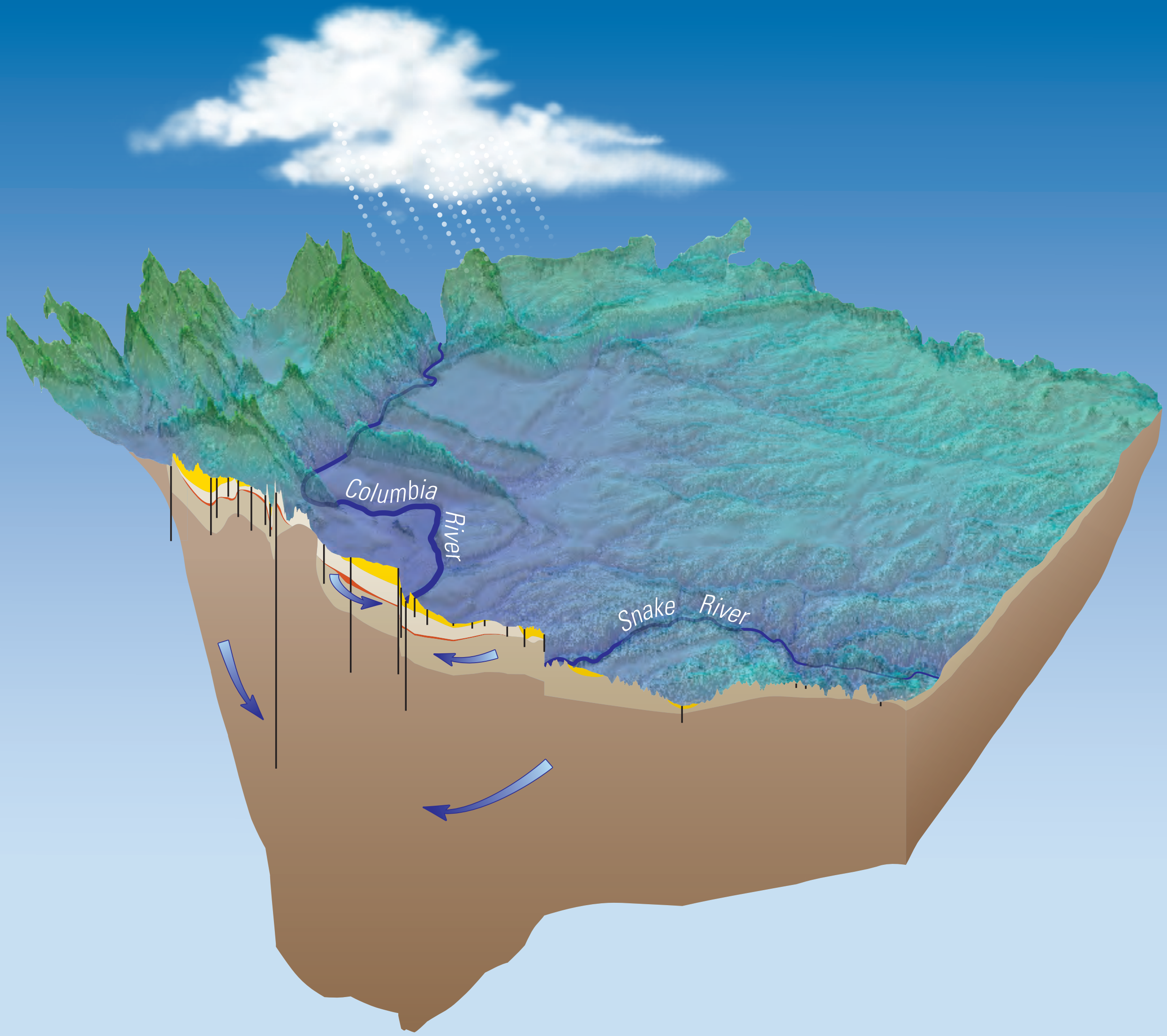
GROUNDWATER RESOURCES PROGRAM

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



Professional Paper 1817

U.S. Department of the Interior
U.S. Geological Survey

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By J.J. Vaccaro, S.C. Kahle, D.M. Ely, E.R. Burns, D.T. Snyder, J.V. Haynes,
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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

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Foreword

Although often overlooked, groundwater is increasingly important to all our lives. Groundwater is the Nation's principal reserve of freshwater. It provides one-half of our drinking water and is essential to U.S. food production while facilitating business and industry in promoting economic wellbeing. Groundwater also is an important source of water for sustaining the ecosystem health of rivers, wetlands, and estuaries throughout the country.

Large-scale development of groundwater resources with accompanying declines in groundwater levels and other effects of pumping have led to concerns about the future availability of groundwater to meet all our Nation's needs. The depletion of groundwater to satisfy the country's thirst and the compounding effects of recent droughts emphasize the need for an updated status of the Nation's groundwater resources. Assessments of groundwater resources provide the science and information needed by the public and decision makers to evaluate water availability and its effects on the water supply, as well as, to manage and use the water resources responsibly. Adding to this already complex task of resource assessment is the analysis of potential future effects due to climate variability, which can further exacerbate an already challenging situation.

The U.S. Geological Survey (USGS) is conducting large-scale multidisciplinary regional studies of groundwater availability, such as this study of the *Columbia Plateau Regional Aquifer System*. These regional studies are intended to provide citizens, communities, and natural resource managers with (1) improved information and knowledge of the status of the Nation's groundwater resources, (2) how changes in land use, water use, and climate have affected those resources, and (3) tools to forecast how these resources may change in the future. Over time, the findings from these individual regional groundwater assessments of principal aquifers can be scaled up to a national synthesis and scaled down to provide information relevant to issues of local concern. This national scale groundwater assessment directly supports the USGS National Water Census.

William H. Werkheiser,

Associate Director for Water

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)

International System of Units to Inch/Pound

Multiply	By	To obtain
	Length	
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F – 32) / 1.8.

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

CBP	Columbia Basin Project
CP-RASA	Columbia Plateau Regional Aquifer-System Analysis study
CRBG	Columbia River Basalt Group
CPRAS	Columbia Plateau Regional Aquifer System
DPM	deep-percolation model
ESA	Endangered Species Act
ET	evapotranspiration
FDR	F.D. Roosevelt Lake
GCM	Global Climate Model
IPCC	Intergovernmental Panel on Climate Change
MAF	million acre-feet
MODIS	Moderate Resolution Spectroradiometer
NWIS	National Water Information System
PDO	Pacific Decadal Oscillation
PWS	public water supply
SCD	Storage Control Date
SNOTEL	Snow Telemetry
SSEB	Simplified Surface Energy Balance
SOWAT	spatially distributed soil-water balance model
SWE	snow water equivalent
3D	three-dimensional
USGS	U.S. Geological Survey
WRIA	Water Resource Inventory Area
YRBAS	Yakima River Basin Aquifer System

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Executive Summary

The Columbia Plateau Regional Aquifer System (CPRAS) covers about 44,000 square miles of southeastern Washington, northeastern Oregon, and western Idaho. The area supports a $6-billion per year agricultural industry, leading the Nation in production of apples, hops, and eight other commodities. Groundwater pumpage and surface-water diversions supply water to croplands that account for about 5 percent of the Nation's irrigated lands. Groundwater also is the primary source of drinking water for the more than 1.3 million people in the study area. Increasing competitive demands for water for municipal, fisheries/ecosystems, agricultural, domestic, hydropower, and recreational uses must be met by additional groundwater withdrawals and (or) by changes in the way water resources are allocated and used throughout the hydrologic system. As of 2014, most surface-water resources in the study area were either over allocated or fully appropriated, especially during the dry summer season. In response to continued competition for water, numerous water-management activities and concerns have gained prominence: water conservation, conjunctive use, artificial recharge, hydrologic implications of land-use change, pumpage effects on streamflow, and effects of climate variability and change. An integrated understanding of the hydrologic system is important in order to implement effective water-resource management strategies that address these concerns.

To provide information to stakeholders involved in water-management activities, the U.S. Geological Survey (USGS) Groundwater Resources Program assessed the groundwater availability as part of a national study of regional systems (U.S. Geological Survey, 2008). The CPRAS assessment includes:

1. The present status of groundwater resources,
2. How these resources have changed over time, and
3. Development and application of tools to estimate system responses to stresses from future uses and climate variability and change.

This effort builds on previous investigations, especially the USGS Columbia Plateau Regional Aquifer-System Analysis study (CP-RASA). A major product of this new assessment is a numerical groundwater-flow model of the system. The model was used to estimate water-budget components of the hydrogeologic units composing the groundwater system, and to evaluate groundwater availability under existing land- and water-use conditions and a possible future climate scenario representing an increase in pumpage demand due to a warming climate. Information from this study also allowed for analysis of:

1. The CPRAS for predevelopment times (pre-1920),
2. Variations from 1920 through 2007,
3. Conditions during 1985–2007 (referred to as "existing conditions"), and
4. Changes in the system from predevelopment times.

The model also is a useful tool for investigating water supply, water demand, management strategies, groundwater-surface water exchanges, and potential effects of changing climate on the hydrologic system.

Water Issues

Groundwater availability is critical to managing water resources in the CPRAS because of the high water demand for agriculture, economic development, and ecological needs and the great competition for the limited resource. Water-resource issues that have implications for future groundwater availability include:

1. Widespread water-level declines associated with development of groundwater resources for irrigation and other uses;
2. Reduction in base flow to rivers and associated effects on water temperature and quality;
3. Limited availability of non-appropriated surface water;

4. Potential capture of surface water appropriated through senior water rights by pumpage of groundwater appropriated through junior water rights; and

5. Current (2014) and projected effects of climate change and variability on increasing pumping demand, groundwater recharge, base flow in rivers, and ultimately, sustainable groundwater yields.

Ongoing activities in the region for enhancement of fisheries and obtaining additional water for agricultural, municipal, and domestic use may be affected by groundwater withdrawals and rules implemented under the Endangered Species Act for numerous stocks of salmonids.

The study addresses some of these groundwater availability issues by improving the understanding of the hydrogeologic system, the status and trends of the groundwater system, the general relation between groundwater and surface waters, current water use, and the water budget for the CPRAS for both predevelopment and existing conditions.

Development of the Hydrogeologic Units

Hydrogeologic units were described for the CPRAS by Kahle and others (2009) on the basis of the CP-RASA; they include the Overburden, Saddle Mountains, Mabton Interbed, Wanapum, Vantage Interbed, Grande Ronde, and Older Bedrock units. A three-dimensional (3D) geologic model was then constructed to refine the geometry of these units (Burns and others, 2011). The process yielded (1) maps that represent upper and lower buried unit boundaries in this complex terrain, (2) improved estimates of unit volumes, (3) refined locations of large structural features, and (4) features that may be important for ongoing groundwater studies. The range in extents, thicknesses, altitudes, and volumes of the units indicate the extraordinary complexity of this aquifer system.

The sedimentary Overburden unit mainly occurs in structural basins and is an important water-bearing unit. The 3D-model derived a thickness of the Overburden unit ranging from 0 to about 2,000 feet and a volume of about 244 cubic miles. The Saddle Mountains unit, a Columbia River Basalt Group (CRBG) unit, covers about 11,700 square miles and its thickness ranges from 0 to about 2,000 feet. The volume of this basalt unit was calculated at 665 cubic miles. The thickness of the Mabton Interbed unit, which underlies the Saddle Mountains unit, ranges from 0 to about 205 feet, and averages 39 feet. The Wanapum unit (CRBG) is the surficial unit covering more than 30 percent of the area and extending over about 24,400 square miles. The unit is an important source of water on the Columbia Plateau and its thickness ranges from 0 to about 3,250 feet. Its calculated volume is 2,160 cubic miles. The thickness of the Vantage Interbed unit, which underlies the Wanapum unit, ranges from 0 to about 80 feet. The Grande Ronde unit (CRBG) is the most extensive unit of the CPRAS—it underlies 96 percent of the study area, extends over about 41,900 square miles, its thickness ranges from 0 to about 16,000 feet (average of about 3,950 feet), and its calculated volume is 31,300 cubic miles. The altitude of the top of the Grande Ronde unit ranges from about -2,200 to 7,900 feet, or a total difference of about 10,000 feet.

The Older Bedrock unit that borders and underlies the CPRAS is composed of various rock types older than the CRBG. The Older Bedrock unit is considered the base of the regional flow system. The Older Bedrock unit is the surficial unit covering only small parts of the study area. A map of the altitude of the top of this unit was constructed to estimate the thickness of the immense Grande Ronde unit.

Development of a Hydrologic Toolbox

As part of a hydrologic toolbox, new applications were developed for estimating evapotranspiration (ET), surface-water use, groundwater pumpage, and recharge from irrigation. The applications can be used over large regional areas and were summarized in Kahle and others (2011). ET is a large component of the water budget; it can account for 100 percent of the annual precipitation in the arid areas and 45–70 percent in the more humid uplands, and historically, has not been estimated. A new Simplified Surface Energy Balance (SSEB) method that uses satellite data was developed to estimate monthly ET. The spatial distribution of landscape ET estimated using SSEB provides an estimate of consumptive use in irrigated areas. The SSEB has allowed for a new understanding of the interrelationship between hydrologic components. A spatially distributed soil-water balance model (SOWAT) was developed to use relations among climatic, soils, land-cover, and irrigation data to compute monthly irrigation requirements and surplus moisture available for recharge in irrigated areas. Estimates of groundwater pumpage and surface-water diversions for irrigation and recharge associated with irrigation were then calculated with ET from the SSEB driving the calculations. Estimates of monthly recharge from infiltration of precipitation were made using regression equations. This combination of methods was used because a major control on groundwater availability (and streamflow) is the quantity and timing of water entering the aquifer system—groundwater recharge. The quantity and timing of recharge also influences how the flow system functions and responds to pumpage.

A web interface tool that allows users to explore the 3D geologic framework also was developed for the project. This tool allows one to view the subsurface geology by drawing diagrams of "well logs" at any site, or building complete geologic cross sections between multiple sites.

Groundwater-Flow Model

A numerical model that simulates groundwater flow was constructed and documented as part of this study (Ely and others, 2014). Compared to previous models, the new model includes a finer vertical spatial discretization, uses a more detailed depiction of the subsurface hydrogeology, and simulates annual water budgets for 1920–2007. The simulation results were used to help assess groundwater availability and sustainability.

The model includes 74 percent of the study area. Its boundaries are nearly identical to the previous CP-RASA model constructed in the 1980s, thus allowing for a consistent assessment of the response of the system to stresses over time. The model domain was represented by a grid of 3-kilometer (9,842.5-foot) cells. Except for the thick Grande Ronde unit, each of the hydrogeologic units was approximately subdivided into 100-foot model layers, yielding 100 model layers. The detailed vertical discretization improved the understanding of the important vertical flow component within the CPRAS. The no-flow lower boundary is the top of the Older Bedrock unit. Internal boundary conditions simulate flow to and from the major rivers, and groundwater discharge to small upland streams, groundwater-controlled surface-water features such as lake complexes, and drains in agricultural areas. Major geologic structures, which are an important control on the flow system and locally limit groundwater availability, were simulated with what are called flow barriers for 38,308 model cells.

The model was calibrated to conditions representing the flow system during two periods—estimates of predevelopment conditions (1920) and annual conditions during 1920–2007. The differences between measured and simulated water levels were small, indicating the model can represent the complex hydrologic system, both laterally and vertically.

The model was used to estimate annual water-budgets for the system, flow between hydrogeologic units, changes in the system from predevelopment conditions, changes in the system if the conditions in 2007 existed through 2050, and potential effects in 2050 of increased irrigation demand owing to climate warming. The model results are used to show the potential usefulness of this tool in providing information for short- to long-term management planning and decisions by numerous stakeholders.

Evapotranspiration and Groundwater Recharge

The estimate of average annual ET for predevelopment conditions (native vegetation with no irrigation) was about 24 million acre-feet (MAF), and spatially ranged from about 1 to 38 inches. As a percentage of precipitation, ET ranged from a low of 10 percent to a high of nearly 100 percent, and averaged 59 percent. The estimate of average annual ET for existing conditions was 28 MAF (an increase from predevelopment conditions of about 3.5 MAF—a quantity of water that could irrigate more than 1 million acres). The complex spatial distribution of this important water-budget component differs from the predevelopment distribution in areas affected by human activities, particularly irrigation. The differences are especially pronounced in the surface-water irrigated areas such as in the Yakima River Basin and Columbia Basin Project (CBP), where increases in ET ranged from about 20 to 36 inches due to consumptive water use by irrigated crops.

Estimated predevelopment groundwater recharge (same conditions as for ET) averaged 11 MAF and annually ranged from 9.6 to 25.6 MAF. The large spatial-temporal variability of this important water-budget component indicates not only the precipitation distribution but also the ET distribution. Average annual recharge for existing conditions was 14 MAF (an increase of 3.6 MAF from predevelopment conditions) and locally ranged from nearly zero to more than 40 inches. Low recharge values throughout much of the central Columbia Plateau indicate a potential limitation on regional groundwater availability. Total recharge for existing conditions includes additional recharge from surface-water and groundwater irrigation that was calculated using the SOWAT model. Estimated average annual recharge in the study area from the delivery and use of irrigation water was 4.2 MAF, with 50 percent occurring in the predominately surface-water irrigated regions—the Yakima and Umatilla River Basins, and the CBP.

Water Withdrawals

Surface-water use and groundwater pumpage were estimated on an annual basis for 1985–2007 for five categories of use:

1. Irrigation;
2. Public water supply (PWS);
3. Domestic (also referred to as exempt wells in the Western United States, as these wells are exempt from State permitting processes);
4. Industrial; and
5. “Other,” which includes mining, livestock, and fisheries (Kahle and others, 2011).

Irrigation water use was estimated using SOWAT for both surface water and groundwater. For the groundwater model, water use for 1920–1984 was estimated based on previously published data (in particular from the CP-RASA study), increase in the number wells over time on the Columbia Plateau, and the start of surface-water irrigation by the irrigation districts. Only withdrawals under existing conditions are summarized here.

Irrigation water use averaged 5.3 MAF during 1985–2007, with 1.4 MAF (26 percent) supplied from groundwater and 3.9 MAF supplied from surface water. Surface-water use was largest in the CBP, followed by the Yakima River Basin and then the Umatilla River Basin. Annually, irrigation water use for the entire study area ranged from about 4.1 to 7.1 MAF, and the amount supplied by groundwater ranged from about 25 to 35 percent of the total. Thus, if the increases in both ET and recharge are considered, more than 12 MAF of water fluxes are associated with irrigation.

Excluding irrigation pumpage, annual pumpage averaged 0.4 MAF during 1985–2007, and including irrigation pumpage, averaged 1.8 MAF. For the pumpage categories, annual PWS averaged 0.23 MAF, and increased from 0.2 MAF in 1985 to 0.27 MAF in 2007. Domestic self-supplied pumpage increased from 0.06 MAF in 1985 to 0.07 MAF in 2007 (average annual pumpage of 0.06 MAF). Industrial annual pumpage averaged 0.05 MAF, and decreased from 0.05 to 0.04 MAF during 1985–2007. Other annual pumpage averaged 0.03 MAF, and increased from 0.02 to 0.04 MAF over the 23-year period.

Groundwater Budget and Changes from Predevelopment Conditions

Recharge is the primary water-budget component of the groundwater system, closely followed by discharge to streams; this relation represents typical Pacific Northwest hydrology, with much of the recharge discharging along short-to-intermediate flow paths to surface-water features. Storage changes are much smaller than recharge and, as with discharge to streams, annual variations in storage changes closely follow recharge variations. Pumpage is about 25 percent as large as recharge but, in major pumping centers, it is the largest water-budget component. The water budget for the individual units follows the same general trend as the total water budget, with recharge and discharge to streams dominating. Excluding recharge and discharge to streams, the water budget for the CRBG units indicates that pumpage is the largest component, highlighting the importance of pumpage and its historical, current (2014), and potential future effects on the system. Downward flow from overlying to underlying units is the next largest component and is nearly three times larger than upward flow. Changes in storage fluxes within the units are about as large as the upward fluxes between units.

Human activities have substantially altered the predevelopment hydrologic system. The construction of hundreds of small-to-large dams and diversion structures for supplying irrigation water and hydropower, coupled with thousands of instream diversions, has resulted in an intensively modified streamflow system throughout the study area. Streamflow characteristics (from hourly to annual) for most streams have changed from the natural streamflow regimen. These changes have affected the aquatic ecosystem and have cascaded through the groundwater system. Indeed, diversions and the need for instream flows have limited the future availability of groundwater withdrawals in some areas. The delivery and application of surface water for irrigation of more than 1.2 million acres has resulted in groundwater-level rises occurring over about 2,400 square miles (with local rises of more than 200 feet) and a net increase in groundwater storage in these areas of more than 11 MAF. The area of rises encompasses about 5 percent of the study area. This increase in storage is the result of the increase in recharge that primarily occurs in the surface-water irrigated areas. Many of these rises have occurred in the Overburden unit where irrigation occurs, but rises also have occurred in the underlying basalt units. For example, water-level rises in the Wanapum unit were more than 200 feet in part of the Quincy Basin, and the overlying Saddle Mountains unit (the largest basalt-unit benefactor of the excess irrigation water) has increased importance as a transmitter and supplier of water because of the increase in the area and volume of its saturated material. The return of excess irrigation water through surface-water drains and groundwater discharge also has contributed to the alteration of the streamflow characteristics and availability of water in the area. As a result, surface-water demands in some locations are met by these return flows; that is, the return flows are relied upon to meet downstream uses.

The groundwater system has been substantially affected by the extraction of groundwater. Groundwater levels have declined over more than 10,000 square miles (about 23 percent of the study area) because of historical and current pumpage. Declines have exceeded 300 feet in parts of Washington and 200 feet in Oregon. The declines due to pumpage have decreased groundwater storage by more than 10 MAF. As documented in this study, these declines are continuing to occur in the areas with large irrigation withdrawals and have expanded to new areas since the CP-RASA study. Concurrently, groundwater quantities moving between units have been altered because of pumpage and surface-water irrigation, resulting in total increased inflow to units from other units exceeding 1,500 cubic feet per second. However, net outflows (discharge to surface-water features, pumpage, and storage changes) for all but the Overburden unit have exceeded these increased inflows since predevelopment times (partly because declining groundwater levels in some areas have resulted in streams losing water).

Groundwater Availability and Sustainability

Groundwater availability is a function of not only the physical processes that govern the quantity and quality of water, but the laws, rules, regulations, and socioeconomic factors that control its demand and uses (Reilly and others, 2008). Groundwater availability and, ultimately, its sustainability in the study area, are issues that are interrelated to groundwater management and the availability and use of surface water. Water management, in turn, generally is intricately related to environmental protection and public health; thus, groundwater availability is related to conflicts between consumptive use and instream uses. Important institutional factors (such as use restrictions, basin adjudication, and surface-water rights/instream flows) limit the availability of water because storage changes due to groundwater pumpage can affect streamflow. Aquifer-system hydraulic characteristics, well yields, the cost of drilling/deepening wells, the cost of energy for pumping water, and the design of the well and pump also can limit the availability of groundwater, and these hydrologic limitations are amplified by the institutional factors.

An overarching control is the laws, rules, and regulations codified in State law that ultimately affect water availability and, thus, sustainability. Entering into this mix are a mosaic of rulings from court cases and Federal government intervention in State water policy in response to a State request or when State law may encroach on the U.S. Constitution. There is limited surface-water and groundwater availability during the “dry” season (when water demand is greatest) in or near large parts of the study area. Limited surface water indicates that groundwater necessarily would need to be part of the future water-availability mix. However, most of the senior (and junior) surface-water rights are senior to groundwater rights and, thus, “dry” season groundwater availability may be further limited in the future.

Water availability and sustainability were addressed by (1) estimating the water in storage in the system, fluxes within and through the system, uses of water, and changes due to human activities; and (2) describing the legal framework. For example, the comparison of the predevelopment system to existing conditions defined the overall effect of human activities and their relation to groundwater availability. Availability was further addressed by analysis of the groundwater system changes simulated by the CPRAS model for long-term (2050) conditions under (1) existing water-management strategies, and (2) a set of conditions estimated to occur with a changing climate that represents average increased groundwater irrigation demand due to climate warming. Increased surface-water demand was not addressed, but that increase would have large repercussions on groundwater availability.

Although pumpage is only about 10 percent of recharge, depletion of aquifer-system storage by pumpage has been substantial in parts of the study area (more than 10 MAF for the Wanapum unit alone). This depletion has occurred because much of the pumpage occurs in areas with minimal recharge. Water-level records and previous studies confirm that large amounts of water were removed from storage in the basalt units prior to 1985 (Vaccaro, 1999). Measured water levels from this study verified continual declines in the basalt units over large areas (Snyder and Haynes, 2010; Burns and others, 2011), and groundwater levels have declined significantly in some areas (Snyder and Haynes, 2010). Between 1985 and 2007, CPRAS simulations indicate that the total storage (associated with recharge variations and groundwater-level declines) has been depleted by an additional 7.7 MAF (Ely and others, 2014).

Model simulation results show even larger areas of water-level declines by 2050. Declines from 2007 to 2050 in the Wanapum unit extend over more than 20,000 square miles, with a concomitant large loss in storage. In these areas of water-level declines, groundwater availability may become limited hydrologically or by regulations, or may be already limited. The water-level declines may result in changes in surface-water quantity and quality, and (or) a decrease in the economic viability of groundwater irrigation because of increased energy costs with the increased pumping lifts. Water-level declines, in turn, can factor into environmental issues by changing and (or) degrading habitats if groundwater discharge to surface-water bodies decreases. These related effects may constitute the primary constraint to groundwater development. For example, under long-term 2050 conditions with 2007 pumpage, groundwater discharge to streams in the model area was simulated to decrease by more than 600 cubic feet per second. Thus, during the summer low-flow period, some streams may not have enough groundwater input to sustain environmental flows, which include codified or “target” instream flows.

In the future, population growth and irrigation demand may increase conflicts over water (Washington State Department of Ecology, 2011). Factoring in projected climate change, without increased storage, the projected changing surface-water regime with earlier runoff because of less snowpack will lead to larger water demands, especially during the summer low-flow season (Climate Impacts Group, 2009; Washington State Department of Ecology, 2011). If the amount of surface water available during the dry season decreases, the amount and timing of groundwater pumpage ultimately may be affected. This effect would be in addition to increased crop-water demand. That is, the crop water demand can be expected to increase in the future and add more competitive demands on the available water supply. The large quantity of irrigated lands in the study area dedicated to perennial crops (such as apples, cherries, asparagus, grapes, hops, timothy hay, and alfalfa) makes changing crop types difficult, but water limitations may result in a changing crop mix. Effects of historical usage indicate that in many areas the groundwater system cannot meet competing demands indefinitely, and any increased groundwater use under a changing climate will increase the competitive demand for the limited resource and (or) result in the loss of agricultural production. In particular, projected climate effects may decrease the number of years in which water demands for agricultural uses are met. Assuming these climate projections are correct, decreases in water storage likely will continue in some areas, perhaps at an accelerated rate.

Since the late 1970s, State and Federal water projects have not expanded with growing urbanization and the increased agricultural and environmental uses of water on the Columbia Plateau. The study area faces ongoing and projected increases in competing demands for water resources, few of which are likely to be met by improvements in agricultural efficiencies. Indeed, except for a few areas, most water available from agricultural efficiencies is being directed to environmental uses. The demand for water resources by people directly competes with environmental uses such as maintaining minimum streamflows and preserving fish habitat, and this competition is expected to increase. The interrelationship between these competing demands and legal constraints likely will strengthen.

Introduction

Groundwater availability in the Columbia Plateau Regional Aquifer System (CPRAS), in northeastern Oregon, southeastern Washington, and western Idaho (fig. 1), is a critical water-resource management issue because of the high water demand for agriculture, economic development, and ecological needs, creating competing interests for the limited resource. These demands generally must be met by groundwater withdrawals and (or) by changes in the way water resources are allocated and used throughout the hydrologic system because surface water in many of the basins in the study area is fully appropriated or over-appropriated; more water has been legally distributed through surface-water rights than actually exists in some rivers and streams. Ongoing activities in the region for enhancement of fisheries and obtaining additional water for agriculture and municipal use may be affected by groundwater withdrawals. Listing of numerous stocks of salmonids under the Endangered Species Act (ESA) has introduced new constraints on the management of water resources in the region.

The development of the groundwater resources and nearly full development of surface-water resources has set the stage for conflict over any remaining water and existing water uses. Water-resources issues that have implications for future groundwater availability in the region include:

1. Widespread water-level declines associated with development of groundwater for irrigation and other uses,
2. Reduction in base flow to rivers and associated effects on water temperature and quality,
3. Limited availability of non-appropriated surface water and constraints on groundwater uses in some areas,
4. Potential capture of surface water appropriated through senior water rights by pumpage of groundwater appropriated through more junior water rights, and
5. Current (2014) and anticipated effects of climate change and variability on groundwater recharge, base flow in rivers, and, ultimately, sustainable groundwater yields.

The economic viability of the area and its ecosystems, especially as related to the iconic Pacific Northwest salmon, depend directly or indirectly on groundwater. Because of intensified competition for available water, there was a need to quantify water resources of the Columbia Plateau and to better understand the spatial-temporal variations in the system to help with future water-use considerations. In response, the U.S. Geological Survey (USGS) assessed the groundwater availability of the CPRAS as part of a National Groundwater Resources Program (U.S. Geological Survey, 2008). The USGS national assessment of groundwater availability was initiated because of the need for improved understanding of these regional resources throughout the United States. The framework for the national assessments is provided in U.S. Geological Survey (2002) and National Science and Technology Council (2004). The framework defines a water-resource assessment of status and trends of water in storage, flow rates, and water use and withdrawals.

The broad goals of the national assessment were to:

1. Characterize the status of the hydrologic system,
2. Identify trends in groundwater storage and use,
3. Assess the relation of groundwater availability to the overall hydrologic system,
4. Estimate components of landscape and groundwater-flow system water-budget, and
5. Quantify groundwater availability.

To achieve these goals, data were collected and analyzed, the hydrogeologic framework was updated, a transferable hydrologic toolbox that incorporates new techniques was developed as part of the CPRAS study, and a regional groundwater-flow model was developed.

The availability and sustainability of groundwater as a source of water supply is a function of many factors—both natural and human—that control its use. Natural factors include the quantity and quality of water, climate, and environment. Human factors include laws, regulations, and economics (U.S. Geological Survey, 2002). As with groundwater availability of the Central Valley Aquifer in California that was assessed as part of the USGS National Groundwater Resources Program (Faunt and others, 2009), water concerns and conflicts can be categorized under three general categories:

1. Natural distribution (both spatial and temporal);
2. Technical-hydrologic; and
3. Political, legal, and social.

Political, legal, and social concerns include fully or over-appropriated waters in some basins, streamflows needed to support ESA listed species, and potential impairment of senior surface-water rights. This study addresses some of these problems and conflicts by contributing to the improved understanding of the hydrologic system and providing an updated description of groundwater availability in the CPRAS. To help improve the understanding of the hydrologic system, a regional groundwater-flow model was constructed for an area referred to as the “model domain.” The model domain includes 74 percent of the study area (fig. 1). Nearly all the agriculture (irrigated and dryland), population, and human activities are within the model domain.

