northeastern part (Goodell, 1988, p. 11). At Grand View (pl. 1), 34 in. of water is used annually for alfalfa, whereas at Ashton, near the extreme northeastern end of the plain, 18 in. is used annually for alfalfa. Water diverted in excess of crop needs (1) evaporates, (2) leaks downward from canals or seeps from fields to the water table, or (3) runs off to surface-water bodies. The U.S. Soil Conservation Service (1977, p. 25) estimated that 40 percent of the water diverted for irrigation on the Snake River Plain is lost to evaporation, seepage, and runoff. Kjelstrom (1986) reported that some canals lose as much as 40 percent of their flow by leakage.

HISTORY OF IRRIGATION

Early irrigation on the Snake River Plain was entirely with surface water. The first reported irrigation was the use of Boise River water as early as 1843 (Caldwell and Wells, 1974, p. 31). Government incentives provided by the Carey Act in 1894 and the Reclamation Act in 1902 and subsequent construction of major surface-water storage facilities and canals resulted in a rapid expansion of irrigated acreage across the plain during the early 1900's. By 1929, about 2.2 million acres of land was irrigated (Lindholm and Goodell, 1986).

After World War II, the use of ground water for irrigation increased rapidly. Ralston and Chapman (1968, p. 4) reported a fiftyfold increase in electrical power consumption for irrigation, mainly ground-water pumping, between 1946 and 1967 in the Mud Lake area of the eastern plain (pl. 1). Rapid increases took place in other areas at about the same time and, by 1966, an area of about 700,000 acres was irrigated with ground water and 2.5 million



Modified from Wood and Low (1988)

FIGURE 21.—Conceptual hydrologic model of Snake River basin geothermal system.

acres with surface water (Lindholm and Goodell, 1986).

Since 1966, irrigated area has remained fairly stable at about 3 million acres. Increases have been mostly small-scale expansion of ground-water-supplied areas across the plain and direct pumping of Snake River water, mainly on the western plain.

IRRIGATION, 1980

Lindholm and Goodell (1986) reported that 3.1 million acres, or 31 percent of the plain, was irrigated during 1980, of which about 2.0 million acres was irrigated with surface water, 1.0 million with ground water, and 0.1 million with combined surface and ground water (fig. 22). Bigelow and others (1987) suggested that conjunctive use of surface and ground water for irrigation is probably more extensive than the 0.1-million-acre estimate.

About 5.2 million acres, or 54 percent of the Snake River Plain, is rangeland and 1.0 million acres, or 10 percent, is largely outcrops of basalt.

Estimates of offstream use of water for irrigation are summarized in reports by Kjelstrom (1986), Bigelow and others (1987), and Goodell (1988). Goodell's report includes a summary of 1980 irrigation diversions from the Snake River and major tributaries by gaged reach. Diversions from the Snake River for irrigation during water year 1980 totaled about 8.9 million acre-ft. About 8.1 million acre-ft, or slightly more than 90 percent, was gravity diversions. Most gravity diversions were in the reach from Heise to Milner Dam (pl. 1). About 0.8 million acre-ft was pumped directly from the river at 445 pumping stations. Most of these are on the western plain, where water is lifted several tens to several hundreds of feet to irrigate uplands adjacent to the river.

Ground water was the primary source of water for about one-third of the irrigated acreage on the Snake River Plain during 1980. On the eastern plain, most irrigation wells are open to basalt and the remainder are open to sedimentary rocks (Goodell, 1988, p. 29, table 8). Wells in basalt typically are completed as open hole; wells in sedimentary rocks are cased and completed with screen or perforated casing. About two-thirds of the almost 400 irrigation wells on the eastern plain for which drillers' logs were available in 1980 had reported yields of 1,500 gal/min or more, and the maximum was 7,240 gal/min. Reported drawdown was less than 20 ft in two-thirds of the wells completed in basalt, compared to about one-half of the wells completed in sedimentary rocks.

On the western plain, most irrigation wells are open to sedimentary rocks and the remainder are open to basalt. Based on information available in 1980, about 1 of every 13 wells completed in sedimentary rocks yielded 1,500 gal/min or more, compared to 2 of every 3 wells completed in basalt. Reported drawdown was less than 20 ft in about one-fifth of the wells, whether completed in basalt or sedimentary rocks.

During a previous study, Young and Harenberg (1971, p. 11) estimated that more than 99 percent of all irrigation wells on the eastern Snake River Plain were electrically powered. Consequently, ground-water pumpage for irrigation during 1980 was estimated from electrical power consumption data using a method described by Bigelow and others (1987).

Bigelow and others (1987) estimated that during 1980, 2.3 million acre-ft of ground water was pumped from 5,300 wells to irrigate 1.0 million acres on the Snake River Plain. Pumpage on the eastern plain was about 1.9 million acre-ft and, on the western plain, 0.4 million acre-ft. Volume pumped was aggregated to show total pumpage within geographic areas that correspond to U.S. Geological Survey 7.5-minute topographic maps (about 54 mi^2). Data were further aggregated to 15-minute areas as shown in figure 23.

OTHER USES, 1980

Goodell (1988, p. 37–42) quantified 1980 offstream water uses other than irrigation on the Snake River Plain. Most industries, such as food processing and the manufacture of fertilizer, are related to irrigated agriculture. The IDWR estimated that water used for industry on the Snake River Plain during 1978 totaled about 71,300 acre-ft. Almost 75 percent was supplied by ground water, 10 percent by surface water, and the remainder by public supply systems (Goodell, 1988, p. 39, table 10).

The major instream use of water is for hydroelectric power generation. During 1980, 52 million acre-ft of water was used to generate 2.6 million MWh of electricity (Goodell, 1988, p. 42).

WATER-USE TRENDS

On the basis of water-use reports issued by the U.S. Geological Survey every 5 years since 1945,

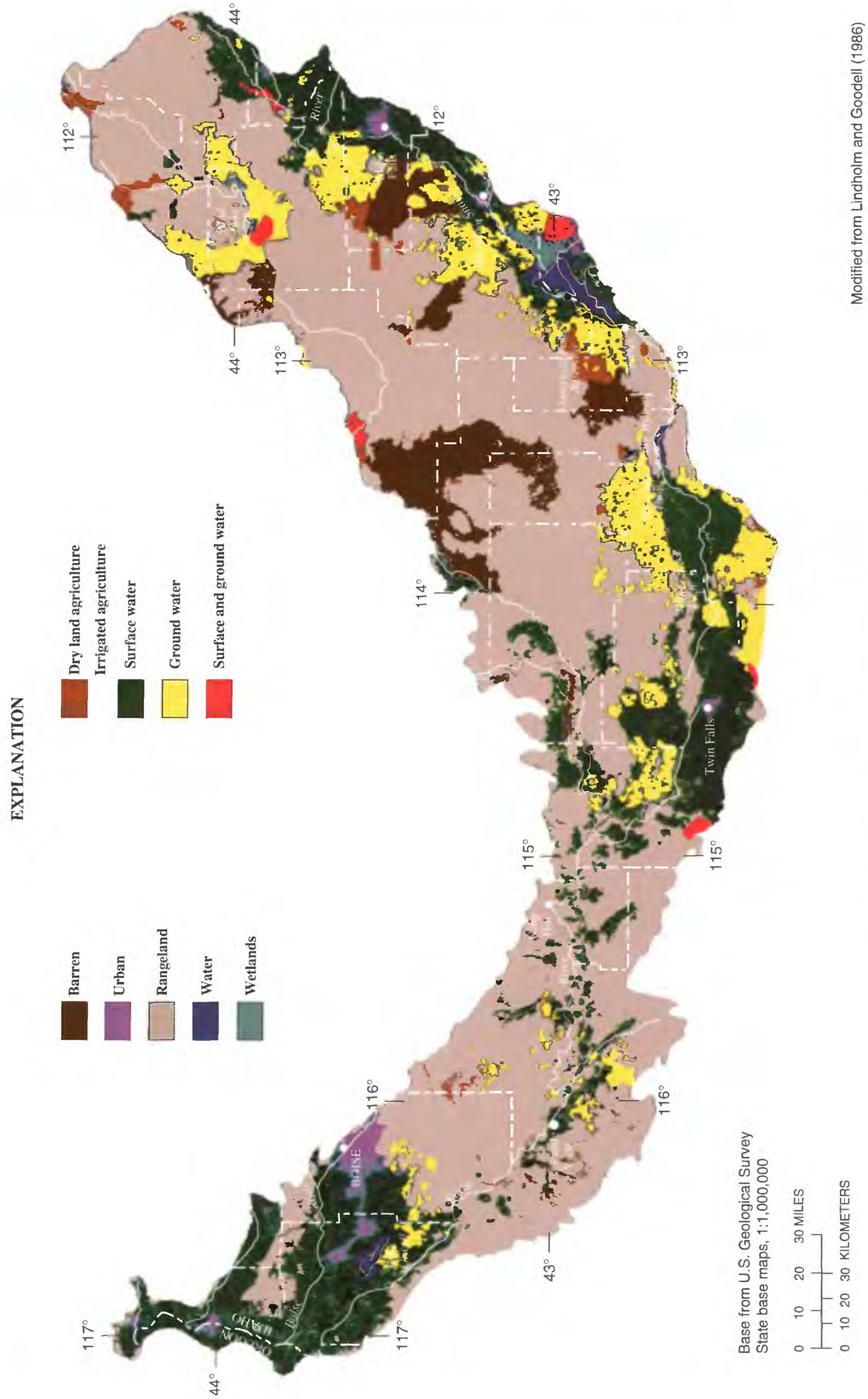


FIGURE 22.—Irrigated acreage and other land uses, 1980.

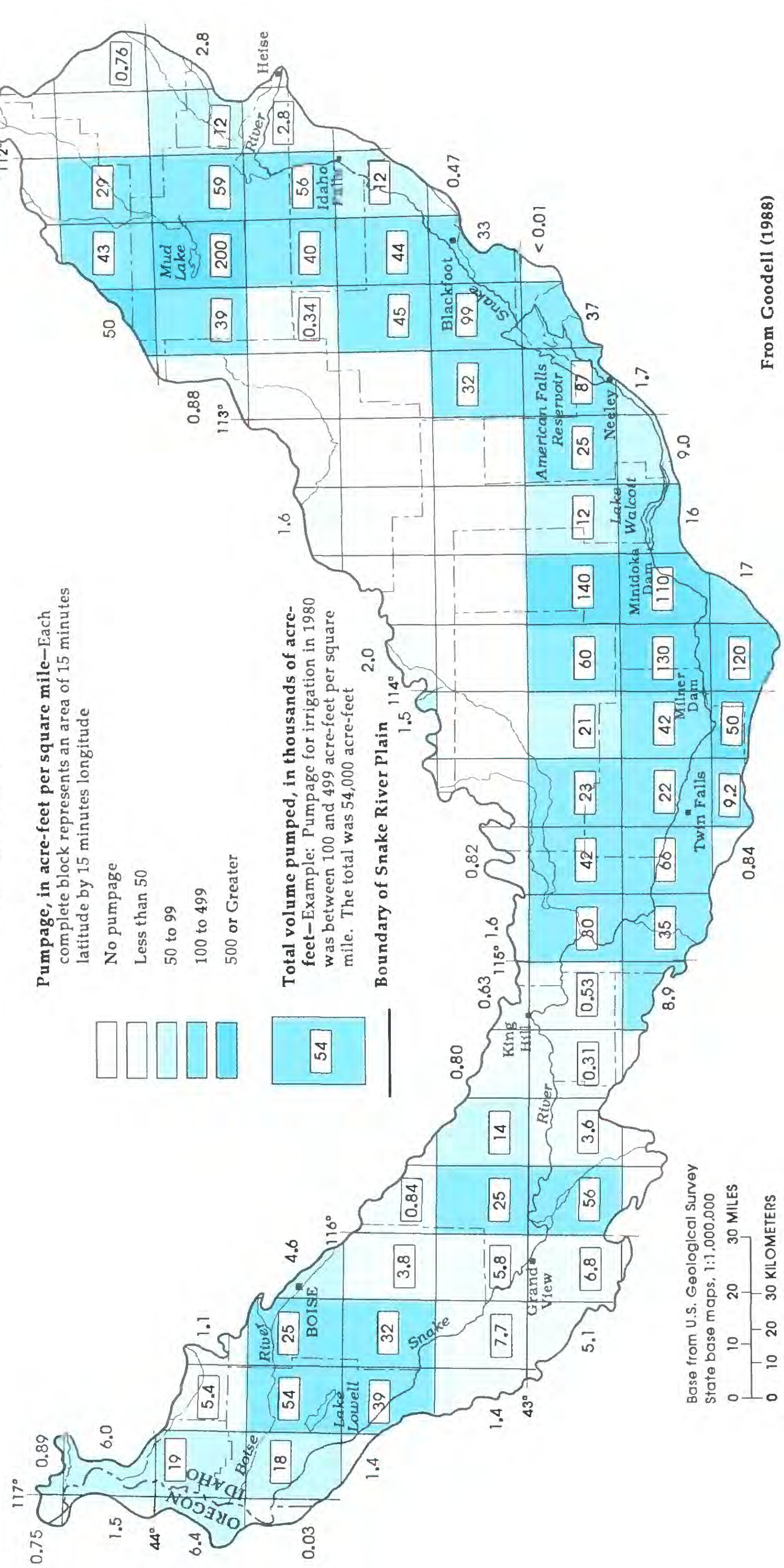


FIGURE 23.—Estimated ground-water pumpage for irrigation, 1980.

