Hydrology of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho

By H. H. Bauer and A. J. Hansen, Jr.

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.0929	square meter
acre	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
cubic mile (mi^3)	4.168	cubic kilometer
inch per year (in/yr)	2.540	centimeter per year
foot per second (ft/s)	0.3048	meter per second
foot per day (ft/d)	0.3048	meter per day
foot squared per second (ft^2/s)	0.09290	meter squared per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
pound per square inch (lb/in^2)	6.895	kilopascal

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

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ABSTRACT

The Columbia Plateau aquifer system underlies about 50,600 square miles in Washington, Oregon, and a small part of northwestern Idaho. The aquifer system is composed primarily of Miocene flood basalts of the Columbia River Basalt Group. Approximately 4,500 square miles of saturated sedimentary deposits (hereafter referred to as the overburden aquifer) overlying the basalts, mainly in the central part, are also a part of the aquifer system.

A five-layer, numerical finite-difference ground-water model covering 32,688 square miles was used to simulate the regional ground-water flow system. The uppermost layer represents the overburden aquifer, and all other layers represent the various basalt formations. The model simulated and was calibrated to data from the period 1983-1985 using a time-averaged steady-state approach. After the time-averaged model was calibrated, the predevelopment (1850's) and hypothetical future flow systems were simulated.

Recharge to the aquifer system from natural precipitation and irrigation, estimated by soil-moisture budgeting, ranges from zero in low-lying areas that receive precipitation of less than 8 inches annually, to more than 30 inches per year in the mountainous and irrigated areas. Recharge was estimated to be 6,566 ft^3/s (cubic feet per second) under predevelopment conditions and 10,205 ft^3/s for 1983-1985 conditions. The increase, 3,639 ft^3/s, is mainly from surface-water-supplied irrigation. Most recharge from precipitation and irrigation follows short flow paths and discharges to nearby streams and drains, especially in the uplands and in irrigated areas, whereas, for low-lying, semiarid areas where no nearby major rivers drain the aquifer system, little ground water discharges locally. Leakage from rivers provides an additional 554 ft^3/s of recharge under predevelopment and 1983-85 conditions.

Initial mapping of hydraulic conductivities derived from specific-capacity data for the basalts exhibited little spatial correlation. Such randomness was initially assumed also to apply in areas lacking data. In order to calibrate the ground-water model, however, much smaller, relatively uniform hydraulic conductivities had to be assumed for the upland areas, and somewhat larger, relatively uniform hydraulic conductivities for the low-lying areas near major rivers. The model-derived median lateral hydraulic conductivity for the overburden aquifer is about $5x10^{-4}$ ft/s (feet per second). The range is from about $5x10^{-7}$ to $1.3x10^{-2}$ ft/s. Basalt conductivities range from about $1x10^{-6}$ to $1x10^{-4}$ ft/s with a median of about $1.7x10^{-5}$ ft/s.

Few data are available for vertical conductances. Model calibration resulted in distributions of vertical conductances that were generally less in the upland folded areas. Vertical conductances used in the two uppermost layers hydraulically connected to major rivers are anomalously large immediately beneath these rivers. Evidence suggests that such large conductances may be caused by deep erosional channels that were backfilled with coarse materials.

Discharge to rivers and drains was simulated to be about 2,754 and 3,944 ft^3/s for predevelopment conditions and about 3,804 and 5,596 ft^3/s for 1983-85 conditions. Discharge from the aquifer system for time-averaged conditions also includes about 1,135 ft^3/s of ground-water pumpage.

Since predevelopment time, water-level rises have been more prevalent and widespread than water-level declines because the areas of croplands irrigated with surface water are larger than those irrigated with ground water, and the irrigation application rate is larger in surface-water irrigated areas. Water-level rises in excess of 300 feet were simulated within the Columbia Basin Irrigation Project, generally east of the Columbia River between Pasco and Quincy. Water-level declines as much as about 200 feet were simulated for the Odessa-Lind area, Horse Heaven Hills area, Walla Walla River Basin area, the Umatilla area, and in some of the small tributary valleys draining to the Yakima River.

A steady-state simulation was made to estimate long-term future changes to the aquifer system from the 1983-85 period, assuming no changes in the 1983-85 rates of pumping and recharge. Although simulated water-level changes were generally less than 10 feet in the overburden aquifer, significant declines were simulated in all four basalt units. Declines of more than 400 feet in the Wanapum unit were centered around large pumping centers in the central part of Horse Heaven Hills, whereas similar declines in the Saddle Mountains unit were simulated in a ground-water-irrigated valley about 8 miles northeast of Yakima. More widespread but smaller declines of as much as 200 feet in the Wanapum were simulated for the Odessa-Lind area. Most other areas, even some that are heavily pumped, were simulated to have relatively small (less than 50 feet) to no water-level declines in any of the basalt units. Heavily pumped areas that have small simulated declines are located within or adjacent to areas of high recharge from either surface-water irrigation or precipitation.

Potential effects of two proposed CBIP expansions, Phase 1 and Phases 1 and 2, were simulated. Recharge increases of 330 ft^3/s and 974 ft^3/s were estimated for Phase 1 and Phases 1 and 2, respectively, assuming the same average irrigation application rate as in the existing CBIP. Water levels for the uppermost aquifers were simulated to rise to land surface everywhere in the expansion areas. Maximum water-level rises in the basalts of about 400 feet and 600 feet for Phase 1 and Phases 1 and 2, respectively, were simulated in the main parts of the expansion areas.

INTRODUCTION

The Columbia Plateau aquifer system underlies about 50,600 mi^2 of the Columbia Plateau of central and eastern Washington, north-central and eastern Oregon, and a small part of northwestern Idaho (fig. 1). The aquifer system consists of Miocene basalt belonging to the Columbia River Basalt Group, Miocene sedimentary rocks interlayered with the basalt, and Miocene to Holocene sediments overlying the basalts. The aquifer system is a major source of water for municipal, industrial, domestic, and irrigation uses. Concurrent with ground-water usage, imported surface water is used to irrigate several areas of the plateau. Use of surface water for irrigation has caused ground-water-level rises of as much as about 300 ft in some areas. Water levels have declined as much as about 200 ft in areas of ground-water pumpage, and the chemical quality of ground water has changed in irrigated areas. An improved understanding of the aquifer system, especially the movement and direction of ground-water flow, is needed to fully address concerns related to these changes.

The Columbia Plateau aquifer system is one of several regional aquifers selected for study as part of the U.S. Geological Survey's regional aquifer-system analysis (RASA) program. The objectives of the Columbia Plateau study are to describe (1) the hydrogeologic framework, (2) hydrologic characteristics of the hydrogeologic units, (3) the area's water budget, (4) the ground-water and surface-water interaction, and (5) the water-quality characteristics and water-rock interactions that occur in the study area. In order to provide the analytical capabilities for assessment of management alternatives and to allow a better understanding of the ground-water flow system, a numerical model that simulates ground-water flow was constructed and its reliability was tested by comparing the simulated and measured water levels and by comparing baseflows of streams with computed ground-water discharges (Hansen and others, 1994).

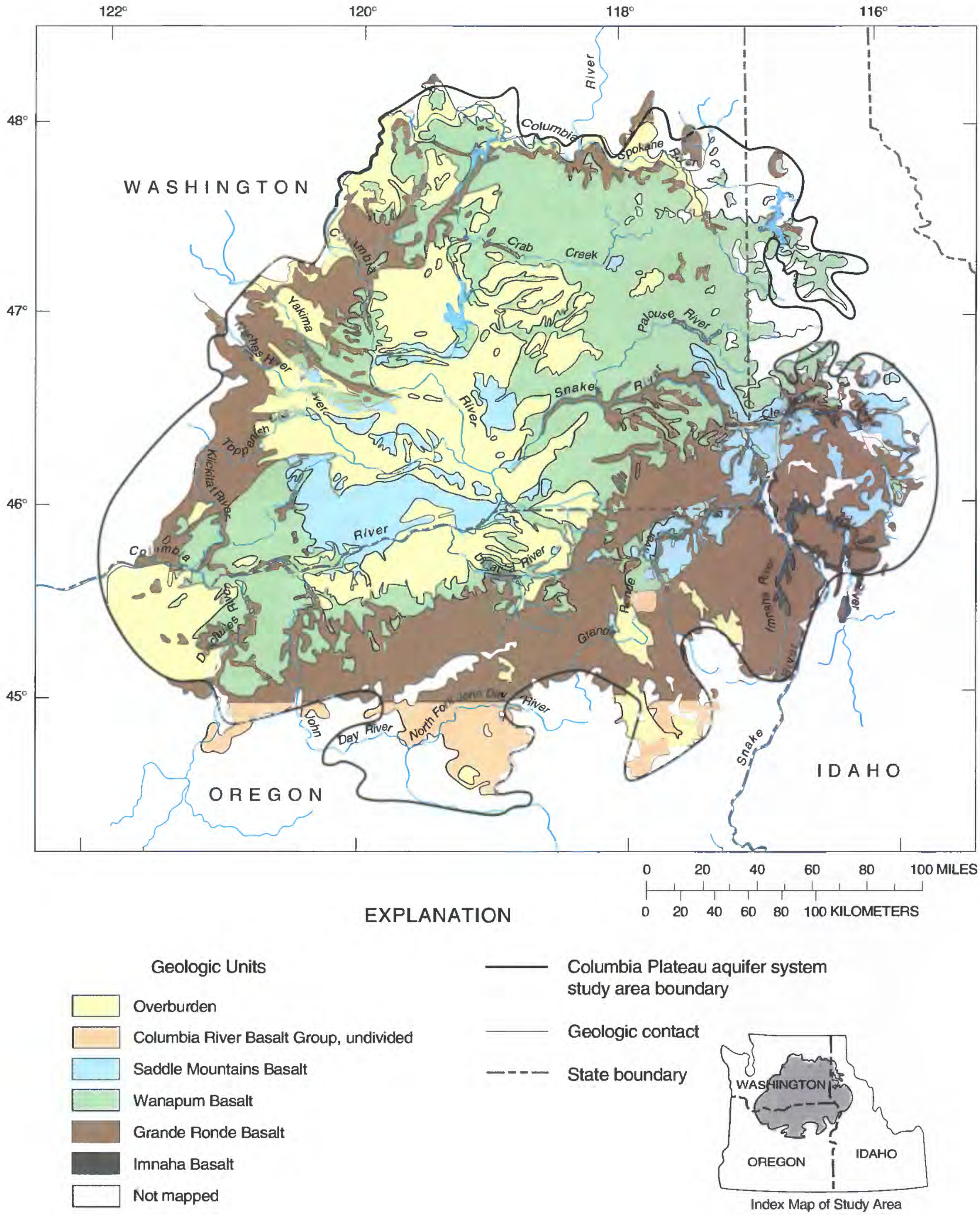


Figure 1. Location of the Columbia Plateau regional aquifer system study area and the extents of the formations of the Columbia River Basalt Group.

Purpose and Scope

This report summarizes the results of simulations made using the numerical model of ground-water flow in the aquifer system. Most of the information presented and described in this report is for the area (about 32,700 mi^2) included within the ground-water model boundaries, and is referred to in Whiteman and others (1994) and in this study as the hydrologic study area. Flow was simulated for the averaged conditions (water levels, pumpage, recharge) observed or estimated during 1983-85 and for predevelopment (1850's) conditions. Hansen and others (1994) describe in detail the development and calibration of the model for 1983-85 and predevelopment conditions; for a more detailed analysis, interested readers are referred to this report, which contains 15 plates that present all relevant items--geologic framework, model grid system, hydraulic characteristics, observed and calculated water levels, pumpage, recharge, and discharge. In addition to summarizing the work of Hansen and others (1994), this report also describes simulations of ground-water flow for several possible future conditions: (1) future equilibrium with 1983-85 stresses and (2) four proposed expansion scenarios of the Columbia Basin Irrigation Project (CBIP). The effects of the expansion were simulated under two proposed phases, Phase 1 and Phases 1 and 2. Additionally, the phases were simulated using two pumpage scenarios--1983-85 pumping rates and reduced 1983-85 pumping rates. This report includes a description of the geologic framework, the hydraulic characteristics, ground-water movement, and the simulated regional ground-water flow system budgets. More detailed analyses of parts of these items is presented in the companion reports of Drost and Whiteman (1986), Gonthier (1990), Drost and others (1990), Bauer and others (1985), Bauer and Vaccaro (1987, 1990), Whiteman (1986), Cline and Knadle (1990), Collins (1987), and Lane and Whiteman (1989).

Description of Study Area

The Columbia Plateau aquifer system lies within the Columbia Intermontane physiographic province (Freeman and others, 1945). The study area is bordered by the Cascade Range on the west, by the Okanogan Highlands on the north, and by the Rocky Mountains on the east. The southern boundary of the aquifer system has no well-defined physiographic boundary but is considered to correspond with the extent of the mapped Columbia River Basalt Group. The deeply incised Grande Ronde River, the Blue Mountains, and their western extension, formed by the Blue Mountains anticline and delineated by a series of outcrops of older pre-Columbia River Basalt Group rocks, form a hydrogeologic boundary between the basalt aquifers to the north and south. This report deals primarily with the more agriculturally developed northern part (the hydrologic study area).

The study area has been further divided by Myers and Price (1979) into three informal physiographic subprovinces: the Yakima Fold Belt, the Blue Mountains, and the Palouse (fig. 1). Together, these subprovinces are a structural and topographic basin. The Yakima Fold Belt, located in the western part of the study area, is characterized by long, narrow, east-west-trending anticlinal ridges with intervening broad to narrow synclinal basins. The Palouse subprovince consists of a gentle, southwest sloping, undeformed series of basalt flows under a rolling topography of loess deposits. The Blue Mountains subprovince, located in the southeastern part of the study area, consists of dissected upland plateaus; the subprovince also includes the Deschutes-Umatilla Plateau in Oregon.

The study area is completely within the drainage of the Columbia River. Major tributaries to the Columbia River within the study area include the Snake, Yakima, John Day, Umatilla, Klickitat, and Deschutes Rivers (fig. 2). These tributaries and their associated tributaries drain the bordering mountainous areas. Land-surface altitudes and precipitation quantities largely determine the types and amounts of natural vegetation found in the Columbia Plateau. As part of this RASA study, a map of the distribution and rate of average annual precipitation for the period 1956-77 (Nelson, 1991) was constructed and presented by Nelson (1991) and is also presented in Whiteman and others (1994). At altitudes from 350 to 2,000 ft above sea level in the central part of the plateau, the precipitation ranges from 6 to 15 inches a year, the vegetation is principally sage and

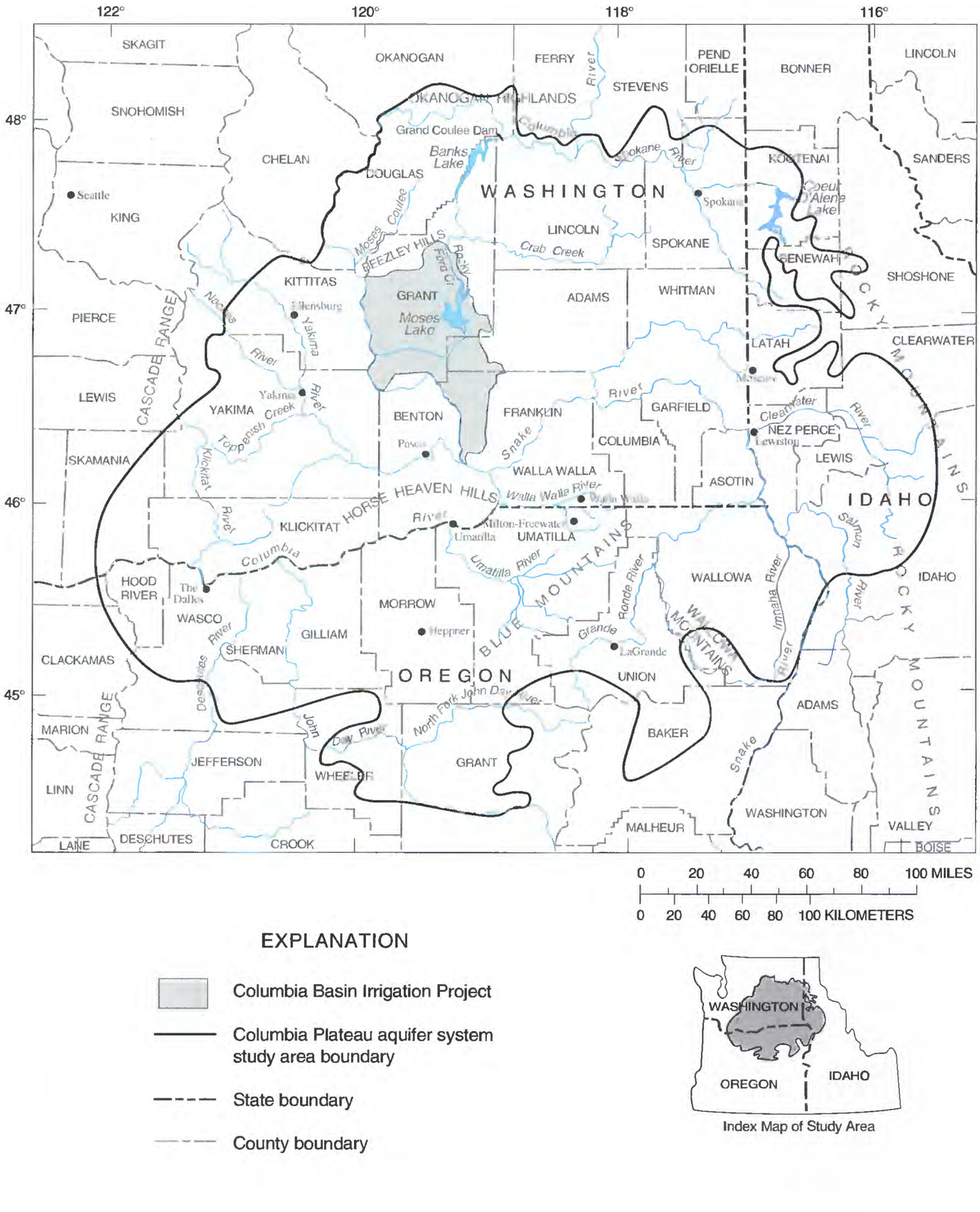


Figure 2. Location of physiographic and cultural features of the Columbia Plateau in the study area.

grasslands, and few streams are perennial. At intermediate altitudes (2,000 to 3,500 ft), precipitation ranges from 15 to 25 inches where the vegetation includes both grasslands and forest. Forest lands predominate at altitudes greater than 3,500 ft and perennial streams are common.

The predominant economic activities in the study area are agriculture and its associated services. In 1984, nearly 780 mi^2 of cropland were irrigated with ground water and about 1,950 mi^2 of cropland were irrigated with surface water (Cline and Collins, 1992). More than 8,000 mi^2 of sage, grasslands, and dryland crop area have the potential for conversion to irrigated crops.

Development of water resources and changes in land use within the study area have been extensive since predevelopment (1850's) time. Numerous dams have been constructed throughout the lengths of the Columbia and Snake Rivers in the study area, and only a few short reaches of these rivers are not impounded. The effect of the reservoirs on the regional ground-water flow system is probably minimal, however, because these impoundments are still areas of ground-water discharge. A much more profound effect on the ground-water system is from the delivery of irrigation water from the impounded river water to large areas. Water-level rises and effects on ground-water flow in the 556,000-acre CBIP (fig. 2) were described by Tanaka and others (1974).

Ground-water pumping for irrigation has lowered water levels in several areas. The effects of this pumping in selected areas is discussed by Cline (1984), Davies-Smith and others (1988), Packard and others (1996), MacNish and Barker (1976), and Lum and others (1990).

Other land-use practices have a much less pronounced but more widespread effect. Most of the current (1980's) agriculture is dryland wheat, which generally is fallowed every other year. Calculations of recharge quantities indicate that this practice has increased consumptive use of water compared with that of native vegetation (predevelopment land cover), thereby slightly decreasing recharge over large areas (Bauer and Vaccaro, 1990).

HYDROGEOLOGY

The Columbia Plateau is underlain by a series of layered basalt flows extruded from vents (located mainly in southeastern Washington and northeastern Oregon) during Miocene time. Collectively, these basalt flows are known as the Columbia River Basalt Group. Individual basalt flows range in thickness from a few inches to as much as 300 ft. Some flows probably cover more than half of the study area. Smaller flows are confined to the source region and (or) mainly fill ancestral river valleys (called intercanyon flows). Generally, the rubbly, vesicular tops of flows readily transmit ground water. The massive central part of a flow contains some joints and fractures but transmits ground water much less readily and impedes the vertical movement of water between flow tops.

A variety of sedimentary materials (the "overburden") from Pliocene through Holocene age overlie about 14 percent of the Columbia River Basalt Group, mainly in the central part of the study area. On average, these materials transmit water more readily than the basalts and also compose an important aquifer.

Geologic Setting

Basalt

The study area is both a structural and a topographic basin and its lowest point is near Pasco, Franklin County, Wash. (fig. 2). The Columbia River Basalt Group covers an area of about 63,700 mi^2 and has an estimated volume of 42,300 mi^3 (Tolan and others, 1989). Basalt flows of the Columbia River Basalt Group are intercalated with and overlain by sediments collectively assigned to the Miocene-to-Holocene-age Ellensburg, Latah, Ringold, Palouse, and The Dalles Formations. Along the borders of the plateau, the basalts are underlain by Precambrian to early Tertiary rock of mostly volcanic and metamorphic origin. Sedimentary rocks underlie the basalts in the Yakima Fold Belt and in adjacent parts of the plateau to the east, and volcanic and metamorphic rocks underlie the basalts in the other subprovinces.

The eruptions of basalt occurred from about 17 to 6 million years before present (B.P.). Most flows, comprising about 42,000 mi^3, were extruded between 17 and 14.5 million years B.P. Eruptions were less frequent and less voluminous, comprising only about 600 mi^3, from 14.5 to 6 million years B.P. (Tolan and others, 1989) allowing time for erosion, deformation, and increased deposition of sediment between eruptions. Basaltic lava was extruded from a system of northwest-trending linear vents in southeastern Washington, northeastern Oregon, and western Idaho (Swanson and others, 1975; Hooper, 1982). Basin subsidence was concurrent with extrusion, thus the lava flows thin progressively outward from the central basin.

Extrusion and cooling of individual flows under different physical settings resulted in the formation of columnar joints, pillow lavas, and brecciated flow tops. Individual basalt flows range in thickness from a few inches to more than 300 ft and average about 110 ft. The internal structure of a typical flow generally consists of, from bottom to top, a flowbase, a colonnade, an entablature, and a flow top (fig. 3). The base of a flow generally has a thin zone of glassy basalt, a vesicular zone, and may include a zone of pillow basalt. Porous pillow-palagonite complexes, caused by underwater cooling, are present at the base of some flows. The colonnade consists of nearly vertical three- to eight-sided columns of basalt that average about 3 ft in diameter and about 25 ft in length. The columns were formed by vertical jointing that occurred during the slow cooling and contraction of the flow interior. Columns are commonly crosscut by systems of joints. The denser entablature consists of small-diameter (averaging less than 2 ft) basalt columns in fan-shaped arrangements. Cross joints in the entablature are less consistently oriented than those in the colonnade. Hackly joints are common in the upper part of the entablature and are often vesicular. The flow top generally consists of vesicular basalt with scoria and clinker and averages about 5 to 10 percent of the total thickness of a single flow (fig. 3). The flow top in combination with the superposed flowbase is called the interflow zone.

The Columbia River Basalt Group has been stratigraphically subdivided into five formations and numerous members (fig. 4) (Swanson and others, 1979c). The Yakima Basalt Subgroup of the Columbia River Basalt Group is the most extensive and consists of, from oldest to youngest, the Grande Ronde, Wanapum, and Saddle Mountains Basalt formations. Pre-Yakima Basalts, which consist of the Picture Gorge and Imnaha Basalt formations, have been mapped only in scattered locations in the southern and southeastern parts of the plateau and these outcrops lie mostly outside the modeled area. Except for a small part of the Imnaha Basalt, the pre-Yakima Basalts were not analyzed in this study because of their limited, peripheral extent.

Interbed sediments occur within and between basalt formations. These sediments were derived from erosion of older rocks surrounding the plateau, from erupting volcanoes in the Cascade Range, and from the basalt itself. The areal extent, thickness, and lithology of interbeds is probably dependent on the time between eruptions, Cascade volcanic activity between eruptions, and topographic position.

Hydrologic data generally are not available for individual basalt flows, many of which may be individual aquifers, because the open intervals of most wells in the study area span more than one basalt flow. Moreover, identification and correlation of single basalt flows from well log data are not feasible. However, when the groups of flows composing the Saddle Mountains, Wanapum, and Grande Ronde Basalt formations are considered, much useful data are available. Additionally, the laterally extensive fine-grained sedimentary interbeds between these formations in many areas impose a degree of hydraulic separation, so that it is logical to treat these groups of basalt flows as separate composite aquifers. These composite aquifers are referred to in this report as "units" and include any intercalated sediments.