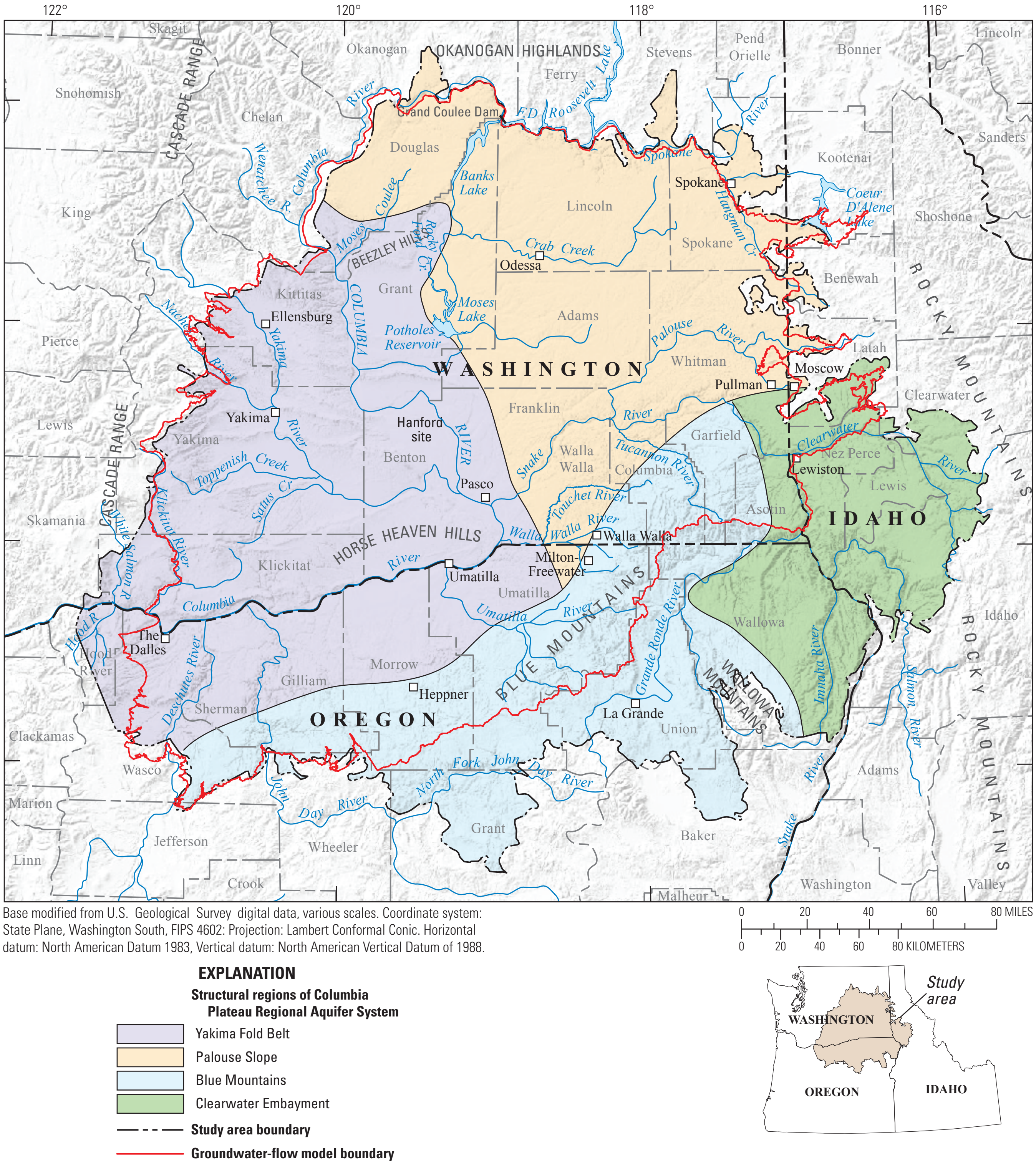


Figure 1. Columbia Plateau Regional Aquifer System study area and structural regions, Washington, Oregon, and Idaho (from Kahle and others, 2011).

Ultimately, groundwater availability and water availability generally have been, are, and will be controlled by State water law and its association with political and social complexities. Water law on the Columbia Plateau, as in most of the Western United States, is the doctrine of “prior appropriation” (principle of appropriative rights—the first in time is the first in right), especially for surface water. A brief overview of the water codes for Washington, Oregon, and Idaho is provided in appendix 1 because of the importance of State water law and its effect on groundwater availability.

Purpose and Scope

This report summarizes a series of reports published as part of the groundwater availability analysis of the CPRAS, and incorporates, to the extent possible, the nomenclature and wording of each published report to provide consistency. Figures from these reports also are incorporated when possible. Detailed descriptions of these reports and results are available in the following previously published reports:

- Ground-water availability assessment for the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (U.S. Geological Survey, 2008)
- Geologic setting and hydrogeologic units of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (Kahle and others, 2009)
- Groundwater conditions during 2009 and changes in groundwater levels from 1984 to 2009, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (Snyder and Haynes, 2010)
- Three-dimensional model of the geologic framework for the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (Burns and others, 2011)
- Groundwater status and trends for the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (Burns and others, 2012)
- A coupled remote sensing and simplified surface energy balance approach to estimate actual evapotranspiration from irrigated fields (Senay and others, 2007)
- Global reference evapotranspiration modeling and evaluation (Senay and others, 2008)
- Characterizing landscape evapotranspiration dynamics in the Columbia Plateau using remotely sensed data and global weather datasets (Senay and others, 2009)
- Hydrogeologic framework and hydrologic budget components of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (Kahle and others, 2011)
- Numerical simulation of the groundwater flow in the Columbia Plateau Regional Aquifer System, Idaho, Oregon, and Washington (Ely and others, 2014)

This report is one in a series of reports summarizing the findings of studies conducted as part of the USGS National Groundwater Resources Program assessment of groundwater availability throughout the Nation. Additionally, to be consistent with the other national summaries, selected section headings and wording also have been incorporated from the following national summary reports:

- Groundwater availability of the Central Valley Aquifer, California (Faunt, 2009)
- Groundwater availability in the Atlantic Coastal Plain of North and South Carolina (Campbell and Coes, 2010)
- Water availability and use pilot—A multiscale assessment in the U.S. Great Lakes Basin (Reeves, 2010)
- Groundwater availability of the Denver Basin aquifer system, Colorado (Paschke, 2011)
- Groundwater availability of the Mississippi embayment (Clark and others, 2011)

The report includes a description of the physical setting, physiography, climatic setting, cultural setting, and water resource and economic development, and the geologic setting to provide an understanding of the generalized background for the CPRAS area. Each of these items is intricately related to water availability. This report includes descriptions of:

- The hydrogeologic units and their characteristics,
- The model of groundwater flow,
- Generalized water budgets for the complete study area,

- Detailed water budgets for the hydrogeologic units in the groundwater-model domain, and
- Changes in the water budget within the groundwater-model domain due to human activities.

When appropriate, the generalized water budgets for the study area are presented for predevelopment conditions and existing conditions. Predevelopment conditions represent the hydrologic system before appreciable land-uses changes, especially agriculture. Existing conditions represent the developed system during 1985–2007, as defined by Kahle and others (2011). The influence and importance of climate variability and projected climate change on the groundwater flow system also is presented. The information described in this paragraph provides for the assessment and presentation of groundwater availability of the CPRAS. The monitoring of the hydrologic system is described because of its importance in understanding groundwater sustainability and, thus, availability.

Background

The CPRAS is in the Columbia Plateau in northeastern Oregon, southeastern Washington, and northwestern Idaho (fig. 1); an overview of the aquifer system is presented in Whitehead (1994). The aquifer system covers about 44,000 mi^2. The area supports a $6 billion per year agricultural industry, and leads the Nation in production of apples and nine other commodities (State of Washington Office of Financial Management, 2007; U.S. Department of Agriculture, 2007a). Surface-water diversions and groundwater pumpage supply water to the irrigated croplands that primarily occur in the arid and semi-arid parts of the study area. These croplands account for about 5 percent of the Nation's irrigated croplands. Groundwater is the primary source of drinking water to the more than 1.3 million people in the study area.

To study such a large and important aquifer system, an approach was developed that included:

- Updating the regional hydrogeologic framework,
- Documenting changes in the status of the hydrologic system,
- Quantifying the predevelopment and existing hydrologic budget (including water withdrawals) for the complete system, and
- Developing a numerical regional groundwater-flow model for part of the system.

The model was used to estimate water-budget components and to evaluate groundwater availability under existing land- and water-use conditions and a possible future climate scenario representing an increase in pumpage demand because of changing climate. The model is based on the USGS CP-RASA groundwater-flow model developed by Hansen and others (1994), and its boundary is nearly identical to the CP-RASA model boundary. The new model incorporates information on the surface-water and groundwater systems that has become available since the original model was developed, includes a higher degree of spatial resolution than previous models, and makes use of the advancements in numerical hydrologic models and computer capabilities that have occurred since the original model was developed.

Description of Study Area

Much of the information presented in this section is based on the presentation in the CP-RASA report of Whiteman and others (1994). This information provides generalized but important information for understanding the study area and its hydrologic system.

Physical Setting

The Columbia Plateau lies within the Columbia intermontane physiographic province (Freeman and others, 1945). It is bordered by the Cascade Range on the west, the Okanogan Highlands on the north, and the Rocky Mountains on the east; its southern boundary is defined more by the extent of the Columbia River Basalt Group (CRBG) than by any physiographic feature. Altitudes in the study area range from less than 300 ft to more than 9,000 ft. About 58 percent of the study area is in Washington, 34 percent is in Oregon, and 8 percent is in Idaho. The Columbia Plateau is drained by the Columbia River and its major tributaries in the study area—the Yakima, Spokane, Clearwater, Salmon, Imnaha, Grande Ronde, Tucannon, Snake, Touchet, Walla Walla, Umatilla, John Day, Deschutes, Klickitat, Hood, and White Salmon Rivers (fig. 1). The headwater areas for most of the rivers are outside of the study area, and nearly all the streamflow entering, flowing through, and exiting the study area is derived from the snowpack. Continuous discharge measurements are available for many streams in the study area and have been measured at more than 208 active and discontinued USGS stream-gaging stations.

Physiography

The Columbia Plateau was divided into four structural regions—the Yakima Fold Belt, Palouse Slope, Blue Mountains, and Clearwater Embayment subprovinces (fig. 1; Myers and Price, 1979; Reidel and others, 2002). The subprovince delineation is important for describing groundwater availability. The Yakima Fold Belt includes most of the western half of the Columbia Plateau north of the crest of the Blue Mountains and is characterized by a series of anticlinal ridges and synclinal basins. The Palouse Slope occupies the northeast quarter of the Columbia Plateau in Washington, north of the Blue Mountains, and extends eastward into Idaho. It consists of nearly undeformed basalt with a gentle southwestern slope. The Blue Mountains subprovince includes the Blue Mountains, a composite anticlinal structure, and surrounding areas. This subprovince is characterized by high plateaus that are deeply dissected by many streams. The Clearwater Embayment marks the eastward extent of the CPRAS along the foothills of the Rocky Mountains. The easternmost extent of this subprovince extends into the Rocky Mountains along the Clearwater River drainage; most of its rugged terrain is forested and relatively unpopulated.

The topography in central Washington, commonly referred to as the "channeled scablands," was produced by catastrophic floods during Pleistocene time (Bretz, 1923; Bretz and others, 1956). Referred to as the “Missoula Floods,” these floods resulted from the breakup of glacial ice dams that impounded immense lakes in western Montana and northern Idaho, and carved spectacular erosional features into the basalt plateau. Floodwaters stripped away overlying sediments and left behind deep canyons and coulees, rugged cliffs and buttes, large gravel bars, and giant ripple marks that measure 20–30 ft in height. The scablands cover about 15,000 mi^2 between the Columbia, Snake, and Spokane Rivers.

Climatic Setting

The climatic setting of the CPRAS controls the natural water fluxes across the landscape. For example, water demand by vegetation is most directly related to precipitation, temperature, growing-season length, and hours of daylight. Much of the area is semiarid, with 57 percent of the area receiving less than 15 in. of annual precipitation (fig. 2). Average annual precipitation ranges from about 7 in. in the center of the study area to more than 45 in. in the surrounding mountains. Precipitation is greater in the Cascade Range to the west than at similar altitudes in the east and southeast. The average annual precipitation from 1895 to 2007 (fig. 2; PRISM Climate Group, 2010) was about 17 in. or 55,000 ft^3/s (about 40 million acre-ft [MAF]). The interannual variability of precipitation generally is similar throughout the study area, but varies in some years. The mean monthly precipitation distribution at selected weather sites in the study area (fig. 3; National Oceanic and Atmospheric Administration, 2013) shows that precipitation generally is greatest in December and January and least in July. Typically, about 75 percent of the annual precipitation occurs during October through April, and 42 percent falls from November through January. Much of the precipitation from October through April falls as snow. Winter snowfall (snow water equivalent) ranges from about 8 to 20 in. in the central Columbia Plateau to more than 70 in. at higher altitudes in the Cascade Range and Blue Mountains. Spatial and interannual variations in mountain snowpack can be large and can indicate the large temporal-spatial variability of climate across the study area that greatly influences water availability.

Minimum air temperatures range from about 3 °C in the low-lying areas to about -3 °C in higher-altitude areas, and maximum air temperatures range from about 30 °C in the central Columbia Plateau to about 12 °C in the mountainous areas. Average daily temperature fluctuations typically range from 8 °C in winter to as much as 20 °C in summer; temperatures vary by about 40 °C between winter lows and summer highs. The percentage of sunshine ranges from about 10 percent in the winter to 75 percent in the summer; it is about 50 percent in the spring and autumn. In response to the climate variations, the growing season ranges from about 220 days near Walla Walla, Washington, to less than 100 days in the Cascade Range and Blue Mountains.

The types of natural vegetation present on the Columbia Plateau are largely dependent on the climatic setting and land-surface altitudes, and this vegetation is defined by the 14 Level IV ecoregions of the Columbia Plateau (Omernik, 1987; http://www.epa.gov/wed/pages/ecoregions/level_iii_iv.htm). In the central part of the Columbia Plateau, where land-surface altitude ranges from 350 to 2,000 ft and precipitation ranges from 7 to 15 in/yr, vegetation primarily is sagebrush and grasslands, and there are few perennial streams. At altitudes ranging from 2,000 to 3,000 ft, vegetation is typical of semiarid-to-transitional humid zones and includes grasslands and forest. These areas generally receive from 15 to 25 in. of annual precipitation, but in the Cascade Range, precipitation can be much greater. Where altitudes generally are greater than 3,000 ft, forests predominate and small perennial streams in deep canyons are common. The generalized land cover and land use in the study area shows the regional pattern of vegetation (fig. 4). The locations of Bureau of Reclamation (Reclamation) projects that provide most of the surface water for irrigation on the Columbia Plateau also are shown in figure 4.

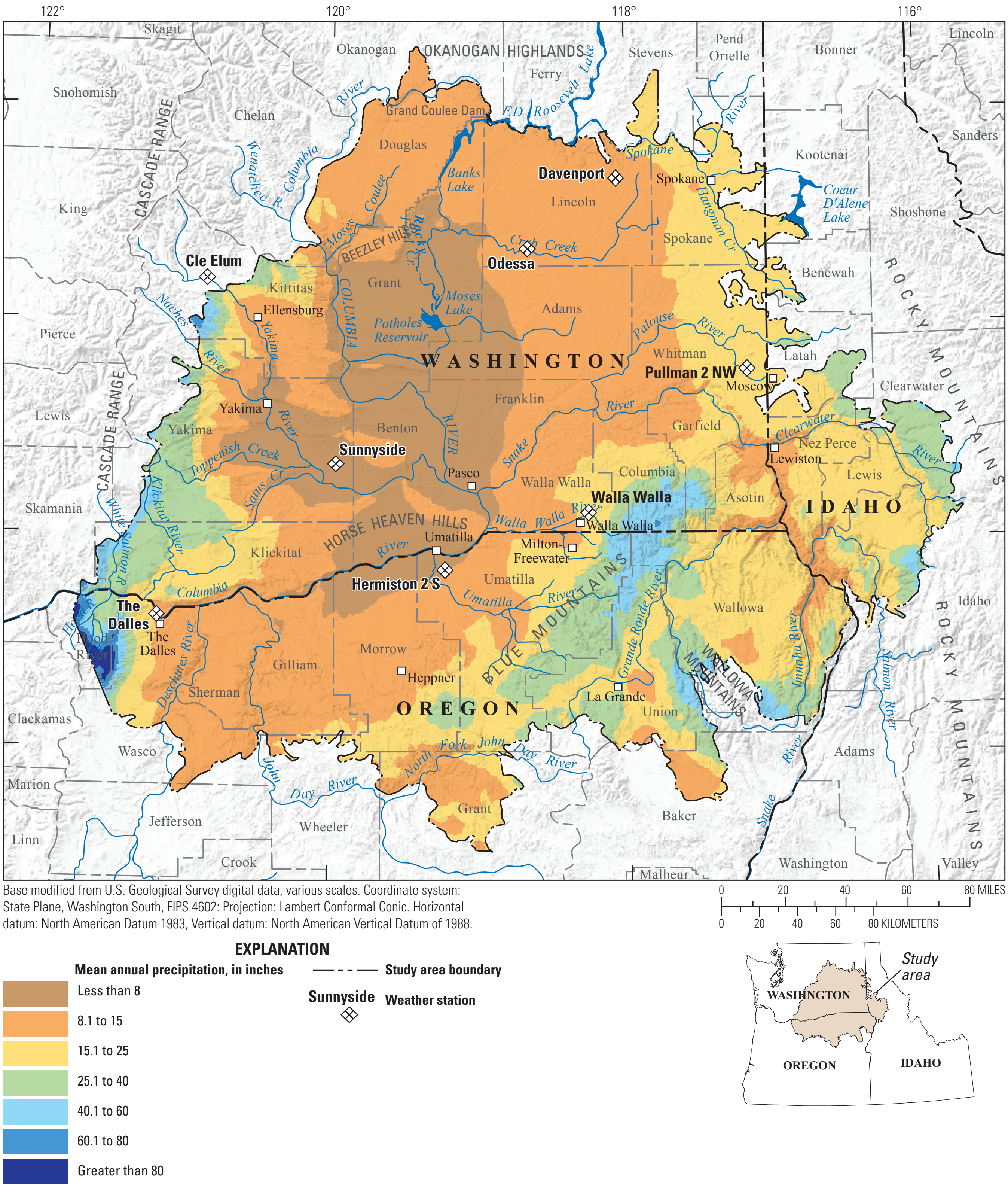


Figure 2. Mean annual precipitation, Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho, 1895–2007 (from PRISM Climate Group, 2010; and Kahle and others, 2011).

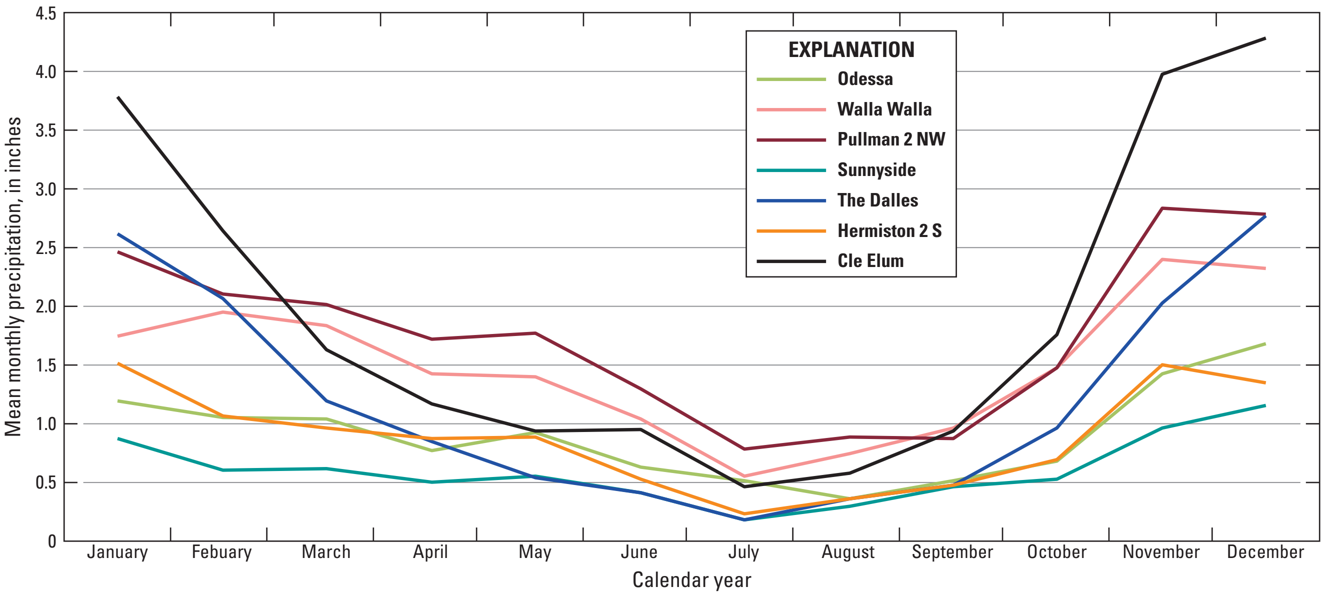


Figure 3. Mean monthly precipitation at selected weather stations, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1951-2010 (from National Oceanic and Atmospheric Administration, 2013). Weather station locations are shown in figure 2.

Cultural Setting

The cultural setting of the CPRAS is intricately linked to the use and development of the water resources in the region. Although there are numerous sources of historical information for the CPRAS, the following summary, mostly from the Washington State Historical Society (2014), provides the context and history of exploration and development.

Lewis and Clark explored parts of southern Washington and northern Oregon along the Snake and Columbia Rivers in 1805. What early explorers found was semiarid land, home to an estimated 14,000 aboriginal people, including about 6,000 Nez Perce. With the arrival of fur traders and the resulting development of the fur trade in the late 1790s, steamboats first appeared along the Columbia River in 1836. Fur traders were followed by missionaries and the establishment of forts, and then by the migration of miners and cattlemen. The Oregon Treaty of 1846 established the 49th parallel as the boundary between British and American lands and the creation of the Oregon Country, which in 1848 became the Oregon Territory. Settlers petitioned for the Oregon Territory to be separated, with a new territory north of the Columbia River. Congress established the Washington Territory in 1853; present-day Idaho was included in both the Oregon and Washington Territories. When Oregon became the 33rd State in 1859, Idaho became part of the Washington Territory, and in 1863, Idaho was made into a separate territory. Washington was admitted to the Union in 1889 as the 42nd State, and was followed the next year by Idaho as the 43rd State.

During the 1850s, the U.S. Government signed numerous treaties with various Tribes in eastern Washington, eastern Oregon, and western Idaho establishing reservations; in 13 months in the 1850s, Governor Stevens signed 10 treaties. Intertwined with the treaties were the Cayuse, Yakama, and Palouse Indian Wars from 1855 through 1858. In 1879, Chief Moses of the Columbia Tribe signed a treaty creating the Moses Columbia Reservation (modified in 1883, creating the Colville Reservation); it was during this period that the Spokane Indian Reservation was established. Lands opened up for settlement as a result of Tribal ceding and relinquishment of tens of millions of acres outside reservations and Federal land grants associated with the railroads. In exchange for ceding and relinquishment of lands, however, the treaties provided Tribes reserved rights, including reserved rights to water in sufficient quantities under the terms of the establishment of reservations; the priority date of each reserved water right is the date of the treaty (appendix 1). These rights, some of which have not been quantified, generally have much earlier priority dates than non-Tribal rights.

The railroads and Columbia River were the main conduits for commerce. The railroads provided access to markets in the rapidly developing parts of western Washington and Oregon. The building of the Cascade Locks and Canal in 1896 and the Celilo Canal in 1915 on the Columbia River provided easy passage for boats to move farther upstream, and provided the means to transport agricultural and logging products to markets. Large dams and surface-water storage reservoirs later

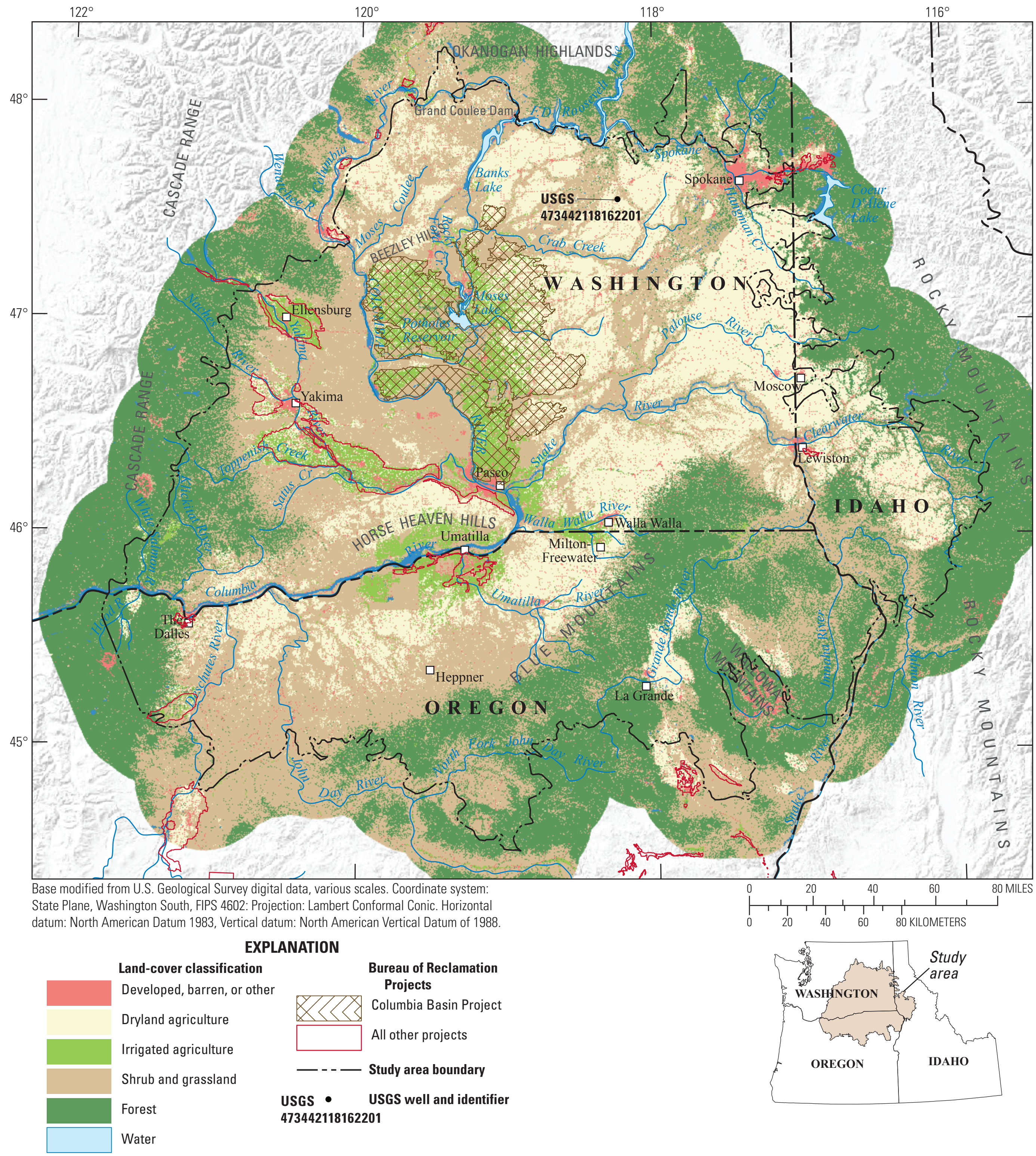


Figure 4. Generalized land cover and land use in the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho (modified from Kahle and others, 2011).

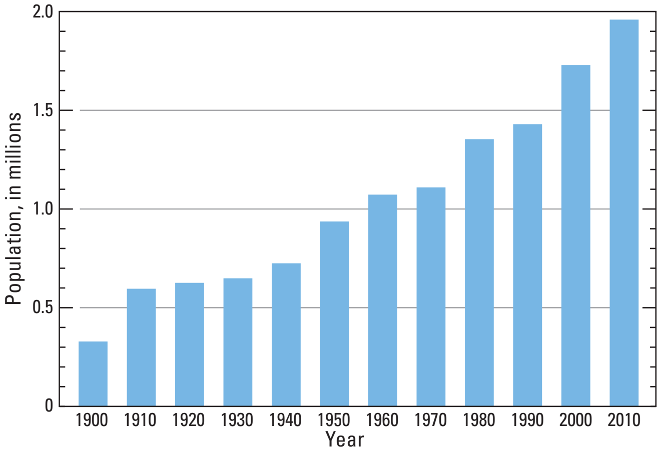


Figure 5. Population of the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho, 1900–2010 (U.S. Census, 2009, 2011).

were developed on the Columbia River system beginning in the early 1900s, and ended with the construction of Lower Granite Dam on the Snake River in 1975. The reservoirs were built to meet the water and energy demands of this expanding agricultural region. The reservoirs on the Columbia and lower Snake Rivers alone have the potential to store more than 43 MAF of water. The stored water is used primarily for hydroelectric power production, irrigation, navigation, and flood control.

Population trends of the Columbia Plateau (fig. 5; U.S. Census, 2009, 2011) correspond to changes in economic conditions and the development of water resources. Population increases from 1900 to 1910 indicate the influx of settlers attracted by the availability of land made accessible by the newly completed railroads. Population leveled out in response to slower economic growth between 1910 and 1930. Construction of the Reclamation Columbia Basin Project (CBP) (see fig. 4), water-power projects, and the Hanford Nuclear Reservation contributed to the steep rise in population in the 1940s. Irrigation water made available by CBP and through drilling of deep wells in the basalts spurred growth from the 1950s through the 1970s.

Water Resources and Economic Development

The cultural and economic development of the Columbia Plateau has depended heavily on the availability of water and the ability to store and redistribute water from the Columbia River and its major tributaries. Irrigation began as early as the 1840s and 1850s at missions in Walla Walla, Lewiston, and the Yakima River Valley. The first known irrigation system was constructed in 1818 by Donald McKenzie of the North West Company at Fort Nez Perces, near the confluence of the Walla Walla and Columbia Rivers (Northwest Council, 2013). Transportation was greatly improved in the late 1800s, when three railroad systems were built across the Columbia Plateau. Large land grants given to the railroads served to attract settlers, to encourage export of crops, and to promote investments in irrigation and agriculture-related businesses. In the early 1900s, the lumber and agricultural industries grew steadily. Small-grain production on dryland farms and dairy and poultry farming were especially profitable because these enterprises did not need large quantities of water.

The dry summer climate of the region forced the early settlers to develop water supplies for irrigation wherever possible. Most early attempts to form and finance irrigation districts and water-user associations failed. By the 1930s, economic growth was relatively slow because of the 1929 depression and severe droughts that occurred after 1919. Those who survived these hardships lived along surface-water bodies or in areas where groundwater was available at shallow depths. A notable exception to this pattern was the Yakima River Basin, where reservoirs, diversion dams, and canals were constructed during 1892–1933. By 1902, there were about 120,000 acres under mostly surface-water irrigation in the Yakima River Basin (Parker and Storey, 1916; Bureau of Reclamation, 1999). Reclamation projects between 1910 and 1933 allowed the irrigated acreage to increase to more than 500,000 acres. These water projects ensured that irrigation water was available.

The start of the CBP with the construction of Grand Coulee Dam creating F.D. Roosevelt Lake (FDR) (fig. 1) in 1933 and construction of the Hanford Nuclear Reservation (located in northeastern Benton County, Washington) in the 1940s brought a large influx of workers and associated service industries. By 1946, about 850,000 acres were irrigated in the study area (Simons, 1953). Much of these lands were irrigated with water supplied by Reclamation projects created under the Federal Reclamation Act of 1902 that enabled the construction of Federal water projects in the Western United States to expand development of the West. The Reclamation Act also allowed settlers to own 160 acres (a quarter section) for irrigating croplands. Irrigation water from FDR became available in 1952, and by 1972 more than 0.5 million acres were being irrigated by this project in Washington, producing more than 60 types of crops. As of 2010, about 2 million acres of croplands were irrigated with surface water and groundwater, with much of the surface water supplied by Reclamation projects (fig. 4). The surface-water withdrawals account for about 75 percent of the total irrigation water (Kahle and others, 2011).

Starting with the advent of new technology in the early 1950s, a rapid and intensive expansion of deep-well irrigation practices took place in areas not served by surface-water irrigation projects. These areas included parts of the Yakima, Pasco, Umatilla, The Dalles, and Walla Walla Basins and the Odessa area in western Adams County, Washington. By 1984, about 0.5 million acres were irrigated with groundwater (Whiteman and others, 1994). Some areas receive sufficient precipitation to support a dryland farming economy primarily based on wheat and barley, but an estimated 1.5 million acres of these lands could be cropped profitably if water supplies were available (Pacific Northwest River Basins Commission, 1971). The dryland agricultural areas on the Columbia Plateau, however, are some of the most productive and profitable in the world, with wheat yields in some areas exceeding 90 bushels per acre.

Earlier groundwater development occurred in areas scattered throughout the Columbia Plateau. Some of the most intensive early development of groundwater was in the Yakima River Basin and near Walla Walla, Washington. As groundwater pumpage increased throughout the Columbia Plateau, groundwater levels declined. In central Washington, declines locally exceeded 150 ft by 1981 (Cline, 1981). By 1984, declines had been identified in the Pullman, Washington-Moscow, Idaho area; the Umatilla area; The Dalles area; parts of the Yakima River Basin; the Walla Walla area; and the south slope of Horse Heaven Hills (Hansen and others, 1994). Data collected as part of this study show that groundwater-level declines have continued to occur from 1984 through 2009 (Snyder and Haynes, 2010). The large declines in the Odessa area in Washington have had economic effects on farmers and the local economy in two ways. First, the declining groundwater levels have led to increased pumping-power costs and, thus, decreased profits; this also has occurred in some of the major groundwater pumping centers in Oregon. Second, to save costs, some farmers who may have been irrigating four quarter-sections now only irrigate two, reducing their irrigated lands by one-half. The economic effects of reduced croplands (and fewer profits), in turn, ripple through the allied sales and service sectors that support the agricultural industry.