Goodell (1988, p. 47–48) noted some water-use trends in Idaho. Statewide trends were assumed to reflect water-use trends on the Snake River Plain. Since 1950, surface-water withdrawals for irrigation have generally decreased and ground-water withdrawals have increased. During 1950, about 2 percent of the 15.4 million acre-ft of water withdrawn for irrigation was ground water; during 1980, about 26 percent of the 17.5 million acre-ft withdrawn was ground water. Throughout the period 1950 to 1980, water use for irrigation in Idaho was second in the Nation. During the same time period, use of ground water for public supplies generally increased, whereas use of surface water for public supplies decreased. Ground water accounted for about 3 percent of total offstream water use during 1950 and about 35 percent during 1980.

WATER BUDGETS, 1980

Although climatologically classified as semiarid, the Snake River Plain receives an abundance of water from surrounding mountainous areas. A water budget for the Snake River Plain is described in Chapter C of this Professional Paper series (Kjelstrom, in press). Ground-water budgets for the eastern and western parts of the plain are described in Chapters F and G (Garabedian, in press; Newton, 1991) and are summarized in this section.

During water year 1980 (October 1, 1979, to September 30, 1980), about 27 million acre-ft of surface water and ground water moved through the plain (table 3). About two-thirds of the total was from the headwaters of the Snake River upstream from Heise and drainage basins tributary to the plain. Most of the inflow from tributary drainage basins is streamflow, about 85 percent of which is gaged (Kjelstrom, 1986). Precipitation on the plain contributed about one-third of the total inflow. During 1980, precipitation exceeded the long-term average of 8.2 million acre-ft (Kjelstrom, 1986) by about 20 percent.

About 43 percent of total outflow from the plain during 1980 was Snake River discharge at Weiser; 53 percent was evapotranspiration. Potential evapotranspiration on the plain ranges from about 19 to 30 in/yr (Goodell, 1988, p. 8), approximately the range for actual evapotranspiration from irrigated land. Evapotranspiration from nonirrigated land is limited by the amount of precipitation, which is 8 to 10 in/yr on much of the plain. Although about one-third of the plain was irrigated during 1980 (fig. 15), nearly two-thirds of the total water evapotranspired was from irrigated land. Increased storage in surface reservoirs and evaporation from surface-water bodies equal less than 4 percent of the total outflow.

The difference between inflow and outflow (0.6 million acre-ft) was assumed to be a decrease in ground-water storage; the amount of water leaving the plain as underflow was assumed to be negligible. Those assumptions are supported by measured ground-water-level declines in the eastern plain during 1980 (Garabedian, 1986, p. 10).

GROUND-WATER BUDGET, EASTERN SNAKE RIVER PLAIN

On the basis of simulation studies, Garabedian (in press) developed a ground-water budget for the eastern plain (table 4). He estimated that 60 percent of ground-water recharge during water year 1980 was from the infiltration of surface water used for irrigation. Canal leakage and field seepage, particularly in areas of flood irrigation, greatly increase the amount of recharge. Actual amounts vary temporally and areally, depending on (1) length and leakage rate of canals, many of which are unlined; (2) number of acres irrigated; (3) soil type; and (4) efficiency of irrigation practices.

The next largest source of recharge is underflow from tributary valleys along the northwestern and southeastern boundaries of the plain (Kjelstrom, 1986). Some streams on the eastern plain, mainly the Snake River upstream from Blackfoot (pl. 1), lose flow to ground water during parts or all of the year. Losing reaches were identified by Kjelstrom (in press), who developed water budgets for reaches of the Snake River. Less than 10 percent of total recharge in the eastern plain was from precipitation on the plain. Garabedian (in press) estimated that recharge from precipitation might be about 3 in/yr in areas of recent lava flows and little soil cover, compared with less than 0.5 in/yr on rangelands where soil thickness is greater than 40 in.

About 86 percent of ground-water discharge in the eastern plain during water year 1980 was seepage and spring flow to the Snake River; the remainder was ground-water pumpage. According to Kjelstrom (1992), about 1.9 million acre-ft was discharged to the Snake River, tributaries, and American Falls Reservoir between gaging stations near Blackfoot and at Neeley (pl. 1). Most gain was from springs, the largest of which discharges to Spring Creek. Spring Creek gained about 0.38 million acre-ft dur-

TABLE 3.—*Water budget, Snake River Plain, water year 1980 (October 1, 1979, to September 30, 1980)*

[Modified from Kjelstrom (1986); evapotranspiration from Kjelstrom (1992)]

INFLOW

Source	Millions of acre-feet
Snake River near Heise	4.7
Tributary streams and underflow	12.2
Precipitation on the plain	9.8
Total	26.7

OUTFLOW

Item		Millions of acre-feet
Snake River at Weiser		11.7
Evapotranspiration		14.6
Irrigated land	9.2	
Nonirrigated land	5.4	
Evaporation from surface reservoirs and Snake River		.3
Change in surface reservoir storage		.7
Total		27.3
Change in ground-water storage		-.6

ing 1980. Numerous springs along the Portneuf River contributed about 65 percent of the 1980 total Snake River gain between Blackfoot and Neeley. Another 4.7 million acre-ft was discharged to the Snake River between Milner and King Hill, all but 0.3 million acre-ft from the north side. Garabedian (in press) estimated that net ground-water pumpage (table 4), the difference between the amount pumped and the amount that returns to the aquifer, was 1.14 million acre-ft during 1980.

The difference between recharge and discharge during 1980 indicates a decrease in ground-water storage. On the basis of measured declines in water levels in the regional aquifer, Garabedian (in press) estimated a decrease in storage of about 0.10 million acre-ft in the eastern plain during 1980. That value compared well with the 0.16 million acre-ft decrease in storage indicated by the water-budget analyses (table 4).

Estimates of total ground water in storage are highly variable because the basalt is heterogeneous and because the storage properties of rocks at depths greater than 500 ft below the water table are generally unknown. Barraclough and others (1981, p. 4) estimated that the ground-water reservoir underlying the eastern Snake River Plain stores 1 billion acre-ft of water. Assuming a specific yield of 0.05 to 0.10, an estimated 200 to 300 million acre-ft of water is stored in the upper 500 ft of the regional aquifer system (Lindholm, 1986, p. 88). That amount is 20 to 30 times greater than the total storage capacity of all surface reservoirs in the Snake River drainage basin upstream from Weiser, Idaho.

TABLE 4.—*Ground-water budget, eastern Snake River Plain, water year 1980 (October 1, 1979, to September 30, 1980)*

[Modified from Garabedian (in press). Pumpage calculated as difference between amount pumped and amount that returns to aquifer]

RECHARGE

Source	Millions of acre-feet
Surface-water irrigation	4.84
Tributary drainage basin underflow	1.44
Precipitation on the plain	.70
Snake River losses	.69
Tributary stream and canal losses	.39
Total	8.06

DISCHARGE

Item	Millions of acre-feet
Snake River gains	7.08
Pumpage (net)	1.14
Total	8.22
Change in ground-water storage (budget residual)	-.16
Change in ground-water storage (estimated from water-level changes)	-.10

GROUND-WATER BUDGET, WESTERN SNAKE RIVER PLAIN

Newton (1991) developed a ground-water budget for the western Snake River Plain (table 5). He estimated that surface water used to irrigate about 700,000 acres on the western plain (fig. 15) was the source of 80 percent of ground-water recharge during calendar year 1980. Irrigation with surface water is intensive in the Boise and Payette River valleys and along the Snake River. On the rest of the western plain, surface water is in short supply and there is little recharge from irrigation. Underflow across the northeastern and southwestern boundaries of the plain contributed about 0.31 million acre-ft of water during 1980. Underflow is greatest through volcanic rocks in the Bruneau area, south of the Snake River (pl. 1).

On the average, only about 2 percent of total annual precipitation on the western plain becomes ground-water recharge (Newton, 1991). Recharge from precipitation is greatest in irrigated areas where soil moisture conditions are satisfied throughout much of the growing season. On the basis of evapotranspiration estimates, Newton assumed that in nonirrigated areas, about 3 percent of precipitation in excess of 9 in. becomes ground-water recharge. Where annual precipitation is less than 9 in., potential evapotranspiration from native vegetation exceeds precipitation, and no recharge occurs.

Almost 83 percent of the 1.75 million acre-ft of annual ground-water discharge in the western plain is to rivers and drains; the remainder is pumpage. Unlike discharge in the eastern plain, which is mostly spring flow, discharge in the western plain

TABLE 5.—*Ground-water budget, western Snake River Plain, calendar year 1980 (January 1, 1980, to December 31, 1980)*

[Modified from Newton (1991)]

RECHARGE

Source	Millions of acre-feet
Surface-water irrigation	1.40
Tributary drainage basin underflow	.31
Precipitation on the plain	.04
Total	1.75

DISCHARGE

Item	Millions of acre-feet
Gains to rivers and drains	1.45
Pumpage	.30
Total	1.75

is mostly seepage to the Snake River and tributaries. Nearly half is to the Snake River, about 30 percent is to the Boise River, and most of the remainder is to the Payette River. River gains from ground water were assumed to be the residual obtained by water-budget analysis. However, because the amount of ground-water discharge to the Snake River in the western plain is less than 5 percent of Snake River flow, gaging errors may be as large as river gains. Newton (1991) estimated that about 580,000 acre-ft of ground-water discharge in the Boise River valley during the winter is to drains, but the amount varies seasonally.

About 300,000 acre-ft of ground water was pumped to irrigate 130,000 acres on the western plain during 1980 (Newton, 1991). In parts of the Boise River valley, some wells are pumped to alleviate water-logging that developed after years of using surface water for irrigation (Nace and others, 1957, p. 65–67).

The budget given indicates that, in 1980, the hydrologic system in the western plain was in equilibrium. That was not true for some areas where pumping for irrigation caused negative changes in storage. Uncertainties in estimating budget components masked local nonequilibrium conditions.

TEMPORAL CHANGES IN THE HYDROLOGIC SYSTEM, 1880–1980

Prior to human settlement, long-term annual inflow to and outflow from the Snake River Plain were about equal and ground-water recharge equaled discharge. Temporary imbalances were natural phenomena and were caused by climatic variations. With development of water resources came an imbalance of inflow and outflow, recharge and discharge. Changes in the quantity, distribution, and quality of ground and surface water have been documented. Changes of greatest magnitude are attributable to the use of water for irrigation.

As use of water for irrigation increased, storage and distribution facilities (dams, reservoirs, and diversions) were constructed on the Snake River and major tributaries to increase and stabilize the amount of water available. Natural flow regimes of rivers and ground-water/surface-water relations changed accordingly. Unlike planned changes in the surface-water system, resultant changes in the ground-water system were largely unplanned.

RECHARGE

The use of surface water for irrigation significantly modified instream flow in the Snake River and its tributaries and increased ground-water recharge in surface-water-irrigated areas. By the early 1900's, natural flow in the Snake River was fully appropriated during low water years. To alleviate water shortages, several storage reservoirs were constructed on the Snake River and its tributaries (Kjelstrom, 1986). The largest, American Falls Reservoir, was completed during 1926 and has a total storage capacity of 1.7 million acre-ft.