Structure contour maps of the top of the formations composing the Yakima Basalt Subgroup (Swanson and others, 1979 a,b) were modified for the Grande Ronde, Wanapum, and Saddle Mountains Basalts by Drost and Whiteman (1986) for Washington and by Gonthier (1990) for Oregon. Additionally, thickness maps were constructed during these studies for the Saddle Mountains and Wanapum Basalts, plus their intercalated sediments. These basalt formations and their intercalated sediments are herein called the Saddle Mountains and Wanapum units to distinguish them from the formations, which do not include intercalated sediments. Similarly, the

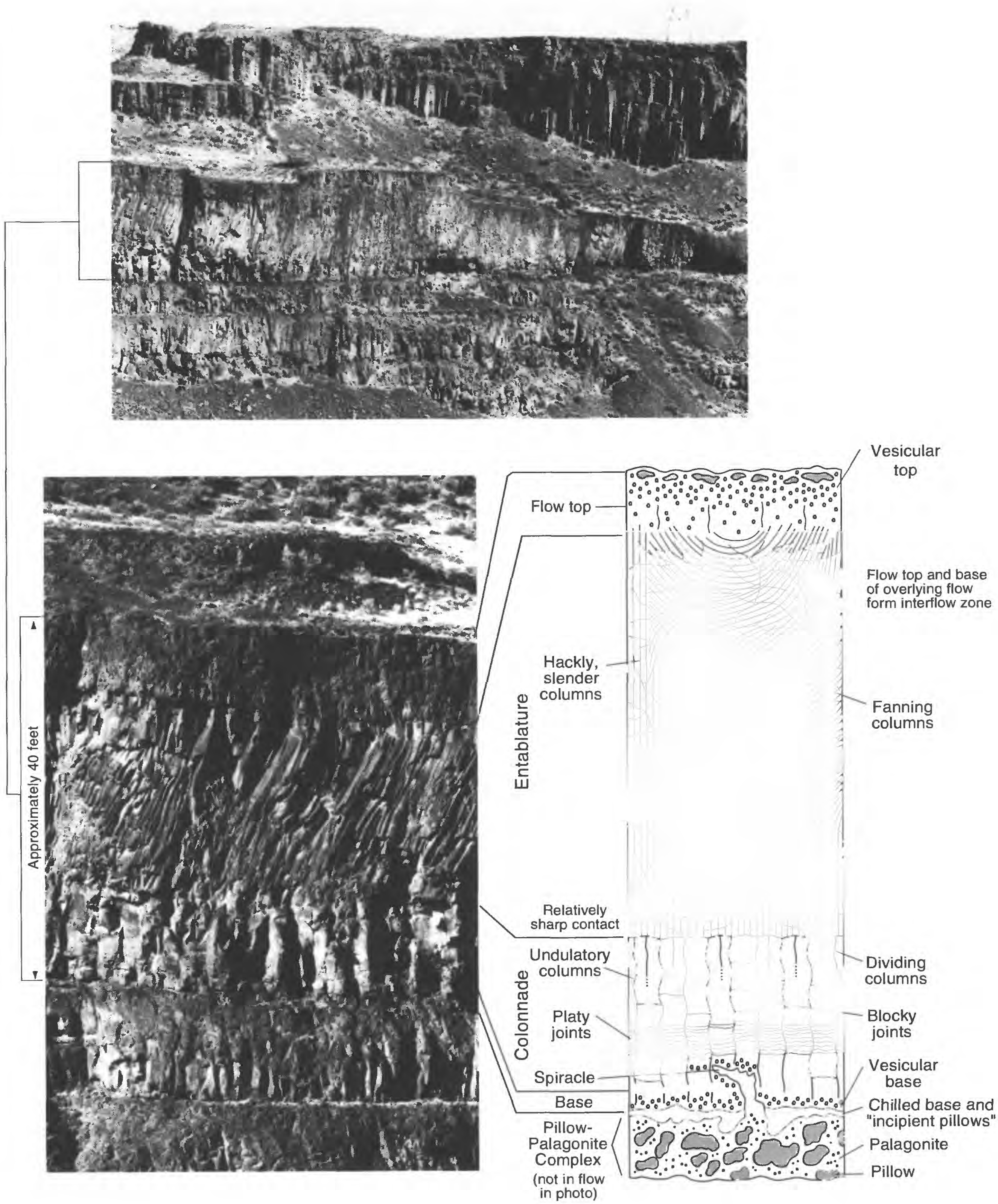


Figure 3. Intrastructure of a basalt flow within a group of basalt flows.

GEOLOGIC FRAMEWORK: BASALT STRATIGRAPHY							GEOLOGIC FRAMEWORK: SEDIMENT STRATIGRAPHY	HYDROLOGIC FRAMEWORK: HYDROGEOLOGIC UNIT		MODEL LAYER NUMBER
							Sediments of Miocene through Holocene age (glaciofluvial, fluvial, lacustrine, eolian, and ash fall materials). Locally includes sediments of the Palouse, Latah, Ringold, and Ellensburg Formations, and the Dalles Group (Farooqui and others, 1981).	Columbia Plateau aquifer system	Overburden aquifer	1
MIOCENE	Upper Miocene, Middle Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Saddle Mountains Basalt	Lower Monumental Member Ice Harbor Member Buford Member Elephant Mountain Member Pomona Member Esquatzel Member Weissenfels Ridge Member Asotin Member Wilbur Creek Member Umatilla Member			Columbia Plateau aquifer system	Saddle Mountains unit	2
MIOCENE	Middle Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Saddle Mountains Basalt			Saddle Mountains–Wanapum interbed	Columbia Plateau aquifer system	Confining unit	2
MIOCENE	Middle Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Wanapum Basalt	Priest Rapids Member Roza Member Frenchman Springs Member Eckler Mountain Member			Columbia Plateau aquifer system	Wanapum unit	3
MIOCENE	Middle Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Wanapum Basalt			Wanapum–Grande Ronde interbed	Columbia Plateau aquifer system	Confining unit	3
MIOCENE	Lower Miocene	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	Grande Ronde Basalt		Magnetostratigraphic units: N_2, R_2		Columbia Plateau aquifer system	Grande Ronde unit	4
MIOCENE	Lower Miocene	COLUMBIA RIVER BASALT GROUP		Picture Gorge Basalt		Magnetostratigraphic units: N_1, R_1, T		Columbia Plateau aquifer system	Grande Ronde unit	5
MIOCENE	Lower Miocene	COLUMBIA RIVER BASALT GROUP		Imnaha Basalt		Magnetostratigraphic units: N_0, R_0		Columbia Plateau aquifer system	Grande Ronde unit	5
Lower Tertiary to Precambrian		Basement rocks (pre–Columbia River Basalt Group)						Columbia Plateau aquifer system	Basement confining unit	

Figure 4. Relation between geologic units, hydrogeologic units, and the computer model layers of the Columbia Plateau Regional aquifer system.

Grande Ronde Basalt and intercalated sediments are referred to as the Grande Ronde unit; for this study, the Grande Ronde unit also includes a small part of the Imnaha Basalt in the southeastern part of the study area.

The mapping work was later extended into Idaho, and maps describing the geologic framework for the Columbia Plateau regional aquifer system have been published by Drost and others (1990). The areal extent of each unit within the RASA study area is shown on figure 1, and a comparison of geologic units, hydrogeologic units, and model layers is shown on figure 4. Generalized hydrogeologic sections (fig. 5) show the configuration of the basalt units and the overlying sediments (overburden).

The Grande Ronde unit underlies all of the area (fig. 1), and constitutes 85 to 88 percent of the volume of the Columbia River Basalt Group (Reidel, 1982; Tolan and others, 1987). It is exposed mainly along the northern, southeastern, and southern margins and in a few deeply incised stream channels in the central part of the plateau. Its thickness varies from a few feet along the northern and southern margins, where it pinches out against older rock, to greater than 14,000 ft in the central and southwestern parts of the study area. The Grande Ronde unit is composed of as many as 130 individual flows (Tolan and others, 1987); most flows are fine grained with microphenocrysts of plagioclase and clinopyroxene. Sedimentary interbeds in the Grande Ronde unit are rare, generally only a few feet thick, and of small lateral extent because of the short time intervals between outpourings of successive flows. A laterally extensive sedimentary interbed that has been given different formation names in different areas lies between the Grande Ronde and Wanapum units. For clarity, it has been named the Wanapum-Grande Ronde interbed for this regional study (Drost and others, 1990; Whiteman and others, 1994). Where present, this interbed averages about 25 ft but is as much as 100 ft thick, and consists chiefly of claystone and siltstone.

A thickness map of the Grande Ronde unit was constructed on the basis of available well logs, magnetotelluric data, exposures of the older "basement" rocks, and on information from partially penetrating deep wells (Hansen and others, 1994). The estimated thickness distribution generally is smooth throughout most of the plateau except in the Blue Mountains, where there are deeply eroded valleys. In contrast to the Blue Mountains, the Yakima Fold Belt, which also has rugged topography principally because of anticlinal folding, the thickness distribution was smooth.

The Wanapum unit is exposed or is covered by a veneer of quaternary sediments throughout most of the northern half of the area. In the southern half, the unit generally is covered by thick sequences of sediments or by the Saddle Mountains unit. The Wanapum unit averages about 600 ft in thickness, varying from a few feet where it pinches out against exposures of the Grande Ronde unit to about 1,200 ft in the southwestern part of the area (Drost and others, 1990; Hansen and others, 1994). The Wanapum unit generally contains about 33 flows (Tolan and others, 1987) and makes up about 6 percent of the volume of the basalts. Most Wanapum unit flows are medium grained and slightly to moderately plagioclase-phyric. Sedimentary interbeds are more common in the Wanapum unit than in the Grande Ronde unit, but are still rare and only a few feet thick. A sedimentary interbed between the Wanapum unit and the overlying Saddle Mountains unit occurs in part of the study area, and for this study it is called the Saddle Mountains-Wanapum interbed. This interbed is as much as 200 ft thick and averages about 50 ft. The interbed consists chiefly of clay, silt, claystone, or siltstone and minor amounts of sand and conglomerate.

The Saddle Mountains unit underlies only the southwestern part of the study area (fig. 1). The unit has a maximum thickness of more than 800 ft and averages about 600 ft (Drost and others, 1990; Hansen and others, 1994). Individual flows in the Saddle Mountains unit vary greatly in texture and composition. Sedimentary interbeds are common, averaging about 50 ft thick. The intercalated Beverly Member of the Ellensburg Formation is areally extensive and stratigraphically and hydrologically important in south-central Oregon and in parts of the Yakima Fold Belt.

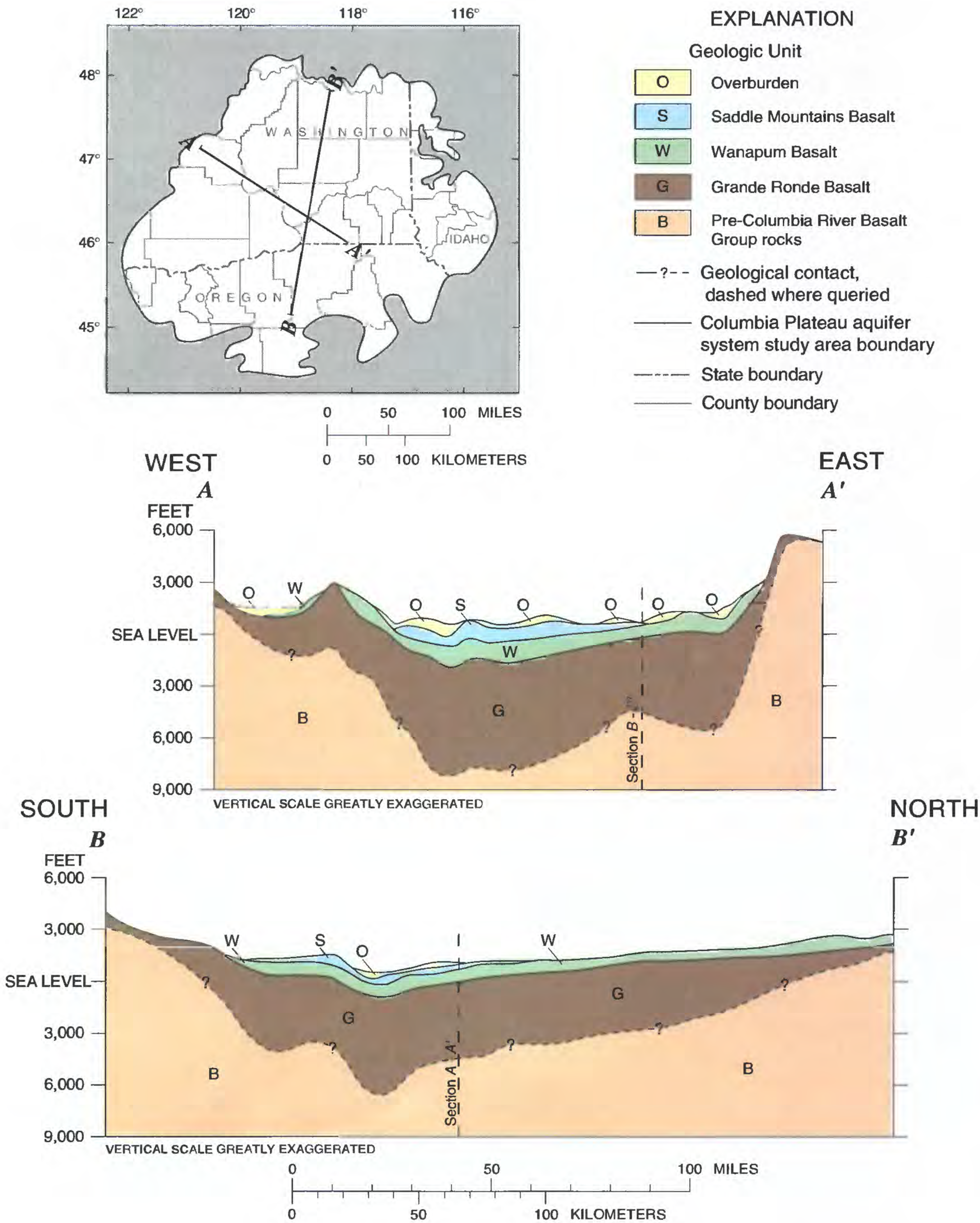


Figure 5. Generalized hydrogeologic sections through the Columbia Plateau. (From Drost and others,1990.)

Overburden

Sediments overlying the Columbia River Basalt Group compose the "overburden." These sediments include Pliocene through Holocene fluvial, glaciofluvial, eolian, and volcaniclastic sediments. Loess occurs at the surface throughout much of the Columbia Plateau, reaching its greatest thickness (as much as 250 ft) and continuity in the Palouse subprovince of southeastern Washington, where it is called the Palouse Formation. Loess deposition was greatest during the Pleistocene, with glacial drift and alluvium the major source of silt.

The extent and thickness of the overburden, generally greater than 50 ft thick, has been mapped and presented by Drost and others (1990), but because the thickness of the loess is highly variable locally and because it is discontinuous, fine grained, and generally not an aquifer, Drost and others (1990) did not include the loess in the overburden as part of the RASA study. The greatest thickness of the overburden is in excess of 800 ft, and the thickest deposits occur in structural basins and in areas adjacent to the Cascade Range. The overburden is herein referred to as the overburden aquifer. The overburden aquifer overlies about 4,500 mi^2 of the basalts (Hansen and others, 1994).

Structural Features

Drost and Whiteman (1986), Gonthier (1990), and Drost and others (1990) present detailed descriptions of the Columbia Plateau's geologic structures. Geologic structures within the plateau are diverse and range from simple monoclines to sharp folds with structural relief of as much as several thousand feet. The major structural features (fig. 6) impose significant controls on the movement of ground water in the aquifer system.

The Yakima Fold Belt subprovince is characterized by long, narrow, faulted anticlines (such as Umtanum, Yakima, and Ahtanum Ridges, fig. 6) with intervening narrow (Wapato) to broad (Kittitas Valley) synclines that trend in an easterly to southeasterly direction from the western margin of the plateau to its center. The anticlines are generally asymmetrical with the steepest limb to the north. Most major faults are thrust or reverse faults whose strikes are similar to the anticlinal fold axes; the faults probably are contemporaneous with the folding. Northwest- to north-trending shear zones and minor folds commonly transect the major folds.

The Palouse subprovince contains basalt flows with a regional dip to the southwest of less than 5 degrees (Drost and Whiteman, 1986). This subprovince is structurally simple, the largest features being broad folds with amplitudes of only a few tens of feet.

The Blue Mountains are a broad anticline that extends from north-central Oregon into southeastern Washington. The anticline is cut by a series of north- to northwest-trending faults that are nearly vertical (Gonthier, 1990). The basement or core of the anticline is composed of folded, faulted, and metamorphosed upper Paleozoic and Mesozoic rocks.

Ground-Water Movement

The generalized description of the occurrence and movement of ground water is described in this section; more detailed discussions based on results of the ground-water model are presented later in the section "Simulated Regional Flow." Ground-water level contour maps for the four aquifer units were constructed and published by Bauer and others (1985) and for the three basalt units by Whiteman (1986), and Lane and Whiteman (1989). The last report also shows ground-water-level changes from spring 1983 to spring 1985. Water-level contours representing the average of 1983-85 conditions for the overburden aquifer and three basalt units are based on these published maps and data used in those investigations; these contours for average conditions have been further described and presented in Hansen and others (1994).

Basalt Units

Ground water in the basalts occurs in joints, vesicles, fractures, and in intergranular pores of the intercalated sedimentary interbeds. The rubbly flow tops generally have the highest permeabilities (fig. 4). The denser, more coherent entablature and colonnade usually have lower permeabilities. In a few areas, saturated sedimentary interbeds are

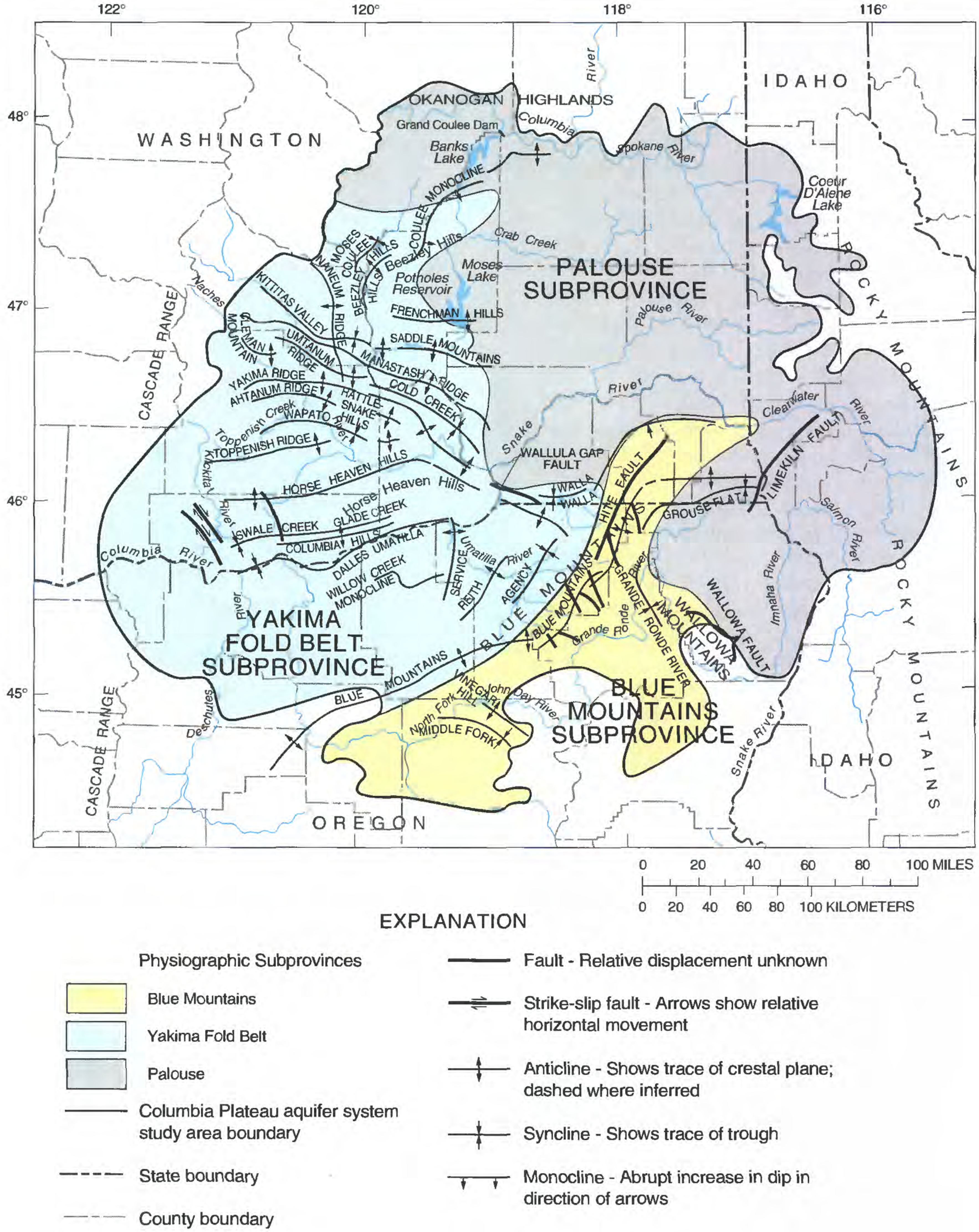


Figure 6. Locations of major geologic structures within the Columbia Plateau.

aquifers where they contain coarse-grained materials. Few hydrologic data exist for the interbeds, therefore in this study their hydraulic characteristics are incorporated into the hydraulic characteristics of the basalts. In most areas, water-table conditions exist in the uppermost basalt unit. Owing to the wide difference between horizontal and vertical hydraulic conductivities, to the presence of sedimentary interbeds, and to the presence of fine-grained materials in parts of the lower section of the overburden aquifer, the deeper basalt units are generally confined. However, because the hydraulic connection between units is sufficient to allow continuous, vertical movement of water between them, the confined units are referred to as being semiconfined.

Water-level data indicate that over most of the plateau, the vertical component of regional flow in basalts is downward except near discharge areas, generally along streams and rivers (Lane and Whiteman, 1989). Localized anomalies to this pattern are caused primarily by geologic structures of both known and uncertain nature and secondarily by ground-water pumping and irrigation.

Previous studies of ground-water flow in the Columbia River Basalt Group have suggested that certain structures affect ground-water movement. Newcomb (1961, 1965, and 1969) cites linear zones of steepened hydraulic gradients caused by lateral-flow impediments such as faulting and (or) sharp folding at locations near Walla Walla, Wash., in the Cold Creek syncline east of Yakima, Wash., and southwest of The Dalles, Oreg. More recent work in the Horse Heaven Hills (Packard and others, 1996) suggests a linear ground-water impediment, possibly associated with shear faulting. Upward ground-water movement occurs in an area where the regional flow is downward, and this anomaly is assumed to be caused by the impediment. Similarly, a study of the ground-water resources of the Umatilla area in Oregon (Davies-Smith and others, 1988) found that just up-gradient (lateral ground-water flow is northward) of the east-west-trending Willow Creek monocline, the vertical flow gradient is upwards instead of the more common downward gradient. Further, the lateral hydraulic gradient steepens near the monocline, indicating the structure's effect on ground-water movement.

Under 1983-85 conditions, the potentiometric surfaces of the Saddle Mountains, Wanapum, and Grande Ronde units (Hansen and others, 1994) roughly parallel the land surface in areas where these units are exposed at the surface. In these areas, these units are directly recharged by precipitation and in some areas also by irrigation water. Lateral ground-water flow is generally toward surface-drainage features where ground water discharges. Ground-water movement in the deeply buried portions of the Wanapum and Grande Ronde units is influenced less by minor surface-drainage features. For the Quincy Basin (fig. 2), for example, such control was described by Lane and Whiteman (1989) and Hansen and others (1994) where ground-water movement within the Wanapum unit, which is at or near land surface, is toward Moses Lake and Potholes Reservoir. Ground-water movement in the underlying Grande Ronde unit, however, is virtually unaffected by these surface-drainage features, and flow is south and west toward the Columbia River, a much larger drainage feature. These differences are due to the fact that movement of water to and from deeply buried portions of the basalts that are not laterally connected to the surface must occur by vertical leakage to and from the overlying and underlying units.

In the Palouse subprovince north of the Snake River, the regional ground-water flow in both the Wanapum and Grande Ronde units is toward the southwest, roughly paralleling the land surface and the regional dip of the basalts. Regional discharge is to the Columbia and Snake Rivers. In the Yakima Fold Belt, ground-water movement is downward from the anticlinal ridges toward the streams and rivers in the intervening synclinal basins. In the Blue Mountains subprovince, water moves from the uplands or mountains toward the Snake and Columbia Rivers. In addition, the deeply incised John Day and Deschutes Rivers provide major control to the ground-water flow system, and water moves from the intervening uplands to these rivers.

Overburden Aquifer

The overburden in the structural basins readily transmits water and comprises water-table aquifers. These aquifers are generally coarse-grained and highly permeable in their upper sections and fine-grained and less permeable at depth. However, where the overburden is thick, such as in the structural basins in the Yakima Fold Belt, extensive coarse-grained layers exist deeper in the section and function as water-producing zones.

The water-level contours for the overburden aquifer roughly parallel land surface (Whiteman, 1986; Lane and Whiteman, 1989; Hansen and others, 1994). Recharge is mainly from infiltration of applied irrigation water and from precipitation. Discharge is to rivers, lakes, drains and waterways, wells, and to the underlying basalt unit. Downward movement of water to the underlying basalts is controlled by intervening fine-grained sedimentary layers and by the head difference between the units. An example of such control on ground-water flow also was described by Hansen and others (1994) in the Quincy Basin (fig. 2), where steeper vertical head gradients have been noted in areas where large thicknesses of clay-rich materials directly overlie the Wanapum Basalt. Where this clay layer is thin or absent, the heads in the overburden aquifer and Wanapum unit are nearly identical. Additionally, with the onset of surface-water irrigation in the Quincy Basin, a rapid increase in heads was observed in both the overburden aquifer and the Wanapum unit. This rapid response to increased recharge was not seen in the more deeply buried Grande Ronde unit, indicating that the overall hydraulic connection between the overburden and the underlying basalt unit generally is better than it is between adjoining basalt units.

Hydraulic Characteristics

The values of lateral hydraulic conductivity for each basalt unit and the overburden aquifer initially were estimated from specific-capacity data. The modified Theis equation (Theis, 1963) for nonleaky artesian aquifers (Ferris and others, 1962, p. 99) was first used to estimate transmissivity values from the specific-capacity data. In order to estimate a hydraulic conductivity value from a transmissivity value, the ratio of the open interval of the well to the unit or aquifer thickness is required. For this study, any basalt well was assumed to 'effectively' penetrate at least one entire basalt flow, and the effective open interval is 55 ft greater than the actual saturated open interval, but not less than 110 ft (the average thickness of one basalt flow; see Hansen and others, 1994). The calculated lateral hydraulic conductivities for the overburden aquifer and the basalt units are shown later in figure 11.

The median lateral hydraulic conductivity for the overburden aquifer is roughly two orders of magnitude greater than that of the basalt units. The smaller median lateral hydraulic conductivity of the Saddle Mountains unit, compared with the other basalt units, is attributed to the numerous intercalated fine-grained interbeds, which generally are absent in the Wanapum and Grande Ronde units. The large range in values for all units indicates the heterogenous nature of both the overburden and the basalts.

Recharge

The source of water to the aquifer system is predominantly from direct recharge from precipitation (Bauer and Vaccaro, 1990). For equilibrium conditions, recharge equals discharge to streams, rivers, lakes, springs, and seepage faces.