Whiteman and others (1994) indicated that, during 1949–82, there had been a steady increase in irrigated acreage but a trend toward fewer but larger farms. The trend in increasing farm size generally continued from 1992 through 2002, with some stabilization and decrease in farm size from 2002 to 2007, and the total number of irrigated acres generally has stabilized (U.S. Department of Agriculture, 2007b). These trends indicate financial hardships that are affecting the owners of small- to intermediate-sized farms. Large-farm operators are better able to survive difficult financial periods, and owners of small farms often work outside jobs to supplement farm income. The primary occupation of a farm operator may be farming or it may be an off-farm occupation; a trend toward more off-farm work is a national trend (U.S. Department of Agriculture, 2007b). In the study area, most farms are owned by individuals or families.

Geologic Setting

The Columbia Plateau is underlain by massive basalt flows of the CRBG, with an estimated composite thickness of at least 14,000 ft at one of the lowest points on the plateau near Pasco, Washington (Drost and Whiteman, 1986; Drost and others, 1990; Reidel and others, 2002). The characteristics of the older rocks overlain by the CRBG are distinguishable only at exposures in the uplands. Sedimentary deposits overlie the basalt over about 33 percent of the study area, exceeding 2,100 ft in thickness in the Yakima River Valley (Jones and others, 2006) and 2,000 ft in the Grande Ronde Valley near La Grande, Oregon (Drost and others, 1990).

The CPRAS includes, from youngest to oldest:

1. The Overburden, a collective term used in this study for all materials (from Miocene to Holocene age) overlying the CRBG;
2. A minor amount of Miocene sediment interlayered with the basalt; and
3. A large thickness of CRBG rocks.

Pre-CRBG rocks underlie the Columbia Plateau and primarily consist of less permeable rocks that form the lower boundary of the CPRAS (table 1).These are sedimentary, igneous, and metamorphic rocks that range from Precambrian through early Tertiary age.

The CRBG underlies nearly all of the study area and it is the thickest, most extensive, and hydrologically most important geologic unit in the CPRAS (Whiteman and others, 1994; Vaccaro, 1999; Kahle and others, 2011). The CRBG consists of a series of flows erupted during various stages during the Miocene age, 17 to 6 million years ago. The basalt lava flowed from fissures and vents in eastern Washington, northeastern Oregon, and western Idaho (Swanson and others, 1975; Hooper, 1982). Flows covered about 63,200 mi^2 of eastern Washington, parts of western Washington, northern parts of western Oregon, and western Idaho to an average total thickness of 3,300 ft. About 95 percent of the basalt was extruded in episodic eruptions during the first 3 million years. Warping and folding of the Columbia Plateau increased late in the eruptive cycle, forming numerous geologic structures associated with faults or folds with large anticlines. More than 300 flows have been identified and individual flows range in thickness from 10 to more than 300 ft.

The physical characteristics of the basalt flows govern the movement of groundwater in basalts and, thus, its availability. Upper zones of the flows were exposed to weathering processes and were broken and fractured by subsequent flows, resulting in the formation of conductive “flow tops.” These flow tops, when combined with the base of the overlying basalt flow, form interflow zones that readily transmit water (Lindolm and Vaccaro, 1988). The interflow zones commonly make up 5–10 percent of the thickness of a flow. The interflow zones are separated by the less transmissive entablature and colonnade in which fractures are typically oriented vertically (Tomkeieff, 1940; Waters, 1960; MacDonald, 1967; Swanson and Wright, 1978; Sublette, 1986; Hansen and others, 1994). These fractures are a result of contraction during cooling of basalt flows (MacDonald, 1967; Long and Wood, 1986) and of later folding and faulting. The greatest density of fractures generally occurs in the entablature (Wood and Fernandez, 1988; Reidel and others, 2002).

Table 1. Names, descriptions, and ages of simplified geologic units in the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

[From Kahle and others (2009). CPRAS, Columbia Plateau Regional Aquifer System. CRBG, Columbia River Basalt Group unit. Notes are summarized from State digital compilations (number of original map units; unit type)]

Geologic unit symbol and color	Age	CPRAS simplified geologic map unit	Idaho [310; MU_SYMBOL]	Oregon [729; MAP_UNIT_NAME]	Washington [746; GUNIT_TXT]
Qs	Quaternary	Sediment	Alluvial, eolian, glacial, glacial outburst flood, glaciolacustrine, landslide, and peat deposits	Alluvial, colluvial, eolian, glacial, glacial outburst flood, lacustrine, landslide, terrace, and peat deposits; artificial fill, ash, debris-avalanche and debris-flow deposits, mine tailings, talus; sedimentary deposits or rocks	Alluvial, eolian, glacial, glacial outburst flood, glaciolacustrine, lacustrine, landslide, and peat deposits; talus; artificial fill
QTi	Quaternary-Tertiary	Intrusives	Not a map unit in Idaho	Not a map unit in Oregon	Mostly Mount Rainier/ Adams intrusives
QTsdr	Quaternary-Tertiary	Sedimentary deposits or rocks	Alluvial gravel, terrace; Conglomerate near Round Mountain; consolidated alluvial and (or) glacial deposits	Alkali Canyon, Dalles, Deschutes, Ellensburg, Madras, McKay, Rattlesnake, and Simtustus Formations; alluvial, fluvial, lacustrine, and terrace deposits; sedimentary rocks; tuffaceous sedimentary deposits and rocks; volcaniclastic deposits	Continental sedimentary deposits or rocks, alluvium, landslides
QTv	Quaternary-Tertiary	Non-CRBG volcanics	Basalt of Cuddy Mountain	Numerous non-CRBG volcanics	Mostly Mount Rainier/ Adams flows, lahars, intrusives, volcaniclastic deposits or rocks
Msdr	Miocene	Sedimentary deposits or rocks	Alluvial gravel, Latah Formation, Deer Creek Beds, Payette Formation	Not a map unit in Oregon	Continental sedimentary deposits or rocks, landslide deposits
Mv(SMB)	Miocene	Saddle Mountains Basalt	Includes Asotin, Grangeville, Onaway, Wilbur Creek, and Weissenfels Ridge Members; and basalt of Cragmont, Lapwai, and Weippe	Buford, Elephant Mountain, and Umatilla members; basalt of Eden, Ferguson Spring, and Umatilla; Pomona basalt	Includes Asotin, Buford, Elephant Mountain, Esquatzel,Grangeville, Ice Harbor, Lower Monumental, Onaway, Pomona, Umatilla, Wilbur Creek, and Weissenfels Ridge Members
Mv(WB)	Miocene	Wanapum Basalt	Includes Eckler Mountain, Priest Rapids, and Roza Members; and basalt of Ferry Creek	Frenchman Springs and Roza members; Basalt of Ginkgo, Lookingglass, Lyons Ferry, Palouse Falls, Powatka, Robinette Mountain, Sand Hollow, and Sentinel Gap	Includes Eckler Mountain, Frenchman Springs, Priest Rapids, and Roza Members

Table 1. Names, descriptions, and ages of simplified geologic units in the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.—Continued

[From Kahle and others (2009). CPRAS, Columbia Plateau Regional Aquifer System. CRBG, Columbia River Basalt Group unit. Notes are summarized from State digital compilations (number of original map units; unit type)]

Geologic unit symbol and color	Age	CPRAS simplified geologic map unit	Idaho [310; MU_SYMBOL]	Oregon [729; MAP_UNIT_NAME]	Washington [746; GUNIT_TXT]
Mv(GRB)	Miocene	Grande Ronde Basalt	Includes upper and lower flows of normal magnetic polarity (N2 and N1) and upper and lower flows of reverse magnetic polarity (R2, R1)	Includes upper and lower flows of normal magnetic polarity (N2 and N1) and upper and lower flows of reverse magnetic polarity (R2, R1)	Includes upper and lower flows of normal magnetic polarity (N2 and N1) and upper and lower flows of reverse magnetic polarity (R2, R1)
Mv(PB)	Miocene	Prineville Basalt	Not a map unit in Idaho	CRBG, Prineville chemical type	Not a map unit in Washington
Mv(PGB)	Miocene	Picture Gorge Basalt	Not a map unit in Idaho	Basalt intrusives and flows (normal and reversed magnetic polarity); Dayville, Monument Mountain, and Twickenham Basalt	Not a map unit in Washington
Mv(IB)	Miocene	Imnaha Basalt	Basalt	Basalt with minor tuff breccia	Basalt
Mv(CRBG)	Miocene	CRBG, undivided	CRBG, undivided	CRBG, undivided; basalt and dikes	Not a map unit in Washington
preM	preMiocene	Pre-CRBG rocks, undivided	Intrusive, metamorphosed intrusive, sedimentary, and metamorphosed sedimentary rocks	Volcanic, metavolcanic, intrusive, sedimentary, and metamorphosed sedimentary rocks; sedimentary deposits (pre-CRBG)	Intrusive, metamorphosed intrusive, sedimentary, metamorphosed sedimentary, and volcanic rocks (pre-CRBG)

When the hiatus between flows was sufficiently long, soil developed or sediments were deposited on the surface of a flow. If these sediments were preserved, a sedimentary interbed occurred between flows. Sedimentary interbeds are more common in younger than older basalt units. During the Pleistocene, the surface expression of the basalt was modified greatly during the repeated catastrophic outburst flooding of the Missoula Floods, which caused erosion of vast channels and ancient waterfalls in places, as well as removal and (or) deposition of overlying sediment (Bretz, 1923; Bretz and others, 1956).

Sediment Stratigraphy

After the eruption of basalt ceased, folding, erosion, and deposition of sediments continued. The Cascade Range has been the primary source of sediments and, thus, the greater sediment thicknesses are in the western part of the study area. The sediments include consolidated–to-unconsolidated deposits of fluvial, lacustrine, volcanic, and eolian origin ranging from Miocene to Holocene age.

Within the Yakima Fold Belt, Miocene sediment of the Ellensburg Formation underlies, intercalates, and overlies the CRBG and composes most of the thickness of the deposits in the basinal areas (Jones and others, 2006). In eastern Washington and west-central Idaho, sediment of the fine-grained Latah Formation underlies, intercalates, and overlies the CRBG (Pardee and others, 1926; Leek, 2006), but occurs mostly beyond the extent of the CRBG. In the Walla Walla River, Quincy, and Pasco Basins in Washington, the overlying sediments are part of the Miocene-Pliocene Ringold Formation, which is at least 500 ft thick in these basins. Eolian deposits of fine Pleistocene loess cover much of the Columbia Plateau and reach thicknesses of as much as 250 ft, but generally are much thinner. The thickest deposits are present in the Palouse Slope subprovince and are part of the Palouse Formation.

The Cordilleran ice sheet that covered the northern and northwestern parts of the Columbia Plateau left extensive deposits of till, stratified drift, and ice-contact materials. Alpine glaciers from the Cascade Range and Wallowa Mountains also reached the plateau margin and left deposits.

Pleistocene deposits from the Missoula Floods were deposited by high-energy flood currents in and along scabland channels, in depositional basins, and in the Columbia River east of The Dalles. Finer-grained slackwater deposits in peripheral areas of basins in the central part of the Columbia Plateau are known as the Touchet Beds (Flint, 1938).

Interbed Stratigraphy

The two interbeds of hydrologic importance are the interbed between the Saddle Mountains Basalt and the Wanapum Basalt (informally called the Mabton Member of the Ellensburg Formation) and the interbed between the Wanapum Basalt and the Grande Ronde Basalt (informally called the Vantage Member of the Ellensburg Formation). In the northeastern part of the study area, the sedimentary interbed in the same position as the Vantage Interbed is assigned to the Latah Formation (Swanson and others, 1979). The interbed units are fairly extensive laterally, but are thin when compared with the thickness of the basalts. The Mabton Interbed generally consists of clay, shale, claystone, clay with basalt, clay with sand, and sandstone, but also may contain small amounts of sand and sand-and-gravel. The Vantage Interbed consists of clay, shale, sandstone, tuff with claystone, and clay and basalt, but also may contain small amounts of sand and sand-and-gravel.

Basalt Stratigraphy

The CRBG has been divided into six geologic formations: Imnaha Basalt, Picture Gorge Basalt, Prineville Basalt, Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt (Swanson and others, 1979; U.S. Geological Survey, 2009; table 1). Flows belonging to the Imnaha Basalt, the oldest known in the CRBG, are present in western Idaho and eastern Washington and Oregon. The Picture Gorge and Prineville Basalt formations are limited to areas in central Oregon at the southern extent of the CRBG. The Grande Ronde Basalt and older basalts constitute about 90 percent of the CRBG by volume and cover most of the area where the CRBG is present (Reidel, 1982; Tolan and others, 1987; Bjornstad and others, 2007; U.S. Geological Survey, 2009). Flows of the widely distributed Wanapum Basalt commonly overlie the Grande Ronde Basalt. Flows of the Saddle Mountains Basalt are less widely distributed and generally are confined to the central part of the study area.

Hydrogeologic Units

The regional hydrogeologic framework was updated in a two-step process. In the first step, a digital surficial geologic map was compiled and simplified, well data were compiled, hydrogeologic units were defined, hydrogeologic sections were constructed, and generalized extents of hydrogeologic units were defined (Kahle and others, 2009). The second step involved building a digital three-dimensional (3D) hydrogeologic framework using the information from step one and data from numerous databases and detailed studies that were completed during the past 3 decades. The 3D framework was developed using geospatial statistical modeling techniques (Burns and others, 2011).

Definition of Units

Generalized hydrogeologic units defined for the CPRAS include the Overburden, Saddle Mountains, Mabton Interbed, Wanapum, Vantage Interbed, Grande Ronde, and Older Bedrock units (table 2; Kahle and others, 2009). The approximate surficial distribution of these units is shown in figure 6*A*; note that the Mabton Interbed does not outcrop and the Vantage Interbed outcrops only in isolated areas too small to show at the scale of this figure. The sedimentary Overburden unit is a composite unit, and is an important source of groundwater. The unit covers about 33 percent of the area and consists of unconsolidated (clay to gravel) to consolidated material (sandstone to shale) that form important water-bearing units, which include water table, semiconfining, and confining units. The unit contains numerous types of sedimentary deposits (table 2). The three basalt units are the Saddle Mountains, Wanapum, and Grande Ronde Basalts and their intercalated sediments. In the southeastern part of the study area, the Imnaha Basalt and any intercalated sediments are included with the Grande Ronde unit. The interbed units are equivalent to the Saddle Mountains-Wanapum and Wanapum-Grande Ronde interbeds, referred to in this study as the Mabton and Vantage Interbeds, respectively (Kahle and others, 2009; Burns and others, 2011). The Older Bedrock unit consists of pre-CRBG rocks that generally have much lower permeabilities than the basalts and is considered the base of the regional flow system—the basement confining unit (Vaccaro, 1999; Kahle and others, 2009). Hydrogeologic sections in figure 6*B* indicate the relative placement of the basalt units; the interbed units are too thin to show at the scale used. Detailed descriptions of the sediment, basalt, and interbed units are available in Drost and others (1990), Whiteman and others (1994), Jones and others (2006), Jones and Vaccaro (2008), Kahle and others (2009), and Burns and others (2011).

Table 2. Correlation chart showing relation between stratigraphy and generalized hydrogeologic units, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

[From Kahle and others (2009)]

<table>
<tr><th>Generalized hydrogeologic unit</th><th>ERA</th><th>PERIOD</th><th>EPOCH</th><th>Sediment stratigraphy</th><th colspan="3">Basalt stratigraphy</th></tr>
<tr><td rowspan="3">Overburden</td><td rowspan="10">Cenozoic</td><td rowspan="2">Quaternary</td><td>Holocene</td><td rowspan="2">Alluvial, colluvial, eolian, glacial, glacial outburst flood, lacustrine, landslide, terrace, and peat deposits; ash, debris-avalanche and debris-flow deposits, talus; Touchet Beds, Palouse Formation</td><td rowspan="3" colspan="3">Quaternary and Pliocene Basalts</td></tr>
<tr><td>Pleistocene</td></tr>
<tr><td rowspan="8">Tertiary</td><td>Pliocene</td><td>Alluvial fan deposits; Alkali Canyon, Chenoweth, Deschutes, Madras and Ringold Formations; Dalles Group; Thorpe Gravel; and unknown continental sedimentary deposits</td></tr>
<tr><td>Saddle Mountains</td><td rowspan="7">Miocene</td><td rowspan="7">Ellensburg, Deschutes, Latah, Madras, Payette, and Ringold Formations; Dalles Group; Snipes Mountain deposits; Deer Creek Beds; and unknown continental sedimentary deposits</td><td rowspan="7">Columbia River Basalt Group</td><td colspan="2">Saddle Mountains Basalt flow members and interbeds</td></tr>
<tr><td>Mabton Interbed</td><td colspan="2">Mabton interbed (Mabton Member of the Ellensburg Formation)</td></tr>
<tr><td>Wanapum</td><td colspan="2">Wanapum Basalt flow members and interbeds</td></tr>
<tr><td>Vantage Interbed</td><td colspan="2">Vantage interbed (Vantage Member of the Ellensburg Formation)</td></tr>
<tr><td rowspan="3">Grande Ronde</td><td>Prineville Basalt</td><td rowspan="2">Grande Ronde Basalt flow members and interbeds</td></tr>
<tr><td>Picture Gorge Basalt</td></tr>
<tr><td colspan="2">Imnaha Basalt</td></tr>
<tr><td>Older Bedrock</td><td colspan="7">pre-Columbia River Basalt Group rocks, undivided</td></tr>
</table>

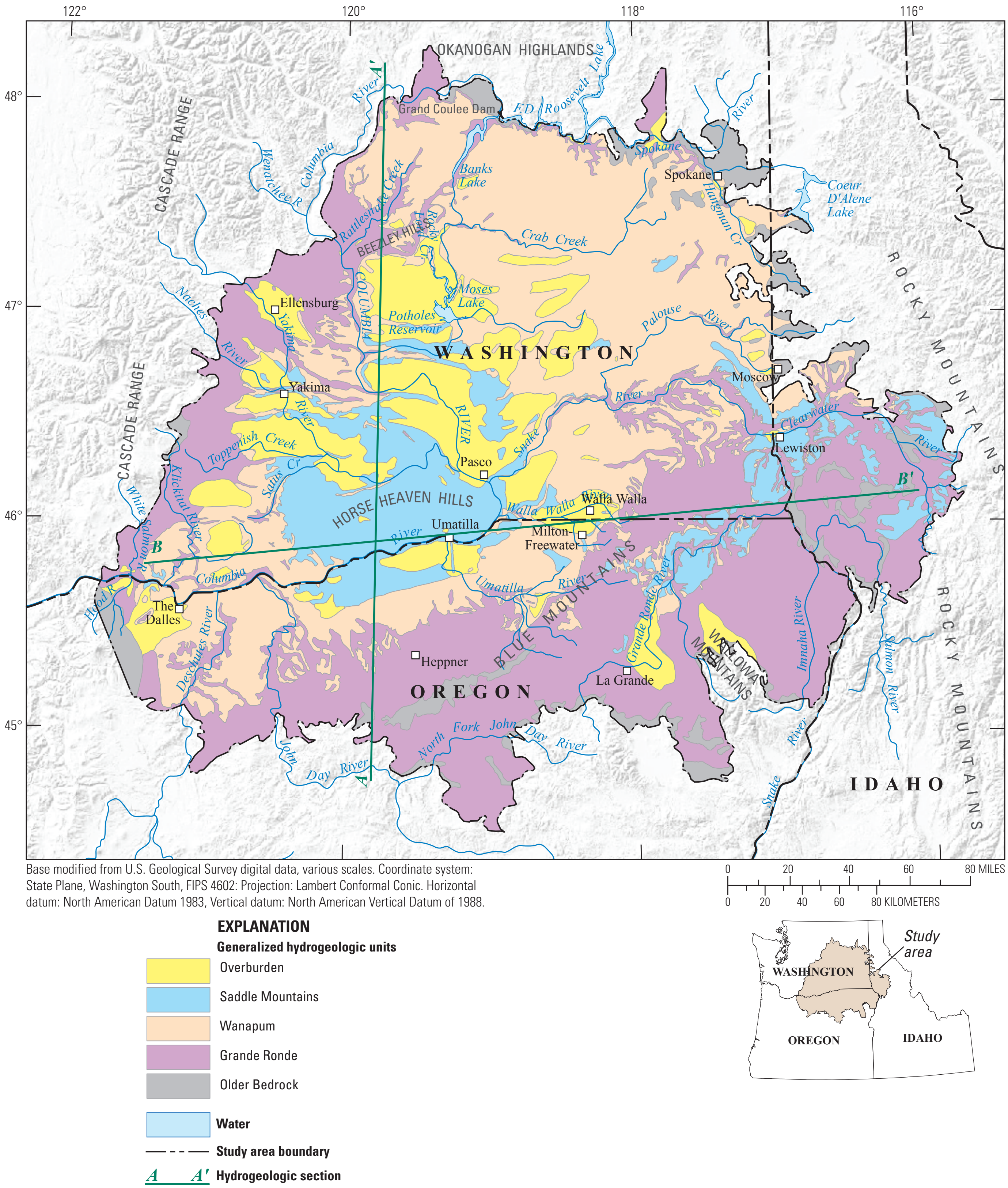


Figure 6. Generalized (*A*) surficial hydrogeologic units (from Kahle and others, 2009), and (*B*) hydrogeologic sections (from Burns and others, 2011) in the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho.

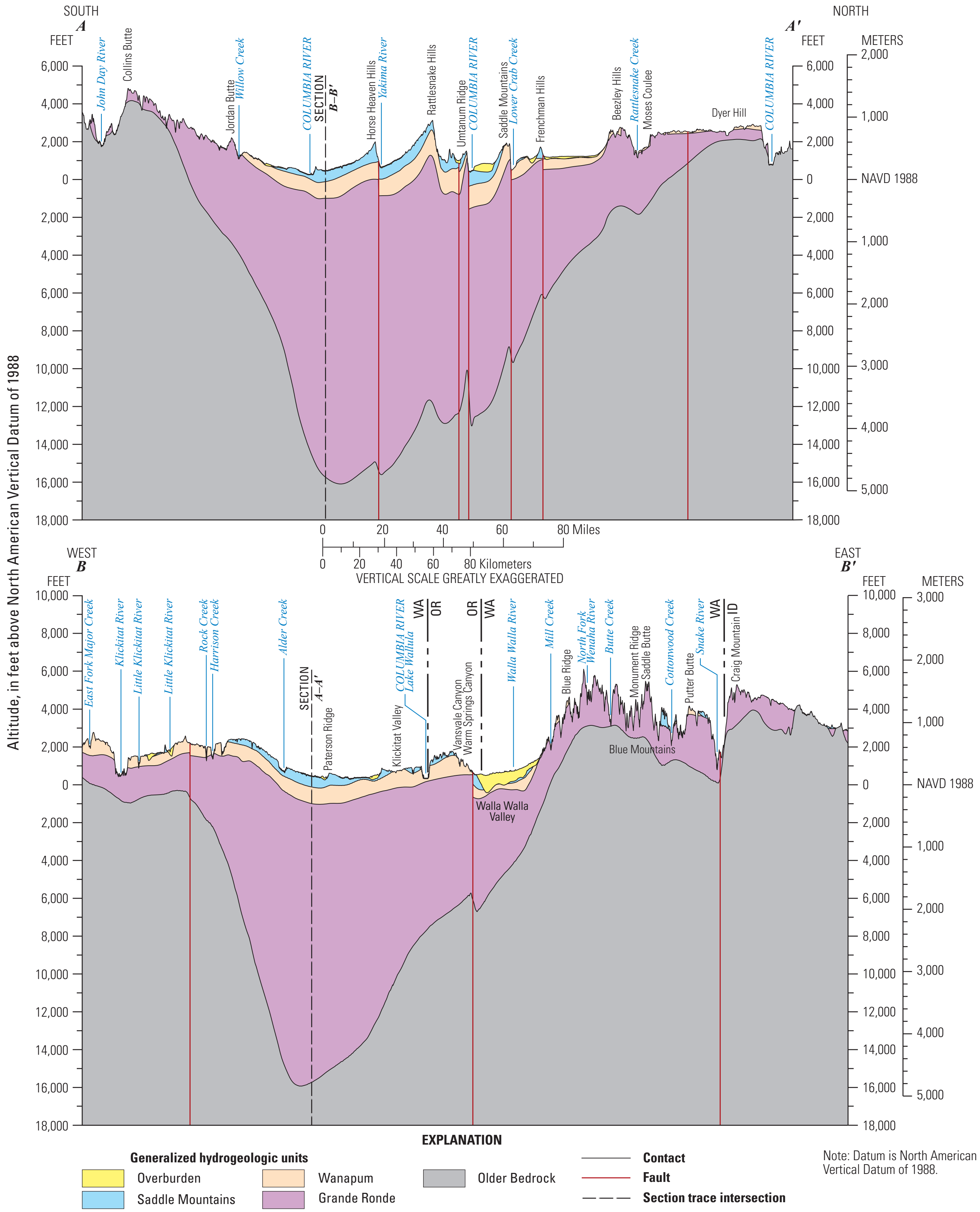


Figure 6.—Continued.

Mapping of Hydrogeologic Units Using Geospatial Modeling

A 3D-geologic model was constructed for the CPRAS to define the general aquifer system geometry (Burns and others, 2011) for use in the regional numerical groundwater-flow model. Simplifications and assumptions were made that were consistent with the uncertainty in the available data and the intended use of the results. The final hydrogeologic units constructed are for the 44,000-mi^2 study area. Data compiled for the model were simplified and used to construct piecewise-smooth trend surfaces that represent upper and lower subsurface unit boundaries in this complex terrain. The modeling process yielded improved estimates of unit volumes, refinement of location of large structural features, and identification of features that may be important for ongoing groundwater studies. Two hydrogeologic sections show the complexity of the aquifer system (fig. 6*B*). Summary descriptions (from youngest to oldest) of the units based on the work of Kahle and others (2009) and Burns and others (2011) are provided in the following sections.

Overburden Unit

For the 3D framework, Burns and others (2011) used the lateral extents of most of the sedimentary deposits in the study area, including those between 0 and 100 ft thick (excluded in the mapping of Kahle and others, 2009). The final distribution of the Overburden unit covers 14,644 mi^2, which is larger than the 6,134 mi^2 estimated by Kahle and others (2009) because the areas with less than 100 ft of thickness were included when constructing the 3D model. The thickness of the unit ranges from 0 to about 2,000 ft (average and median of 88 and 860 ft, respectively), and the unit has a volume of about 244 mi^3. The thickest deposits occur in structural basins and areas adjacent to the Cascade Range.

Saddle Mountains Unit

The Saddle Mountains unit has an extent of about 11,700 mi^2 compared to the 8,000-mi^2 estimate of Kahle and others (2009); the model estimated that this unit is present in additional parts of the Palouse Slope, and other information seems to support this larger extent (Burns and others, 2011). The estimated thickness of the unit (which for the 3D modeling included the Mabton Interbed unit) ranges from 0 to about 2,000 ft. The average thickness of the unit is about 300 ft and the median thickness is 1,154 ft. Where buried, the constructed top-of-unit map indicates that altitudes range from about 500 to 3,000 ft. The total volume of the unit was calculated at 663 mi^3.

Mabton Interbed Unit

The Mabton Interbed unit is located mostly in the west-central part of the study area, and no surficial outcrops of the unit are present within the study area. For the 3D model, the extent was assumed to be the extent of the Saddle Mountains unit. The thickness of the unit was estimated by Burns and others (2011) as a function of distance between the Saddle Mountains and Wanapum unit tops. Calculated thickness ranged from 0 to about 205 ft (average thickness of 39 ft).

Wanapum Unit

The Wanapum unit is a surficial unit that covers more than 30 percent of the study area (fig. 6*A*). Much of the unit lies beneath the Overburden and Saddle Mountain units. The computed area of the Wanapum unit is about 24,400 mi^2, and the calculated unit thickness (which included the Vantage Interbed unit thickness) ranges from 0 to about 3,250 ft (average and median thickness of 476 and 1,115 ft, respectively). Where buried, the altitude of the top of the unit ranges from more than 3,500 ft in the eastern part of the Blue Mountains to less than -1,000 ft at the Hanford Site. The calculated volume for the unit is 2,156 mi^3. The thickness map for the unit and the hydrogeologic sections (Burns and others, 2011) indicate structural basins, effects of geologic structure on the distribution of the unit, and the overall thickening of the unit towards the center of the Columbia Plateau (figs. 6*B* and 7).

Vantage Interbed Unit

Limited surficial outcrops of the Vantage Interbed unit occur in the study area, and for the 3D model, the extent was assumed to be the extent of the Wanapum unit. Generalized estimates of the thickness of the unit were generated as a function of distance between the Wanapum and Grande Ronde unit tops. Calculated thickness values for the unit resulted in an average of about 20 ft and a median of 15 ft, and thickness ranged from 0 to about 30 ft. Drost and others (1990) and Whiteman and others (1994) reported a similar average thickness of 25 ft.

Grande Ronde Unit

The Grande Ronde unit underlies most of the study area (fig 6*A*), and occurs at land surface over more than 30 percent of the study area. The 3D model produced a 41,900-mi^2 areal extent for the Grande Ronde unit. The thickness of the unit ranged from 0 to about 16,000 ft under the assumption that the paleosurface (top of the Older Bedrock unit) was relatively smooth. The average thickness was calculated as 3,950 ft. The altitude of the top ranges from about -2,200 to 7,888 ft, or a relief difference of about 10,000 ft. The total calculated volume for the unit was 31,273 mi^3. A map of the top of the Older Bedrock unit (fig. 8), analogous to the bottom of the CRBG, indicates the complex shape of the basalt surfaces within the CPRAS.

Older Bedrock Unit

The Older Bedrock unit that borders and underlies the CPRAS is composed of various rock types older than the CRBG (Kahle and others, 2009). The Older Bedrock unit outcrops only over a small part of the study area. Burns and others (2011) constructed a map of the top of this unit as part of developing the 3D framework in order to estimate the thickness of the Grande Ronde unit.

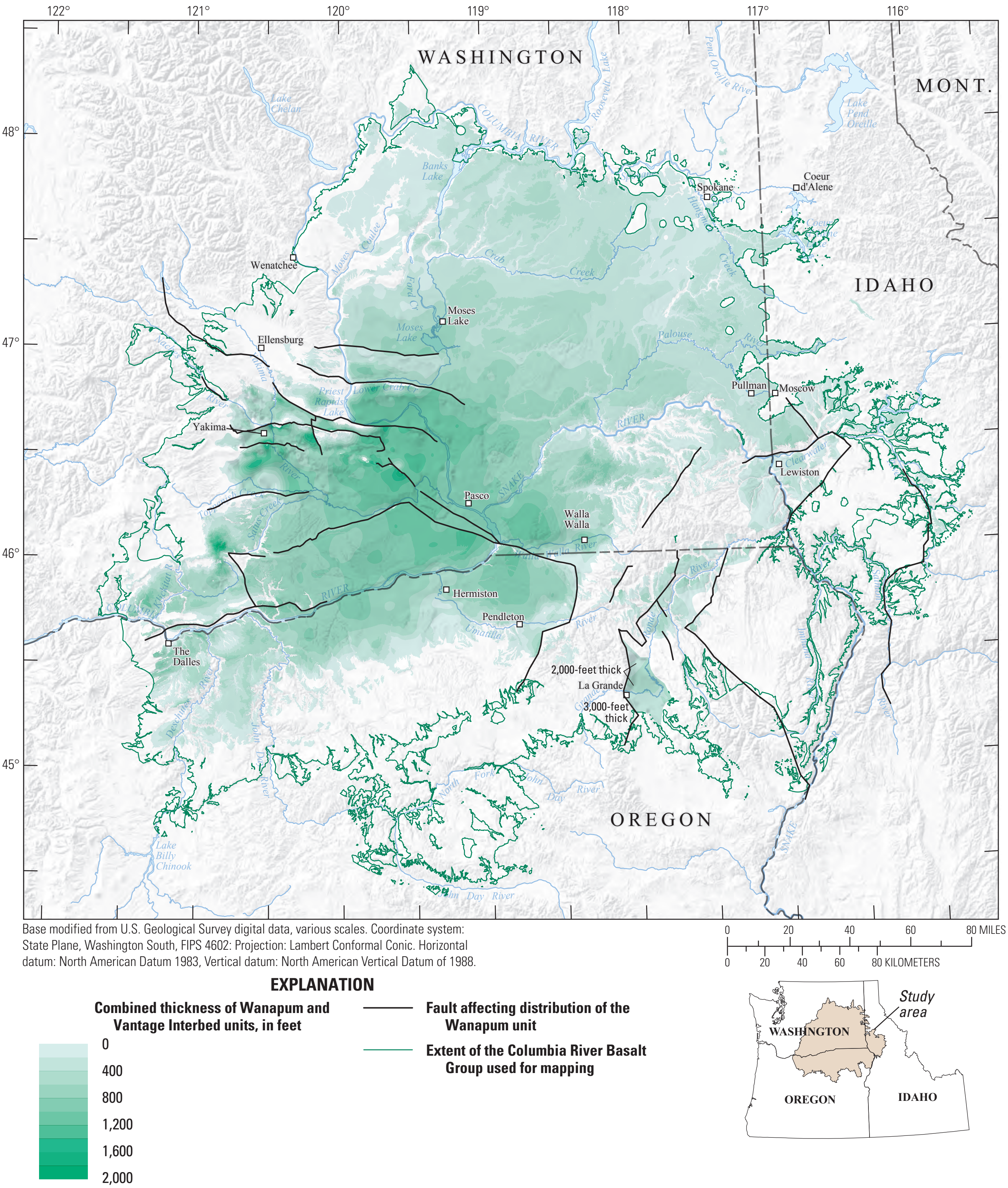


Figure 7. Combined thickness of the Wanapum and Vantage Interbed units, in the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho (from Burns and others, 2011).