Following reservoir construction and until the early 1930's, the amount of gravity-diverted water for irrigation on the eastern plain increased substantially (fig. 24). The amount of recharge likewise increased as reflected by rising ground-water levels (fig. 25). From the early 1930's until the 1950's, increases in surface-water diversions and rises of ground-water levels continued, but at a slower rate.

Although preirrigation ground-water-level data are few, they document that early water-level rises attributed to irrigation were, in places, rapid and of considerable magnitude. Starting in 1905, large tracts of land on the eastern plain near Twin Falls were irrigated with Snake River water diverted at Milner Dam. Mundorff and others (1964, p. 73) reported that water levels in the Twin Falls area (well 10S-17E-20AD) rose as much as 200 ft within 8 years (fig. 25). Water levels in wells in Jerome (well 8S-17E-19BBB1) and near Fort Hall (well 4S-34E-36BD) rose 20 to 40 ft during several tens of years. Mundorff and others (1964, p. 162) reported that the average water-level rise in the eastern plain west of American Falls may have been 60 to 70 ft from the early 1900's to 1959. Average water-level rise over most of the eastern plain was undoubtedly less, perhaps 40 to 50 ft.

Ground-water levels in the western plain (fig. 25, well 2N-1W-4DD) also rose in response to irrigation with surface water, mostly from the Boise River. Water levels rose 100 ft or more in parts of the Boise River valley from about 1915 to 1925 (Mundorff and others, 1964, p. 59), and the reported maximum water-level rise was about 140 ft (Nace and others, 1957, p. 10, 64). Ground-water levels in the western plain have risen little since about 1930.

Since about 1950, ground-water levels have been monitored in most parts of the plain. Hydrographs documenting changes are shown in reports by Nace and others (1957), Mundorff and others (1964), Mundorff (1967), Sisco (1974, 1975, 1976), Haskett and Hampton (1979), Young (1983), Young and Norvitch (1984), Lindholm and others (1987), and

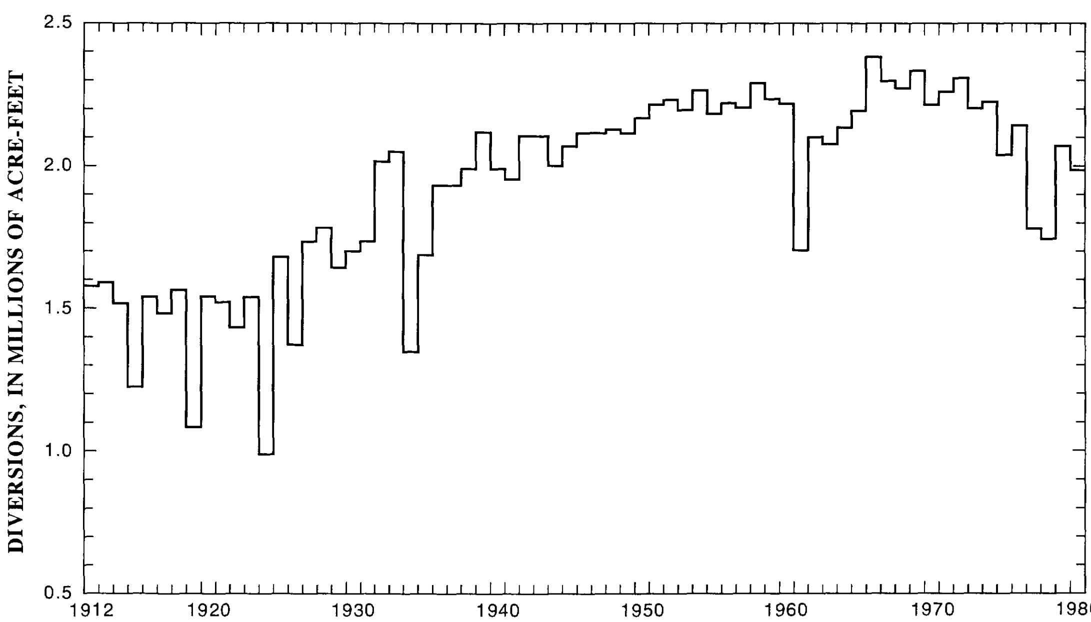
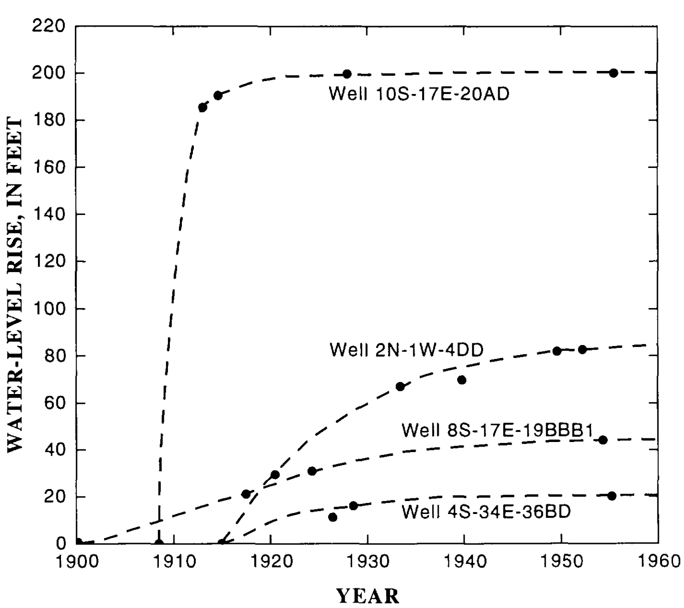


FIGURE 24.—Snake River north-side diversions for irrigation from Lake Walcott and Milner Lake.

Newton (1991). As shown in figure 26, long-term ground-water-level trends apparently are related to precipitation trends, although trend durations appear to differ. Differences occur because most water available to the plain originates as precipitation in mountainous tributary drainage basins. Much of that water is diverted for irrigation after tributary streams flow onto the plain. Therefore, changes in ground-water levels on the plain are related largely to precipitation in tributary drainage basins, rather than to precipitation on the plain. Differences between trends in ground-water level and precipitation also might be attributed to changes in ground-water withdrawals and efficiency of water use.

Long-term ground-water-level trends are similar in much of the eastern plain (fig. 27). The magnitude of water-level change varies, depending on local variations in the amount of recharge and discharge.

Hydrographs in figure 27 indicate that long-term ground-water-level trends in the western plain differ considerably from those in the eastern plain. Water levels in ground-water-irrigated areas in the eastern part of the western plain have declined steadily since the late 1960's. For example, the hydrograph for well 4S-5E-25BBC1, near Mountain Home, shows about a 30-ft decline in water level from 1967 to 1980. In that area, withdrawals exceeded estimated recharge and surface water was in short supply. Declines were serious enough that the IDWR closed the area to further ground-water development. South of the Snake River (well 10S-12E-11DBD1), the Blue Gulch area in Owyhee and Twin Falls Counties (pl. 1) was closed to further ground-water development because water levels declined 40 ft from 1968 to 1980 and annual water-level fluctuations doubled (Newton, 1991).



Modified from Lindholm (1986)

FIGURE 25.—Rises in ground-water levels owing to irrigation. Locations shown on plate 1.

In the Boise River valley, large quantities of surface water are diverted for irrigation. Consequently, ground-water levels in the valley generally have been stable relative to those in the rest of the western plain.

Water-level data from several hundred wells in Idaho, mostly on the Snake River Plain, were analyzed by Young and Norvitch (1984) to determine probable causes of water-level trends from 1971 to 1982. They attributed declines in water levels in several areas on the plain to increased ground-water withdrawals. In other areas, declines were attributed to reduced recharge from surface-water irrigation because of decreased diversions. In areas where irrigators changed from surface-water to ground-water supply, declines were accentuated. The switch from flood and furrow irrigation to sprinklers, a more efficient use of water, reduced recharge and caused ground-water levels to decline.

Short-term (annual) changes in ground-water levels also were analyzed by Young and Norvitch (1984, p. 5–7). They demonstrated how annual water-level highs and lows in nonirrigated areas differ in time from highs and lows in irrigated areas. In nonirrigated areas, water levels fluctuate in response to natural recharge and discharge (fig. 28). Levels are lowest in winter and highest in spring, following recharge from snowmelt. In surface-water-irrigated areas, ground-water levels are lowest just prior to the irrigation season (about April). Levels rise rapidly in response to increased recharge after irrigation begins. Water levels remain high until the end of the irrigation season (October). Conversely, water levels in ground-water-irrigated areas are lowest at the end of an irrigation season and rise gradually until the next irrigation season begins. Where both ground and surface water are used for irrigation, short-term changes in ground-water levels are a composite of the two effects.

Hydrographs in figure 27 also show changes in the amplitude of annual water-level fluctuations due to changes in the amount of recharge and (or) withdrawal. For example, the hydrograph for a well in a surface-water-irrigated area (7N-38E-23DBA1) shows a decrease in annual water-level change, from about 4 to 5 ft/yr during the late 1950's through the mid-1970's to about 3 ft/yr during the late

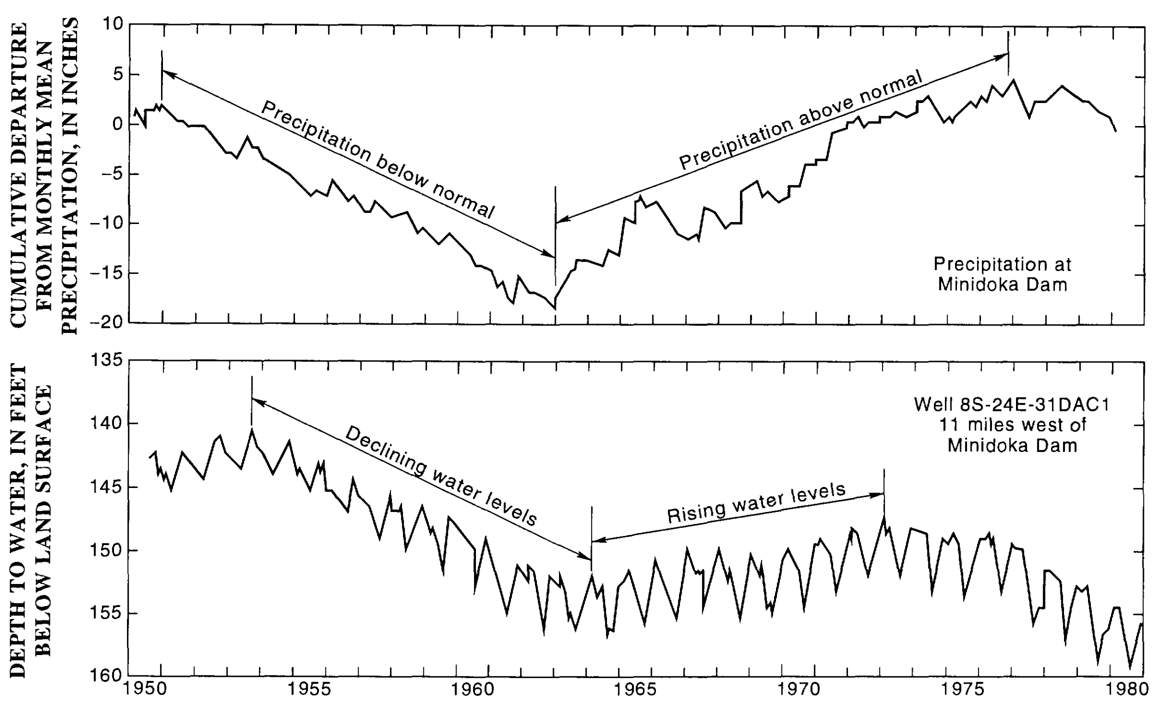
1970's. The decreased amplitude reflects a reduction in recharge owing to decreased surface-water diversions for irrigation and below-normal precipitation from 1976 to 1980. A similar decrease in amplitude of annual water-level change took place in other surface-water-irrigated areas, as shown by the hydrograph for well 5S-31E-27ABA1.