To compute the spatial distribution of recharge over the study area, where annual precipitation varies from about 6 in/yr to more than 40 in/yr, a daily soil-moisture budgeting computer model was developed during this study (Bauer and Vaccaro, 1987). The model computes daily quantities of moisture that percolate downward beyond the root zone (deep percolation) for any specified number of years at any specified number of grid cells, within a drainage area, using readily available meteorologic, soil, land cover, altitude, streamflow, and irrigation-application-rate data.

Deep percolation was simulated for 53 basins and subareas underlain by the aquifer system on a daily time step over a 22-year period, 1956 to 1977 (Bauer and Vaccaro, 1990), and the 22 years of daily values were used to calculate a long-term average recharge. The 22-year period included a large range of climatic variability and therefore was assumed to be representative of overall climatic conditions. Each of these basins and subareas was divided into cells generally ranging from 0.25 to 1 mi^2. The recharge estimates then were aggregated to cells that were 2.5 minutes of latitude by 2.0 minutes of longitude (about 2.88 by 1.62 mi), resulting in an area-weighted average value for recharge. These larger cells correspond with the ground-water flow model grid system, which is described later in the section "Model Grid and Boundary Conditions." Predevelopment deep percolation also was simulated using climatic data from the same 22-year period, but using estimates of predevelopment land cover. A detailed description and analysis of the data and results can be found in Bauer and Vaccaro (1990).

The modeled basins and subareas included most of the irrigated croplands and most of the area with annual precipitation less than 11 in/yr. Recharge for each of the remaining ground-water model cells was then estimated using a polynomial regression equation. The equation related the 22-year average-annual precipitation to the estimated long-term average recharge at the approximately 30,000 recharge-simulation cells of the 53 basins. Figures 7 and 8 show predevelopment and current estimates of recharge for the ground-water model cells (outlines of the basins and subareas for which deep percolation was simulated are shown on figure 13.)

Long-term, time-averaged estimate of recharge for the modeled area for predevelopment land-use conditions was calculated to be about 6,600 ft^3/s and for current land-use conditions about 10,200 ft^3/s. These estimates of recharge are about 7 to 10 percent larger than those reported by Bauer and Vaccaro (1990) due to refinements in estimates made in areas south of the Columbia River (see Hansen and others, 1994).

Pumpage

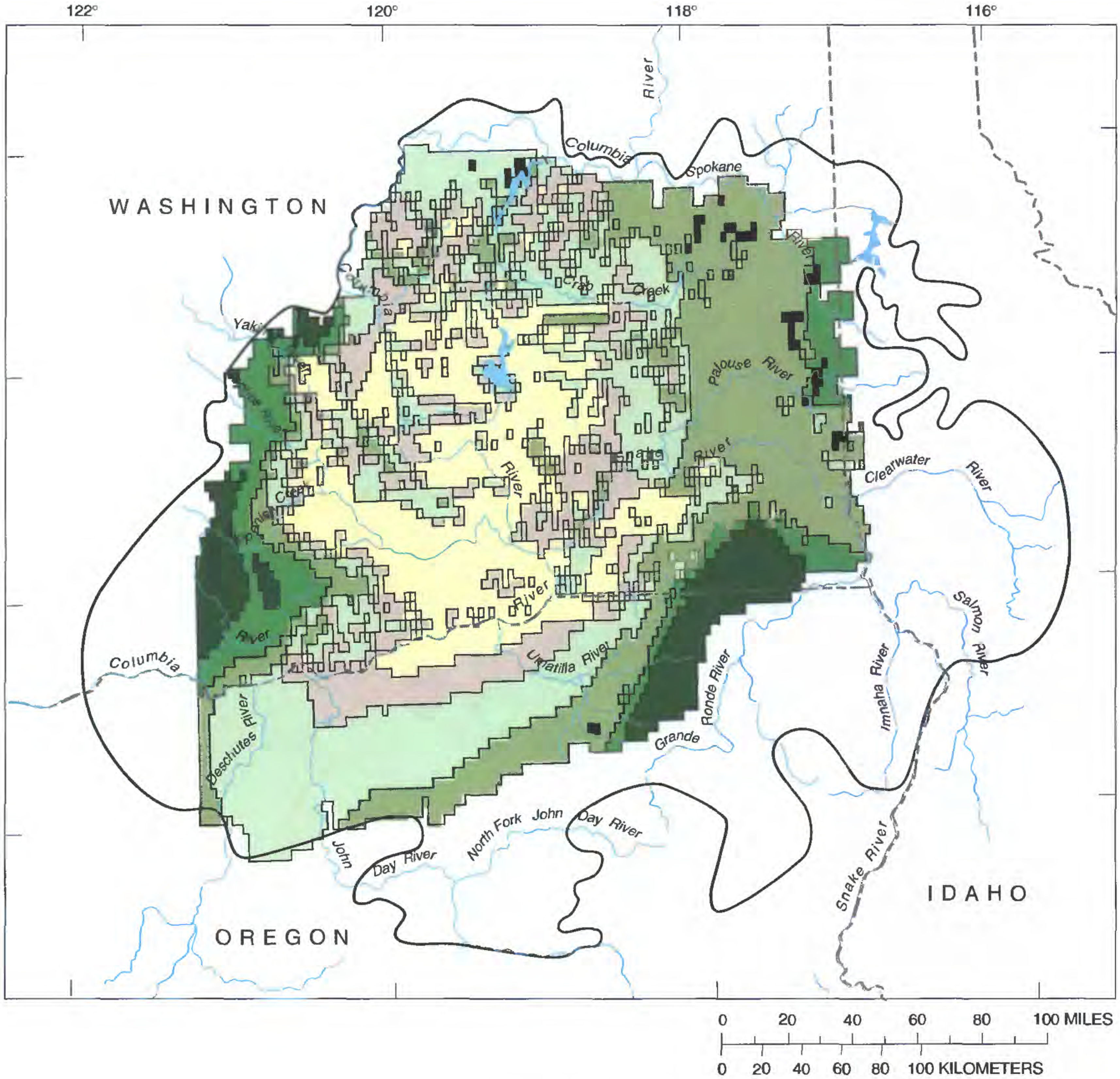
Estimates of ground-water pumpage for 1984 have been made for this study by Collins (1987) for the Oregon part of the Columbia Plateau, and by Cline and Knadle (1990) for the Washington part of the plateau and a small part of Idaho. About 828,300 acre-ft (1,144 ft^3/s) of ground water was pumped from the entire regional aquifer system in 1984 from approximately 3,500 high-capacity wells. Between 85 and 90 percent was for irrigation and the rest for public supply and industrial uses. In 1984, nearly 500,000 acres of cropland were irrigated with ground water. The relatively small quantity of ground water used for domestic purposes and other uses, such as stock watering, was not considered in this regional analysis.

Cline and Collins (1992) also estimated pumpage for 1983, about 813,000 acre-ft (1,123 ft^3/s), and averaged these values with the 1984 values (fig. 9). For wells that tap more than one unit, pumpage was divided proportionally according to the amount of saturated thickness per unit open to the well. About 32 percent of the total pumpage was from the Grande Ronde unit, 40 percent was from the Wanapum unit, 3 percent was from the Saddle Mountains unit, and 25 percent was from the overburden aquifer. Hansen and others (1994) show the pumpage distribution for each ground-water model cell of each unit.

The greatest concentrations of pumpage occur near Hermiston in Umatilla County, Oregon, (south of the Columbia River, east of Willow Creek, west of Pendleton, and south of Heppner), and in three areas in Washington: (1) southwestern Lincoln and north-central Adams Counties (herein called the Odessa-Lind pumping area; this area is east of the CBIP, south of Coulee City, Wilbur, and Davenport, west of Cow Creek, and north of a line connecting Connell and Hooper), (2) the Quincy Basin (Grant County), and (3) southern Franklin County.

SIMULATION OF GROUND-WATER FLOW

The movement of ground water in the Columbia Plateau aquifer system was simulated using the three-dimensional finite-difference ground-water flow model of McDonald and Harbaugh (1988). The model requires the use of a rectangular grid system for discretizing the ground-water system into layers of rectangular cells. Values of lateral hydraulic conductivity must be specified for each cell, and depending on the type of simulation and the flow system, storage, recharge, and pumpage also may need to be specified. If there is more than one layer, vertical conductance between cells of adjacent layers must be specified. Conceptually, vertical conductance (VCON) is the vertical hydraulic conductivity times the area of the cell, divided by the thickness of a low-permeability layer between adjacent aquifer layers. Where no such confining layers exist, VCON is used to represent the equivalent conductance between centers of adjacent layers, in which case VCON per unit area can be expressed as a function of the thicknesses and anisotropies of the adjacent layers.



EXPLANATION

Average recharge, in inches per year

- Assumed zero, area of outcropping impermeable basement rock
- 0 - 0.5
- 0.5 - 1.0
- 1.0 - 2.0
- 2.0 - 5.0
- 5.0 - 10.0
- 10.0 - 28.6

- Columbia Plateau aquifer system study area boundary
- Hydrologic study area
- State boundary

Figure 7. Distribution of estimated recharge within the hydrologic study area for predevelopment (1850's) land-use conditions.

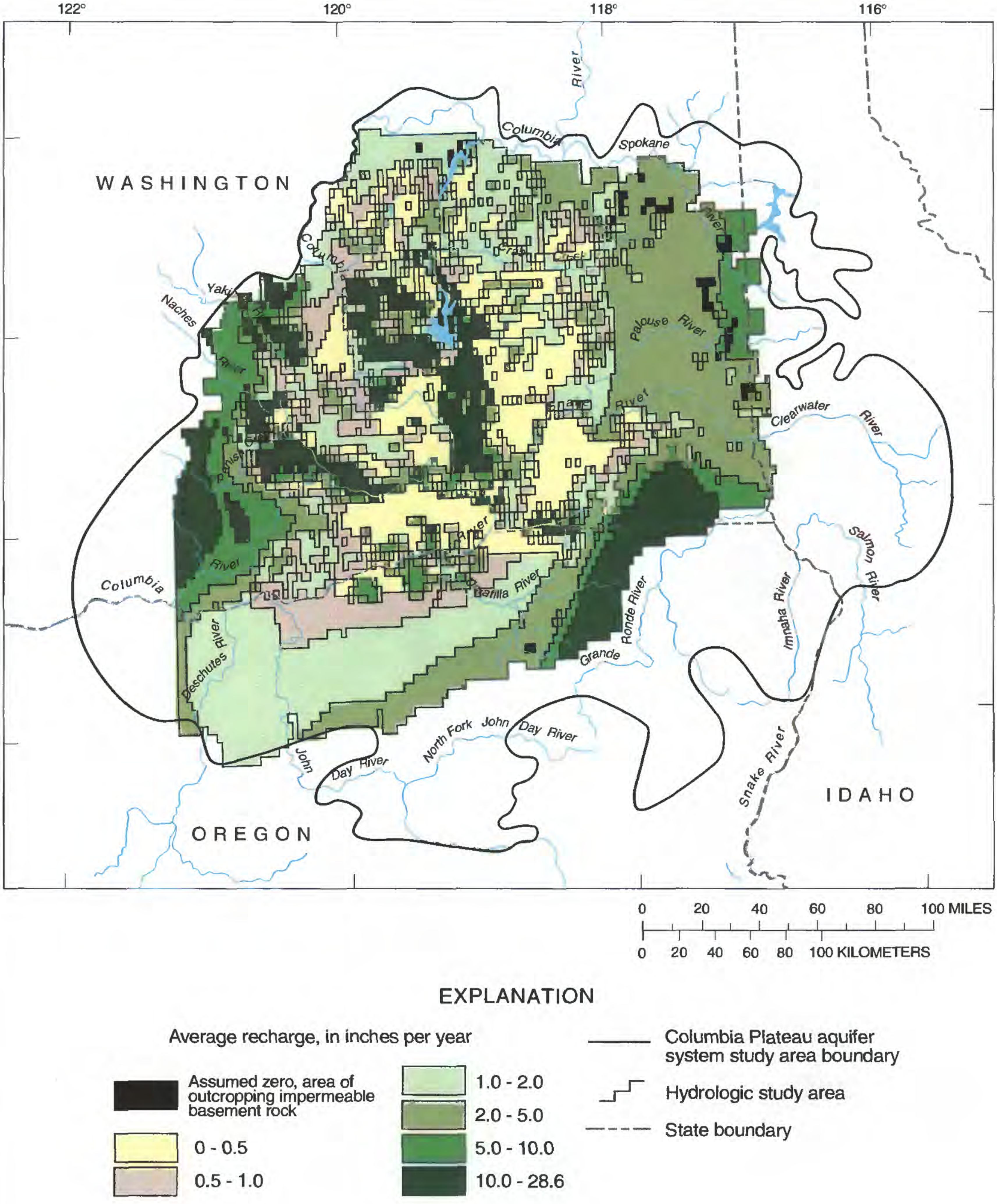


Figure 8. Distribution of estimated recharge within the hydrologic study area for 1980's land-use conditions.

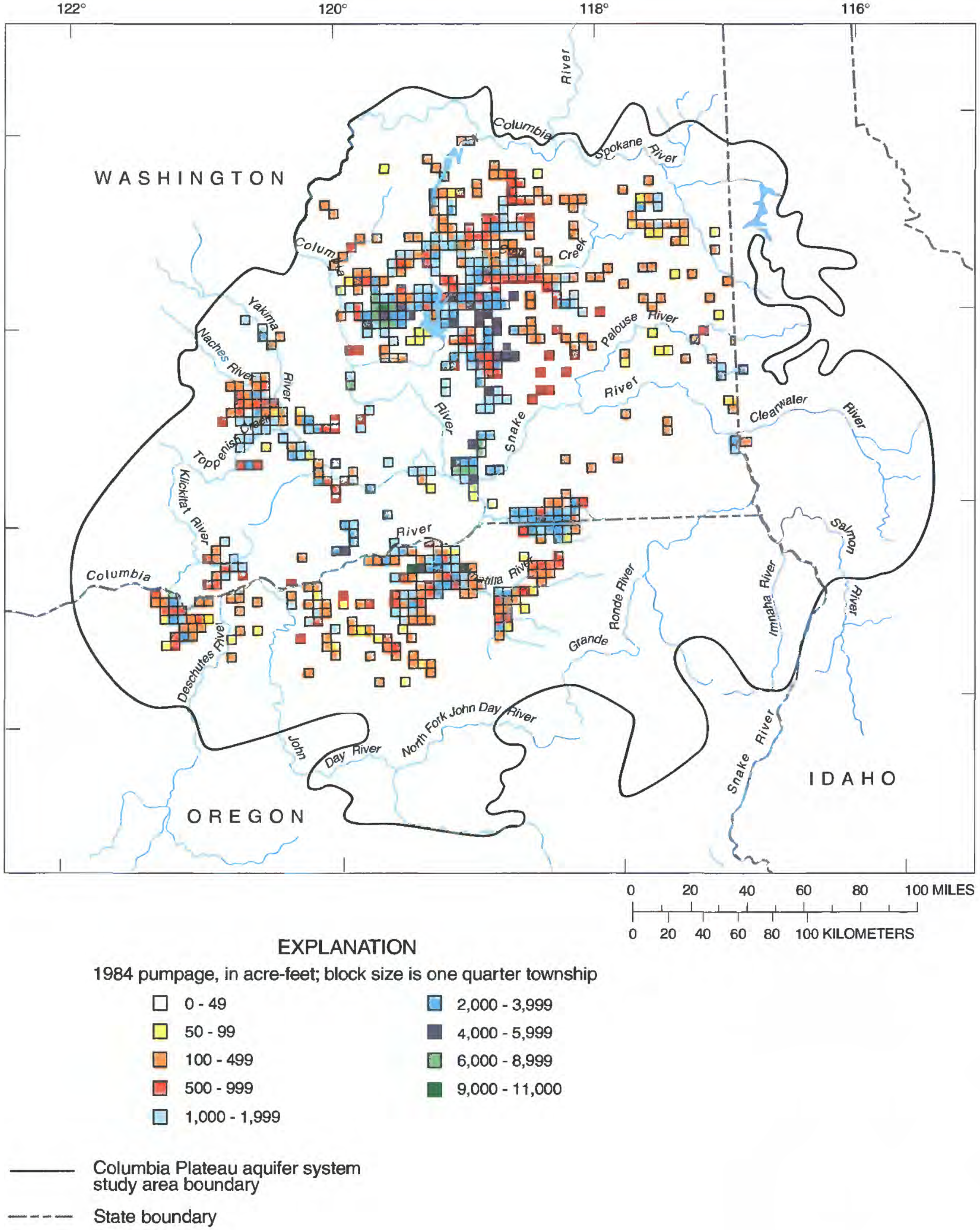


Figure 9. Distribution of 1983-85 ground-water pumpage.

Cell widths, lengths, and, optionally, cell top and bottom altitudes also must be specified. Cell tops and bottoms are required for layers that are to be "convertible," meaning that the cells in such layers can be simulated as for either fully saturated (confined) or partially saturated (water table). Boundary conditions and an initial-head configuration also must be specified for each layer.

The ground-water flow model simulations described in this report are for equilibrium predevelopment conditions, average hydrologic conditions for the period spring 1983 to spring 1985--"current conditions"--and several possible future equilibrium hydrologic conditions. For equilibrium (steady-state) simulations, the storage parameter is not used. All simulations were operated in the "convertible" mode for all layers in order to represent the aquifer system as realistically as possible. The 1983-85 period was not at equilibrium, but was treated as such by using the average head configuration for the period and by incorporating the average rate of change of storage for the period into the pumpage variable. The average change in storage for 1983-85 was estimated using the published water-level changes (Lane and Whiteman, 1989) for this period. Hansen and others (1994) describe this method in greater detail.

The boundary condition specified for each cell at the perimeter of each layer may be no flow, specified head, specified flux, or head-dependent flux. Drains, rivers, and general head boundaries (GHB) are specific types of head-dependent flux boundary conditions. Drains differ from rivers and GHB's in that they are not allowed to supply water to the aquifer and were used for those surface-water features that could not supply large quantities of water to the aquifer system, such as irrigation drains and small streams. GHB's were used to simulate seepage from escarpments of units that are completely truncated by erosion or uplift. For this application, the GHB head is set to the altitude of the bottom of the unit so that no inflow occurs.

The model was modified for this study so that (1) subtotals of water budgets for specified zones and cross sections are calculated, (2) linear features such as faults or narrow canyons are more rigorously simulated, and (3) vertical flow is allowed directly between layers where intervening layers are missing. Hansen (1993) describes these modifications in detail.

Model Grid and Boundary Conditions

A north-south rectangular grid spacing of 2.5-minute latitude by 2.0-minute longitude (2.88 by 1.62 mi, or 4.67 mi^2 on average) was used to discretize the aquifer system. This resulted in 76 rows of latitude and 130 columns of longitude. The cell size was determined in consideration of the size of the study area, available computer storage, data availability, and estimates of the maximum cell size that would describe most of the geologic structures. This grid was imposed on each of five layers, and is presented in Hansen and others (1994). Numbered from youngest to the oldest, the layers representing aquifers and units are:

Layer 1	Overburden aquifer
Layer 2	Saddle Mountains unit + Saddle Mountains-Wanapum interbed
Layer 3	Wanapum unit + Wanapum-Grande Ronde interbed
Layer 4	Upper 2,000 feet of the Grande Ronde unit
Layer 5	Lower part of the Grande Ronde unit not included in layer 4.

The Grande Ronde unit was divided into two layers to better simulate vertical head gradients within the unit, which, overall, is much thicker than any of the overlying units.

Generally, the lateral extent of the grid system for each layer was constructed to coincide with the lateral or hydrogeologic extent (boundary) of the corresponding unit (fig. 1). The upper Grande Ronde layer covers the widest area and, except for only a few locations, forms the outermost edge of the model. The lower Grande Ronde layer is defined as the part of the Grande Ronde unit lying 2,000 ft or more below the top of the Grande Ronde unit.

Wherever a layer pinches out or becomes unsaturated, the peripheral cells are bounded by no-flow boundaries. The boundaries for current conditions for the overburden aquifer and the Saddle Mountains unit covered a wider area than for predevelopment conditions because the amount of saturated areas increased with the development of surface-water irrigation projects. Boundaries for the Wanapum and Grande Ronde units remained the same. For current conditions there were 17,899 active cells.

Certain areas of the Columbia River Basalt Group were not included in the ground-water model because they are hydrologically isolated from the main body and would have added little to the analyses of the main regional-flow system. These areas are outside of the hydrologic study area and are described as follows.

1. The basalts south of the northeast-trending Blue Mountains anticline (fig. 6) are hydrologically separated from those to the north by the anticline that rises as much as 5,000 ft above the relatively flat-lying basalts on either side. The Blue Mountains crest coincides approximately with the anticlinal axis. Exposures of impermeable crystalline rock in the Blue Mountains indicate an impermeable core through which little ground water could move. Thus, the drainage divide along the Blue Mountains crest was chosen as a no-flow boundary in this area. Additionally, much of the area south of the anticline is sparsely populated, and there is little hydrogeologic information available.

2. West of The Dalles, the Columbia River Basalt Group extends along a narrow strip of the Columbia River valley to the Pacific Ocean. Ground-water flow in this strip follows short paths perpendicular to and terminating at the Columbia River. This area does not influence the main ground-water reservoir, therefore layers 3, 4, and 5 (the only layers in this area) were made to end along a selected flow line a few miles west of the deeply incised Klickitat River (fig. 2).

3. A situation similar to that west of the Dalles exists east into Idaho along the Clearwater River. Layers 3 and 4 north of the Clearwater River were made to end along flow lines perpendicular to the Clearwater River east of the confluence (layer 3) and at the confluence (layer 4) with the Snake River. The Wanapum unit generally ends as escarpments along the Snake and Clearwater Rivers well above river level. This is represented by GHB cells in layer 3. The Grande Ronde unit is partially penetrated by and in contact with the rivers. This is represented by river cells in layer 4. Other units are not present in this area.

4. In the extreme southeastern part of the study area, the north-trending Snake River and the east-trending Grande Ronde River cut deep canyons in excess of 2,000 ft that isolate some of the Columbia River Basalt Group to the east and south. Because all measured water levels in this area are much higher than the river stage and also because in some areas impermeable crystalline rock is exposed in the canyon bottom, it is unlikely that basalt aquifers on one side are hydrologically connected to those on the other side. Therefore, layer 4 was made to end and river cells were placed along the Grande Ronde and Snake River Canyons. Other layers are not present along these reaches of the Grande Ronde and Snake Rivers.

5. Similarly, the Spokane River, at the northeastern boundary (fig. 2), cuts through the Wanapum unit and deeply into the Grande Ronde unit, in places exposing older impermeable crystalline rock and isolating areas of the Grande Ronde and Wanapum units to the north. Thus, layer 4 has river cells along the Spokane River and layer 3 ends as GHB cells where the Wanapum unit is truncated in this area. Additionally, just south of this area is a ground-water divide.

6. Moving westward along the Spokane River, then westward and southward along the Columbia River to Wenatchee (southeastern Chelan County), these rivers cut entirely through the basalt and are entrenched in older impermeable crystalline rock isolating relatively small areas of basalt to the north and west. The model boundary, however, was not placed at the river canyon. Instead, layers 3 and 4 were made to end several miles south and west of the canyon, corresponding to a low anticlinal ridge and ground-water divide. The basalt along this line is, for the most part, thinner than on either side and in places is absent, exposing older

impermeable crystalline rock. Incorporation into the model of the "sliver" of basalt between the ground-water divide and the irregular course of the Columbia River to the north and west would have resulted in a complex, fragmented, head-dependent flux boundary that, at the grid scale employed, would have created untenable simulation problems. Layers 3 and 4 are the only layers present in this area.

Adjustments to Estimates of Hydraulic Characteristics

Hansen and others (1994) describe in detail the progression and rationale of adjustments to the initial estimates of hydraulic characteristics used in the ground-water flow model that were necessary for the model to simulate water levels that were in reasonable agreement with observed water levels--the calibration process. The initial estimates and final adjustments are described briefly in this section, relating them to the physical interpretations of the flow system.

Initial estimates of lateral hydraulic conductivities, discussed in the "Hydraulic Characteristics" section, showed little or no spatial pattern within the units. This may, in part, be because of where the wells are drilled. For example, there are many wells in low-lying agricultural and urban areas, where the units tend to be relatively flat-lying, whereas areas of intense folding and faulting usually coincide with steep mountains and (or) ridges upon which few wells have been drilled and therefore little is known, other than estimates of hydraulic characteristics from cursory inspection of outcrops. However, water-level data from areas adjacent to certain of these structural features suggest that hydraulic conductivities are, in general, lower than those in surrounding areas. For example, Frenchman Hills (fig. 6), an anticlinal ridge located just south of the Quincy Basin and just north of the Royal Slope agricultural area, appears to hydraulically separate the Wanapum unit of these two areas (Lane and Whiteman, 1989). Just to the north of Frenchman Hills, water-level contours in the Wanapum unit have a small gradient and ground-water flow is generally to the east. Whereas, just south of Frenchman Hills, where water levels are lower, the gradient is steeper and flow is to the south. If hydraulic conductivities were similar under Frenchman Hills, ground-water flow probably would be south across Frenchman Hills, from the Quincy Basin to the Royal Slope.

Similar impedances to ground-water flow across anticlinal ridges are interpreted wherever sufficient water-level data exist. A ground-water flow model in the Horse Heaven Hills area of Washington and Oregon (see fig. 2; Packard and others, 1996) used hydraulic conductivities at anticlines and faults that were less by a median factor of 0.0167 than the initial gridded values used for these locations. A factor of 0.0167 was therefore used to adjust the initial values at major faults and folds throughout the modeled area. For less severely deformed structures, such as monoclines, a factor of 0.1 was arbitrarily chosen. In order to better simulate these linear impedances to flow, Hansen (1993) provided modifications such that these reductions could be applied to specified model-cell walls without affecting hydraulic conductivities across the other three walls.

For estimating VCON, reported values of vertical to horizontal anisotropy of hydraulic conductivity ranged from about 0.0005 to 0.1 (Packard and others, 1996; Lum and others, 1990; Davies-Smith and others, 1988). The initial estimate used in the model was 0.003. This value was areally adjusted on the basis of the lithology and distribution of interbeds.