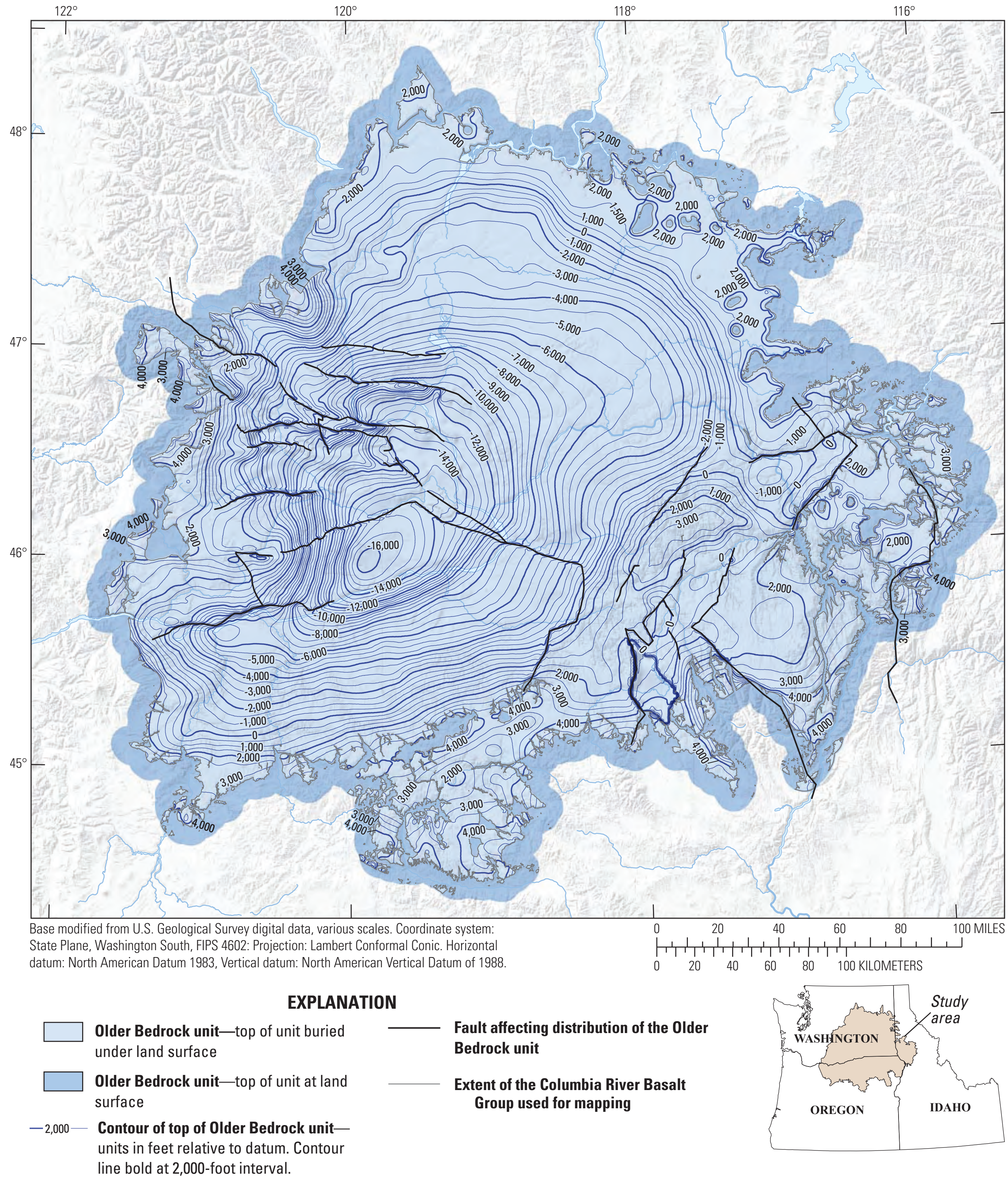


Figure 8. Altitude of the top of the Older Bedrock unit, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (from Burns and others, 2011).

Hydraulic Characteristics

The ability of a groundwater-flow system to store and transmit groundwater (its hydraulic characteristics) determines how it functions and is a major control on water availability. Knowledge of the hydraulic characteristics is necessary to evaluate how the flow system responds to stresses such as pumpage and to climatic variations as represented by variations in recharge, irrigation, and streamflow. These characteristics include lateral and vertical hydraulic conductivity and the storage coefficient. Compilations of previous estimates of hydraulic characteristics provided an overview of the range and median/average for the hydrogeologic units, including the Older Bedrock unit (Vaccaro and others, 2009; Kahle and others, 2011).

Information presented in this section and summarized in table 3 is based on values derived from the calibration of the CPRAS model (Ely and others, 2014), a groundwater-flow model for the Yakima River Basin Aquifer System (YRBAS) (Ely and others, 2011), and the CP-RASA model (Hansen and others, 1994). A detailed discussion of hydraulic characteristics is presented in Ely and others (2014). Hydraulic characteristics of the Older Bedrock unit are not discussed because it typically has as much as five orders of magnitude smaller values of porosity and permeability than the other units (Vaccaro and others, 2009; Kahle and others, 2011).

Lateral hydraulic conductivity is a measure of the ability of a hydrogeologic unit to transmit water laterally. Overburden deposits are diverse in lithology and, thus, so are their hydraulic characteristics. The estimates of this characteristic for the Overburden unit as a whole or its subdivisions indicate that, where saturated, the unit generally is a productive aquifer. However, some subdivisions of the Overburden unit in the YRBAS function as confining units because of the small values of hydraulic conductivity. Values for the Mabton and Vantage Interbeds indicate that they generally function as semiconfining to confining units, which affects water availability by limiting flow into and out of the overlying/underlying basalt unit. The values for the basalt units vary widely (table 3), indicating the heterogeneous nature of these units. The estimated values show that most of the groundwater supply to wells is from interflow zones and that the basalt flow interiors transmit much less water laterally with flow predominantly vertical through fractures. Small values derived for anticlines and other low-permeability flow barriers indicate their ability to compartmentalize the flow system and, thus, limit groundwater availability in some areas. These features are major controls on the flow system, especially in the Yakima Fold Belt (fig. 1), and have been documented on the Columbia Plateau in early studies (Newcomb, 1969). Faults in low-lying areas can impede lateral flow and increase vertical flow.

Vertical hydraulic conductivity is a measure of the ability of a geologic material to transmit water vertically (the impedance to downward or upward flow). It is a major control on the movement of water in the flow system by affecting vertical hydraulic gradients, and, therefore, flow rates into, within, and out of units—the water budget for the aquifer system. The range in values for the Overburden unit (table 3) shows that, in some locations, water will readily be transmitted vertically and, in other locations, it can impede vertical flow. Where flow is impeded, the amount of water that can move into the deep basalt part of the flow system is limited, which, in turn, limits groundwater availability. Vertical hydraulic conductivity values for the Mabton and Vantage Interbeds indicate that the interbeds not only limit lateral movement of water but also vertical movement, adding to the confining nature of these units. Values for the basalt units show that lateral flow dominates over vertical flow, and that flow interiors impede flow. Even so, for the CPRAS as a whole, the net vertical movement would be large because the quantity moving vertically equals the area, which is very large, multiplied by the vertical hydraulic conductivity and the vertical gradient. Locally, vertical hydraulic conductivity can be large, as shown by the rapid and large water-level rises in the Wanapum unit in response to recharge from irrigation supplied by the CBP.

The storage coefficient is a measure of the ability of a unit to store and release water, and is defined as the volume of water that a unit will absorb or release from storage per unit surface area per unit change in head. The storage properties of the CPRAS materials are important for understanding groundwater availability and, ultimately, sustainability. The water table to confined aquifers in the unconsolidated to consolidated materials (the Overburden) has values that range from 0.01 to 0.000025 per foot (ft^{-1}) (Ely and others, 2011; Ely and others, 2014). Where the water table is present in the basalt units, values averaged 0.025 ft^{-1}. Otherwise, values ranged from about 0.0007 to 0.000003 ft^{-1}. Ely and others (2011) also estimated that the flow interiors of basalt flows had values that were one order of magnitude less than the interflow zones.

Table 3. Hydraulic characteristics of hydrogeologic units, derived from regional groundwater-flow models, of the Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

[**Median:** Only median values for vertical hydraulic conductivity were reported for the CP-RASA model. **Abbreviations:** CPRAS, Columbia Plateau Regional Aquifer System (Ely and Burns, 2014); YRBAS, Yakima River Basin Aquifer System Analysis (Ely and others, 2011); CP-RASA, Columbia Plateau Regional Aquifer System Analysis study (Hansen and others, 1994); –, not applicable]

Model	YRBAS				CPRAS			CP-RASA		
Hydrogeologic unit	Lateral hydraulic conductivity, in feet per day									
	Minimum	Mean	Maximum	Constant	Minimum	Mean	Maximum	Minimum	Mean	Maximum
Overburden[1]	1.46	203	1,672	–	3.05	96.0	200	0.04	98.00	1,100
Saddle Mountains, interflow zones	35.8	119	261	–	–	–	–	–	–	–
Saddle Mountains, flow interiors	0.0005	0.0017	0.0036	–	–	–	–	–	–	–
Saddle Mountains, effective value[2]	–	10	–	–	1.07	14.4	27.9	0.20	1.30	2.60
Mabton Interbed	0.36	0.88	1.57	–	1.07	14.1	27.9	–	–	–
Wanapum, interflow zones	25.7	130	278	–	–	–	–	–	–	–
Wanapum, flow interiors	0.00007	0.00035	0.00075	–	–	–	–	–	–	–
Wanapum, effective value[2]	–	13	–	–	1.07	13.0	27.9	0.10	3.20	8.00
Vantage Interbed	–	–	–	9.31	1.07	12.6	27.9	–	–	–
Grande Ronde, interflow zones	4.28	23.0	91.0	–	–	–	–	–	–	–
Grande Ronde, flow interiors	0.00008	0.0004	0.0015	–	–	–	–	–	–	–
Grande Ronde, effective value[2]	–	2.3	–	–	1.07	10.5	27.9	0.10	2.30	9.00
Hydrogeologic unit	Vertical hydraulic conductivity, in feet per day									
	Minimum	Mean	Maximum	Constant	Minimum	Mean	Maximum	Minimum	Median	Maximum
Overburden[1]	0.001	1.81	15.1	–	0.031	0.96	2.0	1.40E-07	2.00	1,400
Saddle Mountains, interflow zones	0.008	0.03	0.06	–	–	–	–	–	–	–
Saddle Mountains, flow interiors	0.003	0.009	0.02	–	–	–	–	–	–	–
Saddle Mountains, effective value[2]	–	0.01	–	–	0.0001	0.003	0.005	–	–	–
Mabton Interbed	0.002	0.006	0.01	–	0.0001	0.0001	0.0001	–	–	–
Wanapum, interflow zones	0.05	0.25	0.5	–	–	–	–	–	–	–
Wanapum, flow interiors	0.00004	0.0002	0.0005	–	–	–	–	–	–	–
Wanapum, effective value[2]	–	0.025	–	–	0.0001	0.001	0.005	–	–	–
Vantage Interbed	–	–	–	0.02	0.0001	0.0001	0.0001	–	–	–
Grande Ronde, interflow zones	0.002	0.01	0.04	–	–	–	–	–	–	–
Grande Ronde, flow interiors	0.0002	0.001	0.005	–	–	–	–	–	–	–
Grande Ronde, effective value[2]	–	0.002	–	–	0.0001	0.0002	0.005	–	–	–
All basalt units[3]	–	–	–	–				0.00005	0.0013	7.17

[1]Overburden unit modeled as one unit with spatially varying values in the CPRAS and CP-RASA models; unit was subdivided into 20 subunits in the YRBAS model.

[2]Effective values based on thickness weighted values for interflow zones and flow interiors.

[3]Range in the vertical hydraulic conductivity was reported for all the basalt units and not individual units for the CP-RASA model.

Hydrologic Toolbox

New tools were developed as part of the study and integrated into a hydrologic toolbox. These tools allow for viewing the hydrogeologic setting of the CPRAS, and include the development of methods for estimating evapotranspiration (ET), surface-water use, groundwater pumpage, and recharge from irrigation practices. The methods are applicable over large regional areas, and are briefly described in this section and summarized in Kahle and others (2011).

A web interface tool was developed that allows users to explore the hydrogeologic framework of the CPRAS in 3D by one of two methods: (1) Drawing diagrams of "well logs" at any site, or (2) building complete hydrogeologic cross sections between multiple sites (Burns and others, 2011). Senay and others (2007) developed a new Simplified Surface Energy Balance (SSEB) method that uses satellite data for land-surface temperature to estimate monthly ET. The spatial distribution of landscape ET can be used as an indicator of vegetation growth in terms of vegetative biomass accumulation, which is directly associated with water use by plants. Furthermore, ET can be used to estimate the spatial-temporal dynamics of the rates and total amounts of withdrawal from aquifer systems in irrigated areas and, in conjunction with water-balance models, can be used to estimate groundwater recharge from both groundwater and surface-water irrigation. SSEB uses elevation-corrected land-surface temperature data from the Moderate Resolution Spectroradiometer (MODIS) sensor to identify “cold pixels” in heavily irrigated areas and “hot pixels” in dry barren or fallow areas. The ratio of the temperature of each pixel to the cold pixel temperature is used to compute ET as a fraction of reference ET. Monthly reference ET is computed using weather data from the Global Data Assimilation System (GDAS), as described in Senay and others (2008). Senay and others (2009) applied the SSEB method to the study area for 1989–2007 (Kahle and others, 2011). This method is described in detail in Senay and others (2008) and Senay and others (2007, 2008).

A spatially distributed soil-water balance model (SOWAT) that uses simple relations among climatic, soils, land-cover, and irrigation data, was developed to compute monthly irrigation requirements and surplus moisture available for recharge during the irrigation season (Kahle and others, 2011). Estimates of groundwater pumpage and surface-water diversions for irrigation and recharge associated with irrigation were then calculated using SOWAT. The SOWAT model includes the concepts of climatic water supply (precipitation) and climatic water demand (ET), seasonality in climatic water supply and demand, soil moisture storage, and irrigation practices. The primary purpose of the model is to estimate (1) the irrigation demand when climatic water demand exceeds climatic water supply and available soil moisture; and (2) the surplus moisture available for deep percolation below the root zone, which is an estimate of recharge to the groundwater system. SOWAT estimates recharge for irrigated lands only and that irrigation use is assumed to be the amount of water needed for plants and soil moisture; for surface water, it is the irrigation use, not the diversion quantity. The model is written in Python and reads all spatial data directly from raster files (L.L. Orzol, U.S. Geological Survey, written commun., April 2010). Data required are land cover and soil properties, spatial-temporal dynamics of climate, and irrigation practices.

Although not strictly part of the toolbox, the groundwater-flow model constructed as part of this study is an important hydrologic tool.

Groundwater-Flow Model

Groundwater flow for part of the CPRAS was simulated using a 3D finite-difference numerical model (USGS MODFLOW-NWT; Niswonger and others, 2011). The model was constructed, calibrated, and documented as part of this study (Ely and others, 2014). Summarized here are the (1) attributes of the model, (2) model calibration process and results, and (3) model scenarios simulated. Results of model simulations for the scenarios are integrated in several subsequent sections of this report. In comparison to the CP-RASA model, the CPRAS model has a finer vertical spatial discretization, uses a more detailed depiction of the subsurface hydrogeology, and, unlike the steady-state CP-RASA model, it simulates annual water budgets on an annual time step for 1920 (approximate representation of predevelopment conditions) through 2007.

Model Attributes

The CPRAS model includes about 32,796 mi^2 (74 percent) of the 44,070 mi^2 study area. A large range in land-surface altitudes is included in the model (fig. 9). The boundaries of the CPRAS model are nearly identical to the boundaries of the CP-RASA model, which included 32,688 mi^2 (less than one-half of one percent difference in area), thus allowing for a consistent assessment of the response of the system to stresses over time. The boundaries differ slightly because a more detailed representation of no-flow boundaries of the system was completed during

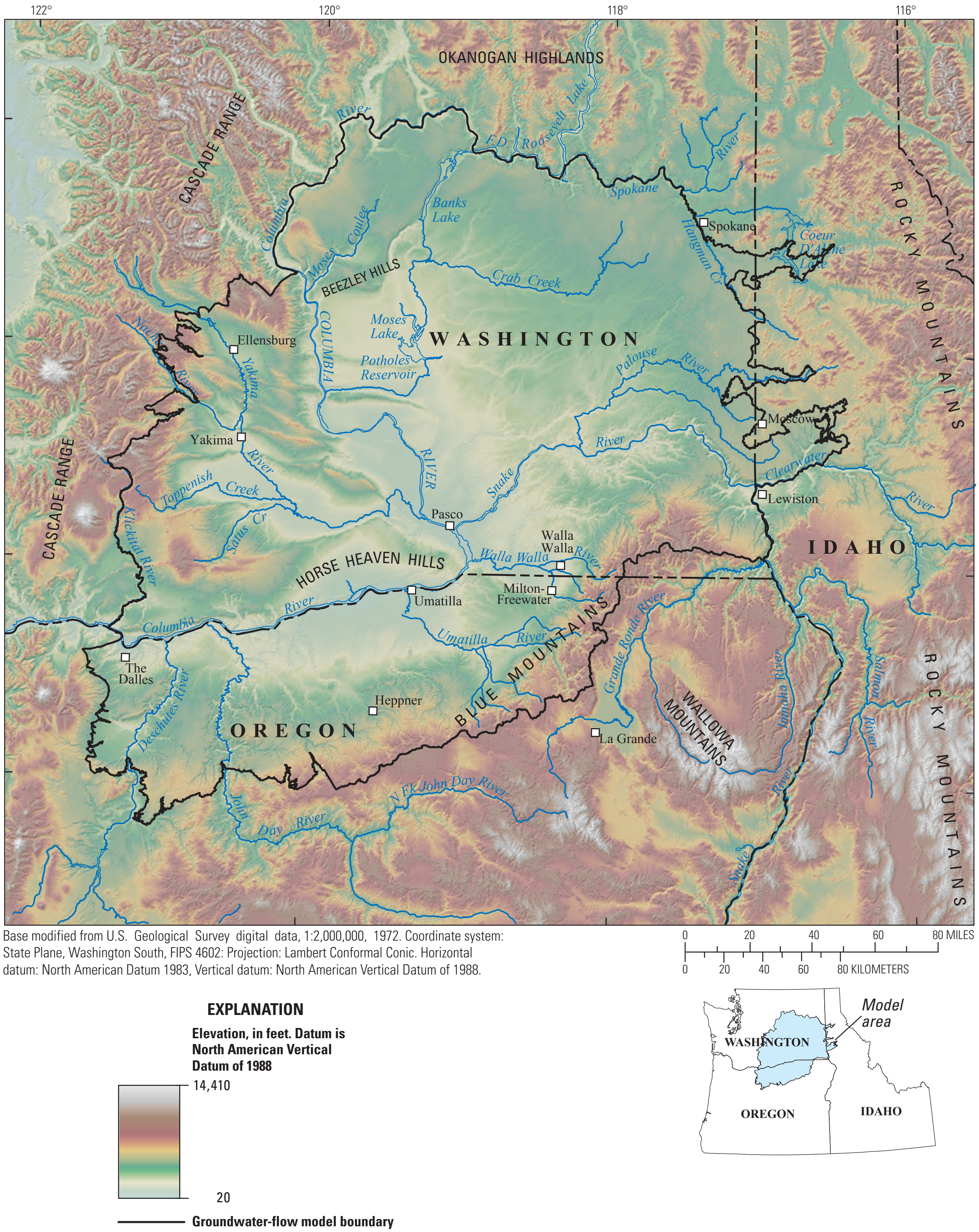


Figure 9. Lateral boundary of the groundwater-flow model, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

this study. The model domain was represented by a grid of 126 rows and 131 columns made up of 3-km (9,842.5-ft) cells. Each of the hydrogeologic units was subdivided (table 4), resulting in a total of 100 model layers generally 100 ft thick. The no-flow lower model boundary at the bottom of model layer 100 simulates the top of the Older Bedrock unit. All lateral boundaries were designated as no-flow boundaries based on the low permeability of the Older Bedrock unit and major mountain divides.

Internal boundary conditions (fig. 10) include flow to and from the major rivers and groundwater discharge to small upland streams, groundwater-controlled surface-water features such as lake complexes, and drains in agricultural areas. Although not strictly a boundary, flow barriers were assigned along the major rivers to prevent flow across the rivers from model layers that were above the river. Major geologic structures (particularly anticlines), which are an important control on the flow system, were simulated with flow barriers comprising 38,308 model cells (fig. 11).

Model Fit

The model was calibrated to conditions representing the flow system during two periods—estimates of predevelopment conditions (steady state approximated for climatic conditions in 1920) and existing conditions (1920–2007). The initial steady-state model was calibrated primarily by using automated parameter estimation techniques (Doherty, 2010; Doherty and Hunt, 2010). The steady-state model included 10,525 observed groundwater levels. The transient model was calibrated manually using 46,460 water-level measurements. Base flow at selected sites also was analyzed during the transient calibration. The relation between measured and simulated hydraulic heads (water levels) (fig. 12) indicates that the model captures the large variation and range (more than 4,000 ft) in water levels throughout the system. An analysis of the differences between measured and simulated water levels (fig. 13) indicates that the average difference was

Table 4. Subdivision of hydrogeologic units by model layers, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

[From Ely and Burns (2014). ft, foot]

Geologic model units (Burns and others, 2011)	Groundwater-flow model layers	Description
Overburden	1–45	Approximately 100-ft layers between the uppermost rock unit and land surface.
Saddle Mountains	11–18	Approximately 100-ft layers between the geologic model top of Mabton Interbed and the geologic model top of Saddle Mountains Basalt. Cells are constructed from the bottom up, with the lowest layer being the most laterally extensive.
Mabton Interbed	19–35	Equally spaced layers between the geologic model bottom of Saddle Mountains Basalt and the next unit rock unit below.
Wanapum Basalt	20–34	Approximately 100-ft layers between the geologic model top of Vantage Interbed and the geologic model top of Wanapum Basalt. Cells are constructed from the bottom up, with the lowest layer being the most laterally extensive.
Vantage Interbed	35	Equally spaced layers between the geologic model bottom of Wanapum Basalt and the next rock unit below.
Grande Ronde Basalt	36–100	Approximately 100-ft layers between the geologic model top of Older Bedrock and the geologic model top of Grande Ronde Basalt. Cells were constructed from the top down, using a trend surface for top of Grande Ronde Basalt as a guide surface, allowing the representation of river and stream incision exceeding model cell thickness.
Older Bedrock	No flow	

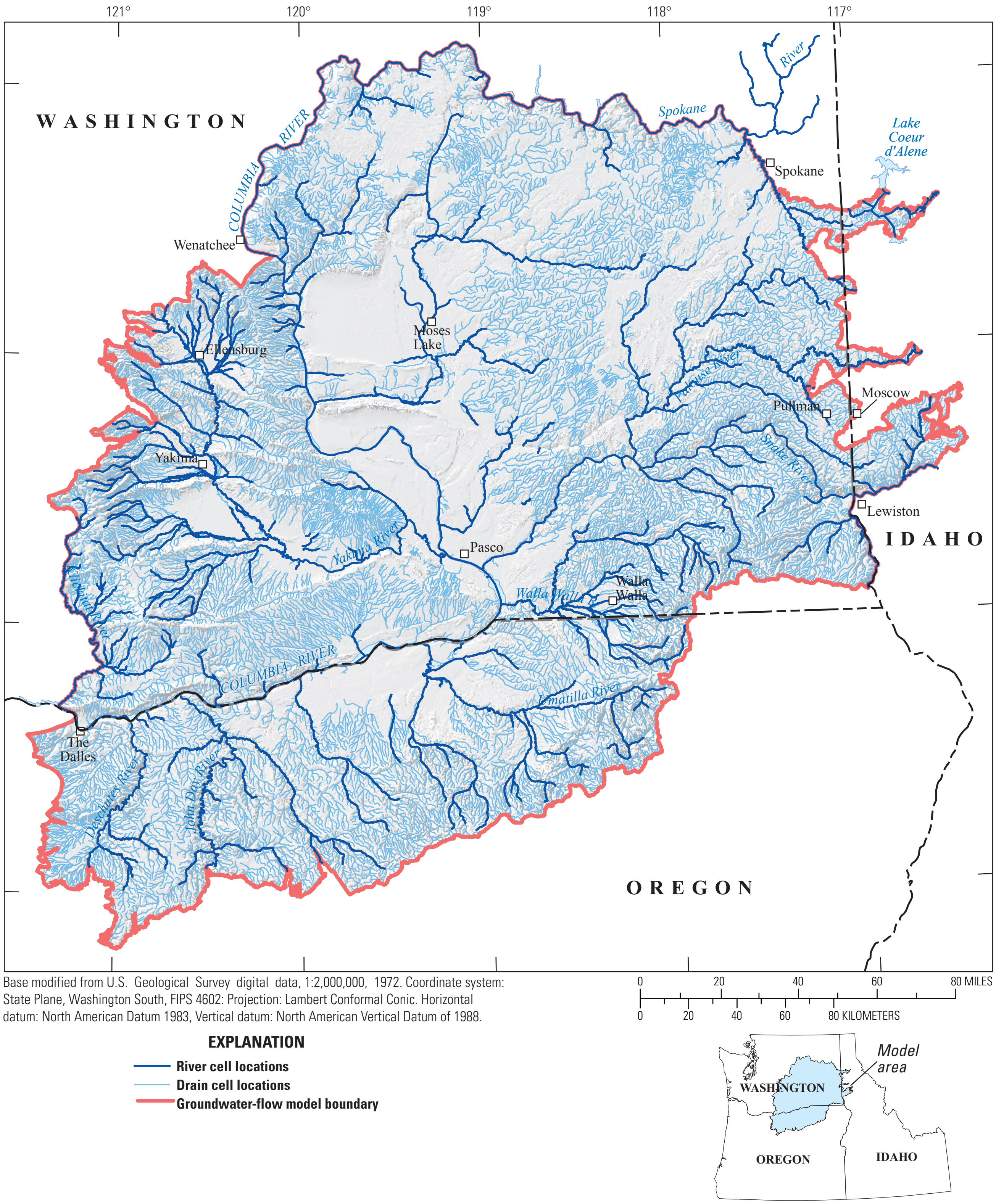


Figure 10. Locations of the river and drain cells, and the groundwater-flow model boundary, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (from Ely and others, 2014).

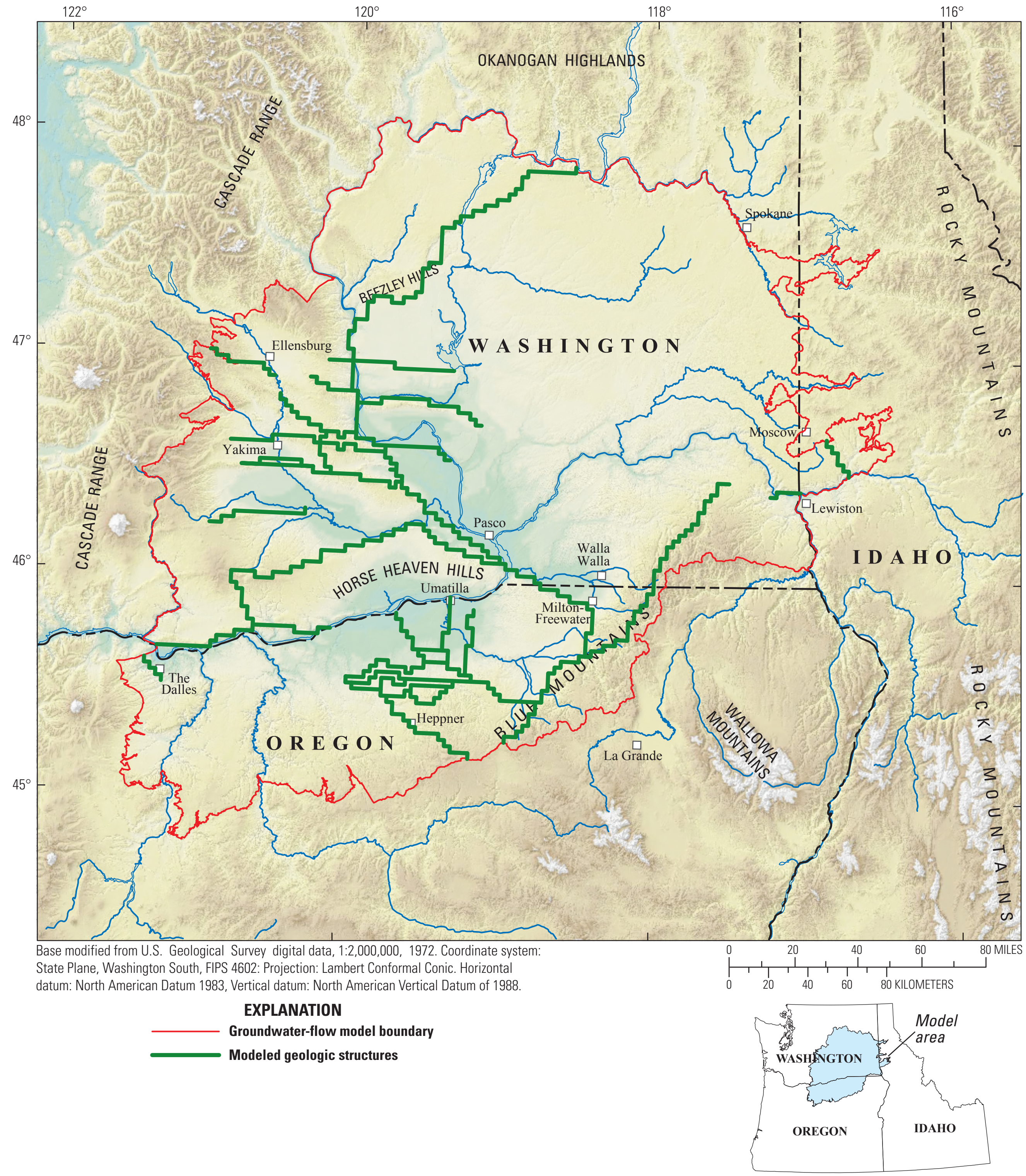


Figure 11. Locations of model geologic structures simulated with flow barriers, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (modified from Ely and others, 2014).