In ground-water-irrigated areas, the opposite takes place. As withdrawals increase, the amplitude of annual water-level change increases. For example, well 5N-34E-9BDA1 is immediately downgradient from an area where large quantities of ground water are withdrawn for irrigation. From 1950 to about 1970, annual water-level change was 3 to 4 ft. During that time, ground-water withdrawals for irrigation gradually increased. During the 1970's, the rate of increase in the use of ground water for irrigation accelerated. As a result, annual ground-water-level fluctuations nearly doubled. During the late 1970's, precipitation was below normal and the combination of increased pumpage and reduced recharge resulted in lower water levels in addition to greater annual fluctuations. A similar but more subtle change is shown by the hydrograph for well 8S-24E-31DAC1, which is in a major ground-water-irrigated area.

GROUND-WATER DISCHARGE

The use of surface water for irrigation increased the amount of ground-water discharge as well as the amount of recharge. Since the turn of the century, added recharge in surface-water-irrigated areas in the western part of the eastern plain raised ground-water levels several tens of feet and increased north-side ground-water discharge to the Snake River between Milner and King Hill (Kjelstrom, 1986). From 1902 through 1911, average annual discharge from Milner to King Hill was about 3.0 million acre-ft (fig. 29). Discharge then increased steadily with relatively minor annual variations until 1951, when it peaked at about 4.9 million acre-ft.

Steady ground-water discharge from the main part of the eastern plain to the Milner-to-King Hill reach from 1952 through 1955 implies a temporary balance between recharge and discharge during those years. From 1955 to 1980, discharge generally decreased except for a minor increase caused by increased precipitation during the late 1960's and early 1970's (fig. 26). Decreased ground-water discharge to the river can be attributed to several fac-



Modified from Young and Norvitch (1984)

FIGURE 26.—Relation of precipitation to ground-water-level trends. Locations shown on plate 1.

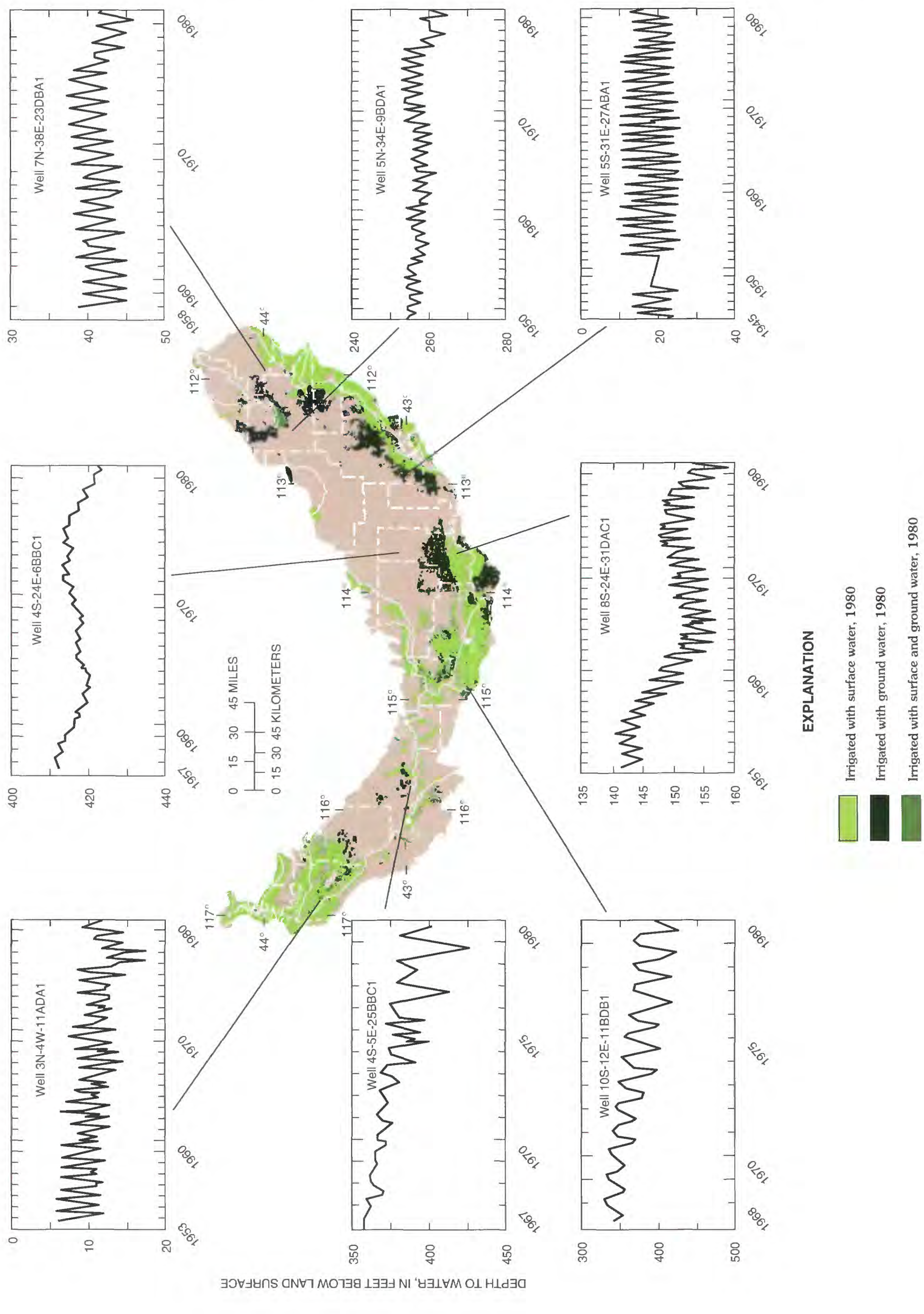
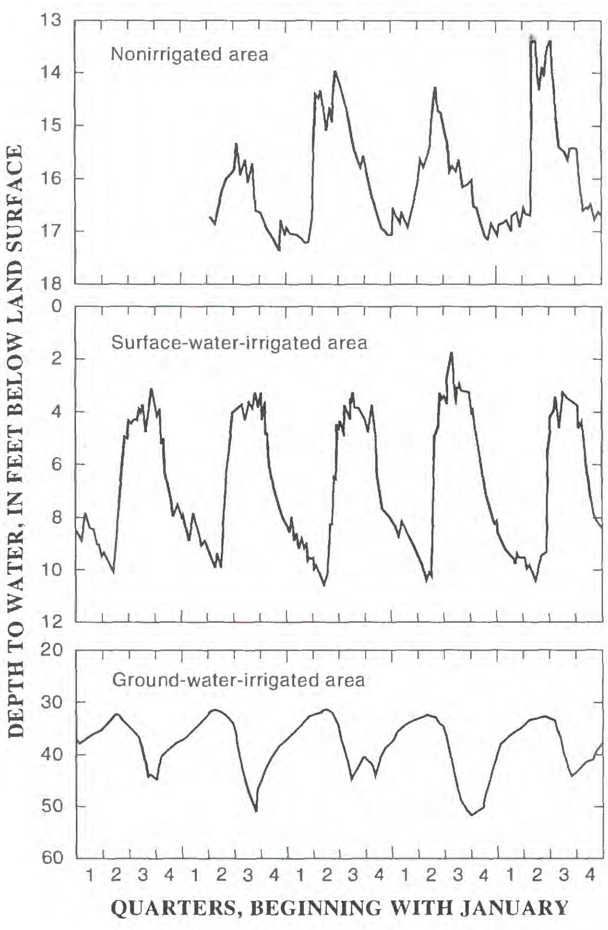


FIGURE 27.—Long-term ground-water-level trends.

tors, one of which is increased ground-water withdrawals. From the mid-1940's to about 1960, the number of acres irrigated with ground water increased rapidly (fig. 30). In about 1960, the long-term increase in surface-water diversions ceased (fig. 24).

Unlike discharge to the Milner-to-King Hill reach, ground-water discharge to the Snake River between gaging stations near Blackfoot and at Neeley (pl. 1) has been relatively stable for many years (fig. 29). Average annual discharge to the reach from 1912 to 1980 was about 1.8 million acre-ft with a standard deviation of 0.08 million acre-ft (Kjelstrom, in press). Kjelstrom used Snake River discharge measurements to estimate that ground-water discharge to the Blackfoot-to-Neeley reach during 1908 was about 1.4 million acre-ft. He attributed the increase in discharge prior to 1912 to increased recharge from surface-water irrigation.



Modified from Young and Norvitch (1984)

FIGURE 28.—Short-term changes in ground-water levels.

Hydrographs of September discharge from four spring-fed creeks to American Falls Reservoir (fig. 31) verify the steadiness of ground-water discharge to the Blackfoot-to-Neeley reach as determined by water-budget analysis (Kjelstrom, 1992). The largest, Spring Creek, contributes about one-fifth of the total ground-water discharge to the Blackfoot-to-Neeley reach.

Long-term hydrologic changes in the western part of the plain are less well defined because pertinent data on tributary inflows, return flows, and diversions were unavailable and values are difficult to estimate.

GROUND-WATER BUDGETS

Ground-water budgets for the main part of the eastern plain (pl. 1, area south of the Snake River from Neeley to Salmon Falls Creek excluded) for 1880 (preirrigation) and 1980 (fig. 32) reflect regional quantitative changes in the hydrologic system resulting from 100 successive years of irrigation. Before large areas were irrigated, total average annual recharge to and discharge from the ground-water system in the main part of the eastern plain was about 3.9 million acre-ft. About 60 percent of the total recharge was from tributary drainage basins, 25 percent was from Snake River losses, and 15 percent was from precipitation on the plain. Ground-water discharge was entirely to the Snake River.

Continued use of surface water for irrigation effected major changes in the regional ground-water system. By 1980, annual ground-water recharge in the main part of the eastern plain was about 6.7 million acre-ft, an increase of 70 percent over recharge during 1880. About 65 percent of the total recharge was irrigation return flow (percolation of surface water diverted for irrigation). Drainage from tributary basins contributed 20 percent of the total during 1980 compared with 60 percent during 1880; precipitation on the plain contributed 10 percent; and Snake River losses, 5 percent. During 1980, about 10 percent of total ground-water discharge was pumpage for irrigation and the remainder discharged to the Snake River. Total discharge during 1980 exceeded total recharge by about 400,000 acre-ft. This implies a decrease in ground-water storage as suggested by Garabedian (1986, p. 10) and Kjelstrom (1992).

Kjelstrom (in press) calculated annual ground-water budgets for the main part of the eastern plain for the period 1912–80. He assumed that differences between annual recharge and discharge estimates reflected changes in ground-water storage. Although absolute values of annual change in storage are subject to estimation errors, cumulative changes in storage (fig. 33) correspond with historical changes in ground-water levels (figs. 25 and 27) and north-side ground-water discharge to the Snake River from Milner to King Hill (fig. 29).

According to Kjelstrom (1992), ground-water storage in the main part of the eastern plain increased about 24 million acre-ft from preirrigation to 1952; about three-quarters of the total increase was between 1912 and 1952. This estimate is comparable to that computed from the average long-term water-level rise of 40 to 50 ft and an estimated specific yield of 0.10 (average for basalt and sediment saturated by water-level rise). Mundorff and others (1964, p. 210) concluded that a 10-ft rise in water levels in the eastern plain represents a storage increase of 5 million acre-ft.

From 1952 to 1964, storage decreased because of below-normal precipitation (fig. 26) and increased withdrawals of ground water for irrigation (fig. 30). Storage increases from 1965 to 1975 coincide with a period of above-normal precipitation. Decreases in storage from 1976 to 1980 can be attributed to below-normal precipitation, which resulted in decreased surface-water diversions for irrigation and increased ground-water pumping.

Temporal changes in water-budget components for the main part of the eastern plain are shown in figure 34. Although there was only incidental collection of ground-water data until the late 1940's, the availability of Snake River discharge data since 1902 and diversion data since 1912 make possible several long-term correlations. Until about 1950, diversion of surface water for irrigation caused major changes in the ground-water system, changes that obscured natural hydrologic stresses, such as the drought of the 1930's. Kjelstrom (1992) noted that during the period 1951–55, ground-water recharge and discharge were almost equal for the first time since the start of irrigation. Since 1955, climatic variations (mainly precipitation) and withdrawals of ground water for irrigation have been major factors affecting long-term hydrologic trends. For example, during the period 1963–76, precipitation was above normal and more water was available for irrigation diversions and ground-water recharge. As a result, aquifer storage and, ultimately, discharge, increased. Several years of below-normal precipitation followed.