For the time-averaged steady-state simulations, the change in stored water resulting from water-level declines and rises in each aquifer, and thus the storage coefficient, had to be estimated. However, it was not necessary to make any estimates of overburden aquifer storage coefficients because virtually no changes in water levels in the overburden were observed for the time-averaged period. Few data exist from which to estimate storage coefficients in the project area. Table 1 shows values estimated from previous investigations. For the basalts, most of the interconnected pore space probably consists of fractures and rubbly zones. An average total porosity of about 4 percent is indicated by bulk and grain densities (Whiteman and others, 1994). In the Horse Heaven Hills area, water-level rises in relation to estimated quantities of irrigation water that recharged the basalt water table suggested a specific storage of about 0.015, whereas pumpage and water-level decline data suggested a specific storage of about 0.006 (A. Hansen, U.S. Geological Survey, written commun., 1989).

Table 1.--*Summary of selected storage-coefficient estimates for the Columbia Plateau*

Geologic unit	Hydrogeologic unit	Storage coefficient/ specific yield	Method[1] of deter- mination	References
Fluvial	Overburden aquifer	0.20	Model	Bolke and Skrivan, 1981
Glaciofluvial	--Do--	0.03-0.2	AT	Newcomb and others, 1972
Ringold Formation	--Do--	$2.0x10^{-4}$		----------Do-----------
Touchet Beds	--Do--	0.1	Model	Prych, 1983
Glaciofluvial	--Do--	0.06-0.2	AT	Bierschenk, 1959
Overburden	--Do--	0.06	AT	---------Do--------
Ringold Formation	--Do--	0.1	AT, Model	Tanaka and others, 1974
Glaciofluvial	--Do--	0.15		---------Do---------
Basalt	Wanapum	$1.2x10^{-4}$ $2.2x10^{-5}$	AT	Eddy, 1976 -------Do--------
Basalt	Saddle Mountains-Wanapum Grande Ronde	$3.2x10^{-2}$ $5.2x10^{-4}$	Model Model	A. Smith, U.S. Geological Survey, written commun., 1984 ------------Do------------
Basalt	Mainly Wanapum	$4.7x10^{-4}$ $9.0x10^{-5}$ $4.75x10^{-3}$	AT	MacNish and Barker, 1976
Basalt	Wanapum	$2.0x10^{-4}$	AT	Price, 1960
Basalt	Wanapum and Grande Ronde	$6.0x10^{-4}$ $1.4x10^{-6}$	AT	LaSala and Doty, 1971
Basalt	Wanapum-Grande Ronde	$1.5x10^{-3}$ $2.0x10^{-3}$ $6.0x10^{-3}$	Model	Luzier and Skrivan, 1973
Basalt	Saddle Mountains, Wanapum, and Grande Ronde	$1.0x10^{-2}$ $1.0x10^{-3}$	Model	F.A. Packard, U.S. Geological Survey, written commun., 1987
Basalt	Saddle Mountains	$2.5x10^{-3}$	AT, Model	Tanaka and others, 1974
Basalt	Not determined	$3.1x10^{-2}$ $1.9x10^{-3}$ $4.6x10^{-4}$ $5.0x10^{-5}$	AT	Oregon Water Resources Department from A. Smith, U.S. Geological Survey, written commun., 1984
Basalt	Wanapum and Grande Ronde	$7.6x10^{-4}$ to $3.0x10^{-5}$	AT	Tanaka and others, 1979

[1] Model, derived from calibration of numerical ground-water flow model; AT, computed from aquifer test data using analytical formula.

Given the estimated porosities and specific-storage values and the thickness of the basalt units, a storage coefficient of 0.01 was used initially with a final derived value of 0.04 for any water-table basalt aquifer. Wherever a basalt aquifer is overlain by another aquifer, it was assumed to be confined. A specific storage that was related to only the compressibility of water and pore space was assumed (the compressibility of the skeletal structure of the basalt was assumed to be negligible). Using a porosity of 0.04, the specific storage of confined basalt aquifers was estimated at about $6x10^{-8}ft^{-1}$ and was used with thickness values to calculate storage coefficients at model cells that had water-level declines over the period 1983-85.

The three types of head-dependent boundary conditions--rivers, drains, and GHB's--used in the model each require a value of conductance, C. Conceptually, for rivers and drains, the streambed is an impeding layer and C is equivalent to streambed vertical hydraulic conductivity, times the area of the streambed, divided by the thickness of the streambed. Initial estimates of vertical conductance for river cells were obtained from Packard and others (1996), Bolke and Vaccaro (1981), and Prych (1983). A value for C of $5x10^{-5}s^{-1}$ was used for all river cells in the overburden aquifer, and a value of $7 \times 10^{-7}s^{-1}$ was used for all river cells in the basalt units.

Initial estimates of C for most drains were made on the same basis as for rivers. Values for C in agricultural drain areas were estimated according to unpublished values used by the authors in a calibrated ground-water flow model during an investigation in the Quincy Basin area of the CBIP. Agricultural drains are spaced at close regular intervals, and for any ground-water model cell, a network of tile drains may exist. For these areas C-values were initially estimated from the drain-line spacings and lengths and the lateral hydraulic conductivity distribution in the water table aquifer. The Dupuit-Forchheimer discharge formula was used in a manner similar to that presented in subsequent paragraphs for determining equivalent river-leakage conductances.

The observed water levels, in general, exhibit downward gradients in successively deeper aquifer units within most of the aquifer system. Only close to major rivers and streams, locally at large pumping centers, or at certain geologic structures, are the gradients observed to be upward. Moreover, the magnitude of the downward gradients is generally much larger than of the upward gradients. Downward head differences of more than 400 ft between basalt units occur in many areas, but upward differences of more than 100 ft are rare. Generally, computed head differences between units did not initially match well with the observed head differences. For areas near major discharge features--the Columbia, Snake, and Yakima Rivers--computed upward vertical gradients were generally hundreds of feet too large, and downward gradients in most other areas were too small. Changes to VCON by global variation of vertical to horizontal anisotropy (FCTR) proved futile; any decrease of upward gradient near the major discharge areas brought about by reducing FCTR would be counteracted by a reduction in downward gradient in the other areas. Complete head collapse over most of the modeled region resulted when FCTR was adjusted to the extent that observed upward gradients were matched. Refinements of estimates of the distribution and lithology of the interbed material between basalt formations and subsequent adjustments to VCON did little to improve this situation.

Simulations using larger river-leakage conductances generally reduced the imbalance of head differences between the discharge and nondischarge areas and led to a different formulation of these conductances. The following is a brief discussion of a formulation for the river-leakage conductances that gives much larger values than were initially estimated on the basis of vertical hydraulic conductivities.

All of the major rivers are deeply incised into the basalts over most of their lengths within the study area and function as major discharge areas. Moreover, it is observed that lateral ground-water-level gradients increase precipitously in most locations near these discharge areas. This suggested that a Dupuit-Forchheimer discharge formulation would be more appropriate than the assumption of strictly vertical discharge through an impeding streambed (McDonald and Harbaugh, 1988). The Dupuit-Forchheimer approximation for discharge to a stream was used to estimate an "equivalent" river-leakage conductance. Discharge from a water-table aquifer to one side of a reach of a stream $(Q_{1/2})$, modified from Bear (1979), may be written as

$$Q_{1/2} = \frac{L_s K}{2x} \left[(h-H_b)^2 - (H_s - H_b)^2 \right] , \qquad (1)$$

where

H_b = the altitude of the streambed, L ;
H_s = the altitude of the water surface in the stream, L ;
x = distance from the stream, L ;
h = the water level in the water-table aquifer at distance x from the stream, L ;
K = the lateral hydraulic conductivity, L/T ; and
L_s = the length of the stream reach, L .

If the model cell head value is assumed to be approximately equivalent to the aquifer head at a distance half way between the stream (lying at the center of the cell) and the cell wall ($x \approx L_c/4$ for a rectangular grid where L_c is the cell width), and if equation (1) is doubled to account for discharge to both sides of the stream, and factored, equation (1) becomes

$$Q = \frac{4 L_s K}{L_c} (h + H_s - 2H_b)(h - H_s) \quad . \qquad (2)$$

For rivers and streams in the study area, $H_s - H_b$ is negligible compared with $h-H_b$ and generally L_s approximately equals L_c for most cells. Using these simplifications, equation (2) becomes

$$Q \approx 4K(h-H_b)(h-H_s) \quad . \qquad (3)$$

Thus, four times the lateral hydraulic conductivity times the average saturated thickness above the streambed for a river cell replaces the streambed conductance (C) .

Results of the simulations using the above formulation for river-leakage conductance improved considerably; however, computed heads were still too high at the rivers. Because most of the surface area of river cells are occupied by large rivers, estimated vertical conductance of the streambed multiplied by river area was also added to C calculated by equation 3; this assumes that vertical flow also contributes to the total discharge. Later in the calibration process, adjustments were made in order to regionalize values.

Using these river-leakage conductances gave computed heads in agreement with observed heads along the major rivers in all aquifers in hydraulic connection with rivers. However, upward head gradients were still too large between many river cells and cells of the layer immediately below in the vicinity of the rivers. Trial-and-error experimentation showed that in order to achieve a reasonable vertical head gradient match, it became necessary to also set the VCON between layers beneath the major rivers sufficiently large while not changing VCON throughout the remaining modeled area. Thus, it appeared that wherever a riverbed was observed to be in a particular basalt unit, there was good connection between the river, the unit in contact with the river, and the next lower basalt unit. Four hypotheses are presented here to explain such connection.

1. Riverbeds are probably more deeply entrenched into the basalt layers than has been mapped. When structure contours of the top of units were mapped, outcrops and well logs were used for altitude control. Smooth structure contours were drawn using these controls, with the constraint that land surface is an upper bound. Thus, under major rivers where there is no control other than streambed altitude, it is almost certain that if the river were deeply entrenched into the basalt units, it would not have been mapped as such. The original assignment of rivers to model layers therefore was probably biased toward the upper units, thereby introducing a greater simulated impedance for discharge from lower units.

2. It is well documented that during Pleistocene time there were enormous discharges down the Columbia and Snake Rivers from the breaching of prehistoric Lake Missoula and Lake Bonneville. These large flood volumes (386,000,000 ft^3/s; U.S. Geological Survey,

1974) scoured and plucked the riverbeds and deposited alluvium to great depths. At Wallula Gap, for example, just downstream of the confluence of the Columbia and Snake Rivers, cobbly gravels below the riverbed are reported to be more than 250 ft thick (Mackin, 1955).

3. Rivers that cut through basalt flows only at scattered locations can increase greatly the "apparent" vertical connection between units. The impedance to discharge can be decreased greatly in such a situation because the lateral hydraulic conductivity of basalt is generally several orders of magnitude greater than the vertical hydraulic conductivity. There actually may be much less vertical flow to the rivers than has been conceptualized because ground water can discharge laterally, probably in places as underwater springs, to where the basalt layers are cut by the river bed. Because of the large spatial scale of this project, many localized cuts would not have been accounted for. Such an enhancement of vertical conductance from bedrock erosion would occur only in areas of shallow water levels and therefore in the discharge areas. Thus, in upland areas where the bedrock topography may be heavily dissected, it has little or no effect on "apparent" vertical conductances because water levels are well below the erosional irregularities.

4. Many of these river cells with large vertical conductances overlie the axis of synclines. The potential exists that deformation might enhance vertical hydraulic conductivity with depth at synclines.

Except for (4), the above discussion does not apply to the lower Grande Ronde, the top of which is far beneath all rivers. During the calibration process, the VCON between the upper and lower Grande Ronde layers, for lack of any data, was formulated in the same manner as that for the VCON between the Wanapum unit and the upper Grande Ronde. This generally resulted in lower VCON values than for those between the upper layers because of the greater thicknesses involved. Again, there were high head problems in the vicinity of the major discharge areas. Generally using larger and more nearly uniform values of VCON between these two layers throughout the model gave reasonable results. This may be justified by the fact that there are few interbeds and saprolites between the Grande Ronde Basalt flows to impede vertical ground-water flow.

In some of the tightly folded upland areas, it was necessary to use values of VCON between the Saddle Mountains and Wanapum units and between the Wanapum unit and the upper Grande Ronde that were smaller than those used for most of the less structurally complex areas. The use of median-range values could not sustain simulated water levels in the uppermost unit, resulting in many desaturated cells. Increasing recharge as much as 30 percent did not help. This structural relation between anticlines and low vertical conductance is not clearly understood. A probable reason for this relation is that compressional forces during folding disrupted and closed the vertical jointing spaces in the colonnade parts of the basalt flows. Evidence for this is seen in exposures of anticlines that have been cut deeply by the Yakima River, a few miles upstream of the City of Yakima. It is difficult to recognize the colonnade structure that is so evident in undeformed exposures of basalt flows.

Final values of VCON were regionalized with larger values along major rivers, and lower values in upland areas. Median values between layers are, from top to bottom, $2.6x10^{-8}$, $2x10^{-11}$, $6x10^{-12}$, and $5x10^{-11}$ s^{-1}.

It was evident early in the calibration process that topography would be a major hydrologic control. That is, the water-table aquifer is drained by rivers, streams, and even some nonperennial streams and coulees. Only in the low-lying areas near the center of the study area, where the water table is deeper, are these topographic controls lacking. Topographic control was simulated by using the drain and river functions. These functions initially were used only along the larger perennial streams and rivers, and as a result, higher-than-observed heads were calculated in many intervening areas. Even a 60-percent reduction of the recharge estimates in these areas did not help; the drains received less discharge and heads were still much too high. It became evident that more topographic control was necessary, especially in the upland areas, which receive large quantities of recharge, such as the southern flank of the Blue

Mountains and the east side of the Cascade Range. In order to lower computed heads, it became necessary to use the drain or river functions for almost all stream channels.

Another alternative for lowering computed heads was to increase lateral hydraulic conductivity values to much larger than median values in areas of large precipitation. However, such a coincidence of large precipitation and large conductivity was not physically plausible and this alternative was not pursued.

Simulated heads were much lower than observed heads in various upland areas that initially were assigned median lateral hydraulic conductivities and that receive relatively small quantities of precipitation--such as in the Yakima Fold Belt, eastern Horse Heaven Hills, Beezely Hills, and Frenchman Hills (fig. 2). In general, hydraulic conductivities in the uplands had to be sufficiently reduced to adequately match observed heads in areas of low recharge, and these values were assumed to prevail in other upland areas that receive more recharge. However, specific-capacity data are scarce for upland areas, but where available, they do not show any consistent differences when compared with other areas. A hypothesis is presented below in support of smaller hydraulic conductivities in the uplands on the basis that upland areas of the Columbia Plateau are known to have numerous faults.

Lateral ground-water flow in basalts is predominantly along the rubbly interflow zones, which typically occupy only 5 to 10 percent of basalt flow thickness (see fig. 3); thus, even minor offsets of the basalt strata would tend to impede lateral flow. On a regional scale, an effectively smaller hydraulic conductivity would be the consequence of such faulting. Locally, however, the conductivity is unaltered; aquifer or specific-capacity tests may not show the smaller regional-scale values unless conducted on a long-term basis at sufficient pumping rates (most wells in the uplands are shallow, small-diameter, low-yield domestic wells) to lower water levels at the faults and observe boundary effects. Thus, a regional ground-water model whose grid spacing is larger than fault spacing can only simulate a faulted area using smaller hydraulic conductivities.

Later in the calibration process, adjustments were made to lateral hydraulic conductivity values for all layers in order to regionalize values. The final model-derived distributions of lateral hydraulic conductivity for each layer (presented in Hansen and others, 1994) when referenced to the median values derived from the specific-capacity data, are (1) smaller in the uplands, (2) smaller in the remaining area but larger than the upland values, and (3) larger in a few locations. Boxplots of calculated and calibrated lateral hydraulic conductivities for the model layers (fig. 10) show that, for all units, the lower quartile, median, and upper quartile values derived during model calibration are less than those derived from the specific-capacity data.

In specific areas unusual problems were encountered during the calibration process.

1. Big Bend area: This area lies north of Pasco, Wash., and generally encompasses the area between the Snake and Columbia Rivers to as far north as about 46.5° latitude (fig. 2). Ground-water flow in all four basalt units in this area generally is southwestward toward discharge areas along the Columbia and Snake Rivers. Simulated heads in the Wanapum and Grande Ronde units were too high, especially in the upper Grande Ronde, using a full range of reasonable values of lateral hydraulic conductivity and vertical conductances. In order to simulate lower heads in this area, it was necessary to use small lateral hydraulic conductivities along an east-west-trending strip just upgradient of this area. This strip corresponds with areas where lateral head gradients in the Wanapum and Grande Ronde units are considerably steeper than to either the northeast (upgradient) or the southwest (downgradient). The physical reason for such a low-conductivity strip in this relatively flat-lying region is not known. The strip appears as an eastward extension of the Saddle Mountains anticline into the subsurface, although the mapped eastward extension of this anticline is short (Tolan and Reidel, 1989). The deeper older basalts might have been folded and faulted along this strip and later covered by the younger, relatively flat-lying Wanapum Basalt flows, so that there is now no surficial expression of such structure. However, because the Saddle Mountains were being uplifted during and after the time of deposition of Saddle Mountains Basalt flows, it is likely that the

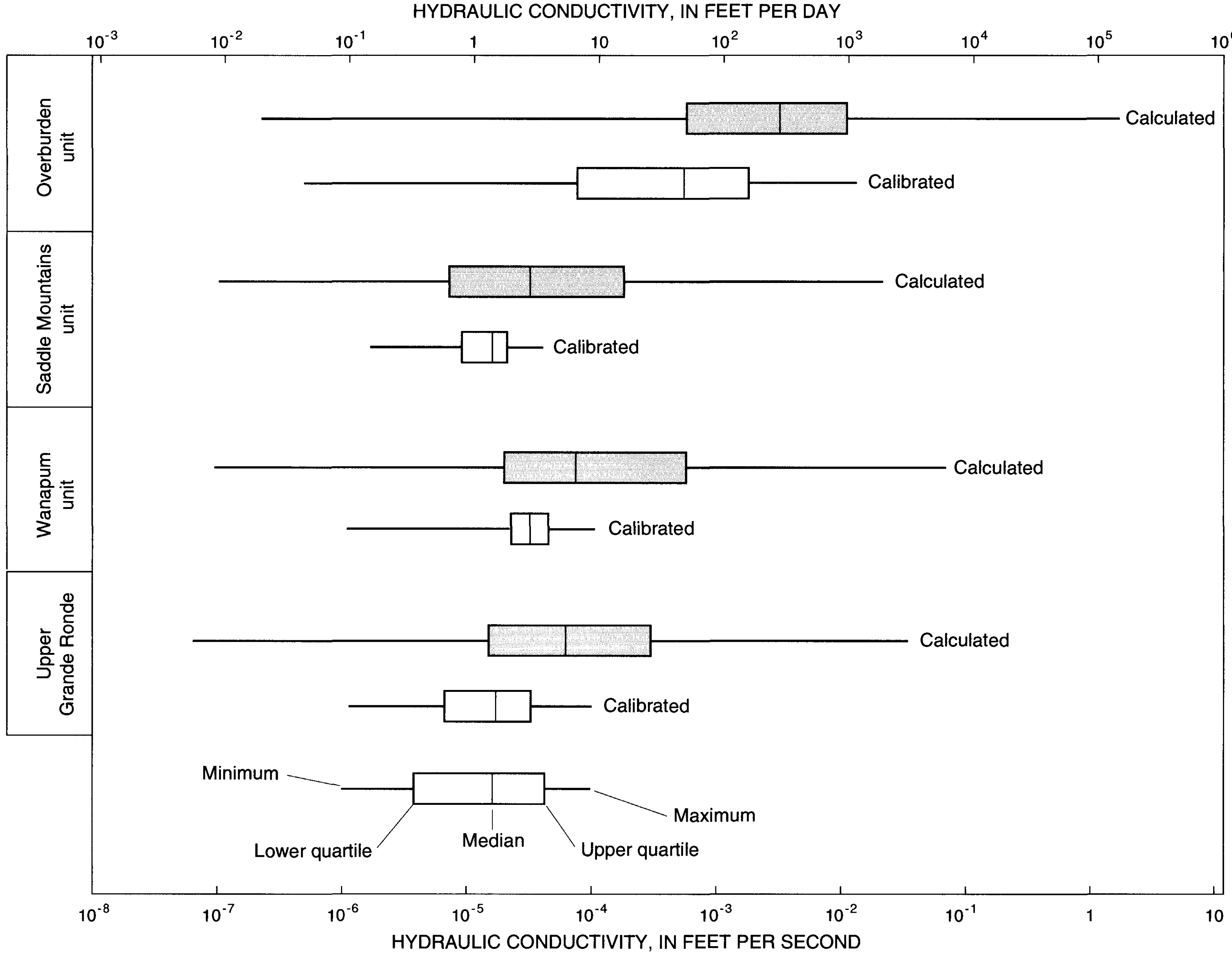


Figure 10. Boxplots of calculated and calibrated lateral hydraulic conductivities for the model layers.

Wanapum Basalt should have been displaced as well. Perhaps such structures have not been mapped because displacements are small and outcrops scarce. As was mentioned previously, slight vertical displacements of basalt flows can decrease regional hydraulic conductivities. Alternatively, basalt flow displacement may be the result of several intercanyon flow members that closely correspond to this strip of the Columbia River Basalt Group (Tolan and others, 1989).

2. Odessa-Lind ground-water-irrigated area: This roughly rectangular area lies south of Crab Creek, west of Cow Creek, east of the East Low Canal, and north of Lind Coulee, Wash. (fig. 2). During the initial time-averaged simulations, a large percentage of Wanapum unit cells went dry in this area, regardless of reasonable adjustments of hydraulic conductivities and vertical conductance. Pumpage from the Wanapum unit, which is exposed in this area, is simply too great to be supplied by only lateral or upward ground-water inflow. As a result, it became necessary to increase recharge from the quantities estimated using the deep percolation model. The most likely source of such additional recharge is the surface water that is present at times in the coulees crossing this area. The water table is well below the bottoms of these coulees, and therefore they do not drain the Wanapum unit. In fact, down-gradient flexures of the Wanapum water-level contours beneath some of the larger coulees suggest recharge through the coulees. Moreover, crest-stage streamflow data for several of these coulees show that for short periods there is a large potential for recharge. Providence Coulee (fig. 2), for example, flowed at the rates of 2,160, 650, and 522 ft^3/s during 1956, 1969, and 1970, respectively (Williams and Pearson, 1985). Actual recharge quantities derived from the streamflow in the coulees could not be estimated, so the smallest quantity of recharge, which would keep most cells in this area wet during simulations, was added along the coulee courses. This amounted to an additional 32 ft^3/s of recharge along the coulees.

3. Moses Coulee: This coulee is second in size only to Grande Coulee in the study area. It cuts deeply into the Grande Ronde Basalt on the northwest upland, referred to as the Waterville Plateau. The Waterville Plateau is bounded on the west and north by the Columbia River, on the east by Grande Coulee, and on the south by Beezely Hills (fig. 2). From the water-level contours, it appears that Moses Coulee drains the Grande Ronde unit over the entire length of the coulee. Jamison Lake, which covers 620 acres of the coulee bottom in the upper reach, has no outlet and yet contains fresh water. The model simulated about 37 ft^3/s of ground-water discharge to the Douglas Creek drainage basin, which is tributary to Moses Coulee, plus about 10 ft^3/s to the lower part of Moses Coulee. However, streamflow records indicate that the simulated flow should be much smaller. When recharge on the Waterville Plateau is reduced so that simulated discharge is more comparable to observed or estimated streamflow, calculated water levels are much too low using reasonable values of lateral hydraulic conductivity. Vertical conductance is not relevant, because only the upper Grande Ronde is present in this area; although the Wanapum unit is present in small discontinuous areas, it was considered part of the upper Grande Ronde. It is reasonable to expect that there may be ground-water outflow through highly permeable alluvium lying in the coulee bottom. Therefore, ground-water discharge to Moses Coulee may be primarily into the alluvium, which eventually discharges to the Columbia River at the coulee's mouth.

4. Peripheral and upland areas: For many areas at high altitudes, simulated heads were considerably lower than observed or estimated heads, even after the downward adjustments of lateral hydraulic conductivities and vertical conductances. Because most observed upland heads are from shallow domestic wells that penetrate only the uppermost part of a basalt unit, such heads are probably not representative of the vertically averaged values of head for the unit, unless the unit is relatively thin. In fact, downward vertical gradients are observed virtually

everywhere in the uplands wherever sufficient data are available. For example, a test well drilled on the crest of Rattlesnake Mountain (fig. 2) within the Yakima Fold Belt (Raymond and Tillson, 1968) shows a downward head difference of approximately 830 ft within approximately 3,200 ft of thickness of the Grande Ronde unit. Thus, if representative water-level data were not available and reasonable values of lateral hydraulic conductivity and vertical conductance were used, simulated heads that were lower than observed were accepted (and assumed to be more representative of the average head of a unit's thickness) in the uplands. In addition to simulating lower heads than those observed in some upland areas, many peripheral upland cells of the uppermost unit would desaturate during simulation. This usually happened in areas where the unit was thin and (or) recharge was small. For example, the entire crest of the Saddle Mountains east of the Columbia River, which is in a low-recharge area, desaturated. Because there are no wells in this area, these dry cells generally were accepted as reasonable despite the original estimates of water levels presented in earlier reports (Bauer and others, 1985; Whiteman, 1986; and Lane and Whiteman, 1989).