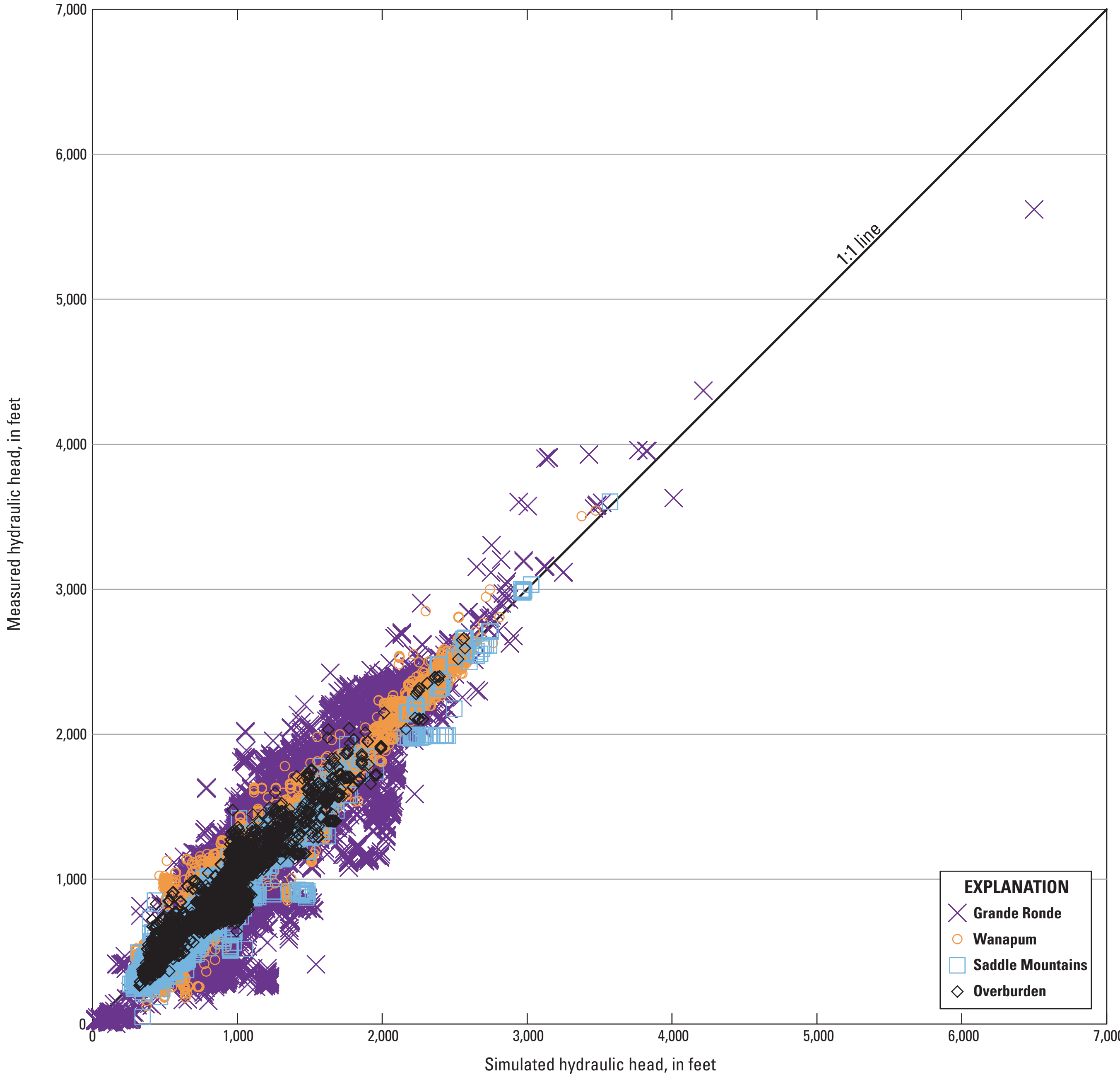


Figure 12. Relation between measured and simulated hydraulic heads (water levels), Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (from Ely and others, 2014).

small. Simulated levels generally were equally distributed between over- and under-prediction. The spatial distribution of the differences indicated some areas with a bias toward over- or under-simulation. The measurements compared to simulated values generally fall along a straight line with a slope of nearly 1. As shown in figure 13, the magnitude of the differences increases with the deeper units; part of these differences is due to the large variations in water levels in the uplands over the spatial dimension of the model cells. For example, water levels may vary by more than 1,000 ft across a cell in the steep uplands, and the model calculates an average value for a cell.

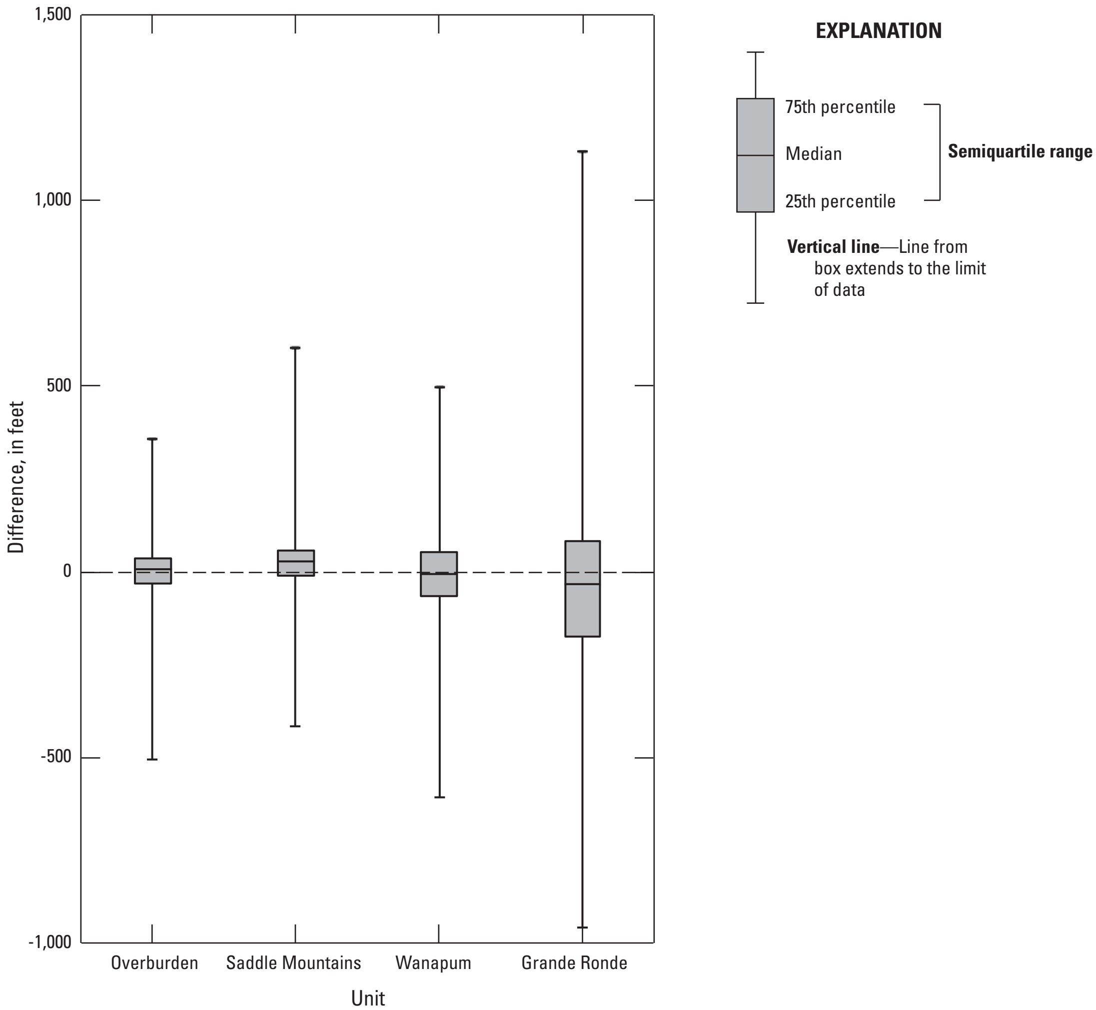


Figure 13. Difference between measured and simulated water levels, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (after Ely and others, 2014).

Model Simulations

Four scenarios were simulated with the model. The first scenario simulated predevelopment conditions (steady state for 1920) using estimates of recharge without the influence of human development, and without groundwater pumpage. The second scenario simulated the period from 1920 to 2007 using an annual time step. The water budget and groundwater-level differences between the predevelopment and 1985–2007 (existing conditions) simulations were used to represent the best estimate of the cumulative effects of human development on the CPRAS. The third scenario simulated annual values from 2008 through 2050, assuming that the pumpage in 2007 continued through 2050, but used average recharge from 2000 to 2007 in order to best represent the potential future recharge that accounted for the most current estimates of recharge with their attendant large interannual variability. Thus, this simulation represents a long-term equilibrium condition under 2007 management practices with 2007 average recharge. The fourth scenario modified the equilibrium conditions (third) scenario to account for potential increased pumpage (13 percent) under projected temperature increases with climate change.

Predevelopment Water Budget

An estimate of the predevelopment water budget is needed to understand the changes in the hydrologic system owing to human activities and, thus, to assess water availability in general and groundwater availability in particular. Predevelopment conditions represent the hydrologic system before appreciable land-use changes, especially agriculture. The predevelopment hydrologic system for the complete study area has six interrelated water-budget components that describe the landscape hydrologic budget. These components are:

1. Precipitation,
2. Snowpack,
3. Surface water,
4. ET,
5. Recharge, and
6. Groundwater.

Lack of information precludes such estimates for snowpack; therefore, snowpack for an average year (2006) is used as a surrogate for comparison with the other components. The magnitude and spatial and temporal variability of the six water-budget components govern the flux and storage of water and affect its availability throughout the study area. Except for snowpack and groundwater storage, the predevelopment water-budget components estimated in this study are for climatic conditions during 1895–2007 and 1985–2007, assuming that the climate is the same for areas with native vegetation as for areas of human activities, such as agricultural lands and cities. The 1895–2007 results highlight the close relation between long-term conditions and the 1985–2007 period. For both periods, the predevelopment water budget represents climatic conditions during those periods but without human influences and allows for a comparison with human effects on the budget. The predevelopment water-budget components for the CPRAS (table 5) are generalized estimates because of the lack of information for the predevelopment period. A detailed accounting of the water-budget components for existing (developed) conditions (1985–2007, the water-budget accounting period used for much of this study) is presented in the section, “Existing-Conditions Water Budget.”

Precipitation

Precipitation is a major component of the water budget (table 5); ultimately, all water in the study area is derived from precipitation, either as rainfall or snowmelt. As noted in the section, “Climatic Setting,” and figure 2, the average annual precipitation in the study area during 1895–2007 was about 17 in. or 55,000 ft^3/s (about 40 MAF). During 1985–2007, average annual precipitation was about 17.2 in. or 55,800 ft^3/s (about 40 MAF). In recent decades, the water-year (October 1 through September 30) precipitation ranged from 12.3 in. (in 2001) to 24.4 in. (in 1997), indicating the large interannual variability that can potentially translate to a large effect on water availability. Precipitation in the study area also shows extensive spatial variability, as indicated in figure 2. For example, during the drought of 2005, precipitation ranged from 3.5 in/yr near Richland, Washington, to 89 in/yr in the Cascade Range in the northwestern part of the study area.

Snowpack

Water that is stored as snow is considered the important “natural” storage reservoir for water availability, in contrast to water stored in reservoirs formed by dams. The snowpack generally accumulates during the late autumn through early spring, and melts during late winter to early summer. The dates for snow accumulation and snowmelt vary spatially and by type of climatic year. The larger streams that traverse the study area (such as the Columbia, Snake, Clearwater, Salmon, Spokane, John Day, Deschutes, and Yakima Rivers) emanate from outside the study area and are fed mostly by

Table 5. Generalized average annual water-budget components for predevelopment and existing conditions, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, for selected years, 1895–2007.

[All values in millions of acre-feet; values rounded; Snowpack is April 1 snowpack for average water year; Recharge is water leaving the roots zone. Streamflow is discharge leaving the study area as measured by the Columbia River at The Dalles. –, not available]

	Predevelopment conditions averaging period			Prior to human activities	Existing conditions averaging period		After human activities
	1895–2007	1985–2007	2006		1985–2007	2006	
Precipitation	40	40			40		
Snowpack[1]	–	–	2		–	2	
Streamflow[2]	144	137			125		
Evapotranspiration	22	24			28		
Recharge	11	11			14		
Water use	0	0			6		
Groundwater storage[3]							
Overburden unit				84			94
Basalt units				800			800

[1]Snowpack is shown for an average representative year; spatially distributed values are not available for full period.

[2]Streamflow is represented by the discharge for the Columbia River at The Dalles, which accounts for most of the streamflow leaving the study area.

[3]Groundwater storage for predevelopment conditions is approximated based on the total volume of the Overburden unit, and for the basalt units the values are estimated based on the upper 500 feet of saturation. Values provide information on the relative magnitude of this "storage reservoir" compared to the other water-budget components.

snowmelt. These streams provide water for multiple uses in the study area, and those uses generally have senior rights to groundwater uses. The snowpack throughout the Columbia River Basin (not just the study area), therefore, is an important source and store of water, especially because most of the study area receives little precipitation during the summer.

The spatial distribution of the snow water equivalent (SWE, the amount of water in the snowpack) is for April 1 (National Operational Hydrologic Remote Sensing Center, 2004), which generally is considered the date of near maximum snow accumulation, and is the primary date for making the important water-supply forecasts for the runoff season. April 1 typically is the start date when most surface-water and groundwater irrigators can use irrigation water based on their water rights. In an average water year such as 2006, the April 1 SWE in the study area was only about 0.9 in. (2 MAF, about 5 percent of the average precipitation during 1985–2007; table 5), and spatially ranged from 0.04 to 52.4 in. The 2006 SWE averaged 11 in. for the 9 percent of the study area that was covered in snow, primarily the Blue Mountains, indicating that the snowpack in the study area mainly feeds streams emanating from the Blue Mountains. Most other streams in the study area are supported by snowpack from outside the study area, and the quantity of streamflow traversing the study area is orders of magnitude greater than the SWE stored within it. For example, the annual average discharge in water year 2006 for the Yakima River at Horlick (where the Yakima River enters the study area) was about 26 in. (Bureau of Reclamation, 2012).

The large interannual variability in the quantity and spatial distribution of SWE in the study area is shown in the Blue Mountains at the Touchet Snow Telemetry (SNOTEL) site at an altitude of 5,530 ft (National Resources Conservation Service, 2012) (fig. 14*A*). The daily SWE for the wettest (large snow accumulation) and driest (small snow accumulation) years in comparison to the average year shows the inherent large interannual variability, from less than 10 in. in 2005 to more than 60 in. in 1997 (fig. 14*B*). In turn, the amount of streamflow generated, water availability, and groundwater recharge is directly related to the SWE and varies greatly between wet and dry years, as shown by the annual average discharge measured at USGS streamgages at three streams that drain the Blue Mountains:

Stream	Discharge, in cubic feet per second	
	Water year 1997	Water year 2005
Walla Walla River near Touchet	1,062	283
Tucannon River near Starbuck	300	84
Mill Creek near Walla Walla	180	63

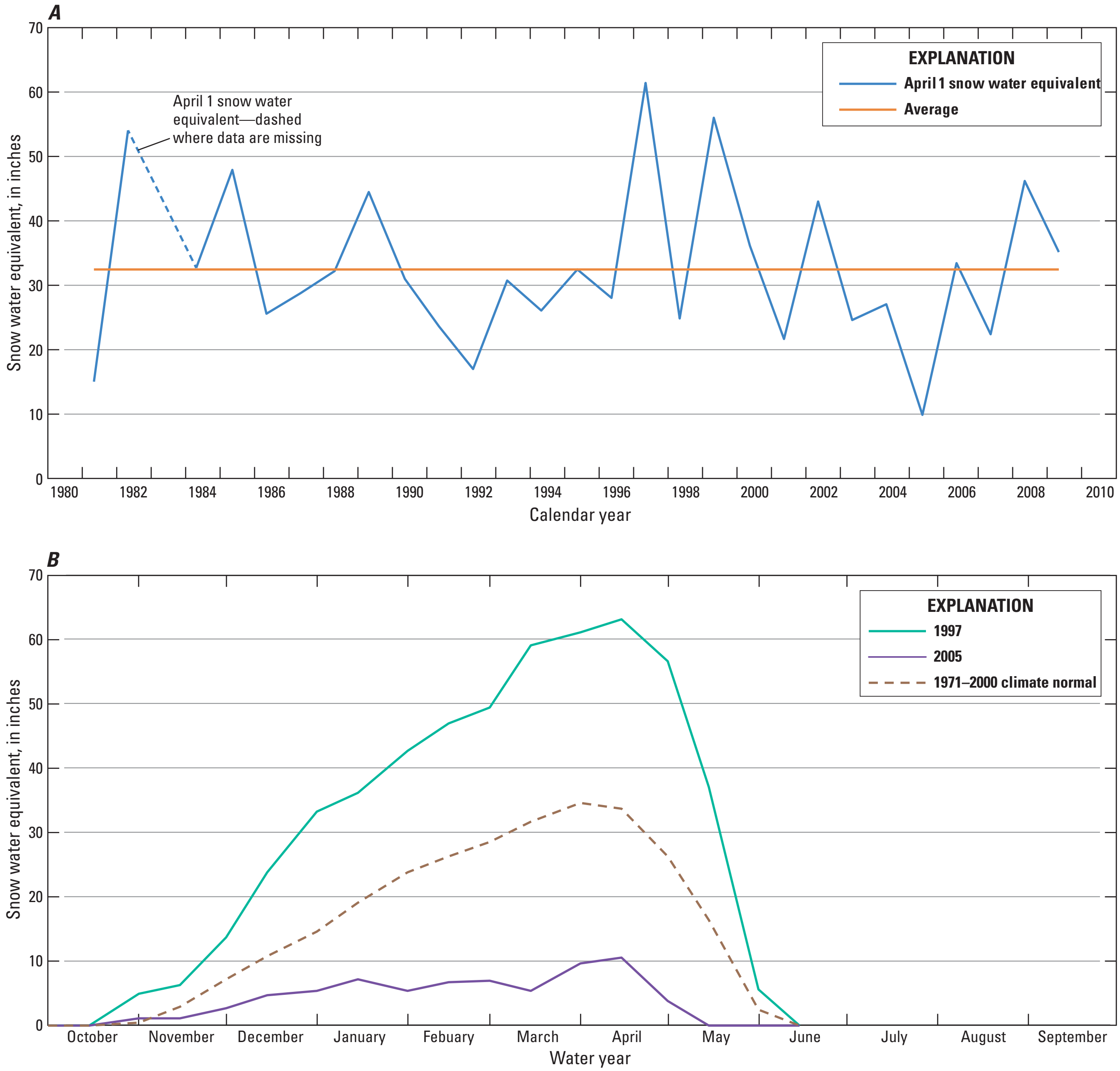


Figure 14. Snow water equivalent for (*A*) April 1 values for 1981–2009, and (*B*) daily values for a wet water year (1997), a dry water year (2005), and the 30-year average (1971–2000), Touchet Snow Telemetry (SNOTEL) site, Blue Mountains, Washington.

Surface Water

The study area contains an extensive system of rivers, creeks, and lakes (figs. 1 and 10), almost all of which are fed by snowmelt. Many of the streams support some species or stock of salmonids, including ESA-listed species. Streamflow magnitude and its interannual variability have a direct effect on groundwater availability and use. More than 7,000 ft^3/s are diverted annually for irrigation in the study area, and groundwater withdrawals can affect these more senior diversions. A brief overview of surface-water resources is provided in this section because of its importance in understanding the regional hydrologic budget; a more detailed assessment was published for the CP-RASA (Nelson, 1991). The emphasis of this section is on providing readers with an overview of the quantities of surface water entering, passing through, and leaving the study area, and the relation of these quantities to the spatial and temporal variations in climate across the area. The surface-water information is presented with respect to water-year values because they are the commonly used and referenced values. For the streams in the study area, annual differences between water year and calendar year values typically are less than 3 percent.

Streamflow generated in the study originates from three areas. The first area is the Blue Mountains, and the mean annual discharge from streams emanating from this area is about 1.24 MAF (1,715 ft^3/s).These streams discharge to both the Snake and the Columbia Rivers. Additionally, two streams (the Grande Ronde and Imnaha Rivers) originate from outside the area in the Wallowa Mountains and from inside the study area in the Blue Mountains. These two streams provide about 0.74 MAF (1,023 ft^3/s) to the Snake River. The second area is downstream of The Dalles, and three rivers contribute a mean annual discharge of 2.6 MAF (3,650 ft^3/s), but, excluding the Klickitat River, most of that discharge originates from outside the study area. The third area where streamflow is generated in the study is the Rocky Mountains in the eastern part of the study area. The Clearwater River is the largest stream, with a mean annual flow of about 10.8 MAF (14,862 ft^3/s), and its discharge to the Snake River is used by Snake River water users. The Salmon River contributes about 30 percent of the flow of the Snake River, but most of its drainage area is outside the study area. Thus, excluding the Clearwater River, about 4.58 MAF of streamflow is partly generated in the study area (about 20 to 30 percent of this quantity is derived from outside the area).

The different climatic regimes in the study area produce a runoff season with different monthly relations (fig. 15*A*, *B*), but indicates that about 70–80 percent of the total tributary runoff to the Columbia and Snake Rivers occurs from January through June. The long-term average percentage of total runoff, accumulated by month, for three of the four largest tributary inflows (Spokane, Salmon, and Yakima Rivers) in the study area and for the Klickitat and John Day Rivers is shown in figure 15*A*. Runoff for these five rivers is representative of different climatic regimes in the study area, with the John Day and Klickitat Rivers representative of the central Blue Mountains and the western extent of the CPRAS, respectively. The average monthly discharge for these rivers (fig. 15*B*) also indicates the variations in streamflow owing to different climatic regimes.

Streamflow entering and leaving the study area can be approximated by the streamflow for the Columbia River at Grand Coulee Dam and at The Dalles, respectively. Streamflow at the USGS Grande Coulee Dam streamgage includes the contribution from the Spokane River (average annual discharge of about 6,600 ft^3/s). Streamflow at The Dalles accounts for all the Columbia River tributary flows in the study area except the contribution from the Hood, Klickitat, and White Salmon Rivers, which have a total average annual discharge of about 3,650 ft^3/s (about 2 percent of the discharge at The Dalles). The Columbia River at The Dalles accounts for about 82 percent of the river's total drainage area of 258,000 mi^2. During 1879–2007, the average annual discharge in the Columbia River at The Dalles, based on water years and calendar years, differed by only 120 ft^3/s. During 1895–2007 and 1985–2007, Columbia River streamflow at The Dalles averaged 186,700 ft^3/s (135 MAF) and 172,700 ft^3/s (125 MAF), respectively. In Washington State, water in the Columbia River in the study area is considered fully allocated during the dry season (July–September), and as of 2011, additional dry-season water (88,000 acre-ft for non-interruptible diversionary uses and 44,500 acre-ft for instream uses) is obtained from increased drawdown from FDR (Washington State Department of Ecology, 2012a). Future 'new' water in quantities greater than the drawdown quantities would need to be derived from new storage facilities (Washington State Department of Ecology, 2012b).

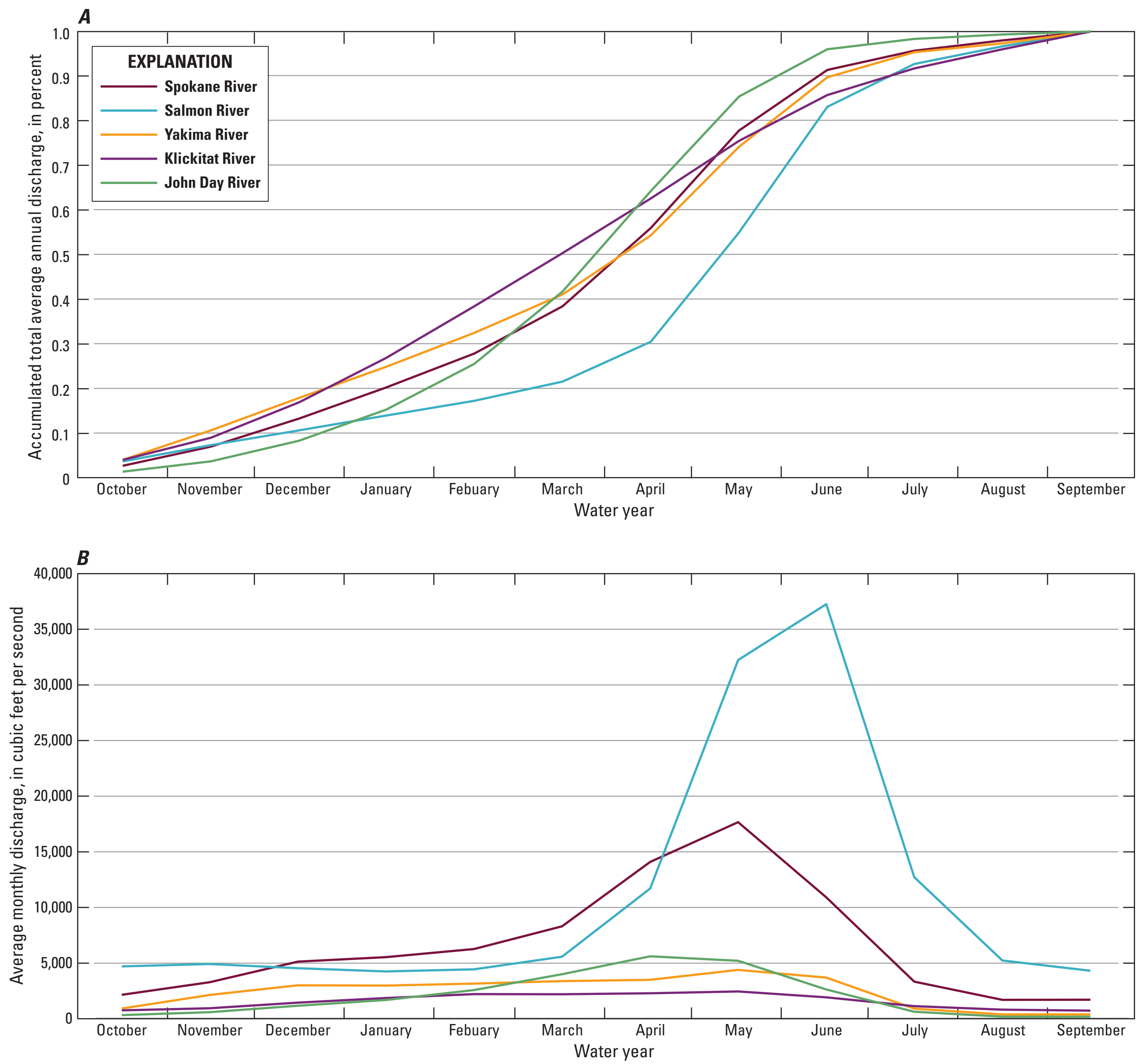


Figure 15. (*A*) Monthly percentage of average annual discharge accumulated over a water year, and (*B*) average monthly discharge for five rivers in different climatic regimes of the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho, period of record 1911–2011. Source: U.S. Geological Survey National Water Information System, accessed September 2, 2012, at http://waterdata.usgs.gov/nwis.

For water years 1914–2002 (the longest period for which data were available for both sites), average annual streamflow at Grand Coulee Dam and The Dalles was 107,000 and 181,000 ft^3/s, respectively. Thus, streamflow at Grand Coulee Dam accounts for about 59 percent of the streamflow at The Dalles. The Snake River accounts for about 29 percent of the streamflow at The Dalles, and the remaining contributions (about 12 percent) are primarily accounted for by the larger tributaries, such as the Yakima River. Streamflow generated in the study area from smaller rivers and creeks contributes little to the total outflow. However, this streamflow is extensively used and relied upon for multiple uses. These percentage contributions to streamflow at The Dalles vary spatially and temporally because in some years, parts of both the study area and the Columbia River Basin may be drier than normal and other parts may be wetter than normal (McDonald and Riggs, 1948). The two largest controls on total streamflow entering the study area and its interannual variability are climatic conditions in the Columbia River drainage area upstream of Grand Coulee Dam and the Snake River drainage area upstream of Clearwater, Idaho. Reservoirs and diversions affect the temporal variability but do not have a large effect on total streamflow.

Much of the measured streamflow at The Dalles represents regulated conditions and water depletions that are primarily due to ET losses (referred to as "streamflow depletions") from irrigated lands and water bodies. Most irrigation water that is not lost to ET returns to the streams as either direct surface-water return flows or groundwater discharge; this discharge contributes to downstream irrigation withdrawals. Simons (1953) estimated these depletions at The Dalles to be about 5 percent of the natural average annual streamflow in 1946, with 70 percent of the depletion occurring in the Snake River Basin (primarily in Idaho outside the study area). Simons also estimated that, in 1946, about 850,000 irrigated acres were in the study area. After 1946, numerous reservoirs were built and surface-water withdrawals increased with a concomitant increase in irrigated croplands. By 2007, an estimated 2 million acres were irrigated in the study area (Kahle and others, 2011). This information suggests that irrigated lands increased by more than two-fold, further suggesting that 2007 streamflow at The Dalles has been depleted from irrigation water use by as much as 10 percent of the natural average annual streamflow. This estimate is similar to the Bonneville Power Administration estimate of about 11 percent depletion at McNary Dam, about 120 mi upstream of The Dalles (Northwest Council, 2013).

Although water-management activities and use of water have changed the streamflow hydrograph, it is useful to compare the monthly average discharge for the Columbia River at The Dalles for different years (fig. 16). The largest measured annual (and monthly) discharge for the Columbia River was in 1894, before major human influences on the river system. There was a distinct runoff season in 1894, with the peak runoff occurring in June. In contrast, in 1926 (the second lowest flow year of record and also a year with minimal human effects on the river system), the hydrograph was much flatter, with a peak runoff in May. The 1926 hydrograph is similar to the 1993 hydrograph (another low-flow year but a year that includes most of the current regulation and water use); however, there are distinct differences with the 1993 hydrograph, which shows the effects of water storage and releases for hydropower generation. Overall, differences between the hydrographs indicate the complex relation between climate and runoff, as further shown by the differences between 1984 (a relatively high-flow year) and 1986 (a median-flow year).

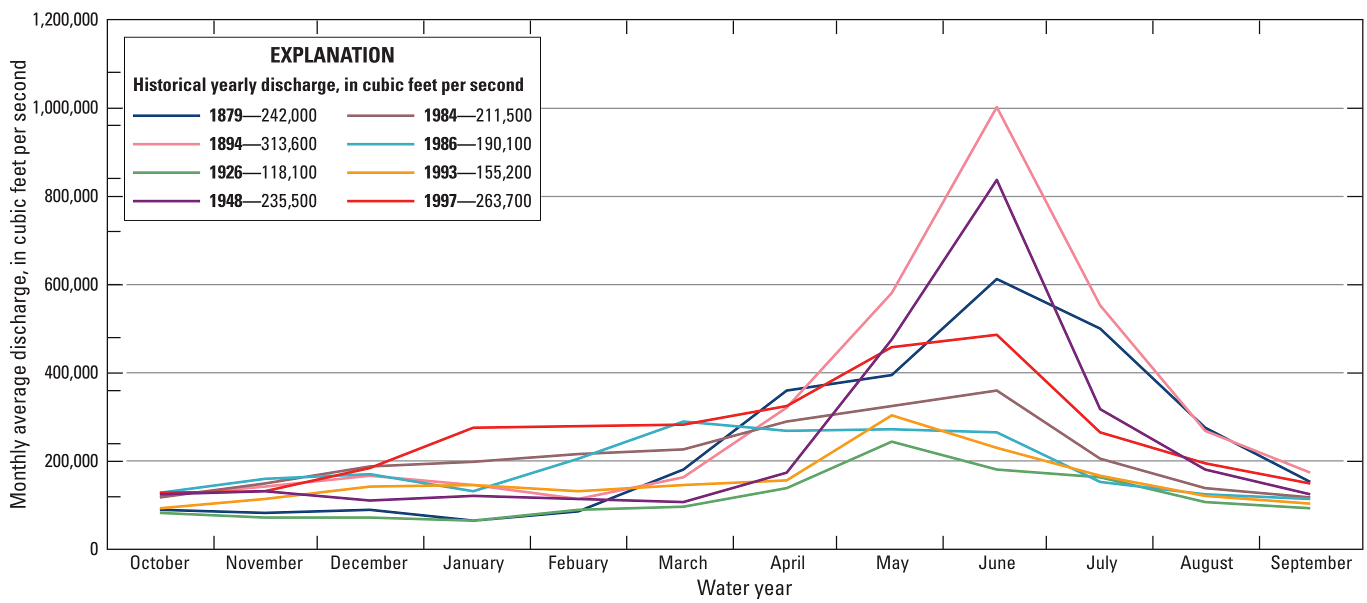


Figure 16. Monthly average discharge for the Columbia River at The Dalles, Washington, for selected years during 1879–1997.

Evapotranspiration

Evapotranspiration is a large but least documented component of the water budget. ET can account for 100 percent of the annual precipitation in the arid parts of the study area and 45–70 percent in the more humid uplands (Bauer and Vaccaro, 1990; Vaccaro and others, 2009). ET was estimated based on several new techniques developed as part of this study that were described previously, including the new SSEB method. Senay and others (2009) applied the SSEB method to the study area during 1989–2007. Kahle and others (2011) used the ET estimates for 1989 to approximate values for 1985–88, resulting in initial estimated values for the period of interest for hydrologic budgeting—1985–2007. For consistency, the ET values are described for this period.

The calculated average annual ET values for areas without human influence were regressed to average annual precipitation for 1985–2007. The regression estimates of ET were used in areas of human influence in conjunction with the SSEB ET estimates in other areas to derive a distribution of ET that was assumed to approximate predevelopment conditions. The resulting ET distribution (fig. 17) shows the large spatial variability of this water-budget component. Average annual ET was about 10.1 in or 33,000 ft^3/s (24 MAF) for the study area (table 5), and ranged from 1.7 to 38.3 in. (fig. 17). As a percentage of precipitation, ET values varied from a low of 10 percent to a high of nearly 100 percent, and averaged 59 percent. Using the regression method, average annual ET was calculated for 1895–2007 at about 9.5 in. or 31,000 ft^3/s (22 MAF) (table 5). The average ET was about 55 percent of the precipitation during that period.