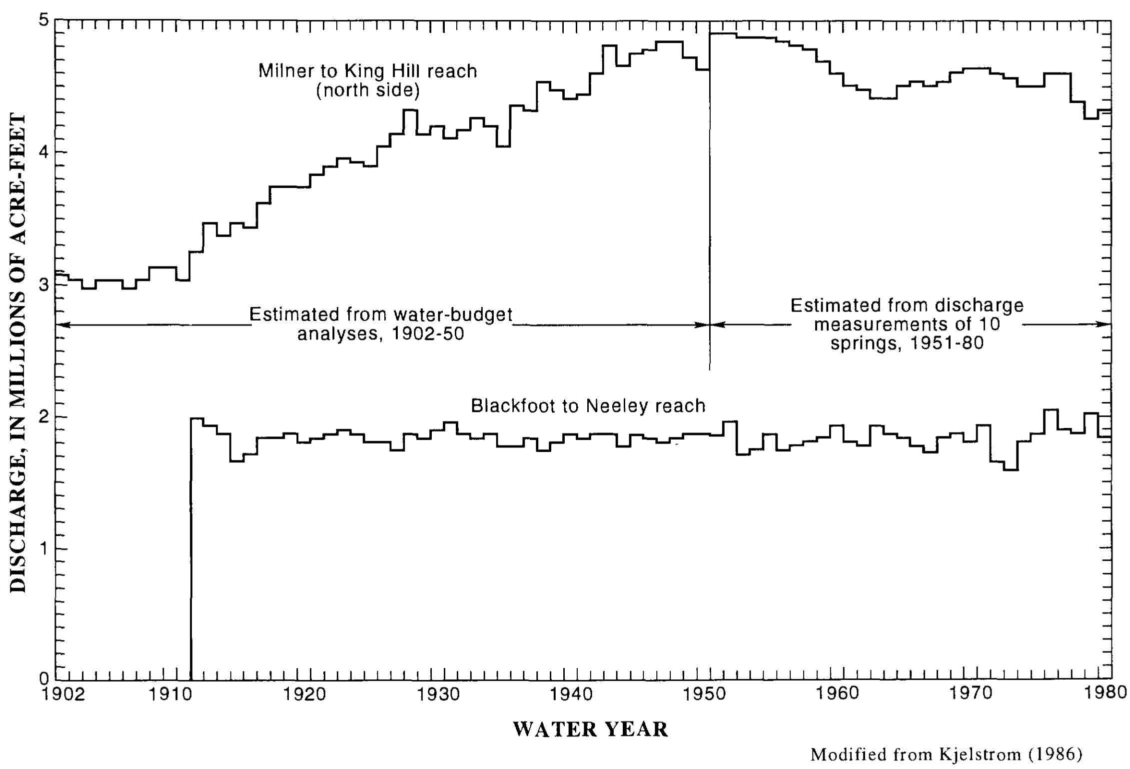
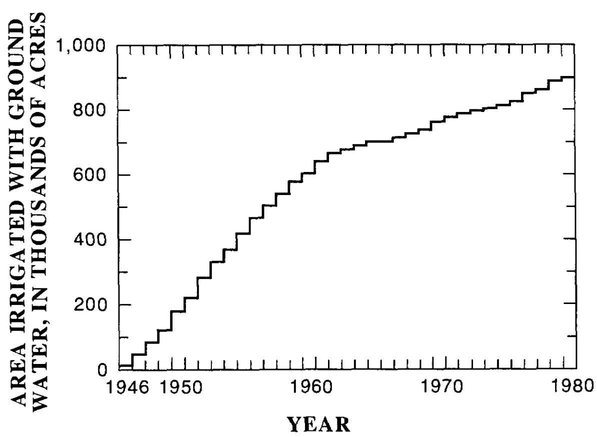


FIGURE 29.—Estimated ground-water discharge to Snake River, eastern Snake River Plain.

Less water was available for irrigation diversions and, therefore, ground-water recharge, storage, and discharge decreased.

Kjelstrom (1992) calculated annual ground-water budgets for the western plain for the period 1930–80. Cumulative change in ground-water storage and 5-year moving average of precipitation for that period are shown in figure 35. Water-level data for well 2N-1W-4DD (fig. 25) indicate major increases



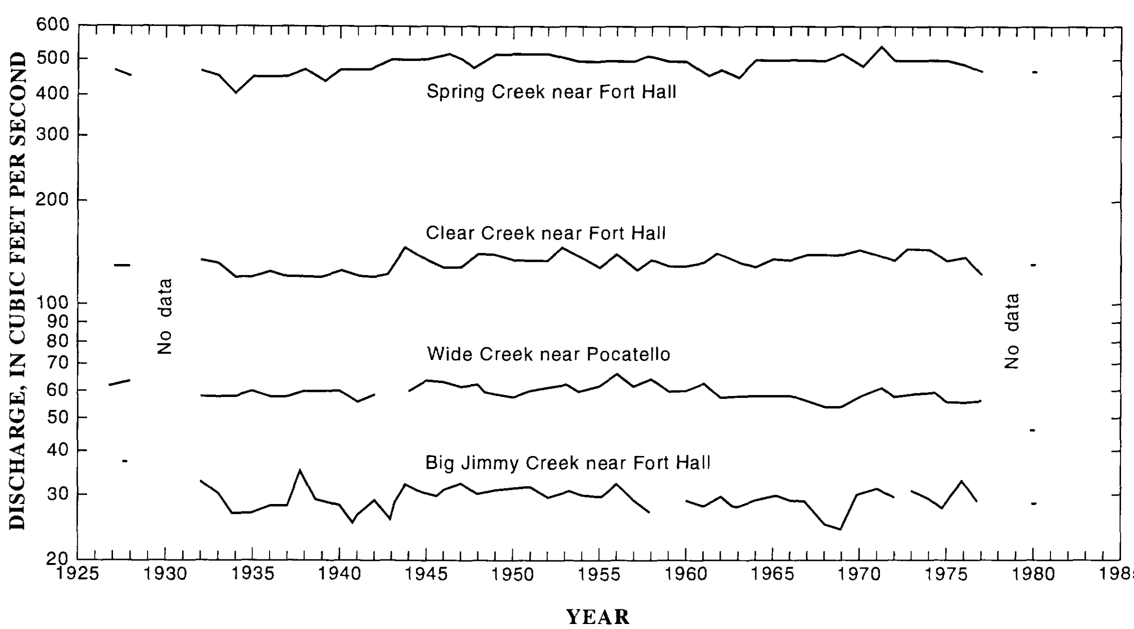
From L.C. Kjelstrom (U.S. Geological Survey, written commun., 1986)

FIGURE 30.—Approximate increases in ground-water-irrigated acreage, eastern Snake River Plain (excluding area south of Snake River from Neeley to Salmon Falls Creek).

in ground-water storage in the Boise River valley between 1915 and 1940. Ground-water storage was increased because storage facilities, such as Arrowrock Reservoir on the Boise River (pl. 1), increased the use of surface water for irrigation (fig. 36). Ground-water storage increased during the 1930's despite below-normal precipitation. The increase in ground-water storage from the early 1950's to the early 1970's can be attributed to increased irrigation with surface water after completion of several major instream storage facilities—C.J. Strike, Anderson Ranch, Lucky Peak, and Cascade Reservoirs. After 1960, water from C.J. Strike Reservoir and the Snake River was pumped to irrigate large tracts of land on the western plain (Bigelow and others, 1987). Pumpage and above-normal precipitation during the late 1960's and early 1970's added to the increase. Storage decreased from the early 1970's to 1980 due to decreased surface-water diversions, increased use of ground water, and decreased precipitation.

GROUND-WATER QUALITY

Temporal changes in ground-water solute concentrations in the Snake River Plain are poorly defined. Low (1987) noted that concentrations of dissolved solids and chloride are generally greatest in areas of fine-grained sedimentary rocks and in intensively irrigated areas. Wood and Low (1988, p. 16) stated



From Kjelstrom (1992)

FIGURE 31.—Discharge to American Falls Reservoir from spring-fed creeks, September measurements.

that, for steady-state conditions, solute load in the eastern plain is from (1) tributary drainage basins, (2) precipitation on the plain, (3) underflow, and (4) weathering of rocks in the aquifer and from human activities. They concluded that about 20 percent of the total solute load is from rock weathering and human activities; the amount contributed by human activities alone is difficult to quantify. They further concluded that irrigation has had little effect on the

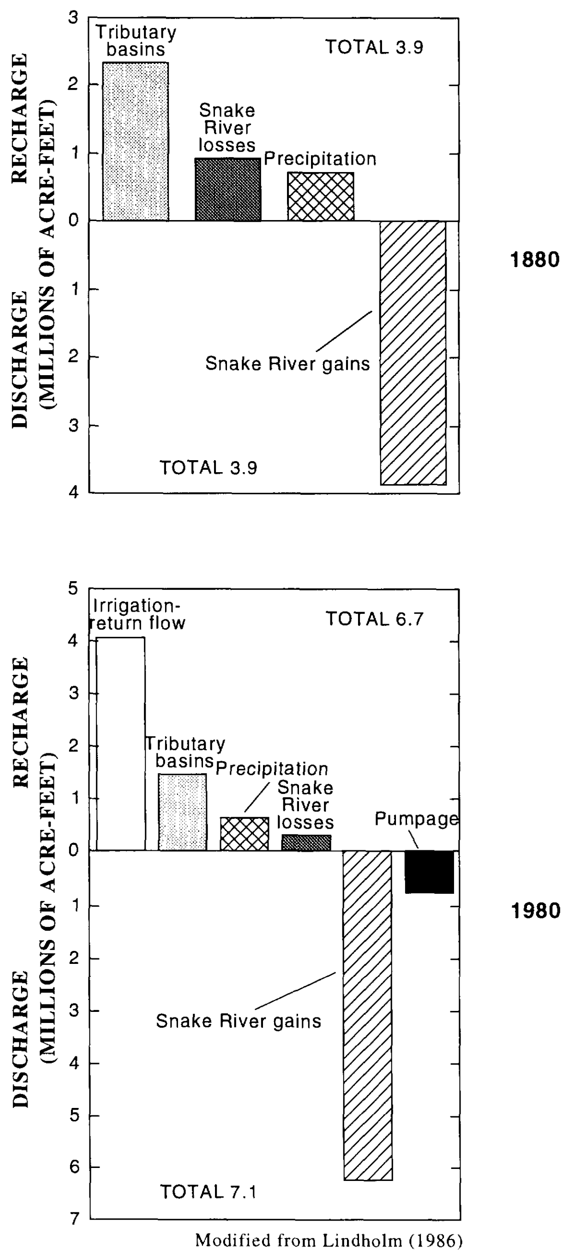


FIGURE 32.—Changes in ground-water budget, 1880 to 1980, main part of eastern Snake River Plain (excluding area south of Snake River from Neeley to Salmon Falls Creek).

concentration of the major solutes (calcium, magnesium, sodium, potassium, bicarbonate, sulfate, chloride, and silica). About 5 percent of the measured increases in sodium and chloride loads might be from sewage effluent and another 1 percent from road salt.

Several earlier investigators considered temporal changes in ground-water quality. Stevens (1962) studied effects of irrigation on ground-water quality, mainly the increase in dissolved-solids concentrations, in Canyon County, Idaho. Norvitch and others (1969, p. 26–30) evaluated changes in the chemical quality of ground water due to irrigation on the eastern plain. They noted increases in dissolved solids, sodium, sulfate, and chloride concentrations and a decrease in bicarbonate concentrations in irrigated areas. Although there are no data on preirrigation ground-water quality, Norvitch and others (1969, p. 28) hypothesized that the major increase in dissolved solids took place with the first massive application of irrigation water during the late 1800's and early 1900's.

During a reconnaissance study of the quality of water from irrigation wells and springs on the eastern plain, Dyer and Young (1971) noted that, in 1970, virtually all ground water in irrigated areas had a specific conductance ranging from 300 to 1,000 μS/cm; the maximum was 1,560 μS/cm. They stated that conductance in the central, nonirrigated part of the plain is probably less than 300 μS/cm. They also noted that chloride and nitrate concentrations were greater in irrigated areas than in nonirrigated areas.

Effects of land use on the quality of shallow ground water in the Boise-Nampa area were investigated by Dion (1972, p. 39–40). Although slight increases in dissolved solids were noted, Dion concluded that quality of water changed little between 1953 and 1970.