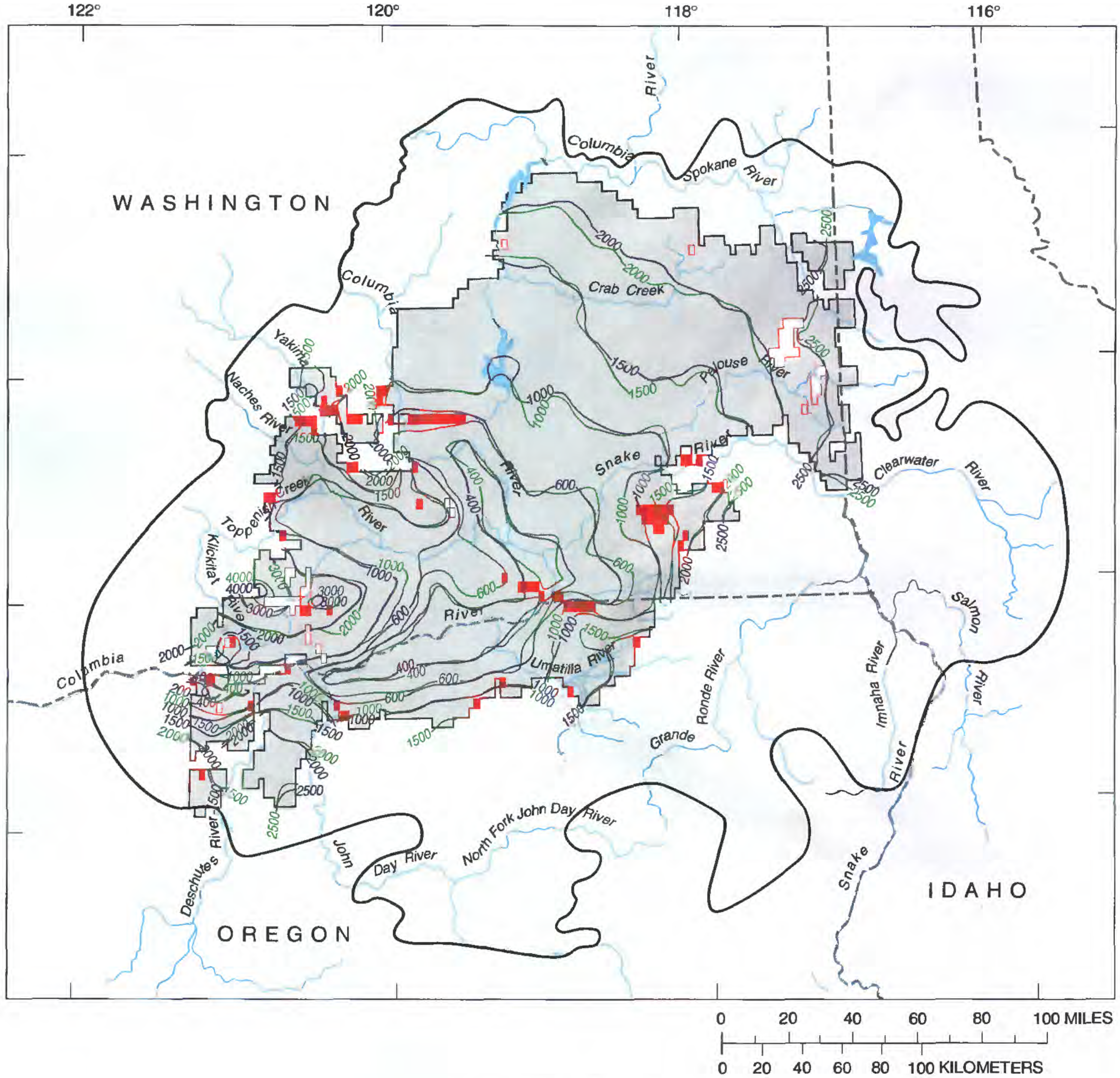
Model Reliability and Sensitivity

The reliability of the ground-water model can be judged by comparing the closeness of fit between computed and measured water levels for four of the five layers (the overburden aquifer, Saddle Mountains unit, Wanapum unit, and upper Grande Ronde) and by comparing estimates of baseflow of streams with computed ground-water discharge for certain drainage basins lying completely within the modeled area. No comparisons were made for layer 5 that represents the lower Grande Ronde because there were no water-level data. As part of the first criterion, differences in water levels between layers can also be compared. The second criterion is much more subjective because estimates of baseflow of streams are difficult to make, especially during wet periods when shallow subsurface discharge cannot be reliably separated from baseflow.

Time-averaged, model-computed and the observed water-level contours and cells that desaturated during the simulation are shown for the Wanapum unit (fig. 11); Hansen and others (1994) present this information for all layers. No data were available to verify whether the aquifer is actually saturated in areas where the cells desaturated. For most areas, the computed and observed water levels appear to match reasonably well. Flow directions and lateral gradients replicate the natural system on a regional scale. Only in certain upland areas are computed water levels significantly different from contoured water levels (water-level data generally were not available for the uplands and water-level contours were estimated).

For the overburden aquifer, agreement between simulated and observed heads is good (as would be expected on a regional scale because the overburden aquifer exists only in relatively flat, low-lying areas). However, during simulations 79 cells in the overburden desaturated at peripheral locations where the unit tends to thin out and turn upward as it pinches out against the underlying basalt. For the Saddle Mountains unit, the greatest differences between simulated and observed water levels were at the crest of eastern Horse Heaven Hills, where computed water levels were as much as 400 ft lower than observed. For the Wanapum unit, computed water levels at the crest of Rattlesnake Hills similarly were 400 ft lower. For the upper Grande Ronde, computed water levels were as much as 500 ft lower in an upland area south of Wenatchee and northeast of Yakima, bounded on the east and west by the canyons of the Columbia and Yakima Rivers, respectively, and as much as 1,000 ft lower between the canyons of the John Day and Deschutes Rivers, in the extreme southwest corner of the modeled area.

The values, in feet, for the mean residual (MR), mean absolute residual (MAR), and root mean square (RMS) for all cells between the time-averaged simulation water levels and the contoured observed water levels for layers 1 through 4 are as follows.



EXPLANATION

- Extent of ground-water model layer 3
- Area of thin or absent unit not included in ground-water model
- Cell simulated as unsaturated
- Columbia Plateau aquifer system study area boundary
- State boundary
- -600- Line of equal simulated water level. Interval, in feet, is variable. Datum is sea level
- -600- Line of equal observed water level. Interval, in feet, is variable. Datum is sea level

Figure 11. Map showing contours of simulated and observed 1983-85 water levels for the Wanapum unit.

Model layer	Mean residual	Mean absolute residual	Root mean square	Number of cells
1	-18	46	71	900
2	-14	72	104	1,092
3	-31	81	124	4,308
4	-122	184	292	6,977

The values for cells where there are observed water levels are as follows.

Model layer	Mean residual	Mean absolute residual	Root mean square	Number of cells
1	-0.30	39	58	74
2	-9.0	67	91	77
3	-45	88	142	307
4	-107	158	253	276

By some standards these residuals are large, but on a regional perspective where the overall observed head relief is more than 5,000 ft, the model simulates the estimated heads reasonably. Accuracy is diminished in the high-gradient areas where lateral head differences between adjacent cells approach 600 ft.

Table 2 shows total simulated discharges from river, drain, and GHB cells within 27 separate drainage basins for which estimates of baseflow were made. Sufficient daily stream discharge data were available for 23 of these basins, from which average annual discharges were computed and also tabulated. These 23 basins are among the 53 basins for which recharge simulations were made (see "Recharge" section). Only low-flow data were available for the other four basins and probably represent minimum values of ground-water discharge. Figure 12 shows the gridded outlines and locations of these basins. There were no major discrepancies between model-simulated discharge and estimates of baseflow. Simulated ground-water discharges were significantly greater than total streamflow in only four basins. One of these is Douglas Creek (in Moses Coulee), which has already been discussed in the "Adjustments to Estimates of Hydraulic Characteristics" section. The reason for the discrepancies at the other three basins--Wilson Creek, Willow Creek, and Ahtanum Creek Basins--is not understood at this time. A possible explanation is that unrealistic simulation of ground-water flow across small drainage basins could result from large cell size and regionalization of parameters. For example, the computed discharge for Glade Creek slightly exceeds observed annual streamflow; however, in the adjacent basins of Pine Creek and Rock Creek, the computed discharge is less than estimated baseflow. Considering both the uncertainty in estimating baseflow and the regional nature of the model, these simulated discharges are believed to be reasonable.

Model sensitivity was tested by changing input parameters (lateral conductivity, vertical conductance, recharge, and pumpage) uniformly over all cells within a range of ±15 to ±25 percent. Generally, within the range of changes tested, the sensitivity increases with depth for all inputs. This is mainly because the rivers and drains are the major control on the water levels in the surficial layer. For example, for the 1983-85 simulation, when the lateral hydraulic conductivity was uniformly reduced by 20 percent, the average head rise in layer 5 was 26 ft but in layer 1 was only 6 ft; when the vertical hydraulic conductance was reduced 20 percent, the average decline for layer 5 was 10 ft and for layer 1, 2 ft. In general, the head changes resulting from the sensitivity tests were less than the mean absolute residuals of the calibrated model (Hansen and others, 1994).

SIMULATED REGIONAL FLOW

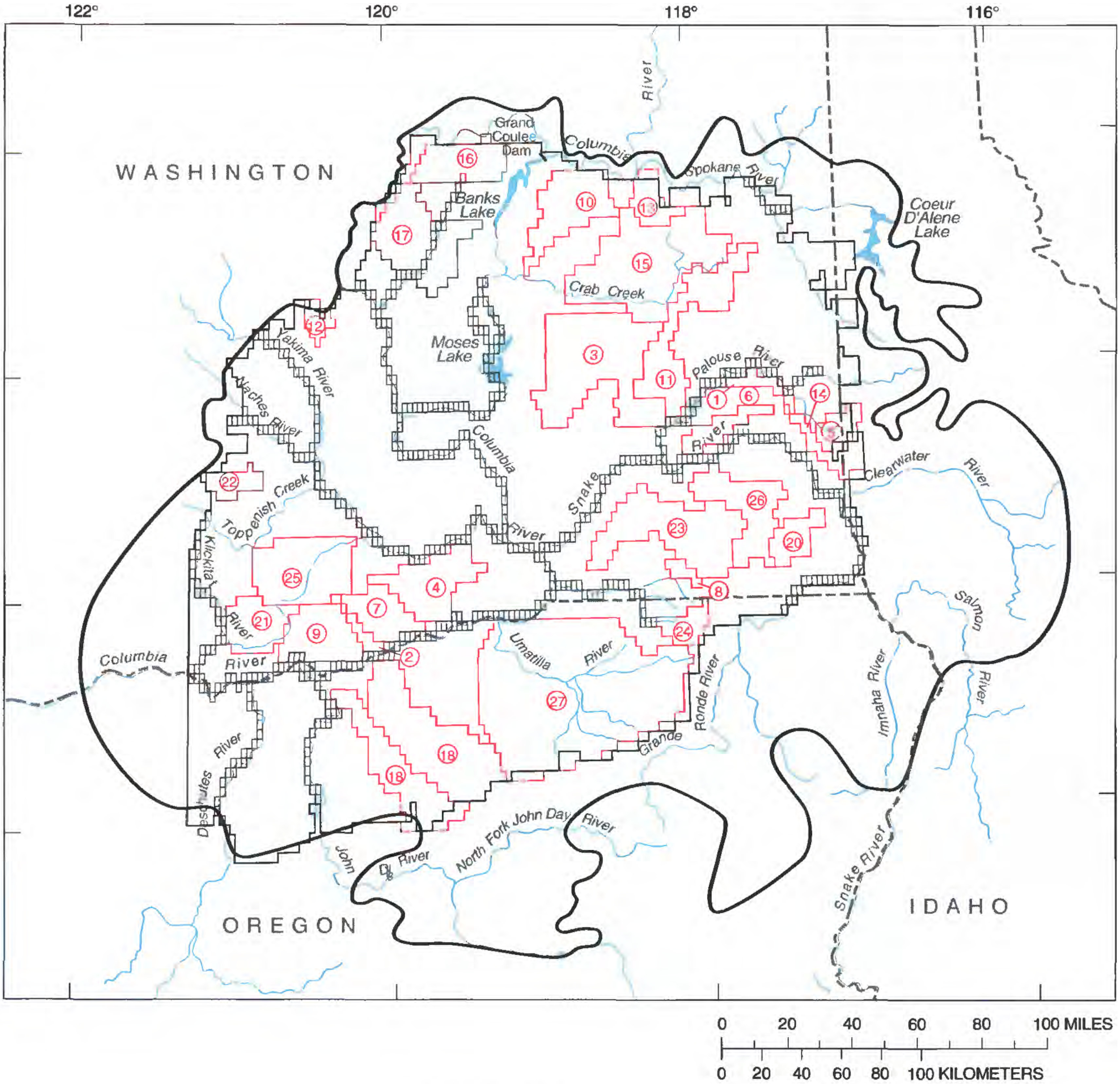
The following sections present information on regional ground-water flow based on results that were simulated by the model. In addition to the 1983-85 time-averaged model results, information for six other simulations are presented, five of which represent potential future conditions. These six are (1) predevelopment, (2) future equilibrium with 1983-85 stresses, (3) Phase 1 expansion of the CBIP retaining 1983-85 pumpage, (4) Phase 1 expansion of the CBIP with reduced 1983-85 pumpage, (5) Phases 1 and 2 expansion of the CBIP retaining 1983-85 pumpage, and (6) Phases 1 and 2 expansion of the CBIP with reduced 1983-85 pumpage. Each of these is described in more detail in the following sections.

Table 2.--*Comparison of simulated ground-water discharge, estimated recharge, and average streamflows for drainage basins with streamflow records within the modeled area*

[Values in cubic feet per second except where noted; Cr = creek, R = river, S. = south, Wash. = Washington, Oreg. = Oregon, and CBIP = Columbia Basin Irrigation Project]

Reference[1] number	Basin	Drainage area, in square miles	Estimated recharge		Streamflow[2]		Predevel-opment	1983-85 time-averaged	1983-85 equili-brium	Phase 1 CBIP expansion		Phases 1 and 2 CBIP expansion	
			predevel-opment	1983-85	total	estimated baseflow				1983-85 pumpage	reduced pumpage	1983-85 pumpage	reduced pumpage
1	Rebel Flat Cr.	79	17.6	17.6	--	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	Pine Cr.	66	4.4	4.4	12.7	6.2	1.6	2.0	2.0	2.0	2.0	2.0	2.0
3	Bowers Coulee	992	74.0	77.5	9.8	0.0	12.3	2.7	1.0	7.3	8.6	254.0	314.9
4	Glade Cr.	427	5.2	22.1	6.4	1.3	0.0	7.9	6.4	6.4	6.4	6.4	6.4
5	S. Fork Palouse R.	125	18.3	18.3	36	18	14.5	8.6	8.6	8.6	8.6	8.6	8.6
6	Alkali Flat Cr.	158	26.9	26.9	--	1.2	9.6	9.5	9.4	9.4	9.4	9.5	9.5
7	Alder Cr.	254	19.3	21.7	17.0	1.2	11.1	9.6	7.8	7.8	7.8	7.8	7.8
8	Dry Cr.	52	16.7	14.7	25.2	7.1	14.3	12.0	12.0	12.0	12.0	12.0	12.0
9	Rock Cr., Wash.	415	36.2	37.1	107	37	21.9	21.5	20.7	20.7	20.7	20.7	20.7
10	Wilson Cr.	437	30.3	51.2	14.5	0.0	16.9	21.6	21.1	21.3	21.5	21.5	22.1
11	Cow Cr.	543	88.4	80.9	24	13	40.9	22.9	11.1	12.0	12.6	15.0	18.9
12	Naneum Cr.	83	52.7	52.7	78	46	23.2	23.8	23.8	23.8	23.8	23.8	23.8
13	Hawk Cr.	168	27.9	27.9	--	8.8	25.9	23.8	23.1	23.3	23.4	23.5	23.9
14	Union Flat Cr.	172	39.1	39.1	35	0.0	24.2	24.3	23.9	23.9	23.9	23.9	23.9
15	Crab Cr.	1,015	129.1	106.3	68	19	62.8	24.6	20.6	23.1	23.4	23.5	26.1
16	Foster Cr.	322	29.9	28.6	--	2.0	30.9	27.4	27.4	27.4	27.4	27.4	27.4
17	Douglas Cr.	598	44.3	36.2	3.1	0.0	43.8	37.1	36.9	37.1	37.1	37.1	37.2
18	Rock Cr., Oreg.	515	58.5	58.5	54	7	56.5	54.6	54.1	54.1	54.1	54.1	54.1
19	Willow Cr.	837	34.3	104.0	31	0.0	64.9	63.2	62.0	62.0	62.0	62.0	62.0
20	Asotin Cr.	173	79.9	80.0	78	44	75.5	75.3	75.2	75.2	75.2	75.2	75.2
21	Little Klickitat R.	287	132.3	132.3	177	22	100.8	79.0	78.4	78.4	78.4	78.4	78.4
22	Ahtanum Cr.	126	104.3	108.6	78	46	99.6	102.4	102.4	102.4	102.4	102.4	102.4
23	Touchet R.	725	164.0	148.0	172	0.8	124.3	109.1	109.1	109.1	109.1	109.1	109.2
24	Walla Walla R.	132	151.1	152.3	325	230	159.4	160.6	160.6	160.6	160.7	160.7	160.7
25	Satus Cr.	577	231.3	231.4	287	134	162.3	164.2	164.0	164.0	164.0	164.0	164.0
26	Tucannon R.	430	212.2	203.5	197	129	174.9	168.7	168.7	168.7	168.7	168.7	168.7
27	Umatilla R.	2,436	680.7	719.8	750	328	553.5	556.5	549.1	549.1	549.2	549.2	549.3

[1] Reference number shown on figure 12 for location of basin.
[2] Average values for periods of record during 1956-77.



EXPLANATION

- ㉑ Basin reference number for basins presented on Table 2
- ▯ River cell locations for rivers presented on Table 4
- Outline of model cells representing a basin
- Extent of model
- Columbia Plateau aquifer system study area boundary

Figure 12. Locations of basins and stream reaches for which water budgets are presented.

Changes from Predevelopment to 1983-85

Development of water resources and changes in land use from predevelopment (1850's) to current (1980's) conditions have affected the regional ground-water flow system. A major objective of this RASA study was to describe and quantify the water budget for the aquifer system and to assess the effects of development. Ground-water budgets, water levels, and ground-water discharge to selected basins for predevelopment and 1983-85 conditions are compared.

Ground-Water Budget

Simulated flows across the various boundaries, recharge from precipitation and irrigation to each layer, vertical flow between layers, and pumpage from each layer for predevelopment and 1983-85 time-averaged conditions are shown schematically in figures 13 and 14, respectively. Table 3 shows the regional ground-water budget including recharge, change in storage, leakage from rivers, pumpage, and discharges to the rivers, drains, and GHB's. This information provides the basis for the following discussions.

For predevelopment conditions, the largest single flow component is 4,131 ft^3/s of recharge from precipitation to the upper Grande Ronde (fig. 13). This is 63 percent of the total recharge from precipitation to the entire system (table 3). Most of this recharge to the upper Grande Ronde occurs in the peripheral areas where the unit is at land surface (fig. 1); these areas correspond with the uplands of the Blue Mountains, the foothills of the Cascades, the Waterville Plateau, and a narrow strip just south of the Columbia River along the northern margin. About 2,970 ft^3/s of the recharge discharges to drains and GHB's in the upper Grande Ronde along the peripheral outcrop areas. Thus, 72 percent of recharge from precipitation to the Grande Ronde unit (45 percent of total recharge from precipitation to the system) discharges in these peripheral areas. This indicates that regional lateral ground-water inflow from areas of large precipitation (large recharge) to lowland areas is limited.

Table 3.--*Regional ground-water budgets based on seven ground-water flow simulations*

[Values in cubic feet per second; CBIP = Columbia Basin Irrigation Project]

Water-budget component	Predevel-opment	1983-85 time-averaged	1983-85 equili-brium	Phase 1 CBIP expansion: 1983-85 pumpage	Phase 1 CBIP expansion: reduced pumpage	Phases 1 and 2 CBIP expansion: 1983-85 pumpage	Phases 1 and 2 CBIP expansion: reduced pumpage
Recharge	6,566	10,205	10,205	10,535	10,535	11,179	11,179
Leakage from rivers	553.6	556.7	576.5	564.0	552.6	553.8	538.5
Rate of change in storage	0.0	186.6	0	0	0	0	0
TOTAL IN*	7,120	10,948	10,782	11,099	11,087	11,732	11,717
Leakage to rivers	2,753.9	3,804.5	3,726.1	3,757.6	3,770.4	3,798.0	3,846.1
Leakage to drains	3,944.8	5,595.9	5,549.0	5,821.3	5,925.9	6,406.8	6,609.2
Leakage to general-head boundaries	425.5	422.6	420.9	424.5	424.6	426.2	426.6
Pumpage	0.0	1,134.7	1,095	1,104.1	974.7	1,114.1	843.2
TOTAL OUT*	7,124	10,958	10,791	11,107	11,096	11,745	11,725

* The totals may not match exactly because they are taken directly from the output of model simulations, which have a certain amount of mass balance error due to non-exact closure of the numerical solution.

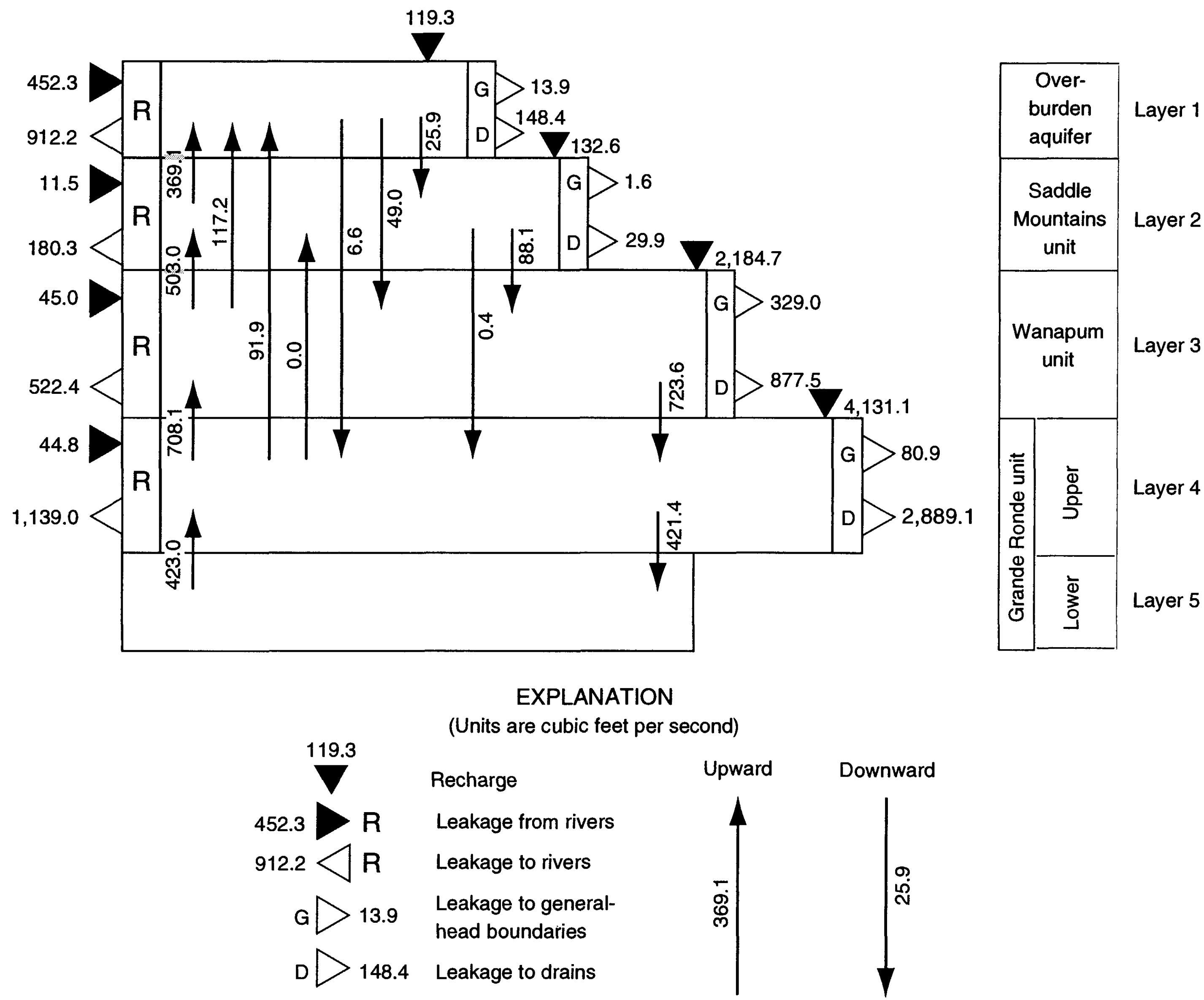


Figure 13. Diagrammatic section showing the model-calculated predevelopment water budget.

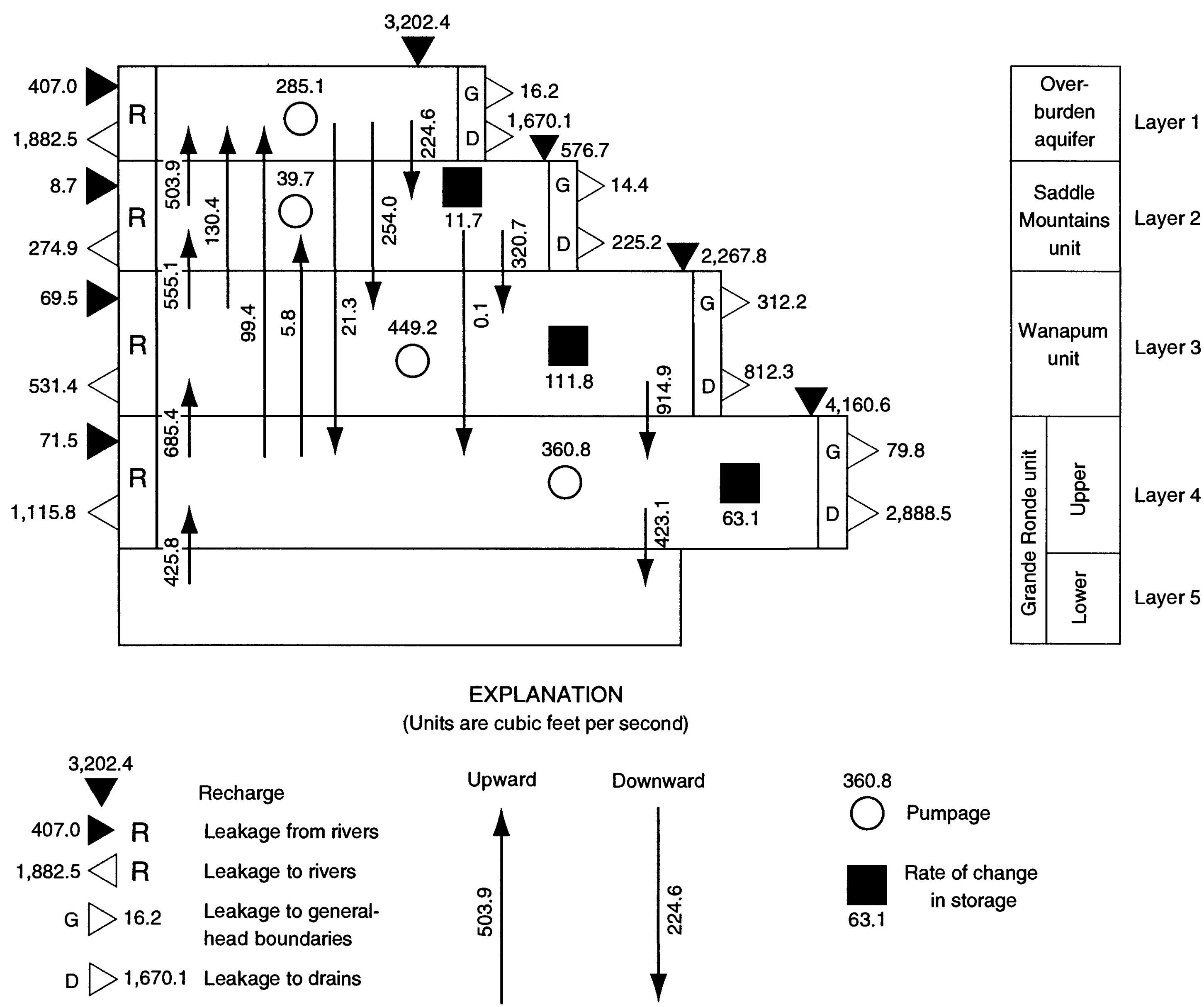


Figure 14. Diagrammatic section showing the model-calculated 1983-85 time-averaged water budget.