Recharge

A major control on groundwater availability (and streamflow) is the quantity of water entering the aquifer system—groundwater recharge. Importantly, the quantity of recharge influences how the flow system responds to pumpage. Recharge from infiltration of precipitation was estimated using a regression equation on the basis of annual precipitation (Kahle and others, 2011). The regression equation was developed by Bauer and Vaccaro (1990), who estimated groundwater recharge to part of the CPRAS for 1956–77 using a deep-percolation model (DPM; Bauer and Vaccaro, 1987) that computes daily values of recharge and all other water-budget components such as soil moisture. Annual recharge distributions were computed for 1895–2007 and average annual values were calculated for 1895–2007 and 1985–2007 for comparison with the other water-budget components (Kahle and others, 2011).

Estimated predevelopment annual recharge for1895–2007 averaged 4.7 in. or 15,300 ft^3/s (11 MAF), and ranged from nearly 0 to more than 25 in. The recharge for 1985–2007 (fig. 18, table 5) was nearly the same (4.6 in. or 14,900 ft^3/s—11 MAF, about 27 percent of the average annual precipitation), indicating a similar amount of precipitation during the two periods. Recharge (1985–2007) annually ranged from 9.6 to 25.6 MAF. The large spatial variability of estimated recharge represents not only the precipitation distribution but also the ET distribution. The low recharge values throughout much of the central Columbia Plateau (fig. 18) indicate a potential limitation on groundwater availability. Additionally, Bauer and Vaccaro (1990) indicated that the regression-based estimates in drier parts of the study area are less accurate. Drier areas are defined by annual precipitation typically less than 11 in., which includes much of the irrigated areas on the Columbia Plateau. A comparison of figure 18 with the mapped estimates from Bauer and Vaccaro (1990) indicates that, in this study, recharge may be overestimated in these areas by about 5–10 percent.

Aquifer Storage

The aquifer system not only conveys groundwater but also stores water. The storage of water in the system directly affects groundwater availability. Generalized estimates of the water stored in the system provide information on the relative magnitude of this “storage reservoir” compared to the other water-budget components. The quantities described in this section represent generalized estimates of storage in the Overburden unit and water stored in the upper, saturated 500 ft of the basalt units. These estimates do not represent extractable water because such extraction would not be economically viable or sustainable, and likely would be ecologically harmful. Additionally, the volume of groundwater in storage is not by itself meaningful in analyses of water availability (Alley, 2007); it is presented here for context.

A simplified method was used to estimate the quantity of water stored in the system. For the Overburden unit, the estimate is for all water stored in its deposits, and the total volume of the deposits was multiplied by 0.1, a conservative estimate of the effective porosity that accounts for variations in overburden lithology and depth to water. About 84 MAF of water in storage was calculated using these assumptions. The storage in the CPRAS basalt aquifers was estimated based on the storage depth of 500 ft, and an effective porosity of 0.04 (Hansen and others, 1994; Vaccaro, 1999). The calculated storage volume was 800 MAF. Throughout most of the study area, this shallow storage wedge of freshwater allows seasonal recharge to add storage to the water table and, thus, to supply water to streams. These two water storage estimates only provide a basis for comparison to the other water-budget components and are not related to the conveyance of groundwater by the CPRAS over the long term, which is on the order of billions of acre-feet.

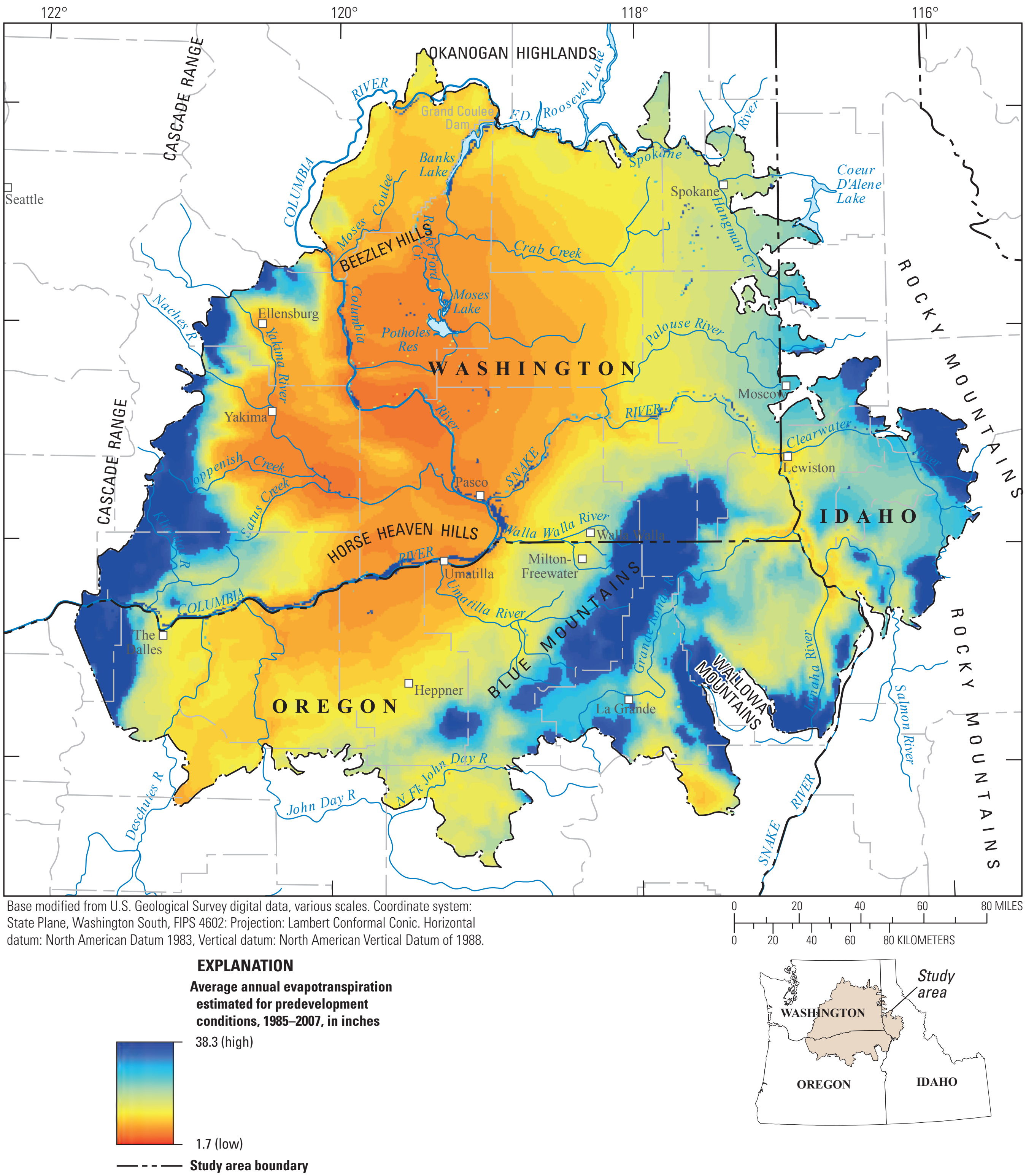


Figure 17. Distribution of average annual evapotranspiration estimated for predevelopment conditions in the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho, 1985–2007.

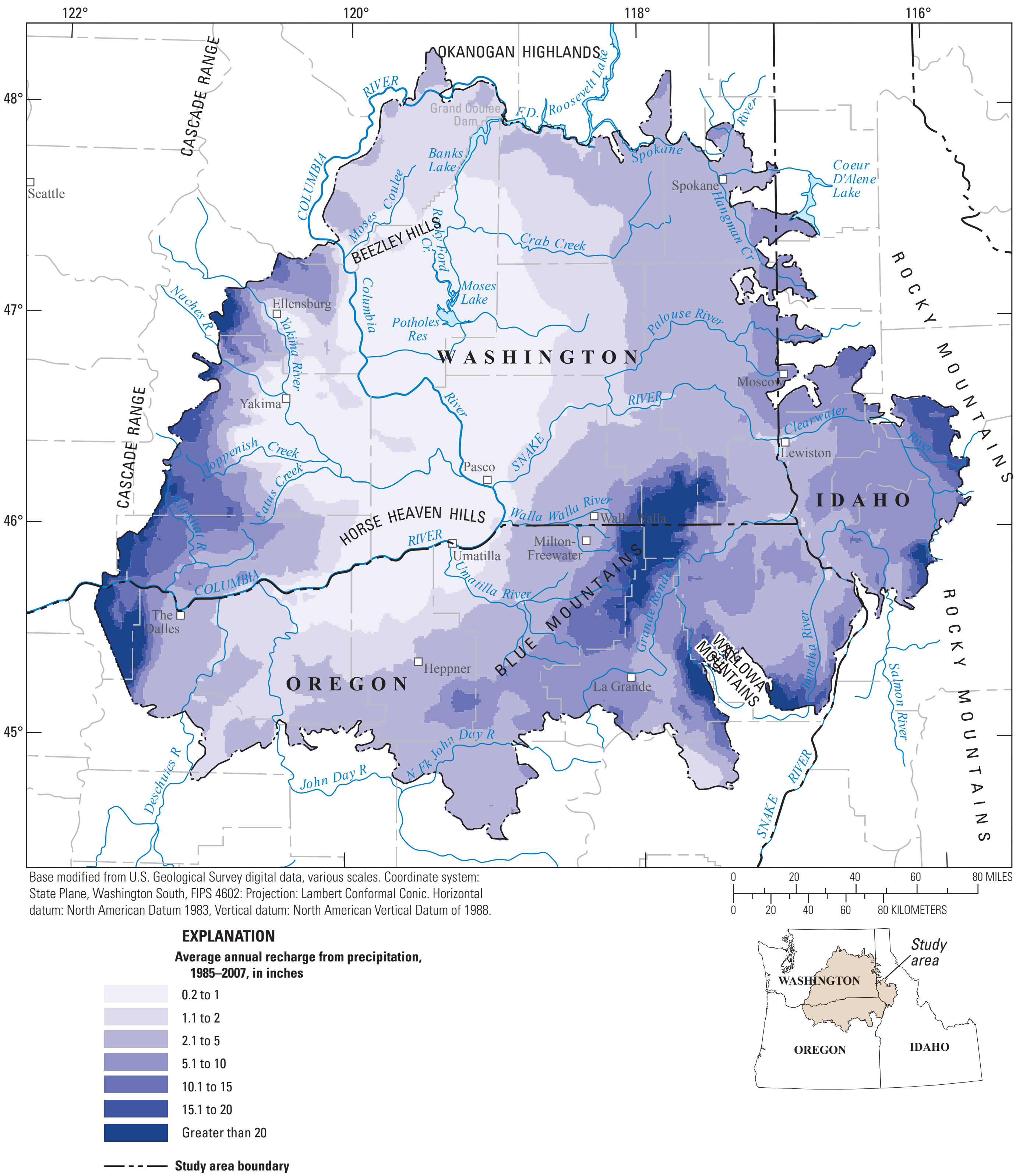


Figure 18. Distribution of average annual recharge from infiltration of precipitation in the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho, 1985–2007.

Existing-Conditions Water Budget

The existing-conditions hydrologic system has the same six interrelated water-budget components (precipitation, snowpack, surface water, evapotranspiration, recharge, and groundwater) as the predevelopment budget, but includes a new component—water use. The components govern the flux and storage of water and affect its availability throughout the study area. Except for precipitation and snowpack, which are assumed to be the same for existing conditions, these components are described for 1985–2007 for the complete CPRAS study area and the model domain. For the groundwater component, generalized values for aquifer storage are described for the study area, and for the model domain, a detailed water budget (including its temporal variability) of the aquifer system is presented on the basis of model results.

Irrigation is the largest use of water in the CPRAS. The major pumping centers occur where groundwater is the primary source of irrigation, and the areas of greatest recharge from irrigation return flow occur where surface water is the primary source of irrigation. The pumping and irrigation recharge budget components have implications for groundwater availability, both regionally and locally, because the use of water for irrigation has affected the system by increasing ET and recharge, and by decreasing storage owing to groundwater-level declines in pumping centers. Increased recharge, in turn, has affected (increased) aquifer storage, as has groundwater pumpage (decreased storage). The increase in aquifer storage has locally increased streamflow, whereas the decrease in storage has locally decreased streamflow—for example, upper Crab Creek in north-central Washington. Kahle and others (2011) showed that the monthly soil-water balance in irrigated lands is dominated by the climatic water demand of ET and the application of irrigation water to satisfy crop water requirements. Precipitation replenishes soil moisture and contributes to groundwater recharge in the late autumn and winter months (November–January). Some early spring ET demand is supplied by soil moisture, but beginning in April, irrigators apply sufficient water to maintain more soil moisture than the maximum allowable depletion. Groundwater recharge in the irrigated lands peaks again in the summer with ET demand and irrigation delivery and applications, and tapers off in the autumn before precipitation increases.

Columbia Plateau Regional Aquifer System

The water-budget components within the complete CPRAS are based on Kahle and others (2011). These components are summarized in table 5, which also presents the predevelopment components. Unless otherwise stated, averages are for 1985–2007, and annual average estimates are presented in figure 19. Columbia River at The Dalles was scaled in figure 19 to show how its interannual variations compare to other components. Similarly, several values in figure 20 are scaled because the main interest is to show the relation of interannual variation between various major streams and the actual values would obscure these variations. For example, in 1997, average discharge in the Columbia River at The Dalles exceeded 260,000 ft^3/s, whereas the Hood River in Oregon was less than 2,000 ft^3/s (fig. 20).

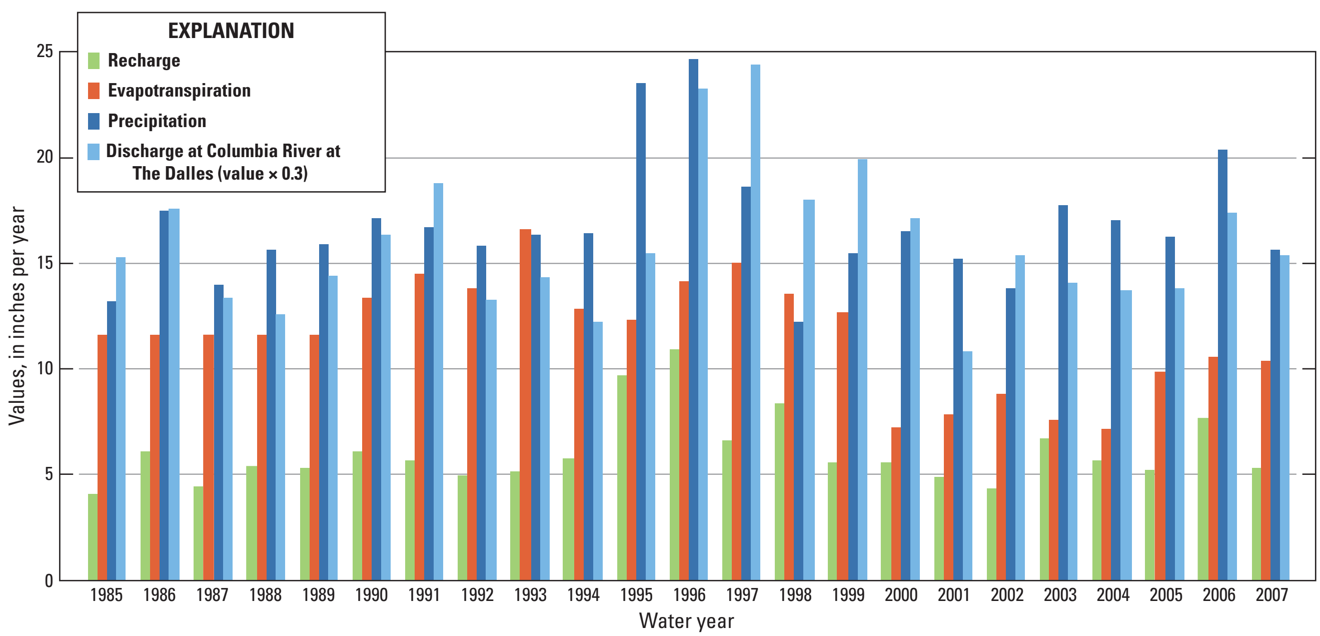


Figure 19. Annual average values estimated for selected water-budget components, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

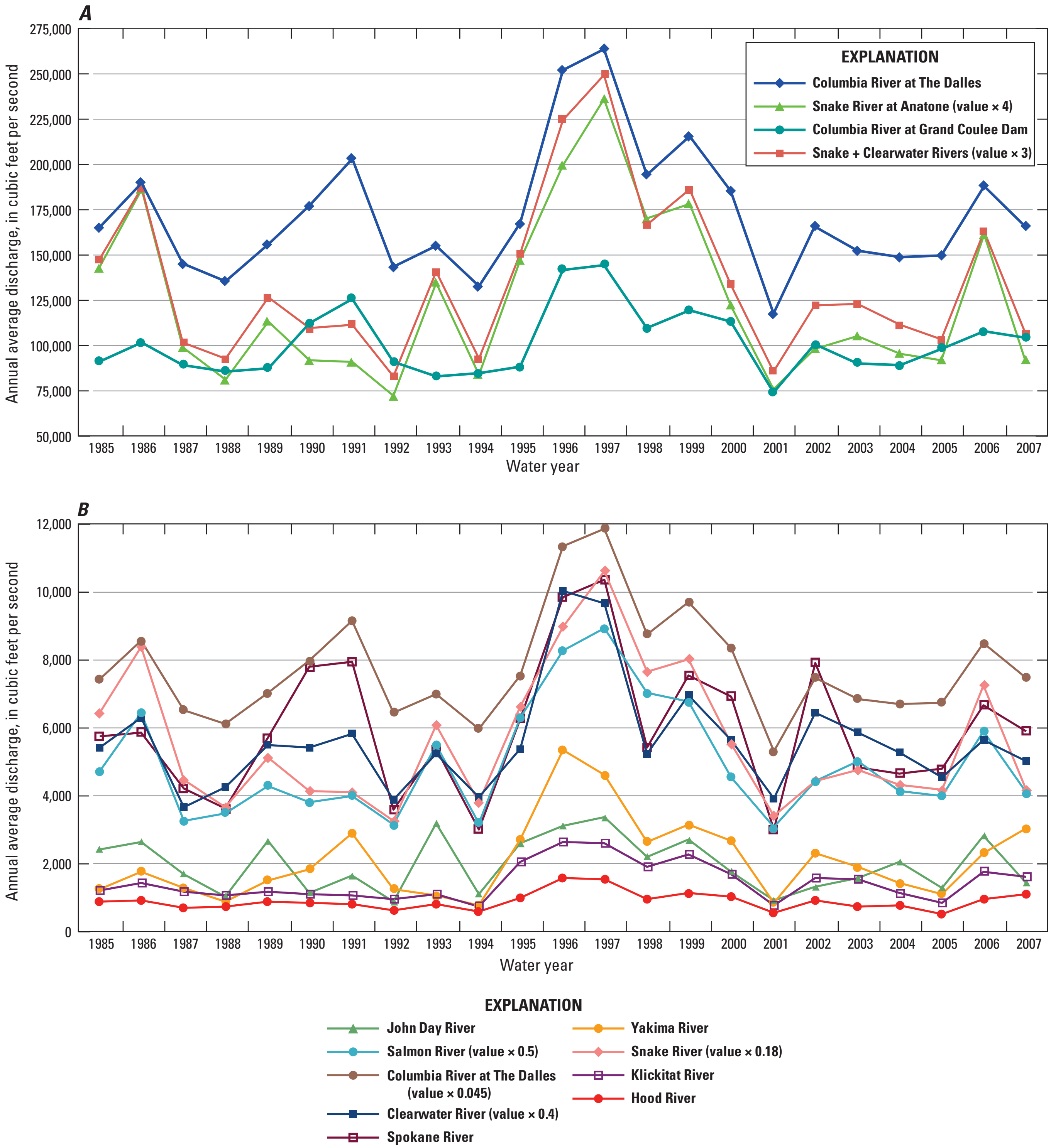


Figure 20. Annual average discharge for (*A*) the Columbia and Snake Rivers, and (*B*) selected rivers in the study area, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

Surface Water

Most of the streams traversing the study area are regulated and (or) have diversions for irrigation or water supply, and streamflow is representative of existing conditions, including streamflow depletions. However, the annual average discharge generally is representative of the type of climatic year (dry to wet—preserving the overall interannual variability) and, thus, water-year values (particularly interannual variations) are presented and discussed.

Annual discharge on the Columbia River at The Dalles averaged 172,700 ft^3/s (125 MAF), which was about 9 percent less than the long-term average. At Grand Coulee Dam, which had a shorter period of record, annual average streamflow was 5 percent less. Interannual variability at The Dalles was large, ranging from 117,600 ft^3/s in 2001 to 263,700 ft^3/s in 1997, and this range (146,100 ft^3/s) was 85 percent of the 23-year period average. The large range in values (indicating the temporal-spatial variations in SWE throughout the Columbia River Basin) affects water use and is correlated to groundwater recharge and, thus, water availability in the study area.

There is general consistency in the temporal variations in annual discharge values between streams, but some inconsistencies occur. The shapes of the hydrographs for the Columbia River at Grand Coulee Dam (measure of inflow to the study area) and The Dalles (outflow) generally are similar, with annual differences in the shapes of the hydrographs for these two sites primarily owing to variations in Snake River inflows; for example, Snake River inflows affected these differences in 1989, 1993, 1997, and 2006 (fig. 20*A*). Hydrographs for selected rivers (fig. 20*B*) also show this type of spatial variation. The Snake and Salmon Rivers follow the same temporal pattern with only a few variations. The Salmon River accounts for about 30 percent of the flow of the Snake River at Anatone, and the Clearwater River (the largest tributary to the Snake River) accounts for an additional 45 percent increase in the annual flow of the Snake River. The other stream hydrographs show that there are distinct interannual differences in the shape of hydrographs across the study area, especially during 1985–94 when all sites had lower average annual discharge than the 23-year average. This period contains two multi-year periods (1987–88, 1992–94) that were considered droughts for water-supply purposes.

Evapotranspiration

The estimates of ET for the study area (Senay and others, 2009) provide the existing-conditions information for this water-budget component. The estimates were for 1989–2007, and the ET estimates for 1989 were used to approximate the annual values for 1985–88, producing values for the period of interest for hydrologic budgeting, 1985–2007.

The average annual estimate of ET was 11.7 in. or 38,000 ft^3/s (28 MAF), and ranged from about 1 to 38 in. (the same range as estimated for predevelopment conditions). The spatial distribution of ET (fig. 21) indicates a strong correlation to precipitation, but also indicates large differences from the estimated predevelopment distribution (fig. 17) in areas affected by irrigation. ET is a larger percentage of precipitation under existing conditions than under predevelopment conditions because of the additional ET from irrigated and dryland croplands. The differences are especially pronounced in the surface-water irrigated areas, such as in the Yakima River Basin and CBP, where increases in ET ranged from about 20 to 36 in. because of the consumptive use by crops.

Recharge

Existing-conditions recharge includes the additional recharge from surface-water and groundwater irrigation that was simulated using the SOWAT model (Kahle and others, 2011). Average annual recharge was 6.1 in. or 19,800 ft^3/s (14 MAF), and ranged from nearly zero to more than 40 in. During the 23-year period, annual recharge ranged from 4.1 to 10.9 in. (fig. 19). The increased recharge in the surface-water irrigated areas is clearly indicated in the spatial distribution of recharge for 2007 (fig. 22). The estimated average annual recharge (1985–2007) from irrigation return flow was 5,800 ft^3/s (4.2 MAF), with 50 percent occurring within the predominately surface-water irrigated regions—the Yakima River Basin, Umatilla River Basin, and CBP (fig. 4).

Surface-Water Use and Groundwater Pumpage

Surface-water use and groundwater pumpage were estimated for the study area on an annual basis for 1985–2007 (Kahle and others, 2011). Groundwater pumpage was estimated for five categories of use: (1) irrigation; (2) public water supply (PWS); (3) domestic (exempt wells); (4) industrial; and (5) “other,” which includes mining, livestock, thermoelectric needs, and fisheries.

Average annual irrigation water use estimated using SOWAT was 5.3 MAF (7,320 ft^3/s) during 1985–2007, with 1.4 MAF or 1,935 ft^3/s (26 percent) supplied from groundwater and 3.9 MAF (5,385 ft^3/s) supplied from surface water (Kahle and others, 2011). Note that, for surface water, this is the irrigation use, which is less than the amount diverted. Surface-water use was largest in the CBP, followed by the Yakima River Basin and the Umatilla River Basin. Annually, irrigation water use ranged from about 4.1 to 7.1 MAF, and the part supplied by groundwater ranged from about 25 to 35 percent. Groundwater pumpage was relatively stable during 1985–2007 (fig. 23), as most of the growth in pumpage occurred from about 1945 to 1979, when the irrigation pumpage estimated for the major pumping centers increased from 0.05 to 0.8 MAF (Cline and Collins, 1992). Most of the variability in irrigation pumpage during 1985–2007 is attributable to climatic conditions and not changes in irrigated crop areas or crop types.

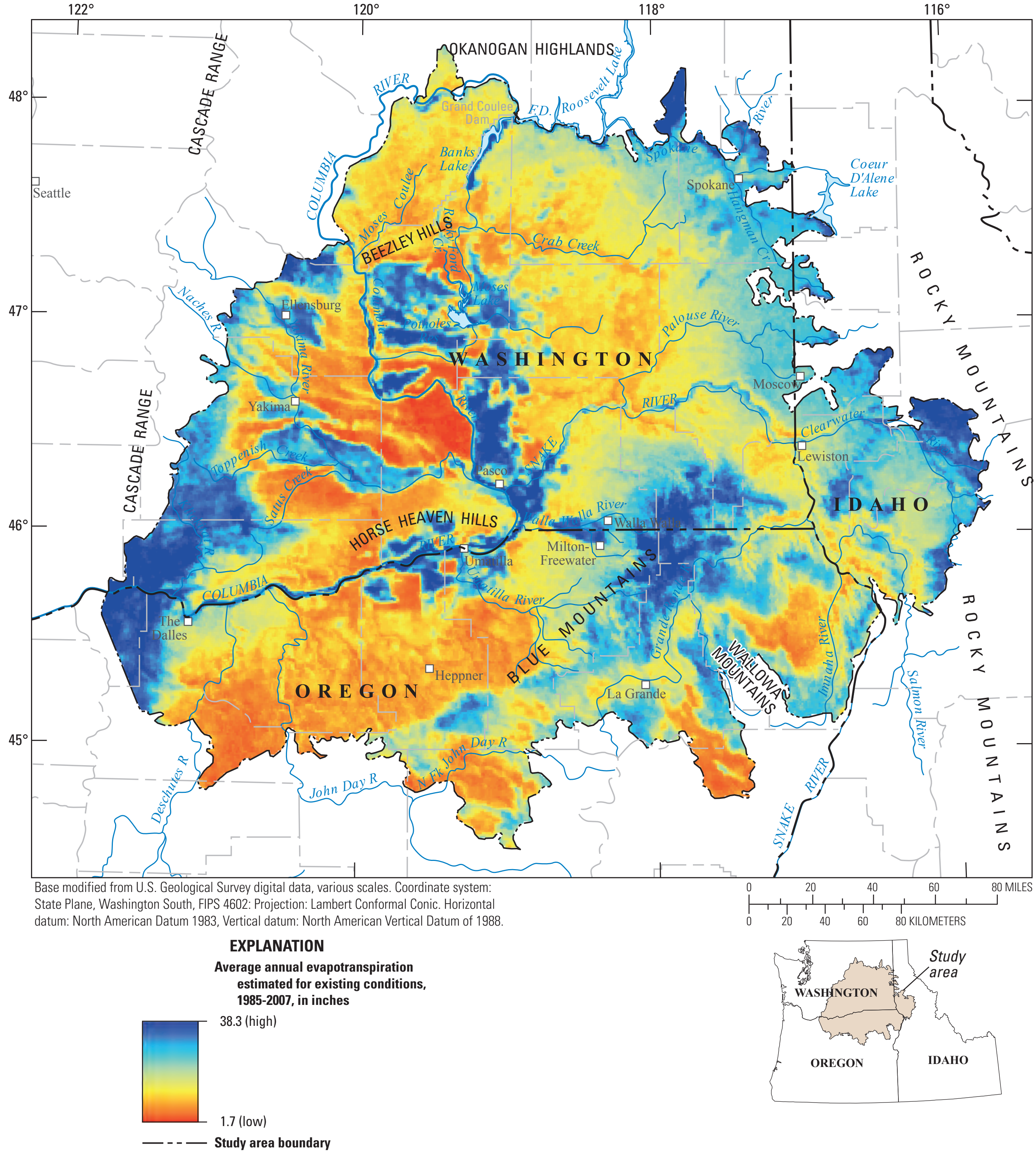


Figure 21. Distribution of average annual evapotranspiration estimated for existing conditions, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

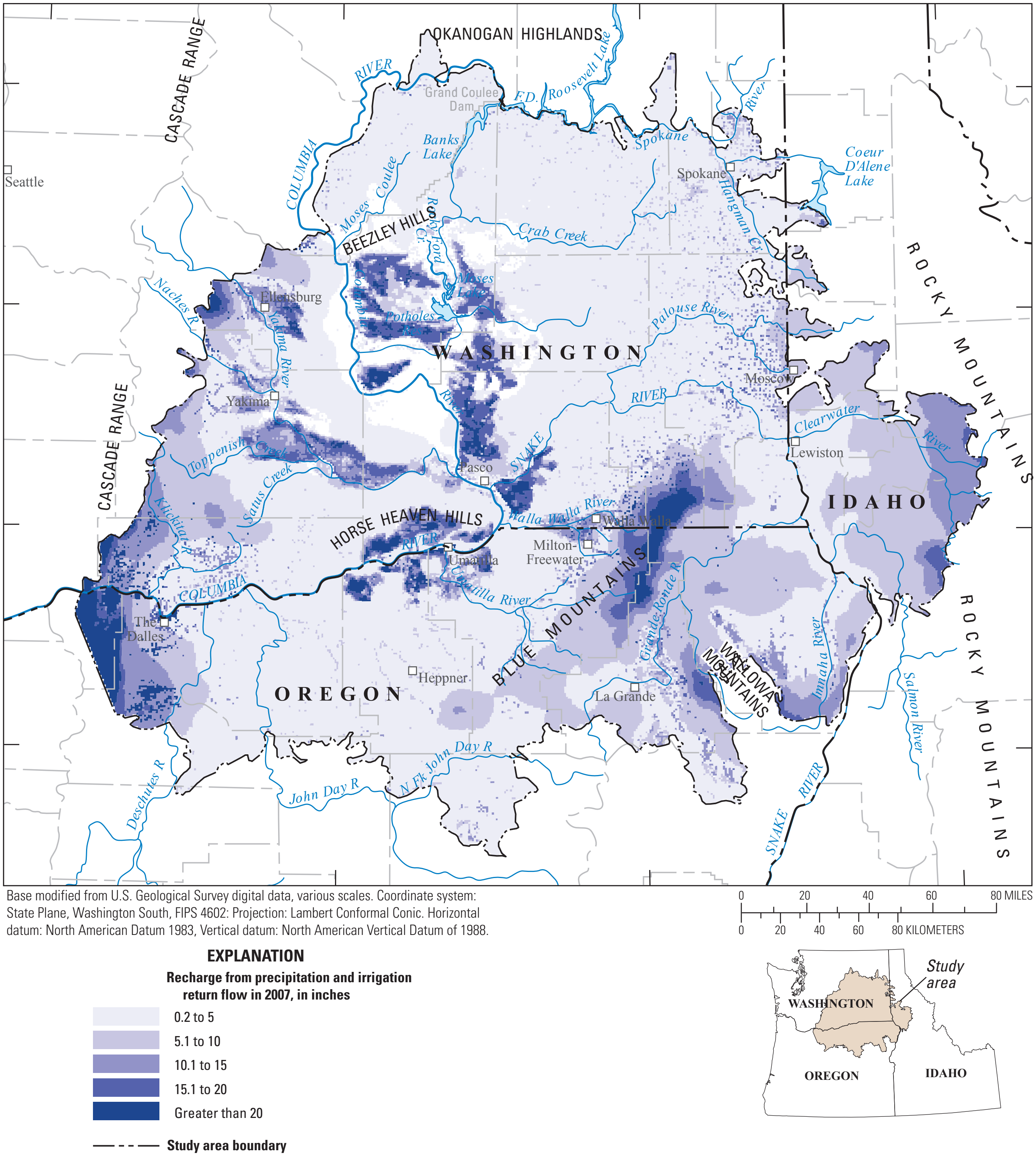


Figure 22. Distribution of annual recharge estimated for existing conditions, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 2007 (from Kahle and others, 2011).