Seitz and others (1977) described the quantity and quality of waste water introduced into the ground-water system through several thousand drain wells in the western part of the eastern Snake River Plain. They determined that suspended sediment is present in most irrigation waste water. The introduction of sediment into ground water makes possible the addition of heavy metals and pesticides that might be adsorbed on the sediment, though none were detected in the samples analyzed. Bacteria were detected in all samples of drain well inflow. As might be expected, bacteria concentrations were greatest in septic tank effluent. Because the volume of water entering the aquifer through drain wells is relatively small compared with the volume of water moving through the aquifer, no adverse regional water-quality effects were noted.

Temporal variations in water-quality characteristics in several parts of the Snake River Plain were described by Parliman (1982b; 1983a, p. 37–41; 1983b, p. 63–73; 1986, p. 54) in terms of specific conductance and dissolved chloride and sulfate concentrations. She noted that "short-term changes most often are due to seasonal fluctuations in volume or quality of recharge to aquifers" (Parliman, 1983b, p. 37). Parliman further noted that "trends may show either improvement or degradation of water quality, but in most instances, reflect the effects of changing land- and water-use practices."

The U.S. Bureau of Reclamation (1979, 1981, 1984) studied the effects of onsite waste disposal systems (septic tanks) on shallow ground-water quality in the Boise area from 1978 to 1983. They determined that sodium, chloride, nitrite and nitrate, total phosphorus, and orthophosphorus concentrations increased significantly with time in onsite disposal areas.

GROUND-WATER FLOW MODELS

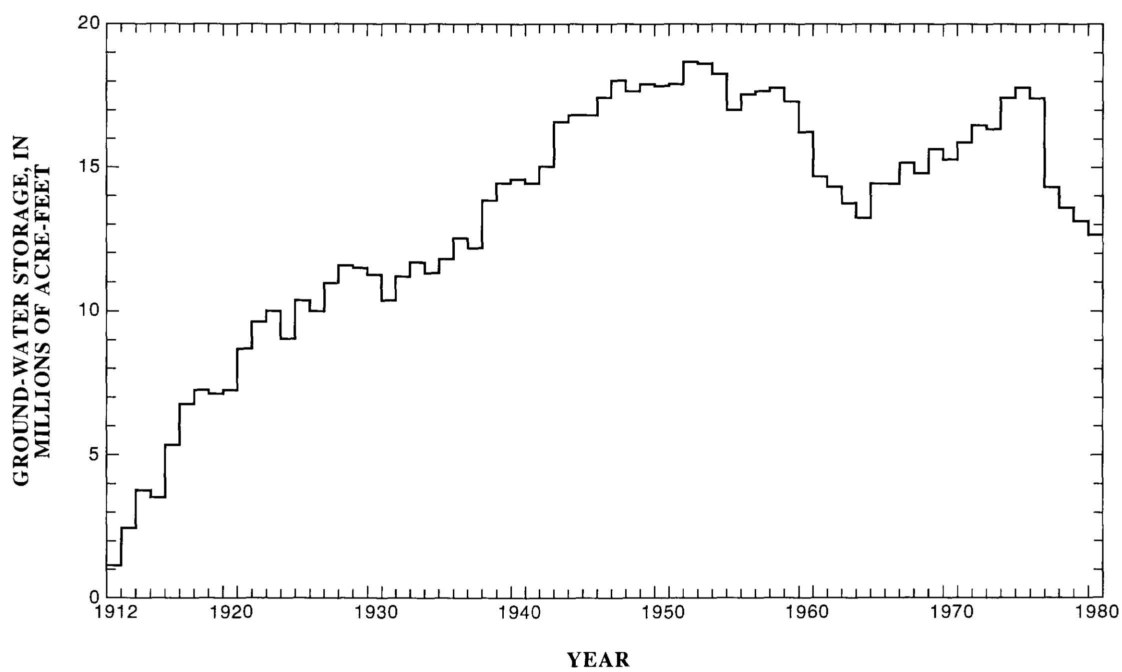
Digital computer models were used to simulate major components of ground-water flow in the eastern and western Snake River Plain. Two- and three-dimensional finite-difference models of the eastern plain were developed by Garabedian (1986; in press) and are described in Chapter F of this Professional Paper series. A three-dimensional, finite-difference model of the western plain was developed by Newton (1991) and is described in Chapter G.

All models were regional in scope, and model detail was commensurate with supporting geologic, hydrologic, and land-use data. On the Snake River Plain, recharge and discharge (particularly spring flow) were better defined and more easily quantified than transmissivity and other aquifer properties; therefore, flux through the regional aquifer system was used for control during model simulations to better estimate values for aquifer and confining unit properties.

EASTERN PLAIN

Modeling the regional aquifer system in the eastern plain progressed from two-dimensional steady-state simulation to three-dimensional steady-state and transient simulations.

A nonlinear, least-squares regression technique was used by Garabedian (1986) to calibrate a two-dimensional steady-state flow model to 1980 hydro-



From Kjelstrom (1992)

FIGURE 33.—Estimated cumulative change in ground-water storage, main part of eastern Snake River Plain (excluding area south of Snake River from Neeley to Salmon Falls Creek).

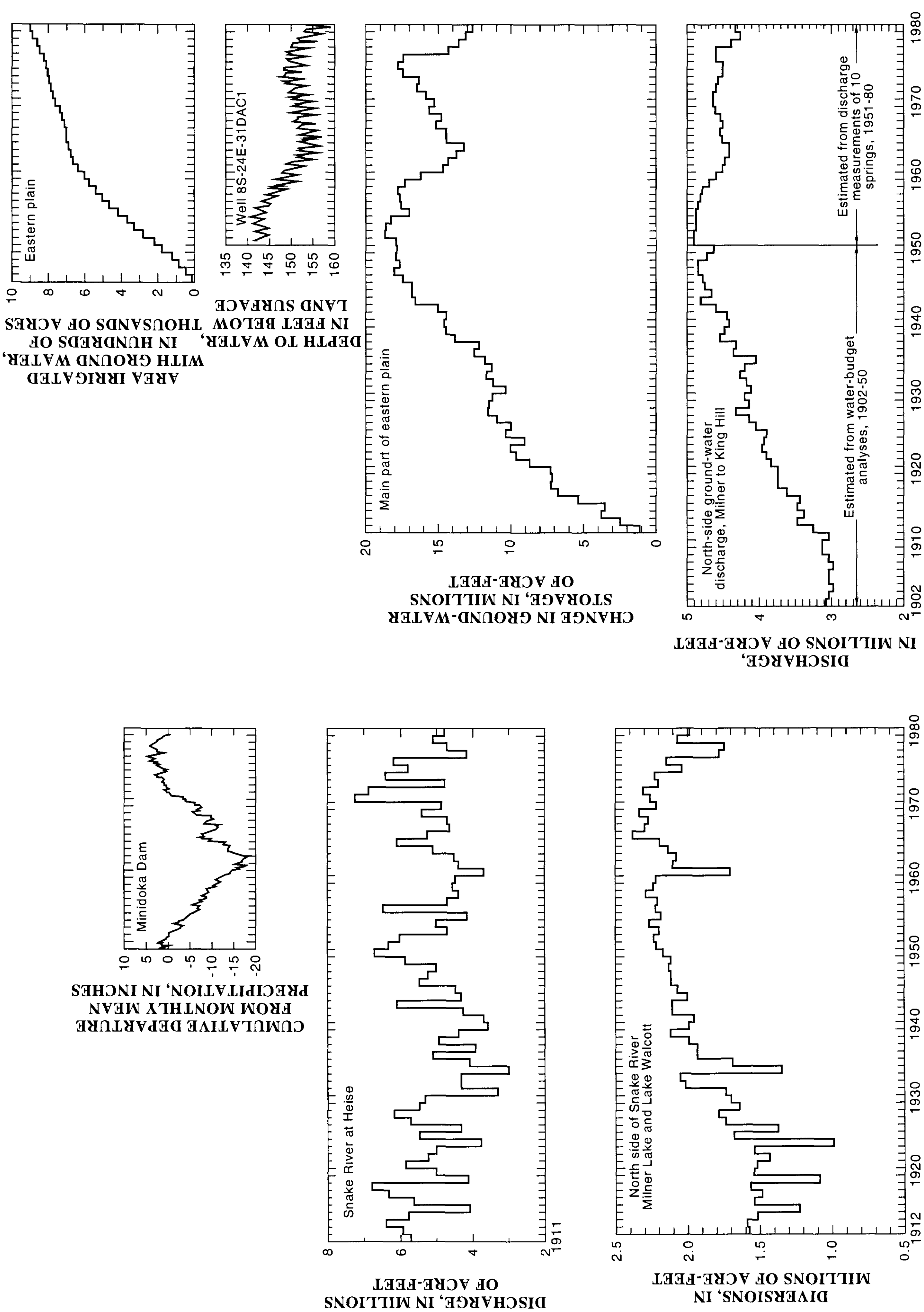


FIGURE 34.—Temporal changes in water-budget components, main part of eastern Snake River Plain (excluding area south of Snake River from Neeley to Salmon Falls Creek).

logic conditions and to make initial estimates of aquifer transmissivity. The eastern plain was divided into 15.6-mi^2 cells that were grouped into 20 model subareas on the basis of geologic and hydrologic characteristics of the aquifer system.

Model results indicated a wide range in average transmissivity, from 4.3×10^3 to 3.8×10^6 ft^2/d. In general, values obtained compared well with those obtained by previous investigators (Garabedian, 1986, table 13, p. 20; and tables 1 and 2 in this report). Comparisons were good for the central part of the plain, where ground-water flow is largely horizontal. Major differences in values were along the margins of the plain, where sedimentary interbeds are more prevalent, the aquifer thins rapidly, and ground-water flow also has a large vertical component.

Transmissivity values from the two-dimensional model were used as initial input for three-dimensional steady-state and transient flow models. To

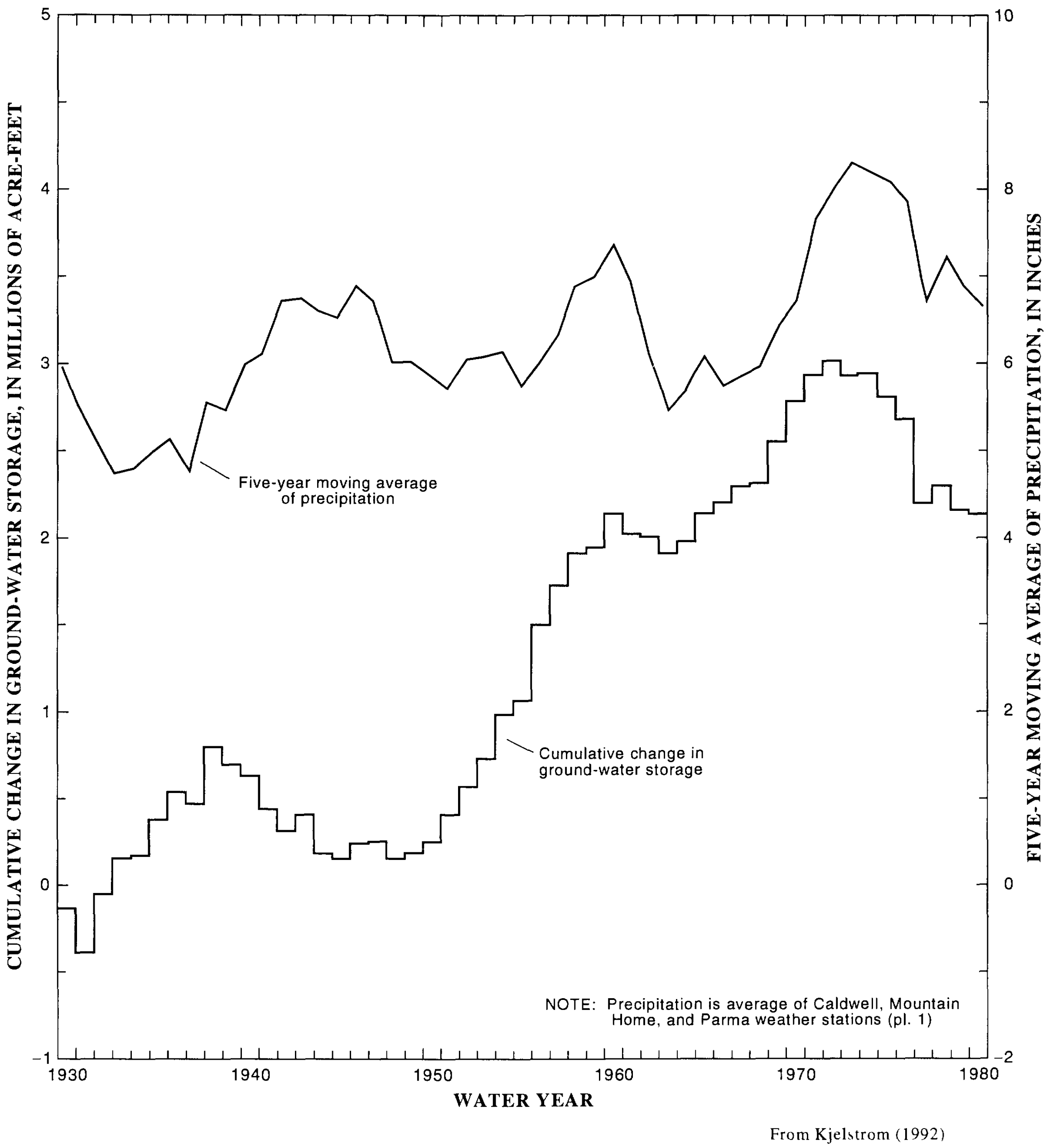


FIGURE 35.—Estimated cumulative change in ground-water storage and 5-year moving average of precipitation, western Snake River Plain, October-March, 1930–80.