For the 1983-85 period (fig. 14), recharge and discharge in the upland outcrop areas (drains and GHB's) from the upper Grande Ronde are nearly equal to the predevelopment values; this occurs even though the upper Grande Ronde was pumped at an average rate of 361 ft^3/s during 1983-85. However, downward vertical leakage to the upper Grande Ronde in areas that are pumped increased by 206 ft^3 while upward vertical flow decreased by 9 ft^3 (figs. 14 and 15). Most of this pumping generally is not in the peripheral outcrop areas (fig. 9), indicating again that regional flow from uplands to lowlands is limited. Most of the recharge in the uplands follows short flow paths to local discharge areas and is not significantly influenced by stresses in the lower-lying areas. Thus, the development of ground water from the Columbia River Basalt Group may be limited by relatively local ground-water recharge that leaks downward to the pumped aquifer. This is further indicated by the fact that simulated discharge to rivers and major streams from the upper Grande Ronde decreased by only 23 ft^3/s (about 2 percent of predevelopment river discharge).

For the Wanapum unit, discharge areas (drains and GHB's) are not as far from pumping areas as for the upper Grande Ronde (Hansen and others, 1994), and the effects of pumping on discharge to drains and GHB's are more pronounced. For example, drain and GHB discharge from the Wanapum unit declined by 82 ft^3/s (7 percent of predevelopment discharge to drains and GHB's). Recharge to the Wanapum unit increased by 83 ft^3/s (figs. 13 and 14). Downward leakage from the Wanapum unit to the upper Grande Ronde increased by 191 ft^3/s (26 percent), and upward leakage decreased by 23 ft^3/s (3 percent; figs. 13 and 14). Therefore, it appears that much of the additional recharge to the Wanapum unit became leakage to the upper Grande Ronde because the head in the upper Grande Ronde was lowered by pumping. These changes in the water budget indicate that, in general, pumping stress in a basalt unit will have a larger local effect on other units than it will have on the pumped unit at large distances.

The recharge-discharge relations and their changes from predevelopment to time-averaged conditions for the Saddle Mountains unit and the overburden aquifer are quite different from those of the Wanapum unit and upper Grande Ronde. Whereas for the Wanapum unit and upper Grande Ronde, most of the discharge is from drains and GHB's in the upland areas, in the Saddle Mountains unit and overburden aquifer, for predevelopment conditions, most (85 percent for each) of the discharge is to the major rivers. This is because precipitation is much less in the central part of the region where those layers are at the surface, water levels are farther below land surface because of lower recharge, and ground-water flow is not drained by stream channels, as it is in the upland areas. These three conditions for the upper two units changed dramatically from predevelopment time. Recharge increased from 119 ft^3/s to 3,202 ft^3/s to the overburden aquifer and from 133 ft^3/s to 577 ft^3/s to the Saddle Mountains unit (see figs. 13 and 14) because of the infiltration of irrigation water supplied primarily from the Columbia and Yakima Rivers and secondarily from the Umatilla and Walla Walla Rivers. As a result of this increase in recharge, discharge to drains and GHB's increased from 162 ft^3/s to 1,686 ft^3/s for the overburden aquifer and from 32 ft^3/s to 240 ft^3/s for the Saddle Mountains unit. The part of total discharge now going to drains and GHB's increased from 15 percent to 47 percent for the overburden aquifer and from 15 percent to 47 percent for the Saddle Mountains unit. Because of the increased recharge, and thus higher water levels in these two units, much of the additional recharge follows short flow paths to local discharge areas (farm drains and wasteways).

Both downward and upward flows between the overburden aquifer and the underlying basalt unit increased dramatically as a result of the large increase in recharge from surface-water irrigation. Downward flow increased from 82 ft^3/s to 500 ft^3/s, more than six-fold, while upward flow increased much less, from 578 ft^3/s to 734 ft^3/s. Upward flow for the predevelopment overburden aquifer was much greater than downward flow.

Downward and upward flows have also increased for the Saddle Mountains unit because of the effects of irrigation: from 88 ft^3/s to 321 ft^3/s, and from 503 ft^3/s to 561 ft^3/s, respectively. As with the overburden aquifer, upward flow for the predevelopment Saddle Mountains unit was much greater than downward flow.

For both the overburden aquifer and Saddle Mountains units, the increase in downward flow was much larger than the increase in upward flow. Some of the increased downward flow is accounted for by pumpage from lower units, and some is accounted for as increased discharge to rivers from the Saddle Mountains and Wanapum units.

Downward flow from the Wanapum unit to the upper Grande Ronde increased from 724 ft^3/s to 915 ft^3/s, and upward flow decreased from 708 ft^3/s to 685 ft^3/s, resulting in a net downward leakage increase of 191 ft^3/s. Virtually all of this increased leakage was accounted for by pumpage from the upper Grande Ronde, which reduced net discharge from and storage in the upper Grande Ronde. Flow to and from the lower Grande Ronde did not significantly change from predevelopment conditions.

Water Levels

The changes between simulated water levels for the 1983-85 time-averaged and simulated predevelopment water levels for all modeled units are shown on maps in Hansen and others (1994). Only a map of the Wanapum unit showing these water-level changes are presented in this report (fig. 15). For the overburden aquifer, which received the largest increase in recharge (3,083 ft^3/s), the average simulated water-level rise was about 40 ft, equivalent to about 16 mi^3 of additional saturated aquifer. This change was the result of infiltration of applied surface water (average of about 4 ft/yr) to croplands (Bauer and Vaccaro, 1990). The largest changes occurred in the CBIP, where, in some areas, water levels rose more than 300 ft. In the wide, low-lying lower Yakima River Basin, where water levels already were near land surface, which is near river level, extensive surface-water irrigation has caused water-level rises of only about 10 ft. Natural and artificial drains remove most of the additional recharge. Similarly, in the surface-water-irrigated areas of Oregon, water-level rises have been small and moderated because land surface is near river level. Simulated water-level declines caused by pumping occurred in relatively few locations within the overburden aquifer. In the Wenas Creek Valley (tributary to the Yakima River), declines of only about 10 ft were simulated, but declines of as much as 40 ft were simulated along the eastern edge of the overburden aquifer in the Walla Walla River Basin. In the remainder of the overburden aquifer in the Walla Walla River Basin, however, simulated rises ranged from 5 to 30 ft.

Water-level rises averaging about 65 ft were simulated throughout much of the Saddle Mountains unit. The largest rises occurred within the lower CBIP north of Pasco, Wash., where, in some areas, they exceeded 200 ft. As in the overburden aquifer, only small rises occurred in the Saddle Mountains unit where it underlies the valley floor in the Yakima River Basin; however, larger rises, in some areas exceeding 100 ft, occurred along the edges of the basin and within tributary valleys of the Yakima River where the top of the Saddle Mountains unit is well above river level. Rises also occurred along the Columbia River in both Oregon and Washington between the Umatilla River and Willow Creek. Water-level rises, caused by both surface-water irrigation and the construction of dams along the Columbia River, saturated an additional 23 mi^3 of the Saddle Mountains Basalt compared with predevelopment conditions. Water-level declines were relatively small and localized, mainly in small valleys within the Yakima Fold Belt.

Simulated water-level changes in the Wanapum unit (fig. 15) were much more widespread than in the upper two units, mainly due to the much larger areal extent of the Wanapum unit. Again, water levels rose in areas of intensive surface-water irrigation--the Yakima River Valley, the CBIP, and parts of Oregon between the Umatilla River and Willow Creek. These rises averaged about 55 ft, but were as much as about 300 ft in the northwestern part of Quincy Basin. Simulated rises greater than 10 ft covered an area of about 3,900 mi^2 (about 19 percent of the Wanapum unit).

Water-level declines greater than 10 ft were simulated over about 7,400 mi^2 in the Wanapum unit (about 36 percent of the Wanapum unit). Simulated declines averaged about 60 ft and were more than 200 ft in some areas. The largest declines occurred in the Odessa-Lind area, in some of the valleys in the Yakima Fold Belt, on the southern slope of Horse Heaven Hills, near Umatilla in Oregon, and in the Walla Walla River Basin. In several areas, the declines were moderated by the rising water levels in nearby surface-water irrigated areas. For example, water-level rises in the CBIP offset the water-level declines of the Odessa-Lind area just east of the East Low Canal.

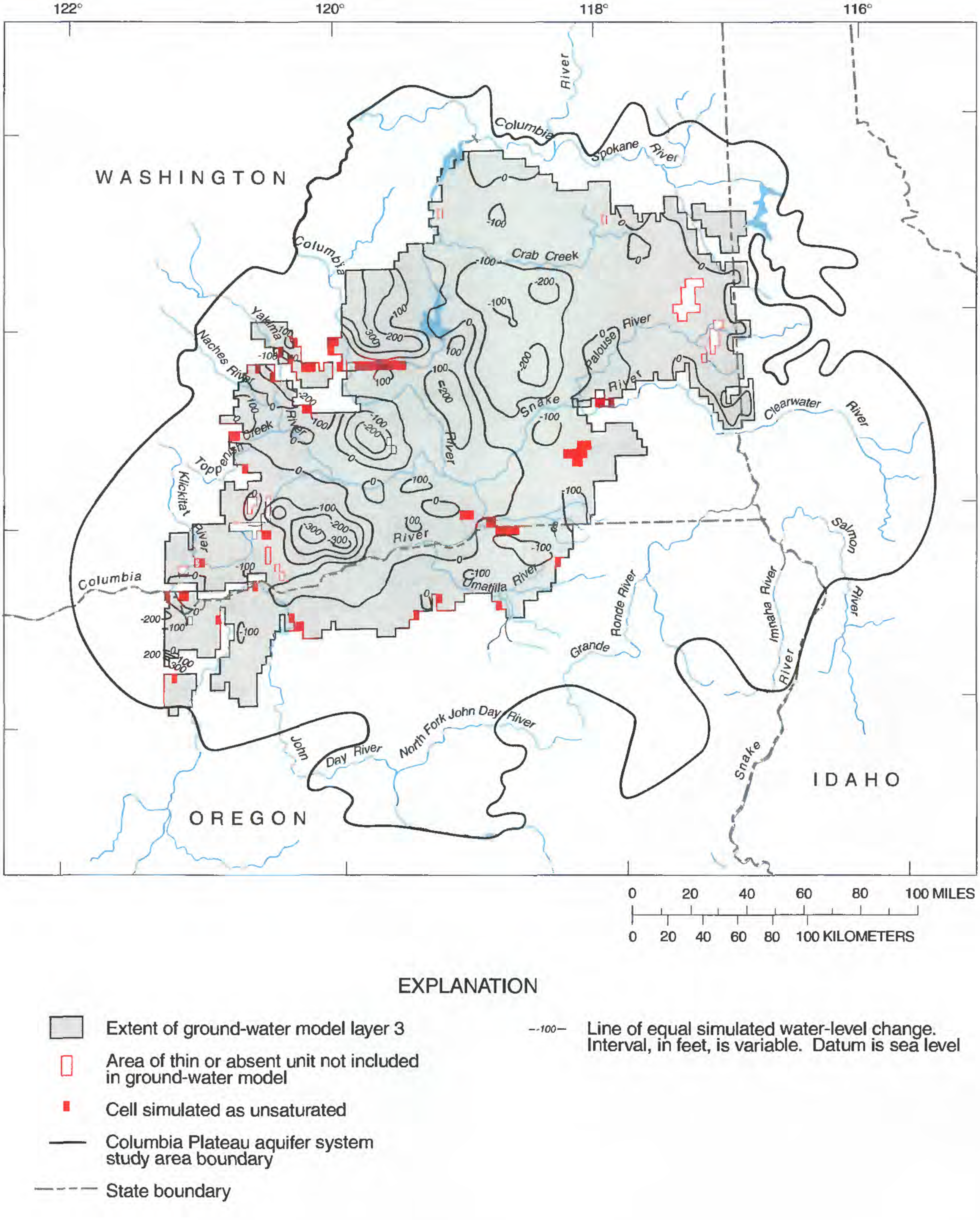


Figure 15. Simulated water-level changes in the Wanapum unit from predevelopment to current conditions.

Water levels in the upper Grande Ronde rose and declined over nearly equal areas. Rises averaged about 30 ft and declines about 35 ft. Maximum simulated rises and declines both exceeded 200 ft. The rises occurred in the surface-water-irrigated areas and along narrow strips of the dammed parts of the major rivers. The largest rises occurred in the northwest corner of the Quincy Basin. Declines were simulated in areas of ground-water pumping, mainly in the Odessa-Lind area in Washington and in the Umatilla area in Oregon. Smaller areas of decline were simulated in the Pullman-Moscow area and in the Horse Heaven Hills area.

The greatest simulated rises for the lower Grande Ronde, about 150 ft, were in northwestern Quincy Basin. Smaller rises were simulated in other surface-water-irrigated areas and along the major rivers. Declines as much as 170 ft were simulated for the Odessa-Lind area and as much as 50 ft for the Umatilla area. The distribution of simulated rises and declines for the lower Grande Ronde were similar to the upper Grand Ronde, but their magnitude was less. Declines in both layers of the Grande Ronde unit spread north and east from the Odessa-Lind area. The southern extent of simulated declines approximately coincides with the narrow east-west strip of low conductivity that acts as a barrier to ground-water flow, previously discussed.

Where historical water-level information is available, the model-calculated and observed water-level changes are similar (Hansen and others, 1994). It is therefore assumed that the ground-water levels in unmonitored areas are also reasonably simulated and that the ground-water budgets presented in the previous section are also reasonable.

Ground-Water Discharge

Results of the model simulation indicate that ground-water discharge to 16 of the 27 selected basins with streamflow data (table 2) and 14 of the 16 selected river reaches (table 4) has changed significantly (more than 1.0 ft^3/s change) from predevelopment to 1983-85 conditions.

Simulated discharge to 14 of the selected drainage basins significantly decreased. The largest percentage decreases (in excess of 40 percent) in ground-water discharge were in Cow Creek, Crab Creek, Bowers Coulee, and South Fork Palouse River Basins. Ground-water discharge in Cow Creek Basin decreased from about 41 ft^3/s under predevelopment conditions to about 23 ft^3/s under current conditions. Similarly, the discharge in Crab Creek Basin decreased by about 38 ft^3/s, from 63 ft^3/s to 25 ft^3/s. Only Glade Creek Basin showed percentage increase of more than 40 percent, which is due to surface-water irrigation.

Simulated ground-water discharge to 7 of the 16 selected river reaches increased by more than 40 percent because of water development (table 4). Ground-water discharge to the upper Yakima River increased from 185 ft^3/s to 304 ft^3/s, and to the lower Yakima River, from 45 ft^3/s to 425 ft^3/s. The upper Columbia River received an additional 540 ft^3/s under 1983-85 conditions when compared to predevelopment conditions; this increase is a direct result of the rise in water levels in the CBIP caused by surface-water irrigation (its delivery, leakage, and application). Simulated discharge in the Rocky Ford-Crab Creek area (located in the vicinity of Potholes Reservoir and Moses Lake, figs. 2 and 12) increased from 11 ft^3/s to 91 ft^3/s, and discharge in lower Crab Creek increased from 76 ft^3/s to 145 ft^3/s. Again, this increased discharge was due to the delivery, leakage, and application of surface water in the CBIP. Unlike the drainage basins, ground-water discharge to the stream reaches showed no decreases in excess of 40 percent.

Potential Future Effects of Current Ground-Water Development

A steady-state simulation was made in order to estimate the potential future changes to the 1983-85 flow system assuming no change in 1983-85 pumpage and recharge. The future equilibrium flow system was simulated by eliminating the 1983-85 rate of ground-water storage change from the pumpage array (see "Simulation of Ground-Water Flow" section). No estimates were made of the rate at which the long-term changes from 1983-85 to equilibrium conditions will occur. Water-level changes are first described below and then the changes in the water budget are described.

Table 4.--*Comparison of ground-water discharge to selected river reaches for the various simulations*

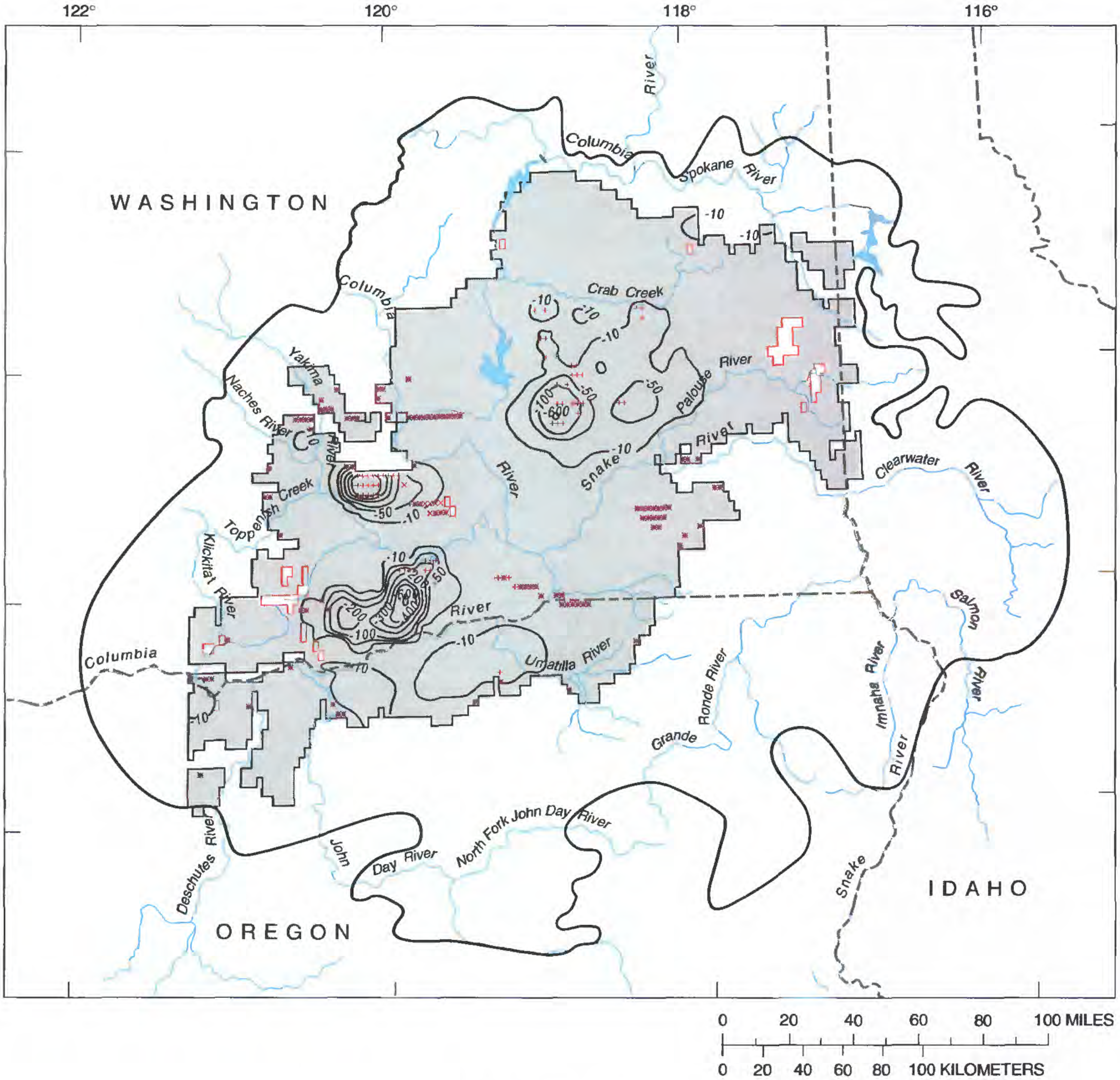
[Values in cubic feet per second; CBIP = Columbia Basin Irrigation Project]

				Phase 1 CBIP expansion		Phases 1 and 2 CBIP expansion	
Stream reach	Predevel-opment	1983-85 time-averaged	1983-85 equili-brium	1983-85 pumpage	reduced pumpage	1983-85 pumpage	reduced pumpage
Upper Columbia River	291.1	831.4	827.1	840.8	842.6	850.6	857.4
Snake River	491.1	435.5	428.0	433.0	434.9	449.0	456.1
Lower Yakima River	45.3	424.8	417.9	418.2	418.3	418.9	419.4
Lower Columbia River	383.9	354.1	333.6	333.7	333.7	333.8	334.1
Upper Yakima River	185.4	303.8	303.4	303.4	303.4	303.4	303.4
Klickitat River	217.2	225.7	225.7	225.7	225.7	225.7	225.7
Palouse River	160.4	164.3	140.5	142.6	144.0	150.1	158.1
Lower Crab Creek	76.3	145.1	140.3	144.6	146.9	152.2	162.8
Walla Walla River	72.1	115.3	114.6	114.8	114.9	115.3	115.5
Naches River	54.7	97.5	95.7	95.7	95.7	95.7	95.7
Rocky-Ford Creek	10.8	90.9	87.6	98.5	104.7	103.1	114.3
Grande Ronde River	74.0	74.0	74.0	74.0	74.0	74.0	74.0
Spokane River	52.4	51.5	51.4	51.4	51.4	51.4	51.4
Deschutes River	47.4	50.6	50.4	50.4	50.4	50.4	50.4
John Day River	42.5	45.9	45.6	45.6	45.6	45.6	45.6
Moses Coulee	11.5	9.8	9.2	9.2	9.2	9.2	9.3

Simulated water-level changes for the four basalt units from 1983-85 conditions to potential future equilibrium conditions caused by average 1983-85 stresses indicate large water-level declines may occur in the future. Changes for the overburden aquifer generally were less than 10 ft and are not shown. The greatest simulated declines were in the Wanapum unit (fig. 16), and the most widespread simulated declines occur about equally in the Wanapum unit and upper Grande Ronde throughout roughly the same areas.

Although water-level declines were generally less than 200 ft, some localized large declines, more than 400 ft in the Wanapum unit, were simulated in the central part of Horse Heaven Hills, centered around large pumping centers. Additionally, three Wanapum unit cells and four Saddle Mountains unit cells were simulated to desaturate. The probable reason for such large declines in this area is that the east-west-trending crest of the Horse Heaven Hills anticline, which is a barrier to ground-water inflow from the north, (fig. 6) lies only 5 to 10 miles north and northwest and upgradient from the pumping areas. Furthermore, the area to the south and east (downgradient) of the pumping centers receives little recharge and is hydraulically separated from this area by a ground-water impediment of uncertain origin (Packard and others, 1996). Only to the west and northwest are there areas of significant recharge that are hydraulically connected to the aquifers in the pumping area. About 8 mi northeast of Yakima, in a ground-water-irrigated valley, large water-level declines in the Saddle Mountains and Wanapum units were simulated. Additionally, four pumped cells in the Wanapum unit and five pumped cells in the Saddle Mountains unit desaturated. The valley is bounded to the north and south by sharp east-west-trending anticlines. The anticlines greatly impede inflow from all units from the north and south. Therefore, inflow must occur mainly upvalley from the east and from the flanks of the anticlines rising from the valley floor. Because the upgradient ground-water drainage area is quite small, local recharge is insufficient to replace the quantity pumped.

On the basis of the simulations, these two areas will have the largest water-level declines in the study area, even though the total quantities of pumpage from these areas is small compared with other areas of concentrated pumping (fig. 9).



EXPLANATION

- Extent of ground-water model layer 3
- Area of thin or absent unit not included in ground-water model
- Columbia Plateau aquifer system study area boundary
- State boundary
- -10 Line of equal simulated water-level decline (negative values). Interval, in feet, is variable
- Cell simulated as unsaturated, both simulations
- Cell simulated as unsaturated, 1983-85 predevelopment simulation only

Figure 16. Simulated future water-level changes in the Wanapum unit from predevelopment to current conditions.

In other areas where much larger quantities of ground water are pumped, no or only slight future declines were simulated because of their proximity to areas of surface-water irrigation and thus large quantities of recharge. During 1983-85, water levels appeared to be stable in the Yakima, Pasco, Milton-Freewater-Walla Walla, and Black Sands (Quincy Basin) areas. For these areas, no change in storage was added to the pumpage term for the time-averaged simulations, and therefore the future equilibrium (steady-state) simulation produced about the same water levels. For example, just north and west and upgradient of the Black Sands area, which lies within the Quincy Basin just west of Potholes Reservoir, imported surface water for the CBIP provides more than enough recharge to support the current pumping rate. A similar situation exists along a north-south-trending area fringing the eastern extent of the CBIP. Water levels generally are stable over most of this fringe area except northwest of Connell, where irrigation blocks served by the CBIP are fragmented and pumpage is locally large. Unlike the Black Sands area, however, the large quantities of recharge in the CBIP are generally downgradient from the pumped areas. As a consequence, this area of large pumpage and stable water levels is much narrower than the Black Sands area.