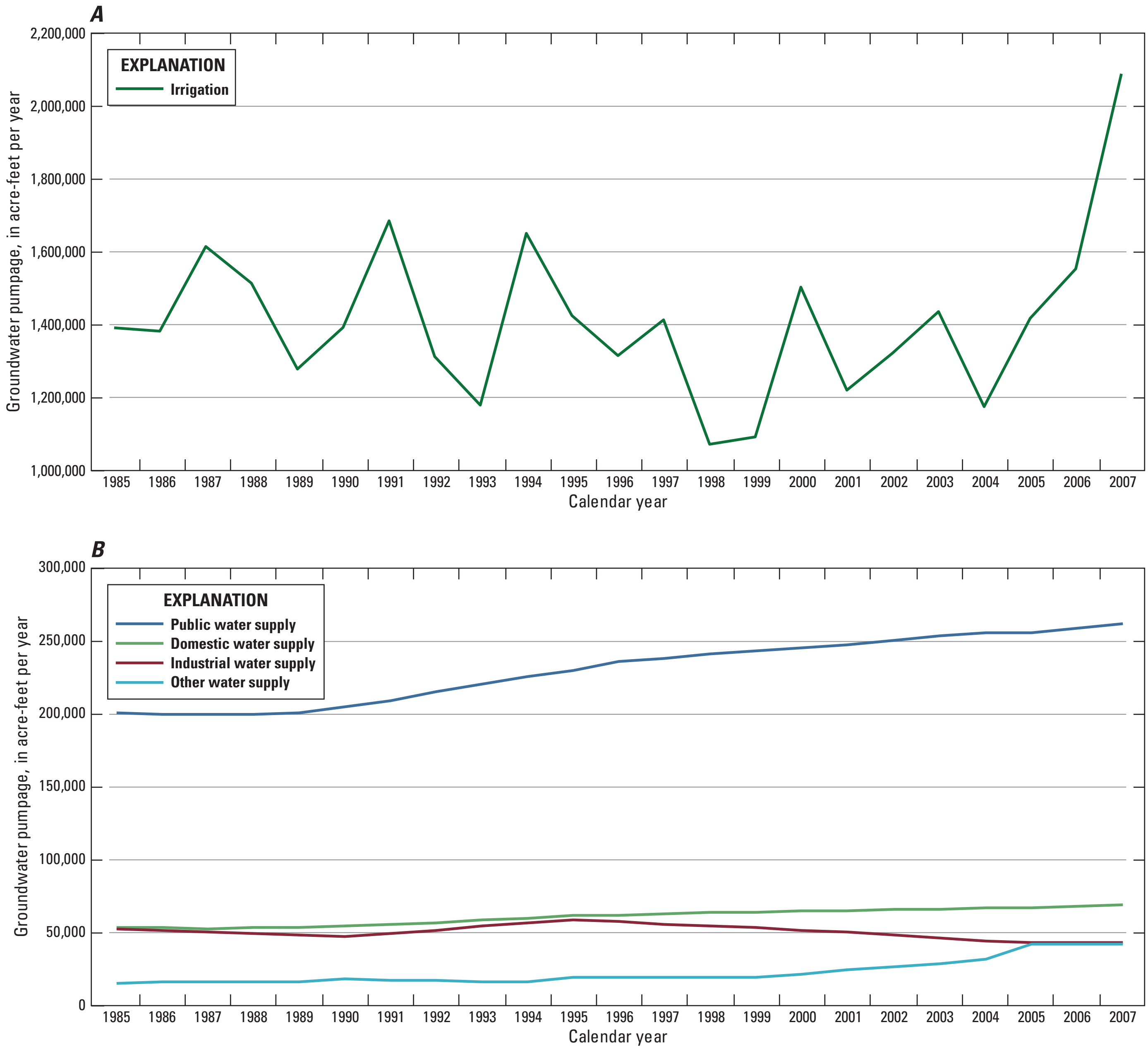


Figure 23. Estimated annual groundwater pumpage for (*A*) irrigation; and (*B*) public, domestic, industrial, and other water supplies, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

Excluding irrigation pumpage, average annual pumpage was 0.4 MAF (about 22 percent of total irrigation pumpage and only 8 percent of total irrigation water use). Total average annual pumpage was about 1.8 MAF. By pumpage category, the average annual PWS was 0.23 MAF, and increased from 0.2 MAF in 1985 to 0.27 MAF in 2007 (fig.23*B*). Domestic self-supplied pumpage increased from 0.06 MAF in 1985 to 0.07 MAF in 2007 (average annual pumpage of 0.06 MAF). The average annual industrial pumpage was 0.05 MAF for 1985–2007, and decreased from 0.05 to 0.04 MAF over this period; this trend in decreased industrial pumpage also was identified by Whiteman and others (1994). The trend is likely attributable to a decrease in industrial production, the adoption of more water-efficient processes, and a shift in the type of industry from those that require large amounts of water (refining and manufacturing of wood products) to ones that use less water (computer server farms). Average annual "other" pumpage (mostly for livestock) was 0.03 MAF during 1985–2007, and increased from 0.02 to 0.04 MAF over the 23-year period. However, livestock use is the most difficult quantity to measure because of water law, and it may be much larger than these numbers.

Aquifer Storage

Hansen and others (1994) estimated that about 10 MAF of water was added to storage from predevelopment conditions through 1985 in the Overburden unit owing to excess irrigation water that raised groundwater levels. This suggests that about 94 MAF of water is in storage for existing conditions based on the estimate for predevelopment conditions described in section, "Predevelopment Water Budget—Aquifer Storage," especially because groundwater level rises in irrigated areas had nearly stabilized by 1985. Irrigation practices have added about 3 MAF of storage to the basalts (about 1.8 MAF in the Saddle Mountains unit) by raising groundwater levels from predevelopment conditions through 1985 (Hansen and others, 1994). However, Hansen and others (1994), measured water levels, and model simulations indicate that groundwater-level declines owing to pumpage also have occurred, and the declines in the Wanapum and Grande Ronde units have been more widespread and of greater magnitude than the rises—resulting in a net loss in groundwater storage in these units. That is, the declines in the groundwater-irrigated areas generally negate the increases in water in storage from surface-water irrigation, and the basalt storage is estimated to approximate the predevelopment basalt storage of 800 MAF (table 5).

Groundwater Model Domain

The estimates of the water-budget components of precipitation, ET, recharge, surface-water use, and groundwater pumpage within the model domain are from Kahle and others (2011), and the groundwater components are from Ely and others (2014). The landscape-process components (precipitation, ET, and recharge) are shown in figure 24. The surface-water component is not described in this section because this component is accounted for and discussed as a part of the system described for the complete CPRAS. The primary emphasis of this section is on the groundwater budget, including the flow between hydrogeologic units.

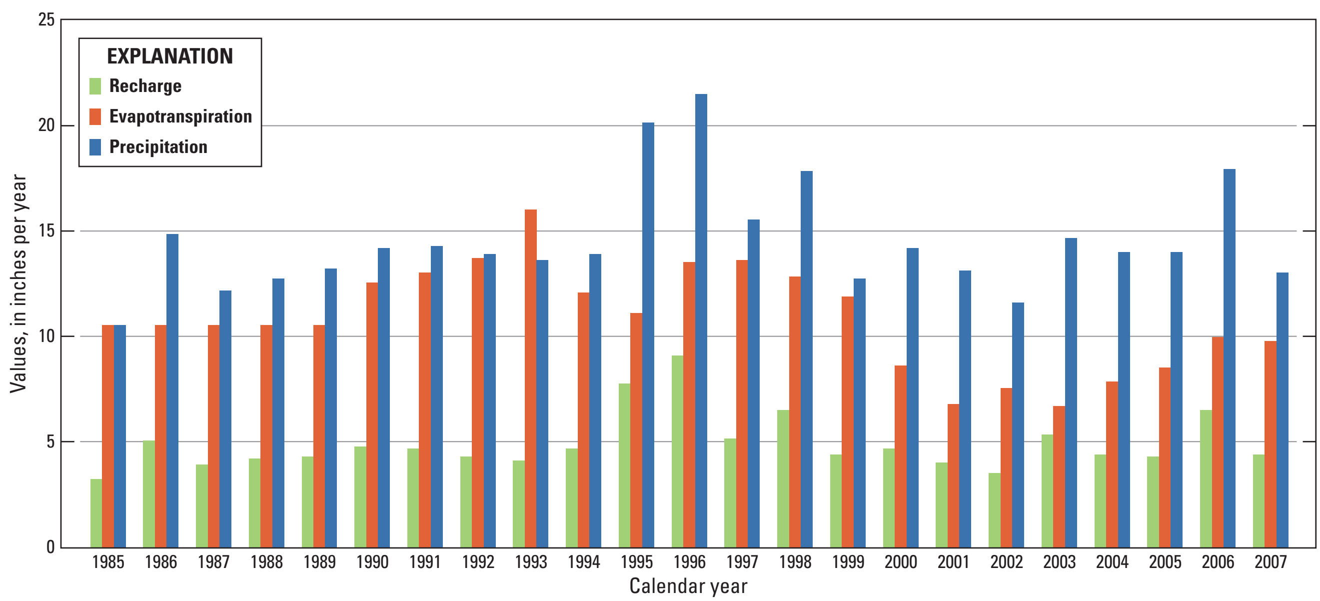


Figure 24. Average annual values for selected water-budget components, Columbia Plateau Regional Aquifer System groundwater-model domain, Washington, Oregon, and Idaho, 1985–2007.

Precipitation

The average annual precipitation in the model domain was estimated as 14.5 in. or 35,000 ft^3/s (25 MAF). The average was about 2.7 in. less than the average for the complete study area because much of the model domain is in the arid to semi-arid part of the CPRAS. Annually, precipitation ranged from 10.6 to 21.5 in., indicating the large temporal variation in the primary landscape hydrologic budget component. During the 23-year period, precipitation spatially ranged from a low of 3.2 in. in the central Columbia Plateau near Pasco, Washington, to a high of 113 in. in the Cascade Range. These large spatial and temporal variations affect ET, recharge, streamflow, and groundwater levels, and, ultimately, water availability. For example, in a dry year, the demand for irrigation water increases, which, in turn, can affect the ability of junior water-right holders to provide the necessary irrigation quantities to their crops—especially for surface-water users. Dry years also have a detrimental effect on aquatic ecosystems because of decreased groundwater discharge and increased water temperatures. In contrast, in wet years, water is available for all users and potential water-level declines can be moderated. Wet years also typically provide for a lower mortality rate than dry years for migrating juvenile salmonids because of increased spring-runoff "flushing" flows owing to increased unregulated runoff or additional reservoir releases (especially for the Columbia and Snake Rivers).

Evapotranspiration

The estimated average annual ET within the model domain was about 10.8 in. or 26,100 ft^3/s (18.9 MAF) over the 23-year period. The average value was only about 1 in. less than the study area average because of the ET from the irrigation of croplands, most of which are within the model domain. Annual values ranged from 6.7 to 16 in. (representing a difference of 22,500 ft^3/s or 16.3 MAF). These large annual variations are primarily influenced by the spatial and temporal variations in precipitation and air temperature, and ultimately affect the groundwater system through the recharge component. The spatial-temporal variations in ET provide new insight into the dynamics of the landscape processes that affect and influence the groundwater-flow system. The results also provide a perspective on the relative contribution of budget items to the total water budget. For example, the 16.3 MAF difference between the highest and lowest annual ET values within the model domain during 1985–2007 is 72 percent of the average annual flow of the Snake River at Anatone for the same period.

Recharge

The interaction between the landscape hydrologic processes of precipitation and ET, and the additional effects from the delivery/pumpage and application of irrigation water controls both the groundwater recharge component of the water budget and the groundwater discharge component to streams. The SOWAT/regression-derived average annual recharge for the model domain was estimated at 3.8 in. or 9,100 ft^3/s (6.6 MAF), which is within 8 percent of the difference between precipitation and ET. The average annual recharge during 1956–77 was estimated at 4.24 in. for the domain of the CP-RASA groundwater model, and differed by only 11 percent from the CPRAS estimate (which included 7 dry years). Estimated annual recharge ranged from 3.3 in. (5.8 MAF) to 9.1 in. (15.9 MAF), and this large range (10.1 MAF) potentially represents a large control on groundwater availability. The large range in annual precipitation and ET (12 and 16.3 MAF, respectively) cascades through the system as large temporal variations in recharge. During the 23-year period, annual recharge was estimated to spatially range from 0 to 92 in. The large spatial and temporal variations in recharge have a profound effect on the groundwater flow system.

Surface-Water Use and Groundwater Pumpage

There is no apparent long-term trend in either groundwater or surface water irrigation (fig. 25). Although information presented in figure 25 is for the entire study area, it also is representative of the model domain because more than 98 percent of the irrigated lands are within the model domain. The information suggests that there may be a small upward trend in the percentage of irrigation supplied by groundwater. Dry years when standby/reserve or supplemental groundwater rights were exercised are apparent (1987, 1988, 1992, 1993, 1994, 2001, and 2005); however, there were other years (1997, 2000, and 2007) that were not considered dry, but groundwater was a larger percentage of total irrigation (fig. 25) relative to most other years. These 3 years were when areas predominately supplied by groundwater had above-normal ET. However, even in dry years, surface-water use is much greater than groundwater pumpage.

The growth of non-irrigation pumpage in the model domain (fig. 26) generally follows the same pattern as for the study area, with PWS as the largest category of use. The PWS use was more than 140,000 acre-ft in 2007, or about 26 percent of total surface water and groundwater irrigation use. In contrast to the study area as a whole, the

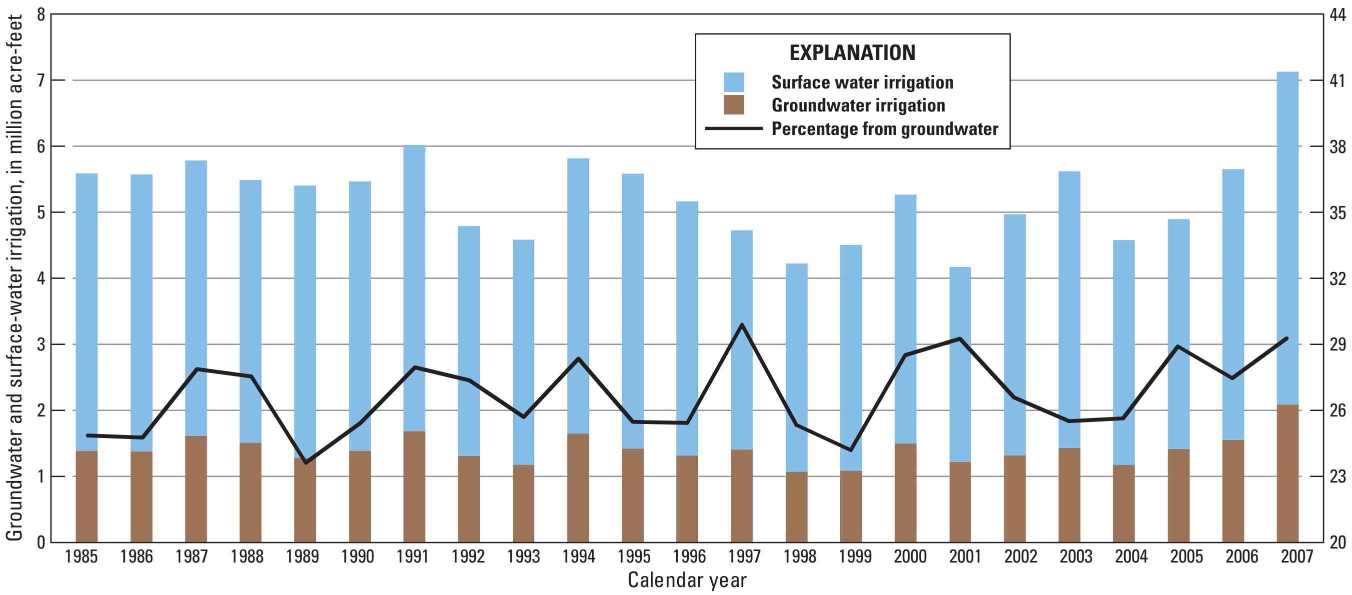


Figure 25. Estimated surface-water and groundwater irrigation, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007 (from Kahle and others, 2011).

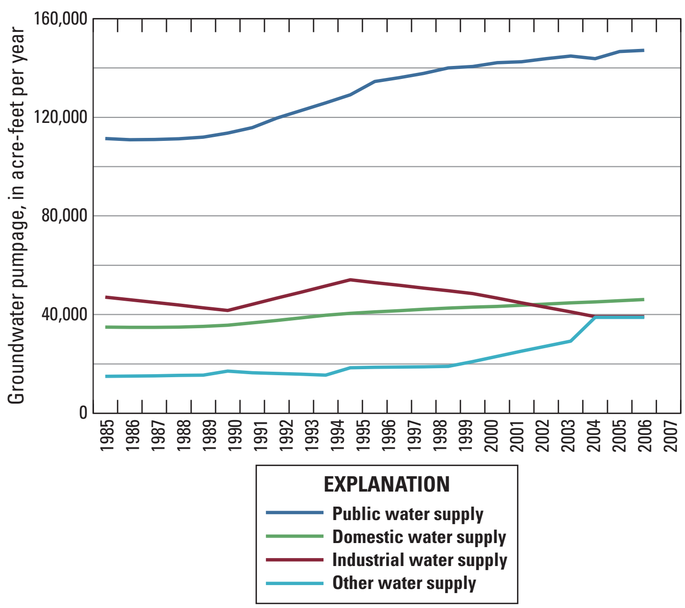


Figure 26. Estimated annual groundwater pumpage for public, domestic, industrial and other water supplies in the groundwater-model domain, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

industrial use through 2002 was larger than the domestic use. During 1985–2002, industrial use ranged from about 41,000 to 54,000 acre-ft, and decreased to 39,000 acre-ft by 2007. Through 2005, the “other water supply” uses were the smallest category, mirroring the study area results. The total non-irrigation pumpage in 2007 was about 193,000 acre-ft, of which PWS accounted for 76 percent.

Groundwater

The groundwater system has undergone large changes since predevelopment conditions owing to the temporal and spatial variations in recharge (partly influenced by the delivery and application of irrigation water) and pumpage. For example, pumpage is negligible until the 1950s and increases significantly, especially during the 1970s and 1980s when it increased by about 0.75 MAF. Pumpage was only about 45 acre-ft in 1920, increased to about 100,000 acre-ft by 1950, and exceeded 1.2 MAF by 1985. Pumpage is only about 20 percent as large as recharge but, in major pumping centers (where recharge is minimal), it is the largest budget component. The connection between year-to-year variations in storage and stream discharges, and variations in recharge, is clearly shown in the model-simulated annual groundwater fluxes for the 88-year period of simulation (fig. 27; Ely and others, 2014). Although storage has increased significantly in the surface-water irrigated areas, there was a net decrease in storage owing to pumpage. Thus, natural recharge is a major control on the water fluxes of the groundwater system, but human activities, in place of irrigation recharge, as represented by pumpage, has affected the overall storage in the system. The control of recharge indicated in the annual water budgets represents typical hydrology with much of the recharge discharging along short-to-intermediate flow paths to surface-water features, with discharge to streams varying by 3.2 MAF over the model simulation period owing to the recharge variations.

Hydrogeologic unit water budgets (fig. 28) show that all units are hydrologically active, with the importance and magnitude of the components varying by units. The budget for the hydrogeologic units indicates that, for most units, recharge is the dominant budget component, and that much of it discharges to streams (which is the second largest component for most units). In contrast to the other units, however, the location (spatial extent and outcrop extent) of the Saddle Mountains unit results in other budget components being more similar to its recharge quantity. Flow between units is relatively large and is representative of the extent of a unit relative to the other units. Overall, downward flows are much larger than upward flows. Annual storage changes seem to be

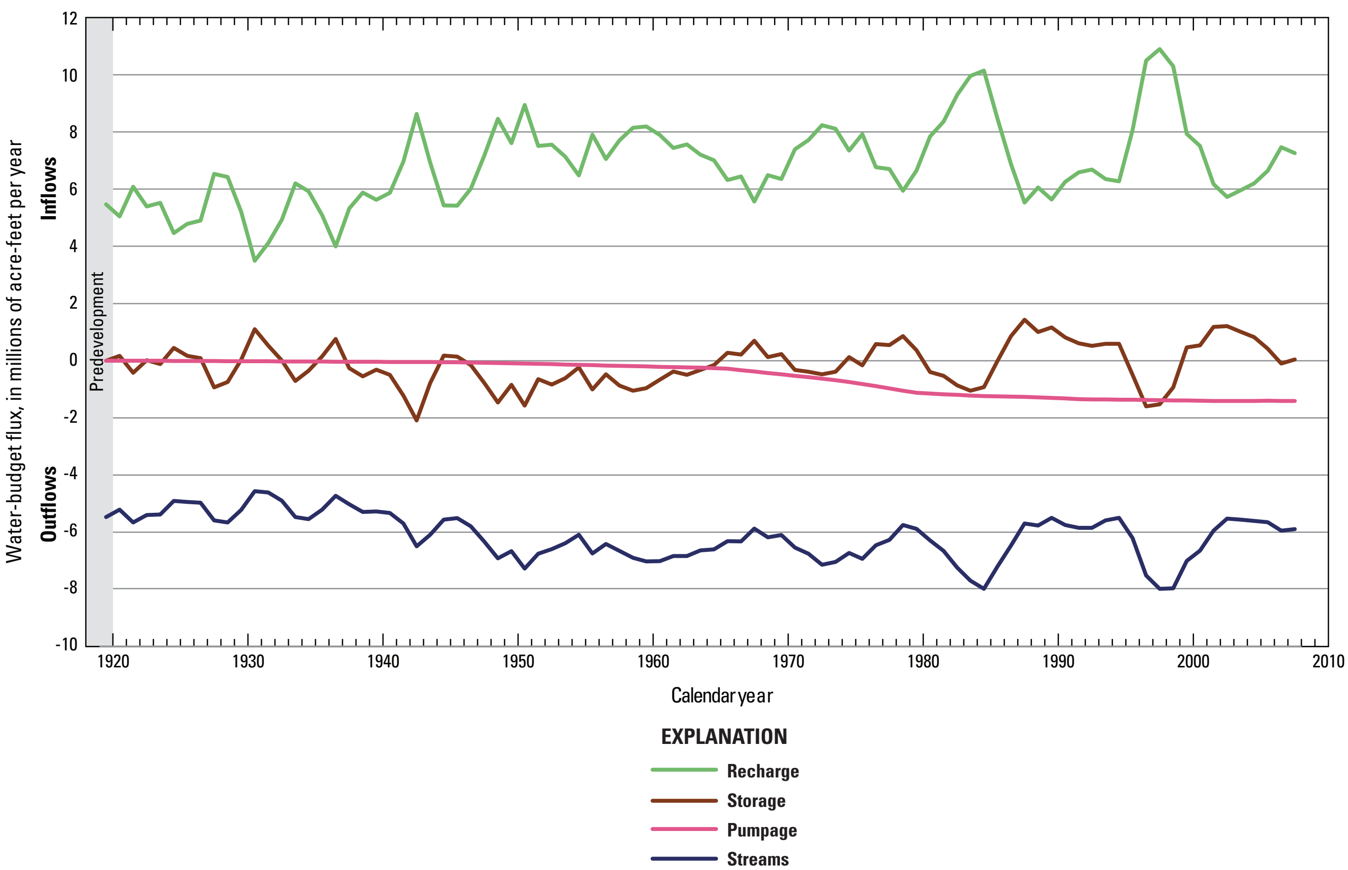


Figure 27. Simulated annual water-budget fluxes for the groundwater-model domain, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1920–2007 (from Ely and others, 2014).

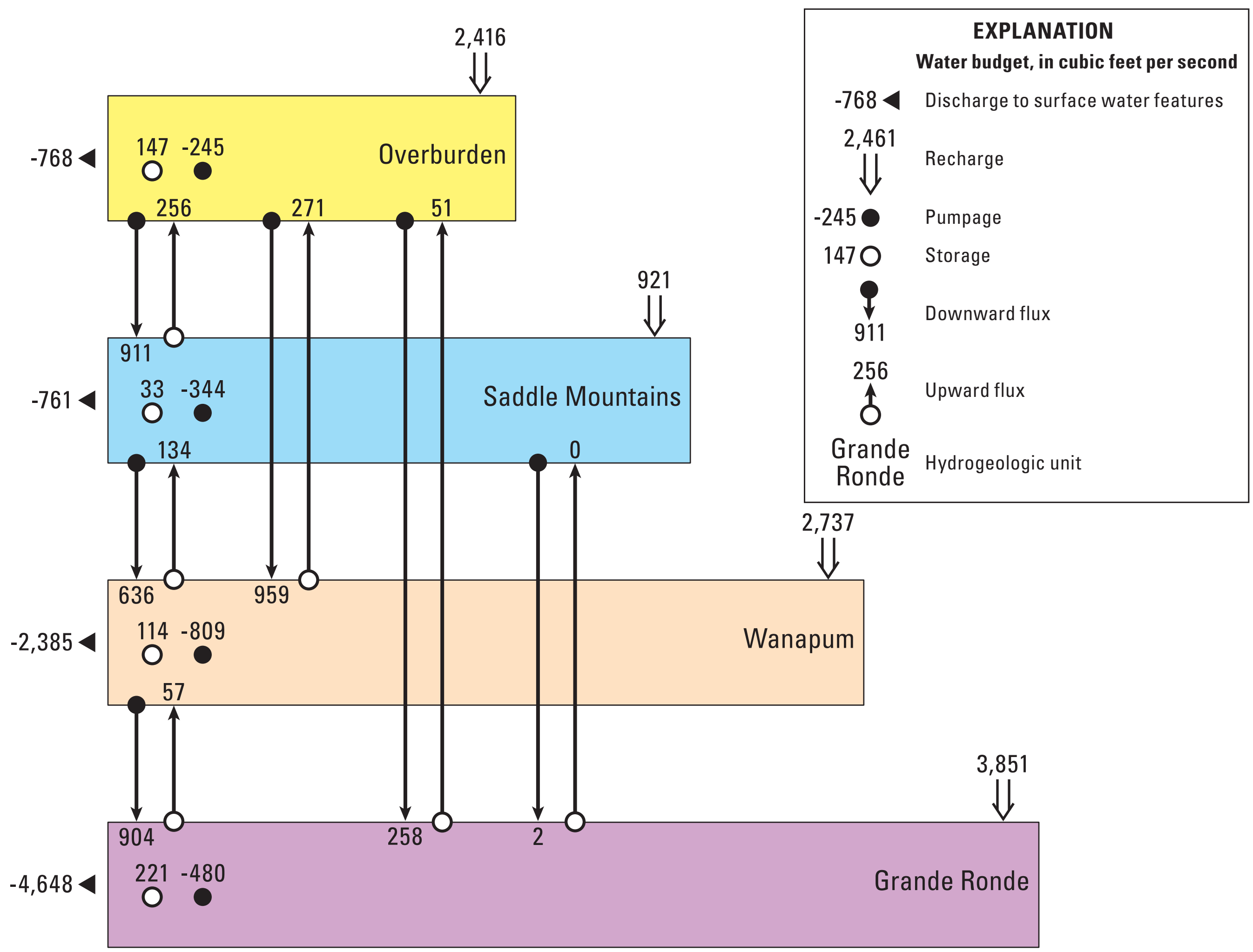


Figure 28. Schematic diagram showing simulated water budget for existing conditions, groundwater-model domain, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho, 1985–2007.

relatively small compared to other components, but even small storage changes represent groundwater-level declines over large parts of the CPRAS.

The water budget for the individual units follows the same general trend as the total water budget, with recharge and discharge to streams dominating. Interestingly, excluding recharge and discharge to streams, the water budget indicates that pumpage is the next largest component (fig. 28), and highlights the importance of pumpage and its historical, current, and future effects on the system. Downward flux from overlying to underlying units is the next largest component and is more than four times larger than upward flux. Indeed, storage changes in the units are about as large as the upward flows between units.

Changes to the Water Budget between Predevelopment and Existing Conditions

Changes in the water budget from predevelopment to existing conditions show the effects of human activities on the hydrologic system. These changes directly influence groundwater availability. The changes are described in terms of the landscape hydrologic processes (surface water, ET, and recharge). As in previous discussions, precipitation and snowpack are assumed to be the same for both predevelopment and existing conditions. Additionally, surface-water use and groundwater pumpage are not described here because the information previously presented on these budget components for existing conditions represent the change from predevelopment conditions when there was no water use in the CPRAS study area. For the model domain, a detailed accounting of the changes to the flow system is presented based on the groundwater-flow model of Ely and others (2014). Changes are referenced to the predevelopment conditions simulated with the model and in most cases are calculated from the existing-conditions period values. However, changes in surface-water fluxes and Wanapum unit groundwater levels are referenced to the model-base conditions of 2000–2007 to provide continuity to the same figures published in the model report of Ely and others (2014).

Surface Water

The surface-water system in the study area has been substantially altered over time with the construction of numerous reservoirs, diversion dams, canals, irrigation return-flow drains, and thousands of diversions. The timing and magnitude of streamflow has changed throughout the area to meet the power, irrigation, and to a much smaller extent, municipal demands that evolved over time. It was beyond the scope of this study to assess the changes in the streamflow throughout the study area. However, the groundwater model was used to estimate the changes in discharge to and from surface-water features from predevelopment through 2007. Changes in discharge have a direct effect on water availability because most of the streams in the study area are fully or nearly fully allocated for withdrawals; the amount available for allocation is on the order of one-thousandth of 1 percent of the total streamflow in the study area. The change in discharge from predevelopment to model-base conditions (fig. 29) indicates a wide range of patterns—from increased groundwater discharge in surface-water irrigated areas to decreases and increases in other areas. Some of these changes are owing to the differences in recharge in 1920 (4.6 MAF) compared to recharge in 2007 (6.7 MAF)—again showing the importance of recharge as a control on the hydrologic system. It should be noted that the sensitivity of the model to recharge and hydraulic conductivity variations, when combined with the water levels calculated over the model grid size, can lead to errors in the estimated surface-water fluxes. Small differences in the calculated shallow water levels may result in a losing reach being calculated as a gaining reach. Some of these differences are directly attributed to recharge differences between 1920 and 2007. This has been observed in the model results for Crab Creek in the northern part of the study area.

Evapotranspiration

The ET water-budget component increased by 2.1 in., from 8.7 in. (15.2 MAF or 21,000 ft^3/s) to 10.8 in. (18.9 MAF or 26,100 ft^3/s). The increased ET is owing primarily to the consumptive use of irrigation water applied to crops. For example, in the Yakima River Basin and CBP, increases in ET ranged from about 20 to 36 in. owing to the consumptive use by crops. Under predevelopment conditions, ET was about 60 percent of precipitation and increased to 73 percent for existing conditions. The percentage increase indicates that irrigation effectively increased ET by 13 percent.

Recharge

The change to the recharge component from predevelopment to existing conditions was about a 20 percent increase because of the infiltration of irrigation water owing to its delivery and application. The increase was from 5.5 MAF (7,600 ft^3/s) to 6.6 MAF. (9,100 ft^3/s). The percentage increase was about the same as for the CP-RASA model domain when comparing values for the CP-RASA modeling during 1983–85, showing consistency between the CP-RASA DPM-derived estimates and the SOWAT-derived estimates. A large percentage of the additional recharge in the surface-water irrigated areas initially increased storage with rising water levels. With the stabilization of water-level rises under existing conditions, most of the additional recharge first fills up the seasonal storage as water-level rises (generally ranging from 1 to 10 ft, but as much as 30 ft in some locations) in the surface-water irrigated areas. Once the seasonal storage is filled, recharge then moves to streams and agricultural drains, with a smaller part discharging as shallow ET.