simulate three-dimensional flow, the aquifer was subdivided vertically into four model layers as shown in figure 37. Layer 1 represented the regional aquifer system from the water table, as defined in March 1980, to a depth 200 ft below the water table. Most wells are completed in that interval. Layer 2 represented the next 300 ft of the regional system. Layers 1 and 2 represented mainly Snake River Group basalt that comprises the upper part of the regional aquifer through which most water was thought to move. Layers 3 and 4 represented undifferentiated Quaternary-Tertiary basalt with interlayered sedimentary rocks.

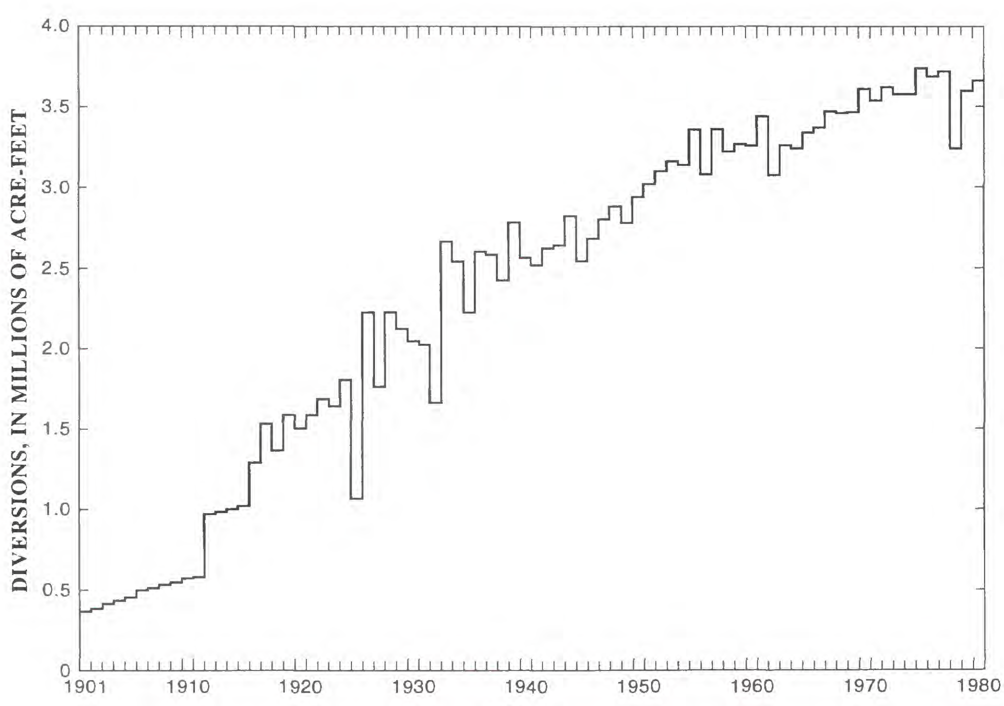
For the three-dimensional model, the eastern plain was divided into 16-mi^2 cells, which were grouped into 40 model subareas on the assumption that aquifer properties throughout the subarea are the same (fig. 38). Average subarea transmissivity of model layer 1 ranged from 1.1×10^3 to 1.8×10^6 ft^2/d.

The model of the eastern Snake River Plain was most sensitive to changes in transmissivity and recharge, as shown by ground-water-level and discharge hydrographs presented by Garabedian (in press). The model was less sensitive to induced changes in other hydrologic parameters—storage coefficient, aquifer leakance, river conductance, ground-water pumpage, and boundary flux. Changes in those parameters might effect significant differences in model response. Different combinations of parameter values might produce the same model response; however, the combinations of values used were constrained within reasonable limits imposed by available data and hydrologic judgment.

Although few ground-water-level measurements were made prior to 1950, estimates of head changes from 1890 to 1980 were simulated. Simulated head changes were in general agreement with reported changes as discussed in the section, "Temporal Changes in the Hydrologic System."

The transient model was used to simulate aquifer response to three hypothetical development alternatives extended through the year 2010: (1) an extension of 1980 hydrologic conditions, (2) increased pumpage, and (3) increased recharge (Garabedian, in press). In reality, some unpredictable combination of the three alternatives might be expected.

Simulation indicated that if recharge and discharge were to continue at 1980 levels for 30 years (1981–2010), ground-water levels could decline 2 to 8 ft in the central part of the plain and could decline even more along the margins. Concurrently,



From Newton (1991)

FIGURE 36.—Surface-water diversions for irrigation, western Snake River Plain.

ground-water discharge to the Blackfoot-to-Neeley and Milner-to-King Hill reaches of the Snake River could decrease about 5 percent.

Simulation further indicated that if average annual ground-water pumpage were increased by about 1.7 million acre-ft/yr to irrigate an additional 1 million acres of potentially arable land, heads across the central part of the plain could decrease an additional 10 to 40 ft within 30 years. River leakage could increase by 50 percent and ground-water discharge could decrease by 20 percent over the same time period (Garabedian, in press).

If 1980 ground-water recharge were increased by 0.6 million acre-ft/yr in selected areas, heads could increase 5 to 10 ft in the immediate area of application; little or no increase in head would be expected in the central part of the plain.

WESTERN PLAIN

Geologic complexities of the western plain and inadequate data for model input dictated that major emphasis first be given to development of a concep-

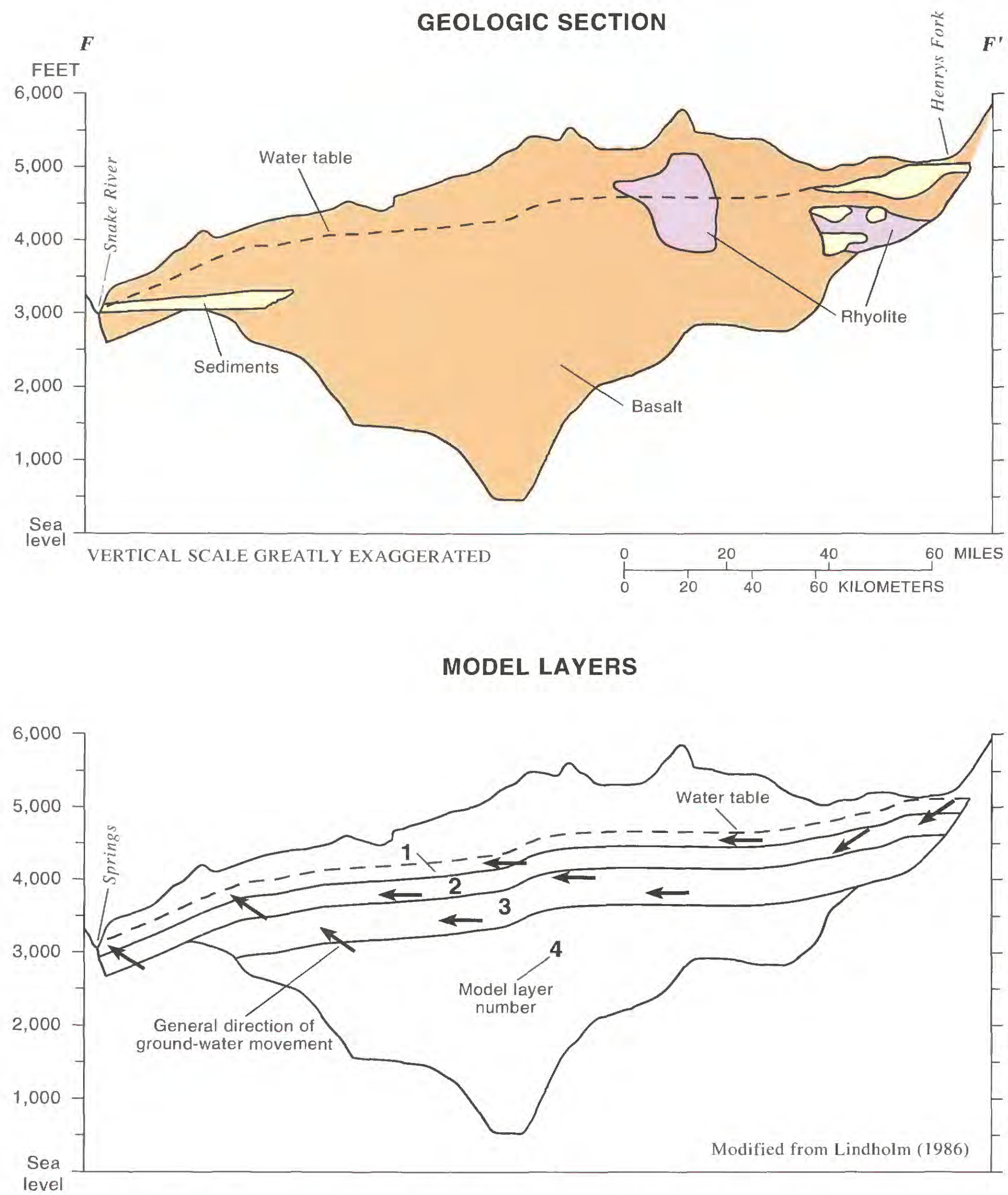


FIGURE 37.—Generalized geologic section and conceptual model, eastern Snake River Plain. Line of section shown in figure 38.