Future simulated water-level declines are small in a few areas with relatively large quantities of pumpage and no surface-water irrigation. The Pendleton area has had water-level declines in the past, but simulated water levels stabilized because of the area's proximity to the abundant recharge (lateral inflow) from the Blue Mountains to the southeast. This result is in approximate agreement with estimates made by Davies-Smith and others (1988). For the Pullman area, future declines of about 10 ft were simulated, suggesting that recharge estimated for the Pullman area is sufficient to supply 1983-85 pumping rates. These results are in approximate agreement with those of Lum and others (1990), who estimated rapid adjustments to pumping stresses. Pullman is near where the basalts pinch out against low-permeability crystalline rocks to the east and north, and the regional ground-water gradient is to the south and west. The area affected by pumping, therefore, is small and rapidly approaches steady-state conditions. The area southwest of Spokane has had no large water-level declines in the past. Recharge in this area appears to be adequate to supply most of the 1983-85 pumping rates. However, areas to the west, near Davenport, had simulated declines, probably because the basalts tend to pinch out against the impermeable basement rocks a few miles to the north.

Generally, moderate but areally widespread future declines were simulated for two large areas. In the Odessa-Lind area, which is east of the stable CBIP eastern fringe, a large quantity of ground water is used for irrigation (Cline, 1984; Cline and Knadle, 1990; and Cline and Collins, 1992) and there is a demand for additional ground water. In this area, simulated declines in the Wanapum unit were generally between 10 ft and 100 ft and occurred mainly south of Crab Creek. Locally, declines as much as 200 ft were simulated and some areas (represented by 25 Wanapum cells) desaturated (fig. 16). Simulated future declines in the upper and lower Grande Ronde were more areally widespread, but generally were less than 50 ft. Declines of about 10 ft in the upper and lower Grande Ronde extended to the northern boundary of the model.

The second area where moderate but widespread future declines were simulated was the area around Hermiston, Oreg. In this area, total ground pumping for irrigation is about 113 ft^3/s (Collins, 1987). Declines, ranging between 10 ft and 50 ft, were simulated for both the Wanapum unit and the upper Grande Ronde. Simulated declines in the Saddle Mountains unit were slightly smaller and were concentrated more to the north. Although the rate of pumping compared with natural recharge from precipitation in this area is similar to that of the Odessa-Lind area, simulated declines were considerably less because of recharge from surface-water-supplied irrigation from the Umatilla River. In addition, 29 ft^3/s net leakage was simulated from the lower Umatilla River into the overburden aquifer, through which it moves westward and downward into the basalts.

As the aquifer system comes to a new steady state under future equilibrium conditions, flows between layers and discharge to rivers, drains, and GHB's will reach new equilibrium values. Total discharge to surface-water bodies was simulated to decrease from the estimated 1983-85 rates because none of the pumped water will come from storage.

Net decrease in discharge to the rivers was simulated to be 79 ft^3/s, or about 2 percent of the 1983-85 total. Decrease in drain and GHB discharge was 47 ft^3/s (about 1 percent of 1983-85 drain discharge) and 1.7 ft^3/s (less than 1 percent of 1983-85 GHB discharge), respectively.

On average, simulated long-term decreases from 1983-85 stream baseflows due to 1983-85 pumpage are small. Locally, however, the simulation results indicate that reductions in the baseflow of some streams would probably be noticeable. Baseflow in the Cow Creek Basin decreased from 23 ft^3/s to 11 ft^3/s, which is the greatest relative decrease of baseflow of the 43 basins and river reaches analyzed (see tables 2 and 4). Simulated ground-water discharge in the Crab Creek Basin and the Palouse River reach decreased from 25 ft^3/s to 21 ft^3/s and from 164 ft^3/s to 140 ft^3/s, respectively. These three areas are adjacent to and overlap onto the Odessa-Lind pumping area, which, as previously mentioned, was simulated to have future water-level declines from the 1983-85 conditions.

Reductions of ground-water discharge to the lower Columbia and Snake Rivers ranged from 354 ft^3/s to 334 ft^3/s and from 435 ft^3/s to 428 ft^3/s, respectively, and discharge to the Umatilla River Basin was reduced from 556 ft^3/s to 549 ft^3/s, all of which are minor quantities in comparison to the streamflow in those rivers. Ground-water discharge to the remaining 37 basins and river reaches analyzed generally was unaffected (tables 2 and 4).

Potential Effects of Proposed Expansion of the Columbia Basin Irrigation Project (CBIP)

The CBIP originally was authorized for the development of 1,095,000 acres of irrigated lands that were to receive Columbia River water; about 556,000 acres are currently developed. Under the proposed expansion, the remaining 539,000 acres would be developed in two phases, with several proposed alternatives for each phase (Water Conservation Steering Committee, 1987). The authors chose to simulate the effects of potential development under Alternative A, Phase 1 and Phase 2, which adds 160,000 and 379,000 acres, respectively, for the total of 539,000 acres. Simulations were made for Phase 1 and Phases 1 and 2. The total expansion area covers most of the Odessa-Lind pumping area.

In areas where the CBIP currently furnishes water for irrigation, the USBR has mandated that CBIP water be the only source of irrigation water. Therefore, on the basis of prior policy, ground-water pumping rates will decline with the proposed expansion as farmers switch over to the new surface-water supply. To account for this in the simulations, for each cell it was assumed that pumpage will decline in proportion to the area served by new CBIP water: For example, where the CBIP would serve 25 percent of the area represented by a cell, the pumping rate was assumed to be 75 percent of the 1983-85 rate. Two additional scenarios using the current pumping rate also were simulated under Phase 1 and Phases 1 and 2. Therefore, four simulations are described below: Phase 1 with reduced pumpage, Phase 1 with the 1983-85 pumping rate, Phases 1 and 2 with reduced pumpage, and Phases 1 and 2 with the 1983-85 pumping rate. The effects on each aquifer unit are described but only the effects on the Wanapum unit water levels, which had the most extensive simulated changes, are presented on a map (see fig. 19).

All scenarios were simulated using an annual surface-water irrigation application rate of 4.0 ft/yr, the recent average rate for the currently operating CBIP. Recharge to those cells caused by the infiltration of this surface water was estimated from the information presented by Bauer and Vaccaro (1990). As a result, it was estimated that recharge would increase by about 330 ft^3/s for Phase 1 only, and by 974 ft^3/s for both phases. The distribution of the estimates of the increase in recharge for the two phases are shown on figures 17 and 18. Additionally, on the basis of the observed historical water-level rises in the existing CBIP, drains were added at every model cell with new surface-water application so that simulated water levels would not rise above land surface. Climate and current (1980's) water-development practices were assumed to be invariant for the scenarios and, because the simulations were steady state, the rate at which the simulated changes occur was not estimated. In fact, in the following discussions, the simulated changes are not compared with 1983-85 conditions, but are compared with the future equilibrium conditions resulting from current

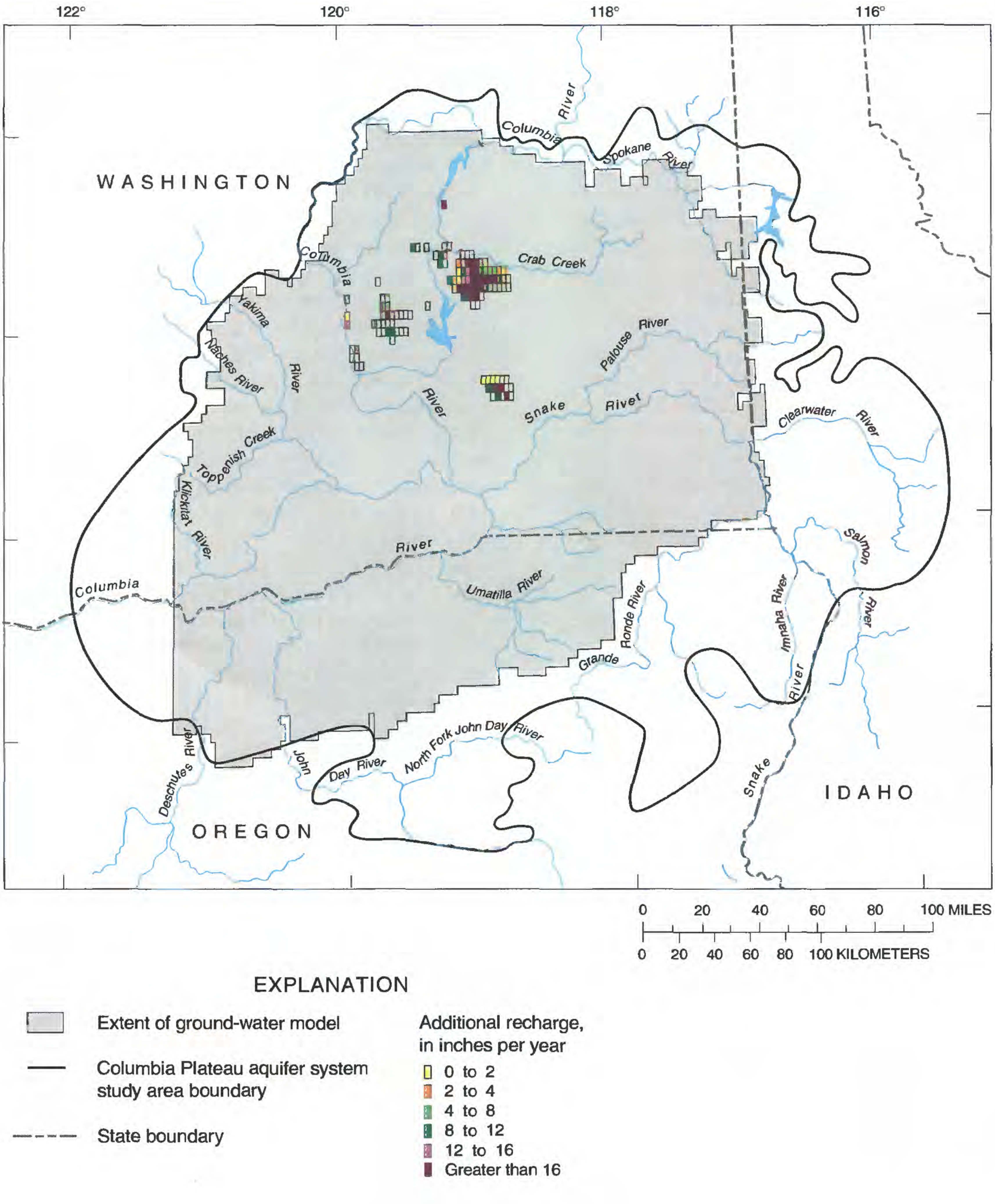


Figure 17. Distribution of estimated increase in recharge resulting from proposed expansion of the Columbia Basin Irrigation Project for Phase 1.

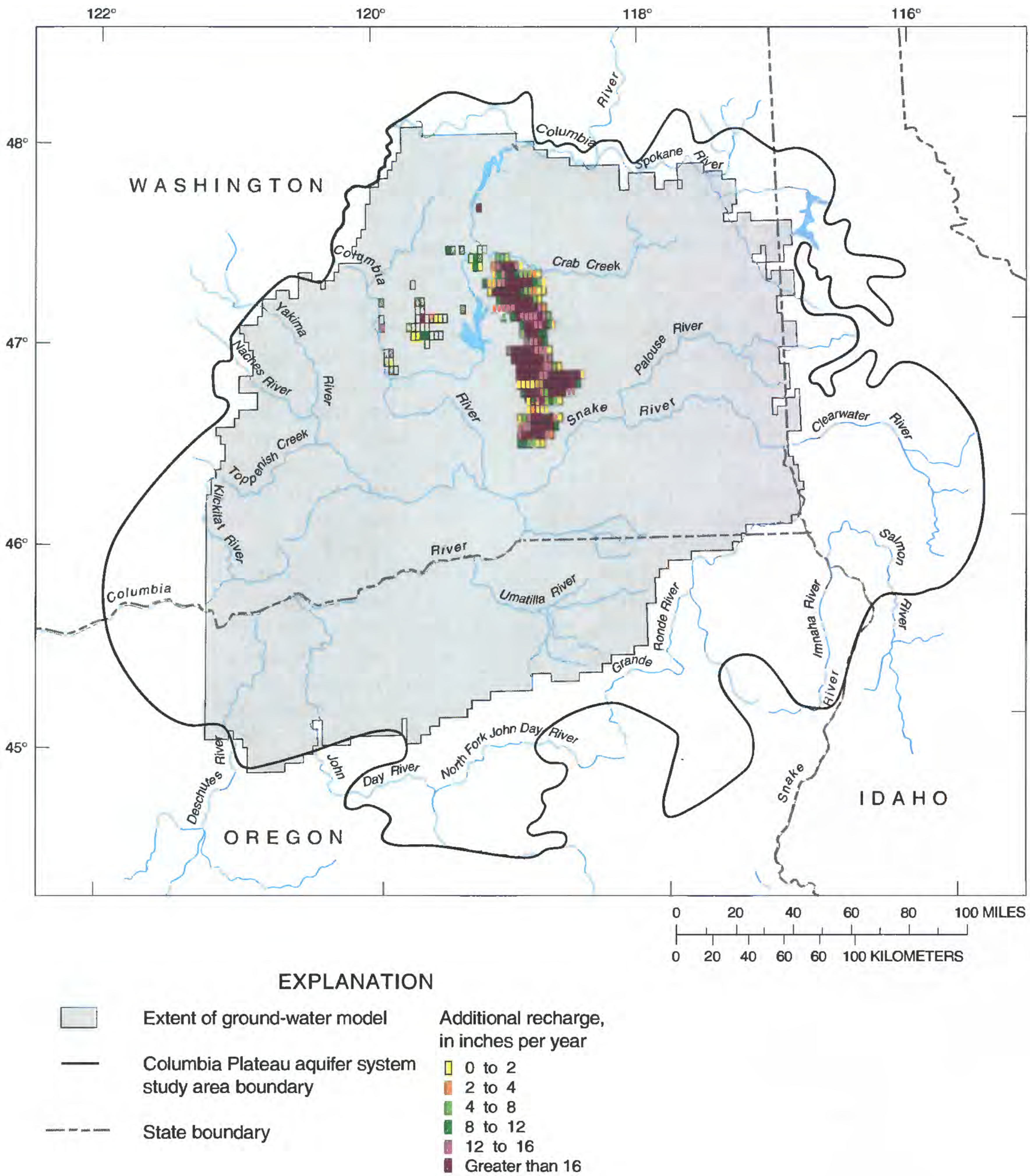


Figure 18. Distribution of estimated increase in recharge resulting from proposed expansion of the Columbia Basin Irrigation Project for Phases 1 and 2.

(1983-85) stresses. In this way, the future long-term effects of additional surface-water irrigation are isolated.

The simulated water-level rises (there are no declines) from future equilibrium conditions that result from the proposed CBIP Phase 1 expansion were greatest in the uppermost unit in the newly irrigated areas. Simulated water-level rises in the overburden aquifer, Saddle Mountains unit, and Wanapum unit were virtually identical for both pumping scenarios. The quantity of additional recharge to these units is far greater than the unit's ability to laterally transmit this extra water and the quantity of ground water removed by pumping is too small to prevent water-level rises; as a result, ground water rises to just below land surface, where it discharges to drains.

In the overburden aquifer, the largest rises, as much as about 50 ft, were simulated in the central Quincy Basin. The areal extent of these rises was limited to that of the irrigation expansion in this area; this is because the surrounding areas currently have both surface-water irrigation and farm drains, and the water levels are already at or near land surface.

For the Phase 1 expansion scenarios, water-level rises of more than 50 ft in the Saddle Mountains unit were limited to a small area in the northeastern part of the unit and did not exceed about 100 ft. Additionally, 14 model cells in the Saddle Mountains unit in the vicinity of this area were simulated to be saturated; whereas in the simulation of the future equilibrium conditions they were not.

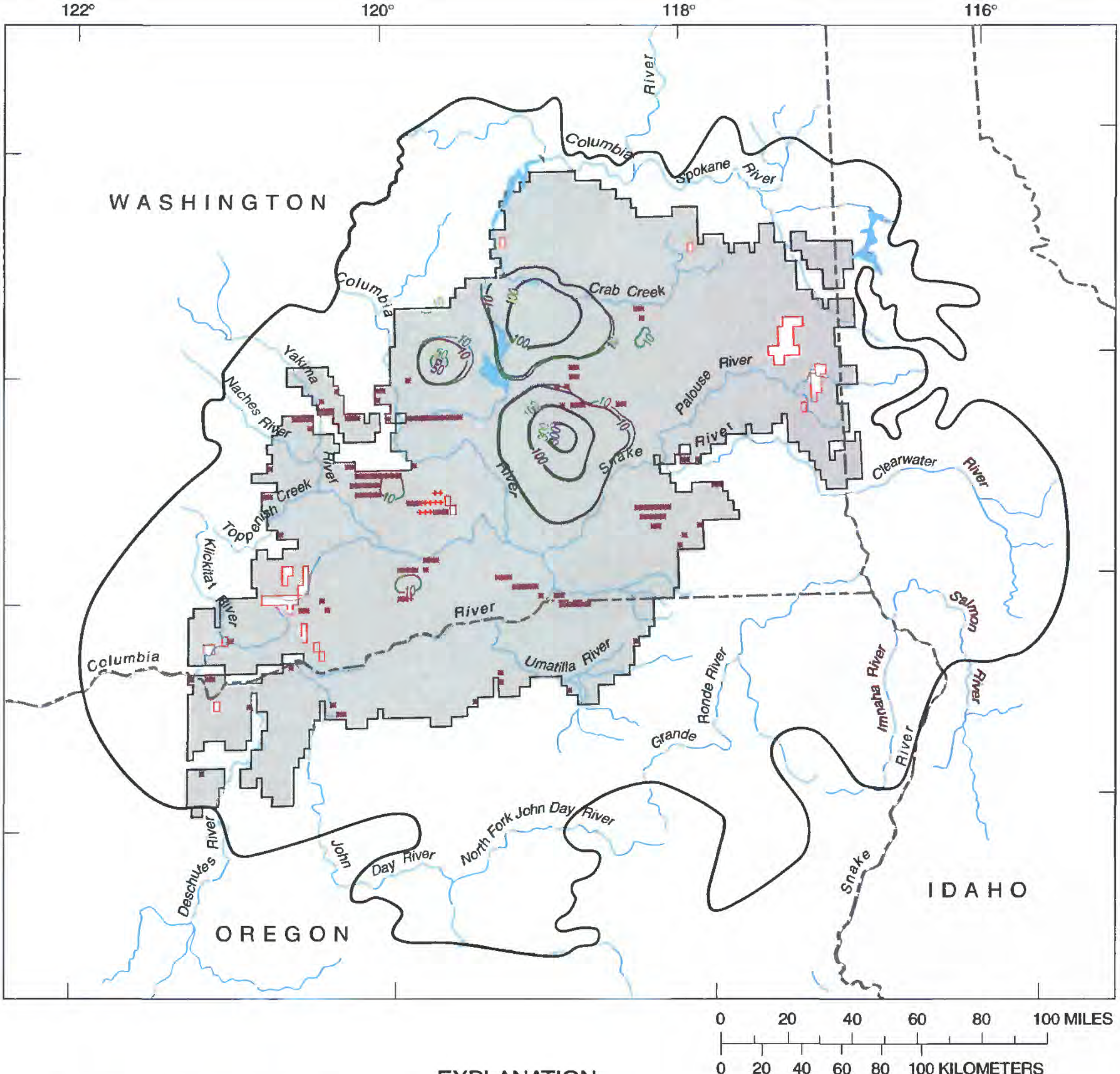
The largest water-level rises occurred in the Wanapum unit; maximum water-level rises were about 400 ft and roughly coincided with the centers of the two main expansion areas of Phase 1 (fig. 19). The location of simulated water-level rises in the Wanapum unit extended beyond the expansion areas, especially in the southeastern part where water-level rises of 50 ft or more extended up to about 15 mi beyond the expansion area. For the larger northeastern part of the Phase 1 expansion, the areal extent of water-level rises in the Wanapum unit was smaller; water-level rises of 50 ft or more extended only as much as about 7 mi south and east of the expansion, and to the north and west of the expansion there were almost no rises. To the west, water levels in the Wanapum unit were already near land surface, and any additional inflow of ground water would merely discharge to drains. To the north, the Wanapum unit is deeply cut by Crab Creek, thereby limiting water-level rises north of Crab Creek.

Simulated water levels were almost invariably within a few tens of feet of land surface in the unit that is closest to land surface in the areas of new irrigation. Thus, water logging is likely to occur in most areas of the proposed expansion unless farm drains also are constructed.

Water-level rises in the underlying upper and lower Grande Ronde layers generally were much less but more widespread than in the other layers. For example, for both pumping scenarios of Phase 1, water-level rises of more than 10 ft occurred throughout about twice as much area as for the Wanapum unit. However, areas with larger rises in the Grande Ronde unit than in the Wanapum unit extend only upgradient, to the north and northwest; this is probably because of the east-west strip of low conductivity north of the Big Bend area, described previously. For the reduced pumping scenario, water-level rises of more than 50 ft were less widespread (about half the area as for the Wanapum unit). For the 1983-85 pumping scenario, there were almost no areas of water-level rises greater than 50 ft.

For the reduced pumping scenario of Phase 1, maximum water-level rises in the upper and lower Grande Ronde were about 100 and 50 ft, respectively. For the current pumping scenario, maximum water-level rises in the upper and lower Grande Ronde were about 50 and 35 ft, respectively. Thus, for the Grande Ronde unit, the quantity of pumpage is an important control on water levels, even though recharge to the overlying units is at its maximum. This is because recharge to the unit must move through all of the overlying materials and is thus limited by the vertical conductivity of either fine-grained interbeds or the basalt flow centers.

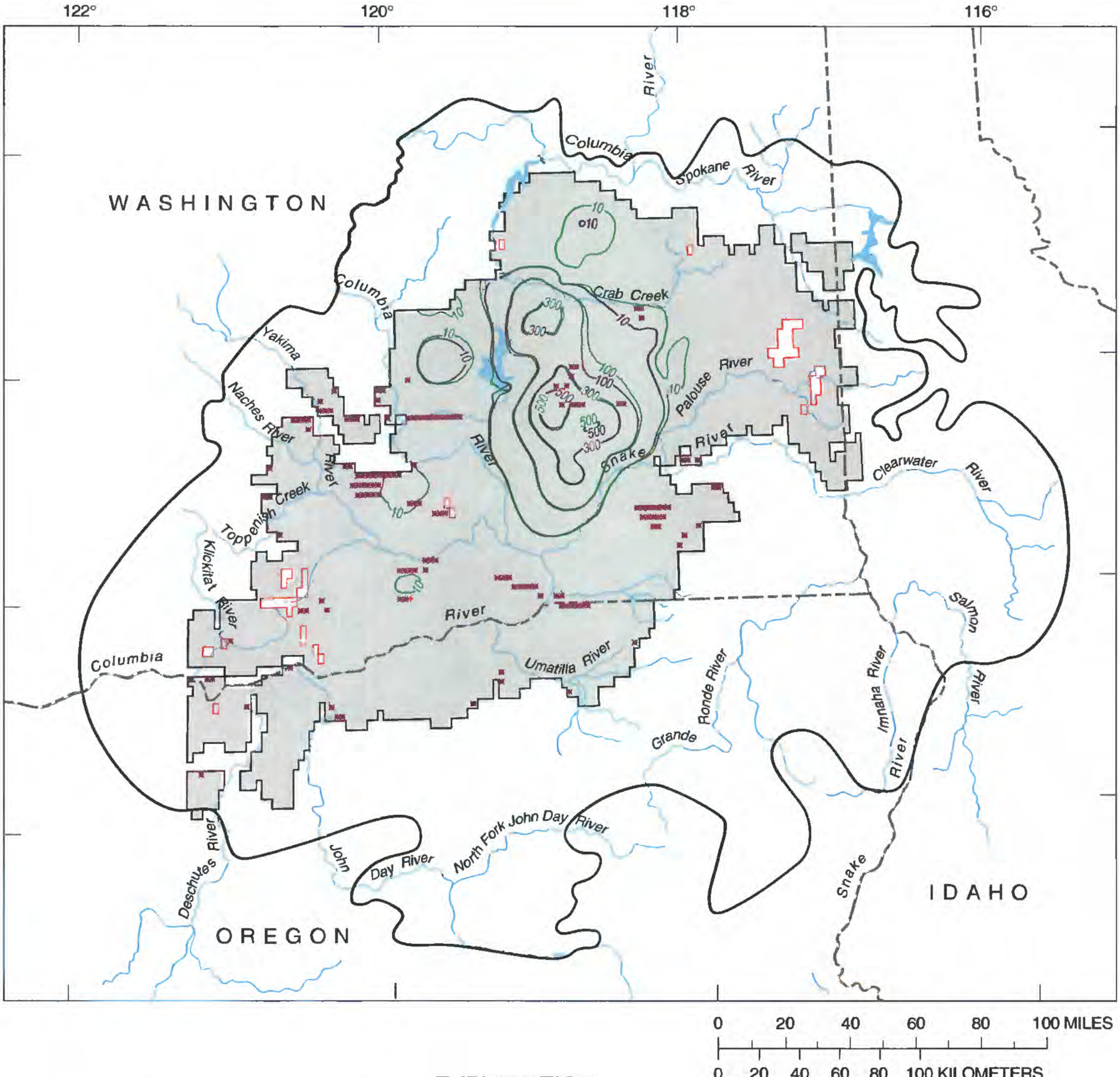
Simulated water-level rises, relative to future equilibrium conditions, resulting from the proposed CBIP irrigation expansion, Phases 1 and 2, are typical of those for the Wanapum unit (fig. 20). Comparing figures 19 and 20 indicates that the conclusions regarding the simulated effects of Phase 1 only are also applicable to the effects of Phases 1 and 2: where there is new irrigation, water levels rose within a few feet of land surface and the largest



EXPLANATION

- Extent of ground-water model layer 3
- Area of thin or absent unit not included in ground-water model
- Columbia Plateau aquifer system study area boundary
- State boundary
- — 10 — Line of equal simulated water-level rise, 1963-85 pumpage. Interval, in feet, is variable
- — 10 — Line of equal simulated water-level rise, reduced pumpage. Interval, in feet, is variable
- Cell simulated as unsaturated, both simulations
- Cell simulated as unsaturated, 1983-85 equilibrium simulation only

Figure 19. Simulated water-level rises in the Wanapum unit under future equilibrium conditions resulting from the proposed expansion of the Columbia Basin Irrigation Project, Phase1.