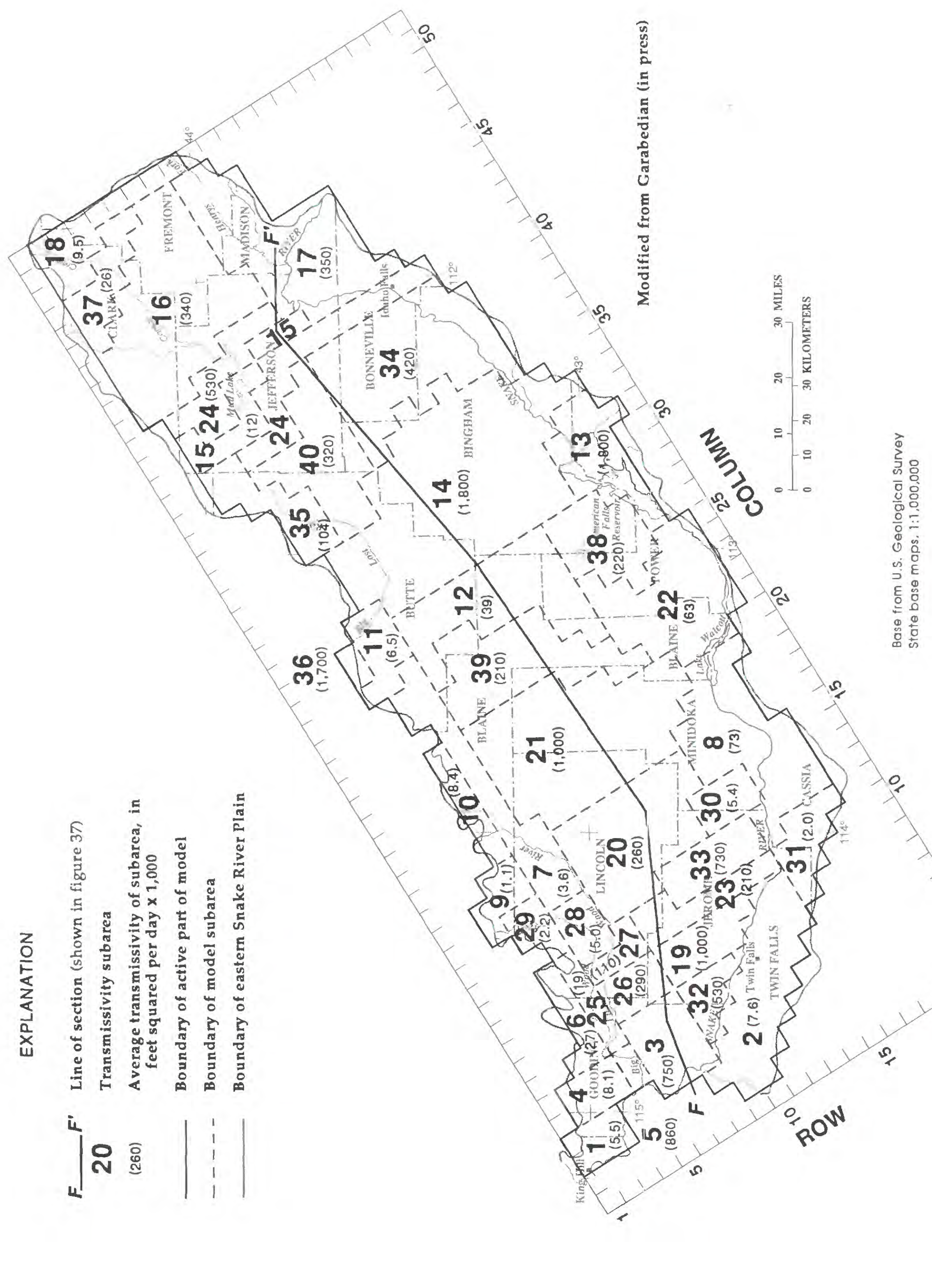


FIGURE 38.—Model grid and transmissivity of subareas for layer 1 in three-dimensional model, eastern Snake River Plain.

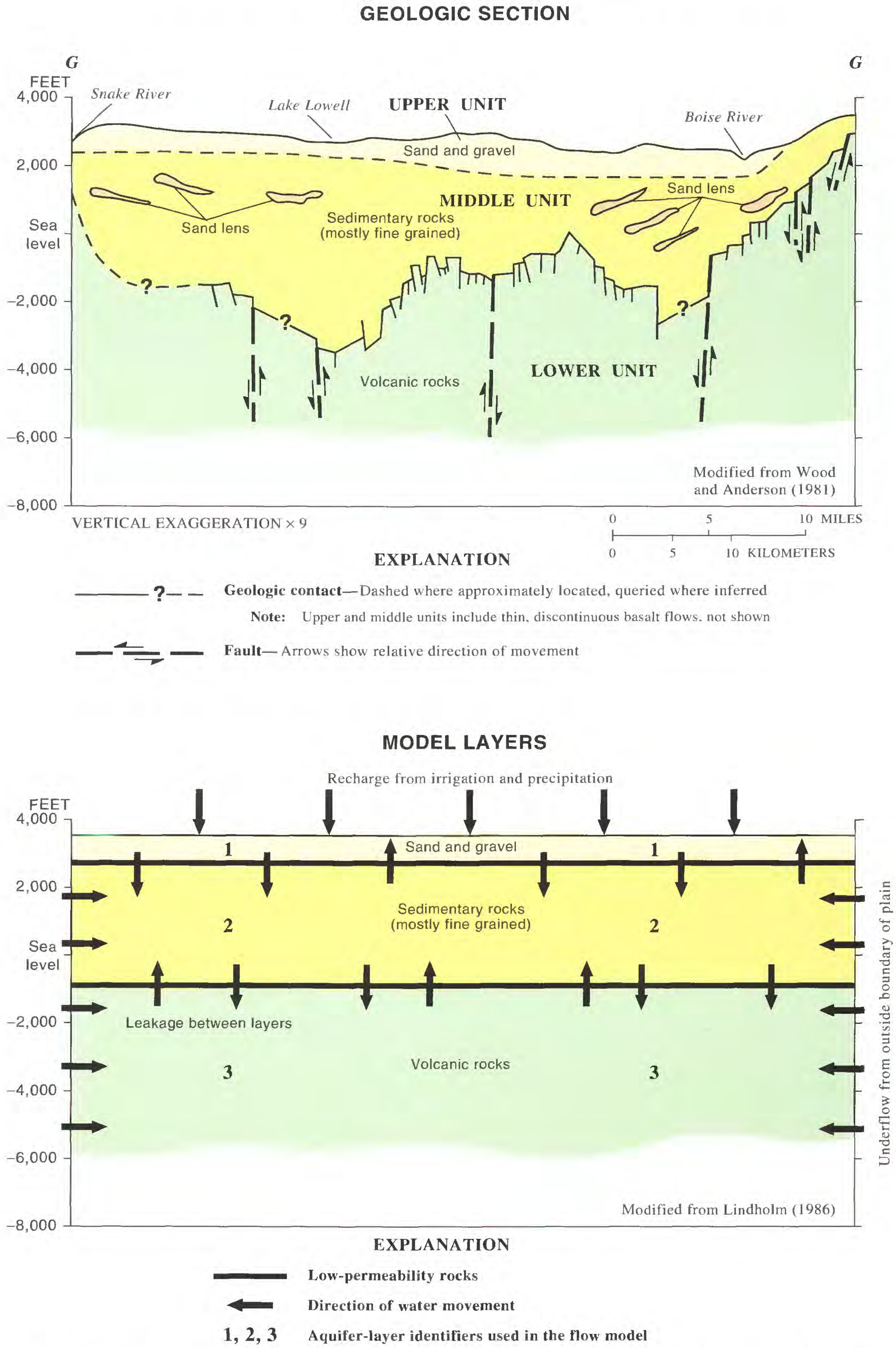


FIGURE 39.—Generalized geologic section and conceptual model, western Snake River Plain. Line of section shown in figure 40.

tual ground-water flow model. On the basis of that model, Newton (1991) developed steady-state and transient numerical models of the western plain, where water is withdrawn from numerous geologically discontinuous but hydraulically connected aquifers.

The regional aquifer system in the western plain was subdivided vertically into three model layers as shown in figure 39. Layer 1 represented about 500 ft of Quaternary sand and gravel in the Boise River valley and basalt of the Snake River Group and Quaternary-Tertiary sedimentary rocks of the Bruneau Formation and Idaho Group in the rest of the western plain. Most wells are less than 500 ft deep; some are completed in confined aquifers. In the Boise River valley, most wells are less than 200 ft deep and are completed in largely unconfined sand and gravel aquifers, which are part of model layer

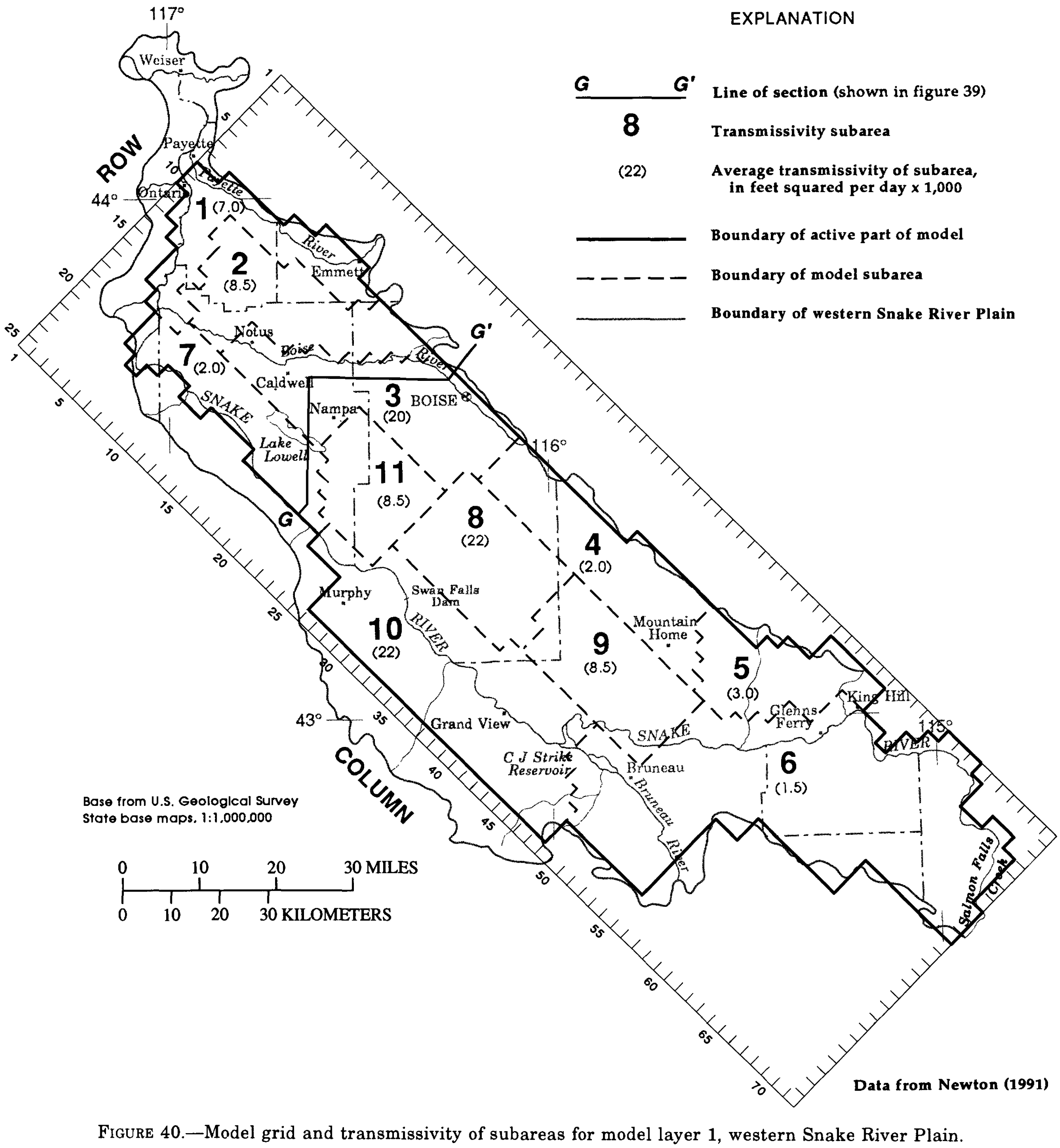


FIGURE 40.—Model grid and transmissivity of subareas for model layer 1, western Snake River Plain.

1. Model layer 2 represented several thousand feet of predominantly fine-grained Idaho Group sediments; layer 3 represented several thousand feet of Tertiary volcanic rocks. Water in aquifer layers 2 and 3 is largely confined. Geothermal water is present in aquifer layer 3 along the margins of the plain and perhaps underlies the entire western plain.

The western plain was divided into 4-mi^2 cells which were grouped into 11 model subareas on the basis of geologic and hydrologic characteristics of the aquifer system (fig. 40).

The steady-state model was calibrated to 1980 hydrologic conditions, primarily spring 1980 ground-water levels, to determine initial values of transmissivity, boundary flux, vertical leakage, and recharge. The assumption that recharge and discharge were almost equal during 1980 is supported by water-level hydrographs (fig. 27), most of which show little or no change in storage for that year. However, the assumption of steady-state conditions was not valid for all parts of the western plain. Water levels declined 35 ft in the Mountain Home area (pl. 1) from the mid-1960's to the early 1980's (Newton, 1991). During the same time period, water levels in the Blue Gulch area declined as much as 40 ft and seasonal water-level fluctuations doubled. Similar declines took place in parts of northern Owyhee County.

Sensitivity analysis indicated that heads in the Boise River valley were controlled largely by the altitude of the river and drains (Newton, 1991) and were less sensitive to changes in recharge, transmissivity, and other aquifer parameters. Values of discharge from drains were highly sensitive to changes in aquifer properties and riverbed conductance. The model also was sensitive to changes in vertical hydraulic conductivity, which controls upward leakage to aquifers in model layers 1 and 2.

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