EXPLANATION

- Extent of ground-water model layer 3
- Area of thin or absent unit not included in ground-water model
- Columbia Plateau aquifer system study area boundary
- State boundary
- — 10 — Line of equal simulated water-level rise, 1963-85 pumpage. Interval, in feet, is variable
- — 10 — Line of equal simulated water-level rise, reduced pumpage. Interval, in feet, is variable
- Cell simulated as unsaturated, both simulations
- Cell simulated as unsaturated, 1983-85 equilibrium simulation only

Figure 20. Simulated water-level rises in the Wanapum unit under future equilibrium conditions resulting from the proposed expansion of the Columbia Basin Irrigation Project, Phases 1 and 2.

effects were in the Wanapum unit. Water-level rises in the overburden aquifer were nearly identical to those for Phase 1 because additional irrigation under Phase 2 is only in areas east of the Quincy Basin where the overburden aquifer is absent.

Water-level rises of more than 110 ft were simulated at the easternmost part of the Saddle Mountains unit. Moreover, 32 model cells in the Saddle Mountains unit became saturated. Maximum water-level rises of about 600 ft were simulated in the Wanapum unit (fig. 20). These maximum rises occurred in about the center of the main part of the new irrigation area that is east of the East Low Canal; this was the area with the large simulated water-level declines under future-equilibrium conditions (fig. 17). Water-level rises of more than 50 ft in the Wanapum unit extended from this main part as much as 20 mi upgradient to the northeast and as much as 17 mi downgradient to the southwest. Westward and northward extension of water-level rises in the Wanapum unit were limited for the same reasons given for Phase 1 only.

Water-level rises in both the upper and lower Grande Ronde were more widespread and of greater magnitude than those simulated under Phase 1 for both pumping scenarios. For example, for the reduced pumping scenario, water-level rises of more than 50 ft in the upper Grande Ronde covered a roughly circular area of about 65 mi in diameter (about three times as great as for Phase 1), and maximum rises were about 300 ft (compared with 100 ft for Phase 1 only). For the 1983-85 pumping scenario, water-level rises in the upper Grande Ronde of more than 50 ft covered a roughly circular area of about 40 mi in diameter, whereas Phase 1 had almost no areas with rises of greater than 50 ft. For both pumping scenarios, water-level rises in the lower Grande Ronde of more than 50 ft covered an area almost identical to that for the upper Grande Ronde. The area of water-level rises was more than three times that of the reduced pumping scenario and more than two times that of the 1983-85 pumping scenario of Phase 1. Thus, for the Grande Ronde unit, both the area served by new irrigation and the quantity of future pumpage were critical to the configuration of future water levels. Moreover, for any particular scenario, the upper and lower Grande Ronde layers are affected to about the same magnitude and extent.

Both phases of the CBIP simulations show that most changes to the ground-water flow system would be within the proposed expansion areas. In the reduced pumping scenario, the increased discharge to drains would be 114 percent and 109 percent of the increased recharge for Phase 1 and Phases 1 and 2, respectively. The simulations show that most of the new recharge would follow short flow paths to nearby drains; also, discharge from drains would increase where water levels rise because of reduced pumping rates. Where pumpage is reduced in the units underlying the uppermost unit, water levels would rise. This rise would increase the upward flow to the upper units, for eventual discharge to drains. In the 1983-85 pumping rate scenario, the increased discharge to drains would be 82 and 88 percent of the increase in recharge for Phase 1 and Phases 1 and 2, respectively.

Quantities of recharge and discharge simulated for Phase 1 and Phases 1 and 2 for each pumping scenario are shown in table 3. The simulated changes in the water budget from future equilibrium conditions resulting from the proposed CBIP irrigation expansion for Phase 1 and Phases 1 and 2 (reduced pumping scenario) are shown in diagrammatic sections in figures 21 and 22, respectively. The greatest changes for both phases were in the Wanapum unit, because it directly underlies a veneer of loess over most of the CBIP expansion areas. For the reduced pumping scenario, 78 percent of the additional recharge to the Wanapum unit would discharge locally to drains for Phase 1 and 99 percent for Phases 1 and 2. For the overburden aquifer, drain discharge exceeded the increased recharge for both phases and both pumping scenarios.

For the reduced pumping scenario, the amount of change in the vertical flow between layers is much smaller than the increased recharge. For Phase 1, recharge to the Wanapum unit increased by 227 ft^3/s; downward flow from the Wanapum unit increased by only 8 ft^3/s, and upward flow from the Grande Ronde unit by only 14 ft^3/s. For Phases 1 and 2, the increase in recharge to the Wanapum unit was 750 ft^3/s; downward flow from the Wanapum unit decreased by 1 ft^3/s, and upward flow from the Grande Ronde unit increased by 55 ft^3/s.

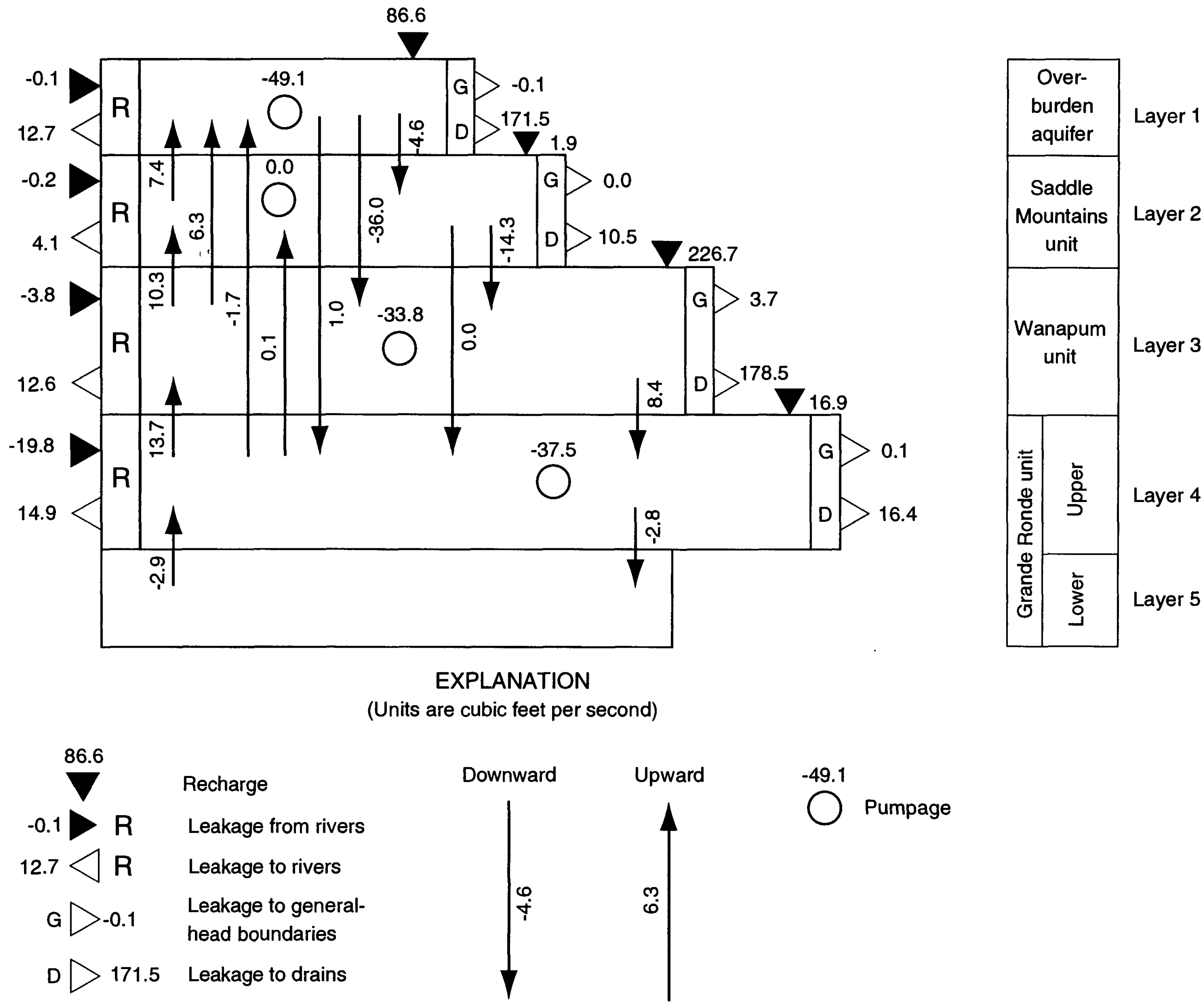


Figure 21. Diagrammatic section showing simulated water-budget changes from future equilibrium conditions resulting from the proposed expansion of the Columbia Basin Irrigation Project, Phase 1.

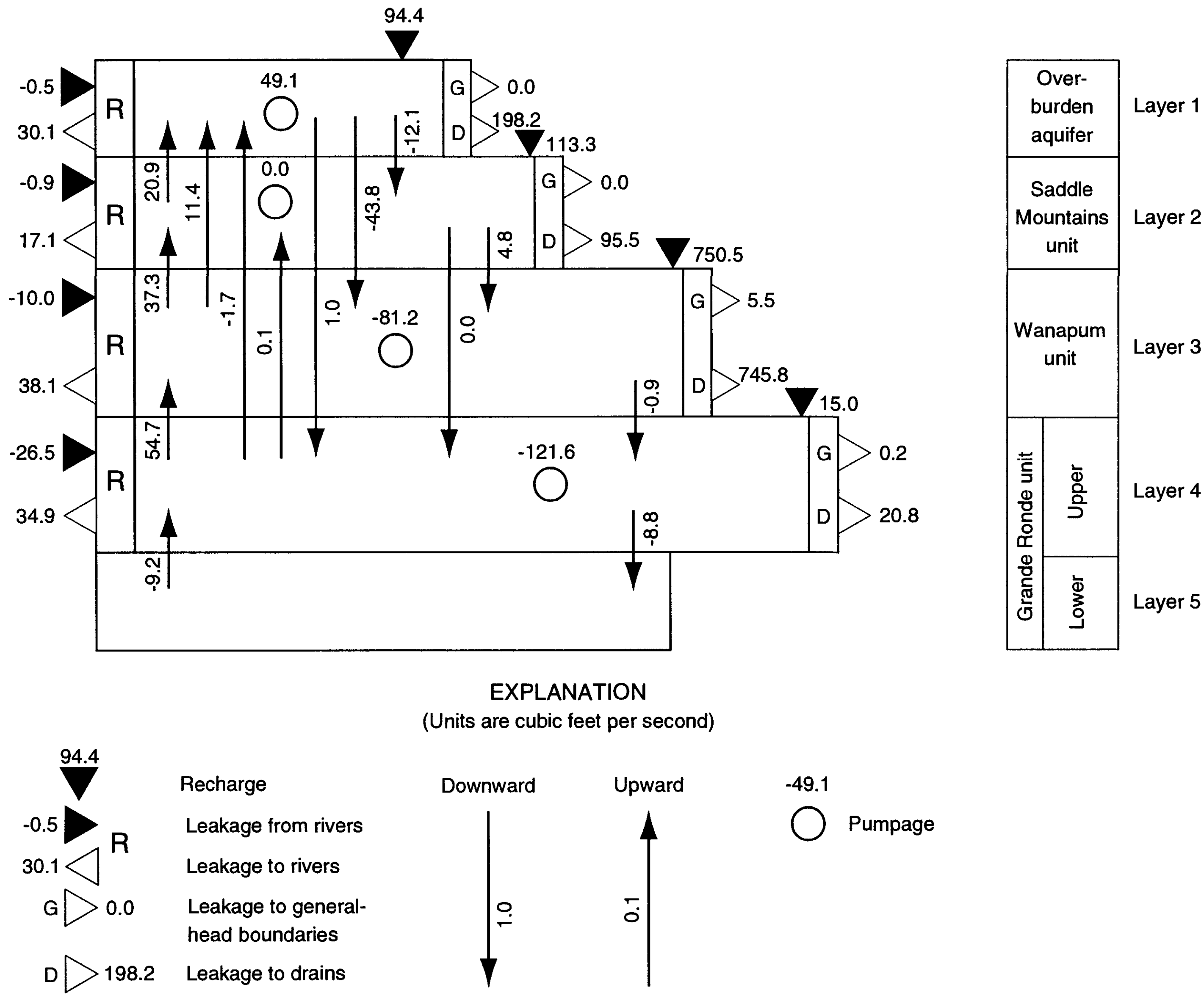


Figure 22. Diagrammatic section showing simulated water-budget changes from future equilibrium conditions resulting from the proposed expansion of the Columbia Basin Irrigation Project, Phases 1 and 2.

SUMMARY AND CONCLUSIONS

A study of the aquifers in both basalt rocks and overlying unconsolidated sediments of the Columbia Plateau was undertaken as part of the U.S. Geological Survey's Regional Aquifer-System Analysis program. In order to obtain a better understanding of the area's water budget, to provide capabilities for assessment of management alternatives, and to improve the understanding of the regional ground-water flow system, a three-dimensional finite-difference numerical model of ground-water flow was constructed and used. The model was used to quantify both the components of the ground-water flow system and the effects of current and potential future stresses on the aquifer system.

Regional ground-water flow in the study area generally is from upland peripheral areas, where recharge from precipitation ranges from about 4 to more than 10 in/yr, toward the Columbia and Snake Rivers where they cut through the low-lying central part of the study area. Most ground water originating in the uplands discharges locally to small streams. Natural recharge from precipitation in the low-lying areas is generally less than 1 in/yr, but where there is extensive surface-water-supplied irrigation, recharge has increased to more than 10 in/yr. Water levels are only a few feet below land surface in these areas. Ground-water pumping for irrigation from the basalt aquifers has caused declines of more than 200 ft.

The aquifer system was discretized into five layers for modeling purposes; one for the overlying unconsolidated sediments representing the overburden aquifer, one for the Saddle Mountains Basalt plus minor amounts of intercalated and immediately underlying sedimentary interbeds, one for the Wanapum Basalt including immediately underlying sedimentary interbeds, and two for the Grande Ronde Basalt. The Grande Ronde Basalt, which is generally much thicker than any of the overlying units, was divided into two layers to better simulate vertical variation of head. The aquifer system within the modeled area underlies 32,688 square miles and was discretized into 17,899 cells, each of which covers 2.5 minutes of latitude and 2.0 minutes of longitude with an average area of about 4.67 mi^2.

Boundary conditions for the model consisted of no-flow boundaries, where the Columbia River Basalt Group pinches out against older rock of low permeability, and head-dependent flux boundaries at rivers, streams, canyon walls, farm drains, and wasteways. Hydraulic characteristics were initially estimated from specific-capacity data, published reports, and ongoing investigations. Long-term average ground-water recharge for both predevelopment (1850's) and current (1980's) land-use conditions was independently estimated for 53 drainage basins and subareas within the study area using a soil moisture budgeting model. For the remainder of the area, recharge was estimated using a regression equation relating long-term average annual precipitation to long-term average annual recharge on the basis of the results of the soil moisture model for the 53 areas. Total recharge to the aquifer system was estimated to be 10,205 ft^3/s during 1983-85. Ground-water pumping was independently estimated for 1983 and 1984 and the average during 1983-85 was about 1,135 ft^3/s.

The ground-water flow model was calibrated to the observed water levels for the period spring 1983 to spring 1985. These water levels were not yet at equilibrium but were simulated as such by using the average of the 1983-85 conditions and by incorporating changes in ground-water storage during this period into a source term of the numerical model.

Calibration of the model resulted in distributions of lateral and vertical hydraulic conductivities that were not evident in the specific-capacity data. In order to reasonably simulate water levels in the basalt units, much smaller lateral and vertical hydraulic conductivities were required in uplifted anticlinal and monoclinal areas, whereas, much larger values were required in discharge areas. Smaller hydraulic conductivities in the uplands are possibly due to the numerous faulted offsets of the more permeable but thin interflow zones. Large, apparent vertical hydraulic conductivities beneath major rivers may, in part, be due to unmapped deeply incised channels that have been back-filled with coarse material.

Calibrated lateral hydraulic conductivities for the basalts ranged from about 10^{-6} to 10^{-4} ft/s and have a median of about $1.7x10^{-5}$ ft/s. This median is about the 30th percentile of the values computed from specific-capacity data. Calibrated lateral hydraulic conductivities for the overburden aquifer ranged from about $5x10^{-7}$ to $1.3x10^{-2}$ ft/s and have a median of about $5x10^{-4}$ ft/s. The median of values computed from the specific-capacity data is about

$2.8x10^{-3}$ ft/s. Median values for the calibrated vertical conductances between layers are, from top to bottom, $2.6x10^{-8}$ s^{-1}, $2x10^{-11}$ s^{-1}, $6x10^{-12}$ s^{-1}, and $5x10^{-11}$ s^{-1}. The unconfined storage coefficient for the basalts, where water-level changes were observed, was calibrated at 0.04. A storage coefficient for the overburden aquifer was not determined because this unit was at approximate equilibrium for the time-averaged simulation.

The model reasonably simulates the observed and estimated water levels. Accuracy is diminished in the steep-terrain areas where lateral head changes can approach 600 ft over a model cell. However, calculated heads in the steep terrain areas may be more representative of the vertically averaged head over a unit's thickness than are the observed water levels that are mostly from shallow wells. Root mean square residuals for cells with observation wells, from layer 1 to layer 4, were 58, 91, 142, and 253 ft, respectively.

The model was used to estimate the regional ground-water budget for 1983-85 conditions using the independent estimates of recharge (10,205 ft^3/s) and pumpage (1,135 ft^3/s). Leakage to drains, which generally were used to represent small perennial and intermittent streams, was the largest discharge component at 5,596 ft^3/s. Leakage to rivers was 3,804 ft^3/s and is the next largest discharge component. Leakage to general head boundaries, which represent seepage faces where a unit is completely truncated, was only 423 ft^3/s. The rate of change in storage based on water-level declines from 1983 to 1985 was about 187 ft^3/s. Of the total recharge, 4,161 ft^3/s recharged the upper Grande Ronde; this layer mainly crops out in the upland and peripheral areas of the plateau. Discharge to drains in the upper Grande Ronde unit was about 2,888 ft^3/s. Thus, most of the recharge in upland and peripheral areas follows short flow paths and discharges to nearby streams and canyons.

After the time-averaged steady-state model was calibrated, six other simulations were completed: (1) predevelopment (1850's) conditions, (2) future equilibrium conditions with 1983-85 stresses, (3) Phase 1 expansion of the CBIP retaining 1983-85 pumpage, (4) Phase 1 expansion of the CBIP with reduced 1983-85 pumpage, (5) Phases 1 and 2 expansion of the CBIP retaining 1983-85 pumpage, and (6) Phases 1 and 2 expansion of the CBIP with reduced 1983-85 pumpage.

The most pronounced change in the regional ground-water flow system from predevelopment to 1983-85 conditions is a rise in water levels in areas irrigated by surface water. In the overburden aquifer, the average of the simulated water-level rises is about 40 ft, with a maximum of more than 200 ft in northern Quincy Basin, Wash. For the Saddle Mountains unit, simulated water-level rises average about 65 ft, with a maximum of more than 200 ft in the southern CBIP, north of Pasco, Wash. An additional 23 mi^3 of the Saddle Mountains unit has been saturated in the areas of water-level rises. Only small, localized water-level declines due to pumpage were simulated for either of these units. For the Wanapum unit, however, about twice as much area had water-level declines as had rises. Generally, areas of rises in the Wanapum unit correspond with those of the overburden aquifer and the Saddle Mountains unit. Water-level rises in the Wanapum unit averaged about 55 ft, with maximum rises of as much as 300 ft in the northwestern part of the Quincy Basin. Areas of water-level declines occur in the Odessa-Lind, Wash., area, within some of the valleys in the Yakima Fold Belt, on the south slope of Horse Heaven Hills, Wash., in the Walla Walla River Basin, and along the lower Umatilla River, Oreg. Declines in the Wanapum unit average about 60 ft, but were more than 200 ft in some areas.

Water levels in the upper Grande Ronde have risen and declined over approximately equal areas. Rises in the upper Grande Ronde occurred in the surface-water irrigated areas and along narrow strips under and adjacent to the dammed parts of the major rivers. Rises averaged about 30 ft and declines averaged about 35 ft. Maximum simulated rises and declines both exceeded 200 ft. Rises and declines for the lower Grande Ronde are similar to those of the upper Grande Ronde, but the maximums are attenuated by about 80 to 100 ft.

From predevelopment time to 1983-85, estimated average recharge increased from 6,566 to 10,205 ft^3/s, while pumpage increased to 1,135 ft^3/s. One hundred eighty-seven cubic feet per second of pumpage was taken from storage, and an extra 2,698 ft^3/s of water was being discharged to rivers, drains, and seepage faces during 1983-85. Most of the simulated 1,651 ft^3/s increase in discharge to drains is to the farm drains and wasteways; this indicates that most recharge in the intensively surface-water-irrigated areas follows short flow paths to discharge locations. Net discharge to rivers increased by 1,048 ft^3/s while discharge to seepage faces decreased by 3 ft^3/s. Discharge quantities in the peripheral and upland areas generally were not changed from predevelopment conditions; this indicates that the large amounts of recharge in these areas generally are not available for movement to the existing areas of concentrated pumpage. The simulated effects of water development on the regional aquifer system presented above generally agree with available historic data and are believed to be a reasonable representation of actual effects that have not been historically monitored.

The ground-water flow model was used to simulate the long-term future (equilibrium) conditions of the aquifer system under the 1983-85 recharge and pumpage stresses. Simulation results indicate significant water-level declines in all four basalt layers but none in the overburden aquifer. The greatest declines, more than 400 ft in the Wanapum unit, are indicated for the pumping areas of Horse Heaven Hills because of the small amount of recharge and contributing area and relatively poor hydraulic connection to the aquifers in other areas. Water-level declines of similar magnitude in the Saddle Mountains and Wanapum units are simulated about 8 mi northeast of Yakima in a ground-water-irrigated valley that is bounded by anticlines. Water-level declines in the Odessa-Lind area are simulated to be as much as 200 ft in the Wanapum unit and 50 ft in the Grande Ronde unit. Simulated ground-water discharge to rivers, drains, and seepage faces decreased by 127 ft^3/s. Ground-water pumpage decreased by 40 ft^3/s because of desaturation of some cells with pumping.

The CBIP was originally authorized to develop 1,095,000 acres for irrigated agricultural crops using Columbia River water; about 556,000 acres are currently developed, and 539,000 acres are available for potential future expansion. Under a proposed plan to develop the remaining acreage, the expansion would proceed in two phases--Phase 1 (160,000 acres) and Phase 2 (379,000 acres). Four model simulations were made to estimate the effects of increased recharge due to the additional surface-water irrigation. The increased recharge was made on the basis of average current CBIP application rates. Two simulations (Phase 1 and Phases 1 and 2) retained the current (1983-85) ground-water pumping rate, and in the remaining two simulations pumping was eliminated in areas to be served by the CBIP expansion.

For any particular expansion phase, water-level rises in the overburden aquifer, Saddle Mountains unit, and Wanapum unit, where they outcrop, were identical for the two pumping scenarios. All four simulations showed water levels rising up to land surface in those parts of the uppermost unit directly underlying the irrigated areas. This is because the amount of increased recharge to these units exceeds their capacity to laterally and vertically transmit this water; as a result, ground water rises to just below land surface, where it discharges to drains. The amount of ground water removed by pumping was too small to prevent such water-level rises. Compared with the Wanapum and Grande Ronde units, only small parts of the overburden aquifer and Saddle Mountains unit were simulated to have water-level rises (only a small part of each underlies the expansion areas).

The largest simulated rises occur in the Wanapum unit; about 400 ft for Phase 1 and about 600 ft for Phases 1 and 2. For Phase 1, water-level rises of more than 50 ft in the Wanapum unit extend as far as about 15 mi beyond the southeastern part of the expansion area and about 7 mi beyond the northeastern part. For Phases 1 and 2, water-level rises of more than 50 ft in the Wanapum unit extend about 20 mi beyond the northeastern part of the expansion area and about 17 mi beyond the southwestern part. Water-level rises in the Wanapum unit do not extend appreciably to the north because the unit is cut on the north by Crab Creek.

Water-level rises in the underlying upper and lower Grande Ronde units were much smaller but more widespread than the overlying Wanapum unit. For both pumping scenarios of Phase 1, water-level rises of more than 10 ft covered about twice the area as they did for the Wanapum unit. For the reduced pumping scenario of Phase 1, water-level rises in the Grande Ronde of more than 50 ft covered only about half the area as for the Wanapum unit. Maximum water-level rises in the upper and lower Grande Ronde were about 100 ft and 50 ft, respectively. For the 1983-85 pumping scenario of Phase 1, there were almost no areas of water-level rises of more than 50 ft in the upper Grande Ronde and 35 ft in the lower Grande Ronde.

Simulated water-level rises for Phases 1 and 2 in the upper and lower Grande Ronde were more widespread and of greater magnitude than for Phase 1 only. For the reduced pumping scenario, water-level rises of more than 50 ft in the upper Grande Ronde covered a roughly circular area about 65 mi in diameter (about three times as great as for Phase 1), and maximum rises were about 300 ft (compared with 100 ft for Phase 1 only). For the 1983-85 pumping scenario, water-level rises in the upper Grande Ronde of more than 50 ft covered a roughly circular area of about 40 mi in diameter, whereas, Phase 1 had almost no areas with rises of greater than 50 ft. In the lower Grande Ronde, for both pumping scenarios, water-level rises of greater than 50 ft covered an almost identical area as for the upper Grande Ronde. This area is more than twice that as for the reduced pumping Phase 1 in the Grande Ronde unit. Thus, for the upper and lower Grande Ronde, both the area served by new irrigation and the amount of future pumpage probably are important controls on the potential configuration of water levels. Moreover, for any particular scenario, the upper and lower Grande Ronde are affected to about the same magnitude and extent.

The CBIP simulations show that most changes to the budget components of the ground-water flow system would be within the proposed expansion areas. For the reduced pumping rate scenario, the increased discharge to drains would be 114 percent and 109 percent of the increased recharge for Phase 1 and Phases 1 and 2, respectively. The simulations showed that most of the new recharge would follow short flow paths to drains nearby. Reduced pumping in the units underlying the uppermost unit causes water levels there to rise, causing increased upward flow to, and decreased downward flow from, the upper units. For the 1983-85 pumping rate scenario, the increased discharge to drains would be 82 and 88 percent of the increase in recharge for Phase 1 and Phases 1 and 2, respectively.

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