Groundwater

The changes in water budgets for the hydrogeologic units are most pronounced for recharge, flow between units, discharge from the system, and pumpage (fig. 30). Changes in recharge are largest for the Overburden unit because of its association with surface-water irrigation in the numerous irrigation districts on parts of the Columbia Plateau. The additional recharge has increased water levels (storage)

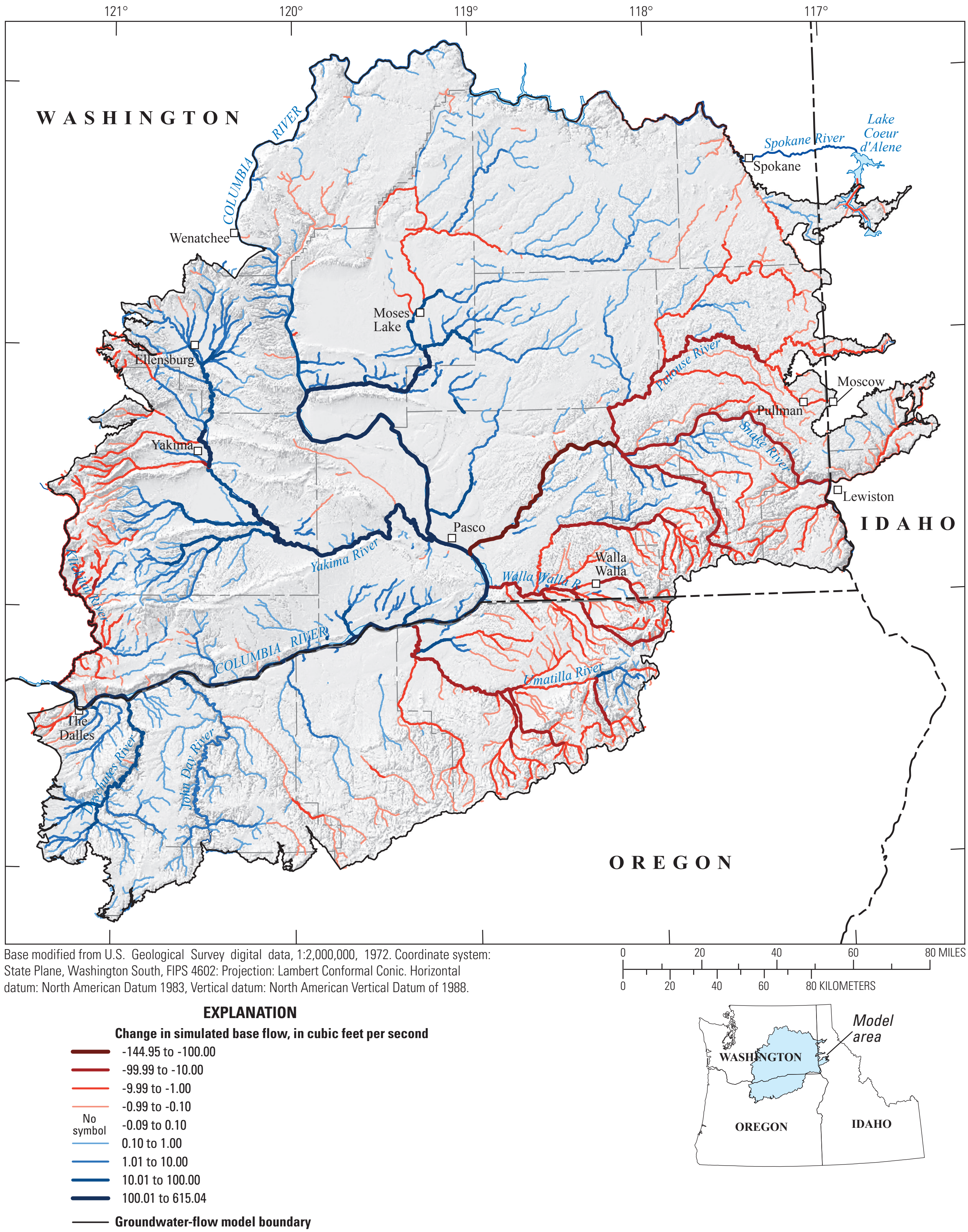


Figure 29. Change in simulated surface-water fluxes (base flow) from predevelopment (pre-1920) to model-base conditions (2000–2007), Columbia Plateau Regional Aquifer System Washington, Oregon, and Idaho (from Ely and others, 2014).

and, consequently, also has increased discharges from these two units to surface-water features and flow between units. Concurrently, water-level declines and change in storage (in response to pumping) generally have been mitigated by the increased recharge (particularly in the Overburden unit); that is, surface-water irrigation has provided a new source of water to wells. Similar conclusions were described for the CP-RASA by Hansen and others (1994; p. 70): *"The general effect of water development on the upper two units has been to raise the water-level altitudes over most of their extent… Declines in these units were small and not widespread."* In contrast, groundwater-level declines owing to pumpage in the Wanapum (fig. 31) and Grande Ronde units have resulted in the loss of storage. Importantly, pumpage from basalt units is larger than the increase in recharge (fig. 30). For the Wanapum unit alone, model simulations suggest that pumpage has caused a total loss in storage of more than 10 MAF and that declines have encompassed more than 14,000 mi^2. However, surface-water irrigation has resulted in rising water levels in the Wanapum unit where it underlies surface-water irrigation districts. These rises have generally balanced the declines as shown in figure 30, but model simulations and observed data indicate a net loss in storage after 1976. This loss in storage is continuing as of 2015 and likely into the future.

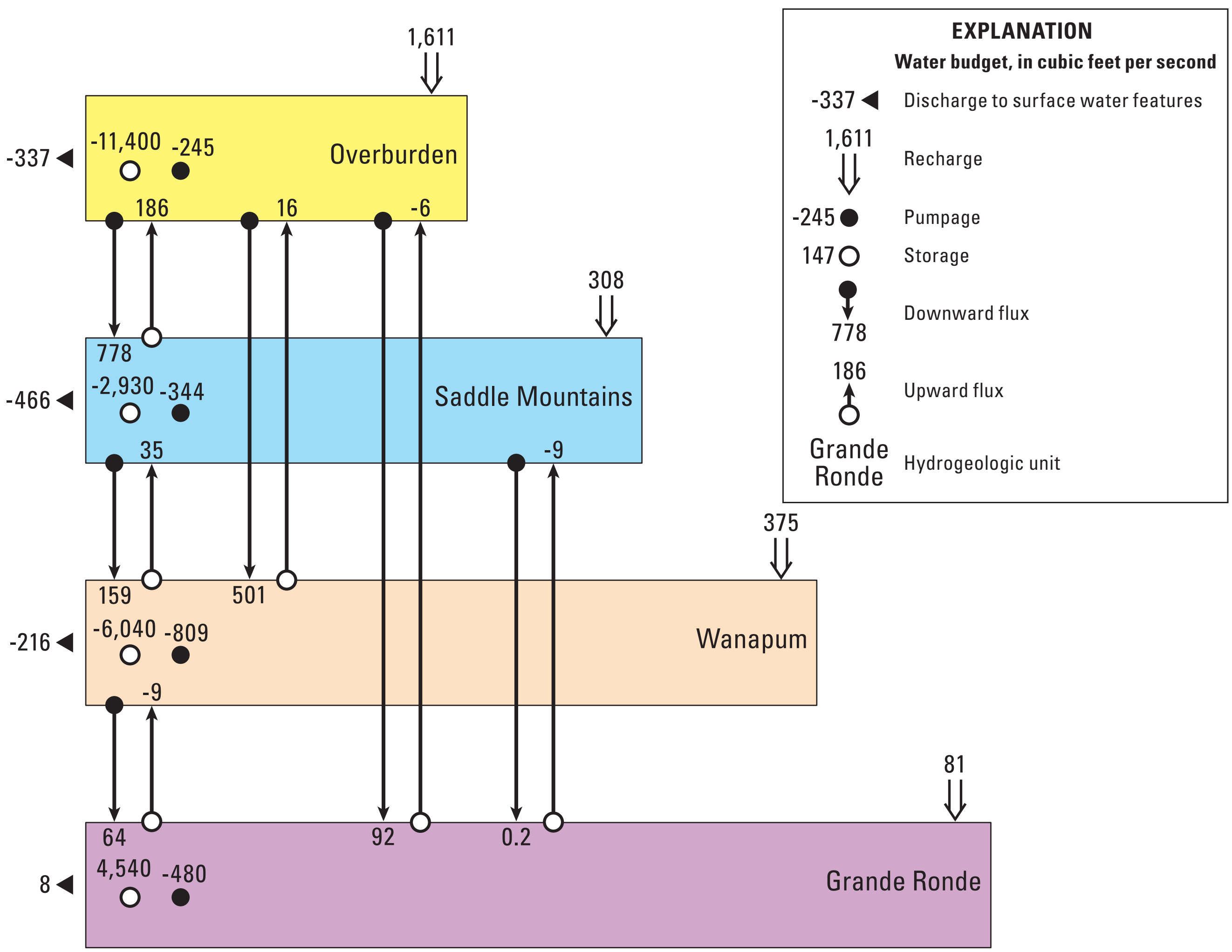
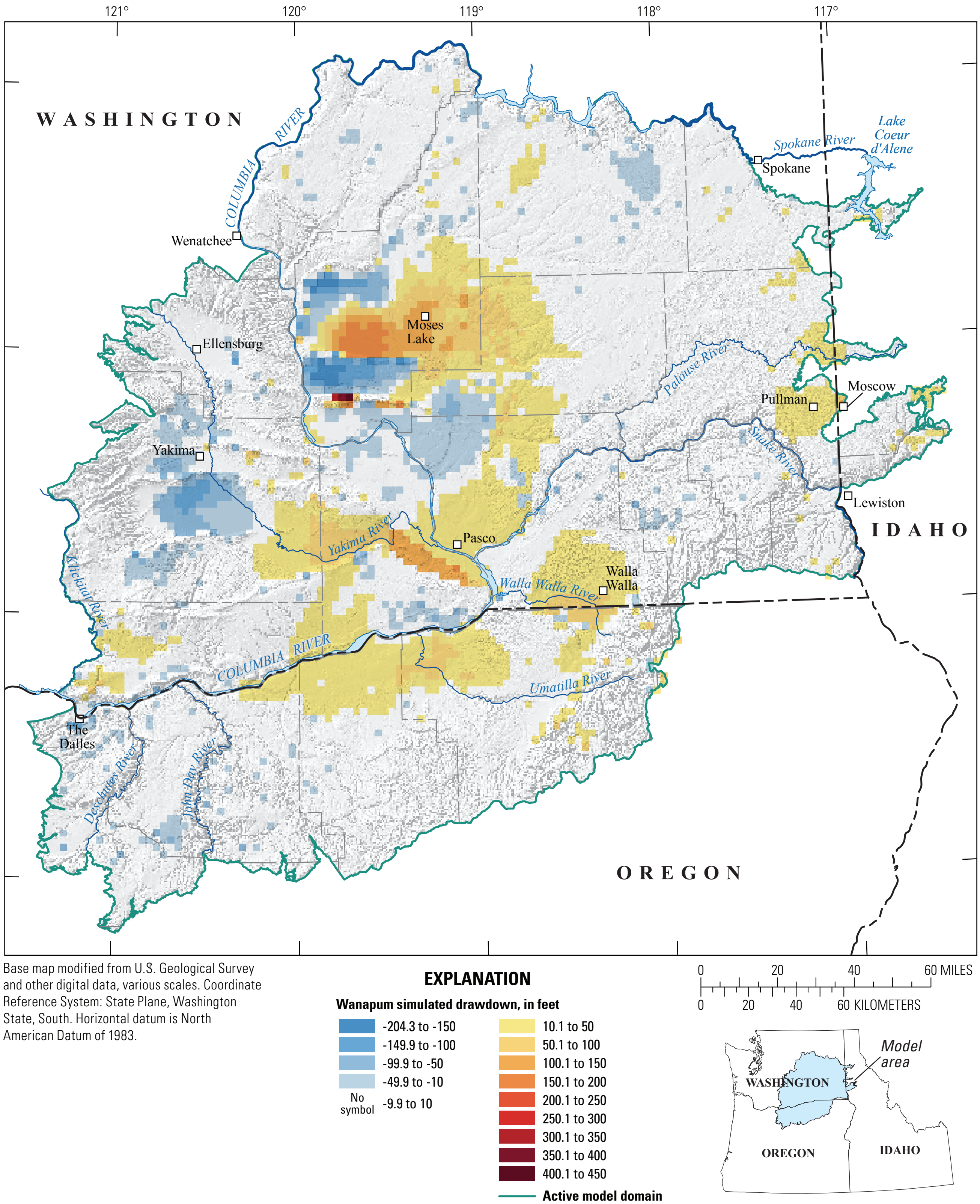


Figure 30. Schematic diagram showing simulated water budget change from predevelopment (pre-1920) to existing conditions (1985–2007), groundwater-model domain, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.



Base map modified from U.S. Geological Survey and other digital data, various scales. Coordinate Reference System: State Plane, Washington State, South. Horizontal datum is North American Datum of 1983.

Figure 31. Simulated changes in groundwater levels in the Wanapum unit from predevelopment (pre-1920) to model-base conditions (2000–2007), groundwater-model domain, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho (from Ely and others, 2014).

Irrigation practices, and to a smaller extent leakage from uncased wells, has changed the flow between units. The largest of these changes (fig. 30) are owing to the additional recharge from surface-water irrigation practices that have saturated more material in the system by raising water levels. The increase in storage has been well documented prior to this study. For example, Drost and others (1997) documented changes in storage exceeding 10,000 acre-ft/yr in an area covering 900 mi^2 in Franklin County, Washington, that includes the southern part of the CBP and a small part of Benton County that includes a surface-water irrigation district in the Yakima River Basin. They estimated that storage has been increased by more than 5 MAF in this area since predevelopment time, and has largely altered the flow system. Overall, downward flow into the Saddle Mountains, Wanapum, and Grande Ronde units is a large component of the changes. Relative to upward flow, downward flow has increased in magnitude since the 1940s. This additional water to the units, in turn, has increased discharge to surface-water features in some areas. Indeed, agricultural drains (some more than 10 ft deep) have been constructed throughout the surface-water irrigated areas to prevent waterlogging of croplands. Although the change in storage in the units is not a large component of the changes, this change has resulted in declines exceeding 300 ft in some areas, which have affected water availability in the major pumping centers. Declines have exceeded 10 ft/yr in parts of the Odessa subarea in western Adams County, Washington.

Climate Variability and Climate Change

The water resources of the CPRAS and, thus, groundwater availability, are intricately connected to interannual to interdecadal climate variations, which, in turn, are tied to global and North Pacific sea-surface temperature and atmospheric pressure patterns (Namias, 1976; Wallace and Gutzler, 1981; Ropelewski and Halpert, 1986; Yarnal and Diaz, 1986; Cayan and Peterson, 1989; Redmond and Koch, 1991; Cayan and Webb, 1992; Mantua and others, 1997; Vaccaro, 2002). The study and interpretation of natural climate variability is important for improving the understanding of the potential effects of climate change on precipitation and air temperature and, thus, on evapotranspiration, streamflow, and groundwater recharge. For example, the response of the hydrologic system during dry years in the historical record can be used as an indicator of possible changes in the landscape water fluxes and groundwater budgets during future droughts. Similarly, wet years in the historical record can be used as indicators of possible changes during future wet periods. The effects of interannual variations in climate on the snowpack and streamflow water-budget components are shown in figures 14, 16, and 20, especially the large differences between wet and dry years. For wet years, the changes in snowpack may not be as pronounced with warming temperatures.

Ultimately, climate variability is propagated through the groundwater system, first as groundwater recharge and then as storage changes (changes in groundwater levels). The changes, in turn, affect groundwater discharge to streams. Interannual variations in estimated predevelopment recharge in the lower Naches River Basin near Yakima, Washington (Vaccaro and Olsen, 2007), indicate the magnitude of variations owing to climate effects (fig. 32). Recharge variations are propagated through the system as interannual to interdecadal water-level changes, as shown by the water-level hydrograph in the upper 120 ft of the Wanapum unit for a long-term monitoring well (USGS site identifier 473442118162201) located west of Spokane, Washington (fig. 33). These data are from the U.S. Geological Survey for the period of record (1989 is missing) and Washington State Department of Ecology (transducer data from October 1, 1997 through March 31, 2010; John Covert, Washington State Department of Ecology, written commun., 2011). These water-level variations are correlated with precipitation variations as shown by the annual and cumulative departure from average values of precipitation for the same period (fig. 34) at a nearby weather station (Davenport weather station, National Weather Service cooperative station number 45-2007) located in Lincoln County, Washington. Wet years and dry years clearly stand out in figure 34, as does the persistence of wet and dry periods. This climatic variability and its subsequent effects have large implications for water-resource planning, management, and operations.

In a seminal study of streamflow generation in western Washington, Gladwell (1970) showed that streamflow variability is "more climatically controlled than physically controlled." Thus, changes in the climatic regime should be represented in streamflow characteristics for regions where streamflow variability is coherent (or in phase) with the climatic variability. The cumulative departure curve for the Columbia River at The Dalles (the longest hydrologic record in the study area) shows distinct shifts from wet periods to dry periods (fig. 35*A*). For about the first 25 years, streamflow was generally greater than average, followed by about 20 years of near-average streamflow, and then 25 years of less than-average. From 1977 to 2010, streamflow tended to be less than the long-term average but with a distinct, nearly decadal cycle, which is shown more clearly in the inset graph based on a shorter period of record (fig. 35*B*).

Superimposed on the natural climate variability and its effects on the groundwater-flow system are changes in water use and water-budget components owing to this variability. For example, large variations in existing-conditions (referenced as current conditions by Vaccaro and Olsen, 2007) recharge in the lower Naches River Basin owing to variations in precipitation input and use of surface water for irrigation are shown in figure 32. In this case, irrigation allows for the soil moisture to be replenished and, as a result, recharge mimics precipitation variability. For some streams (for example, the Columbia River), the cycles described in the preceding paragraph are important in that junior "interruptible"

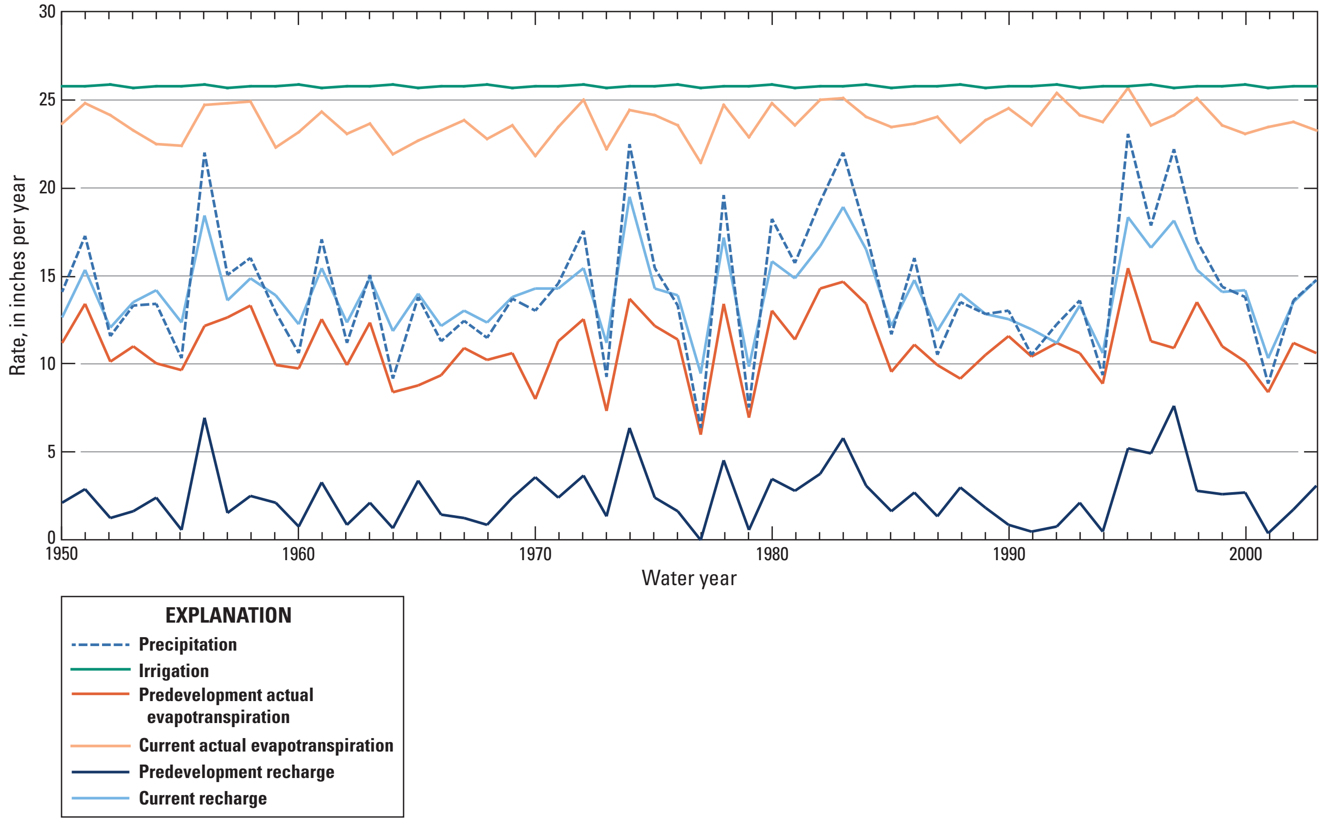


Figure 32. Calculated annual values of selected water-budget components for predevelopment and existing (current) conditions, lower Naches River Basin, Washington, water years 1950–2003 (from Vaccaro and Olsen, 2007).

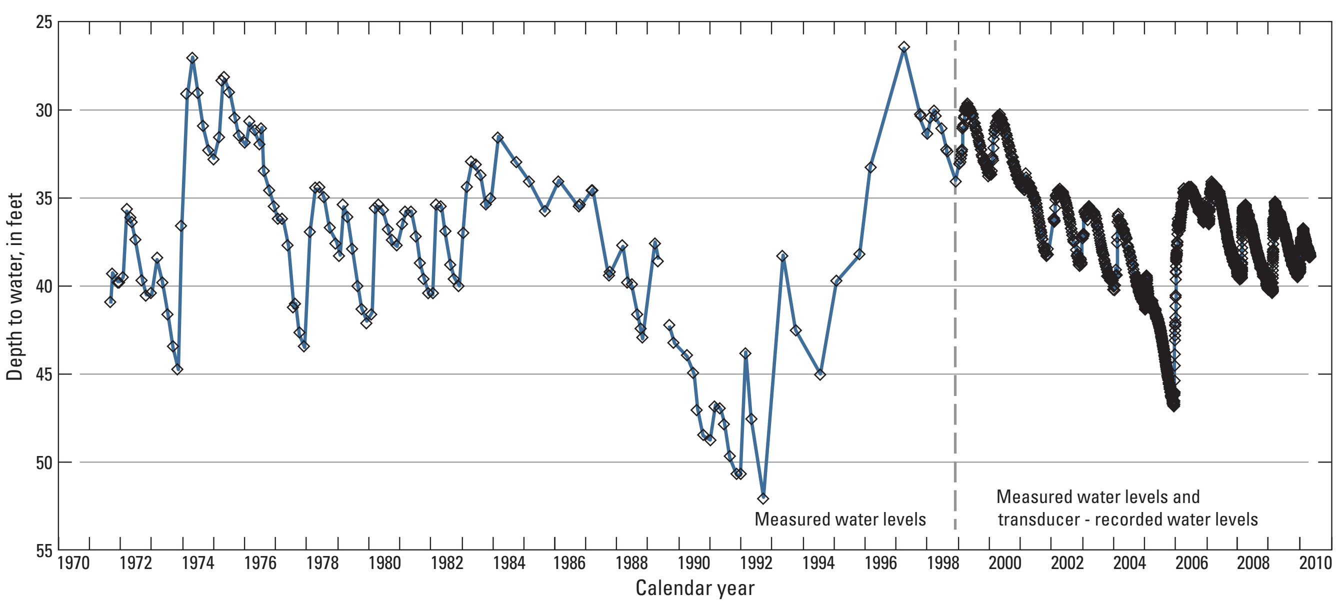


Figure 33. Water levels for the Davenport monitoring well, Lincoln County, Washington, 1971–2009. Monitoring well location is shown in figure 4.

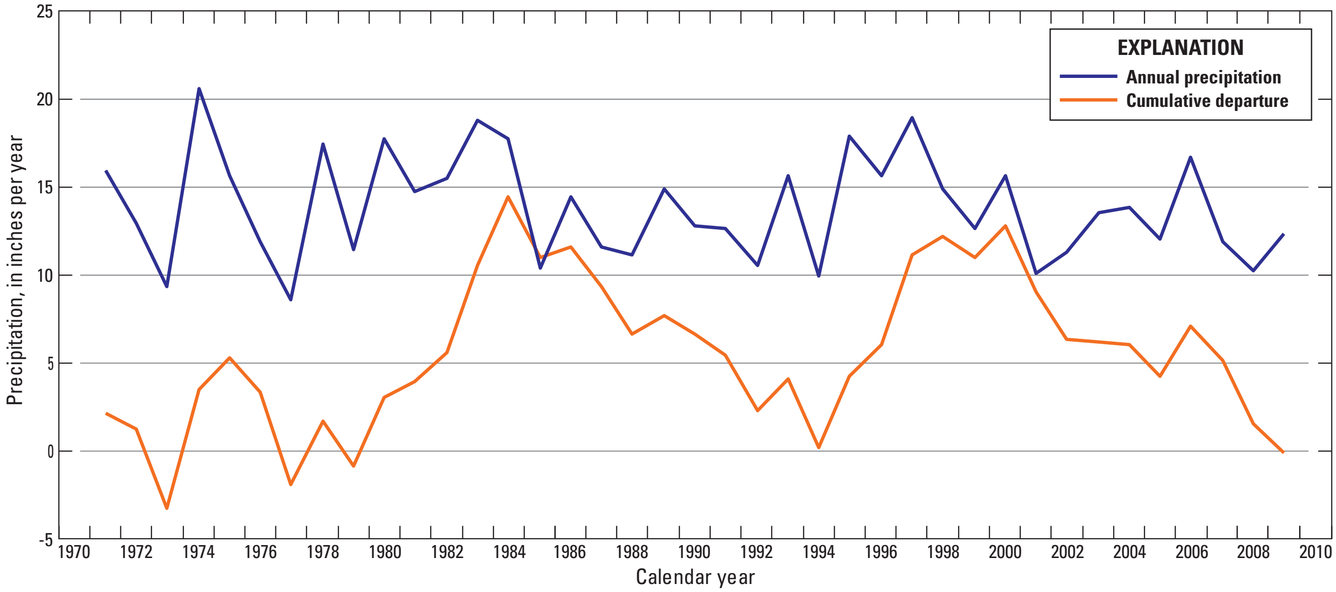


Figure 34. Annual precipitation and cumulative departure from average annual precipitation for the Davenport weather station, National Weather Service cooperative station number 45-2007, Lincoln County, Washington, 1971–2009. Weather station location shown in figure 2.

diversions can be limited or turned off to preserve water for more senior instream-flow rights. This is in contrast to junior surface-water users receiving less water in drought years to preserve water for more senior diversionary rights. Both cases, however, have the same effect of reducing irrigation recharge and, thus, return flows. In such drought years, some junior surface-water users switch to groundwater (supplemental or standby/reserve irrigation rights) to make up for their lack of water, which can locally aggravate groundwater-level declines (Vaccaro and others, 2009) and reduce streamflow.

Previous studies have identified “shifts” in the mean climate at interdecadal scales that are part of the natural variability (Vaccaro, 1995; Mantua and others, 1997; Vaccaro, 2002). Although large shifts such as those associated with the Pleistocene-to-Holocene climate change are important for understanding large-scale natural variability, much smaller changes have a large effect on regional water resources, especially considering the typical time frame of many water-resource planning horizons and the near-total use of water resources in some parts of the study area. These smaller “shifts” to different regimes propagate through the system with respect to water use. Three major shifts in the Pacific Northwest occurred in about 1928–31, 1947, and 1977 (Vaccaro, 1995), which were related to atmospheric circulation (Vaccaro, 2002) and to Pacific Ocean sea-surface temperatures as defined by the Pacific Decadal Oscillation (PDO; Mantua and others, 1997). The first period was drier than normal, the second wetter than normal, and the third drier than normal.

Such shifts affect water management throughout the Columbia River Basin. For example, in the Yakima River Basin in the western part of the study area, there are five Reclamation reservoirs with a total capacity of 1.1 MAF that supply water for the irrigation of about 500,000 acres. Water demands are initially met by unregulated streamflow and then by reservoir releases, and the date of the first releases is termed the storage control date (SCD). During 1926–2010, the average SCD was June 24 (Julian day 175). The SCD not only has varied over time (fig. 36), but also has changed character with much more variability starting around the 1977 climate shift. Indeed, of the 34 occurrences of releases before June 24, 17 occurred during the dry period after 1976 (50 percent of the early releases occurred during 50 percent of the post-1976 record). Ten of the remaining 17 occurrences were before 1947 (the other dry period). For the post-1976 period, SCDs were earlier by an average of 31 days compared to the complete pre-1977 period, indicating highly variable and more difficult reservoir operations. The cumulative departure of the SCD from the 1926–2010 average (fig. 37)

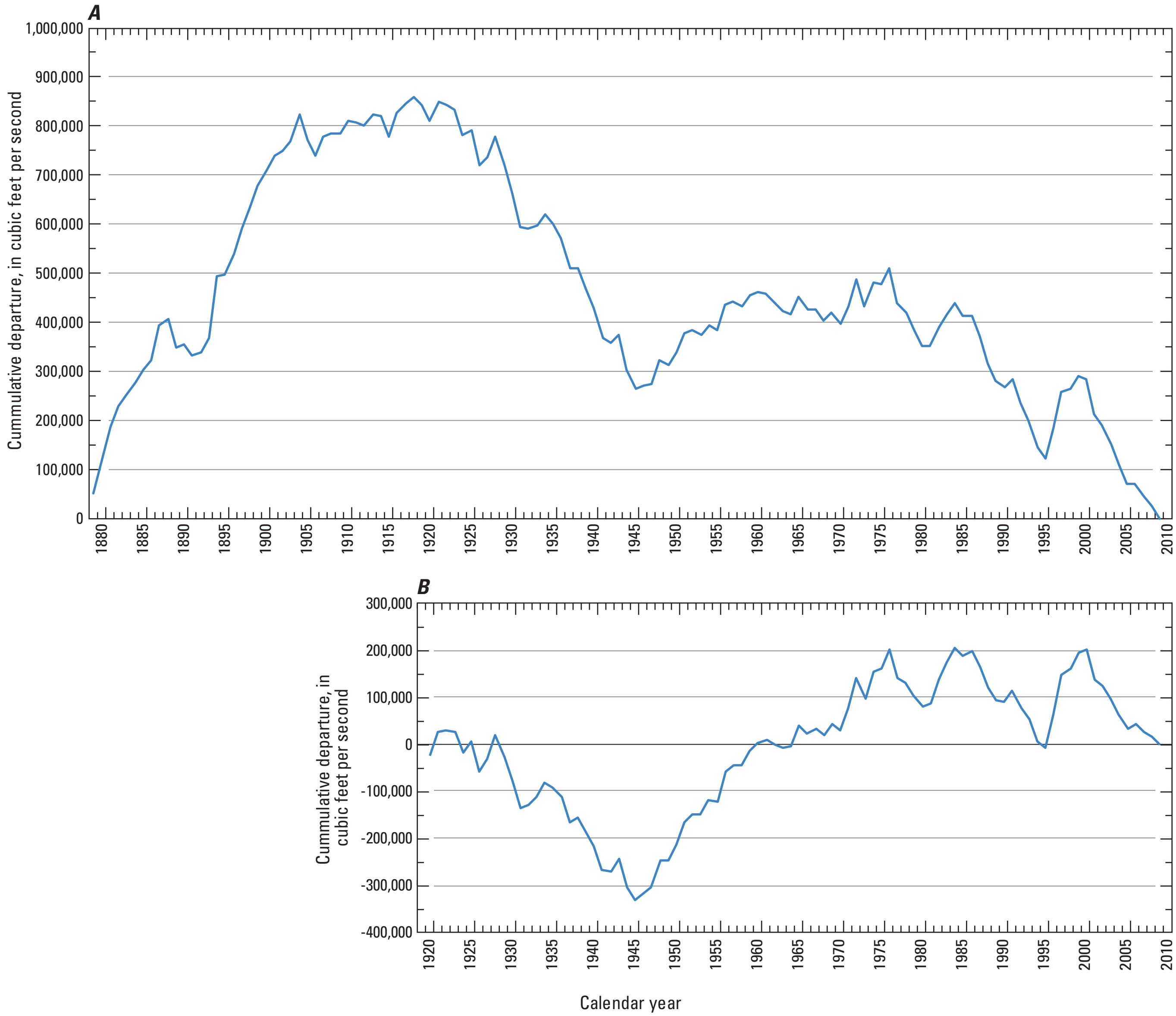


Figure 35. Cumulative departure of annual streamflow from average annual streamflow for the Columbia River at The Dalles, Washington, (*A*) 1879–2009, and (*B*) 1920–2009.

indicates these three broad periods, especially the earlier SCDs of releases after 1976. The general relation to the PDO is recognizable in the SCD pattern, as is a general relation to the Southern Oscillation Index—a measure of the El Nino-Southern Oscillation phenomena (fig. 37). Most of the early (pre-May 31) SCDs after 1976 correspond to years in which junior surface-water users obtained less appropriated water and groundwater pumpage increased because of the use of standby/reserve water rights. Thus, these interdecadal climate variations have a large effect on water use, water management, and water-budget components.

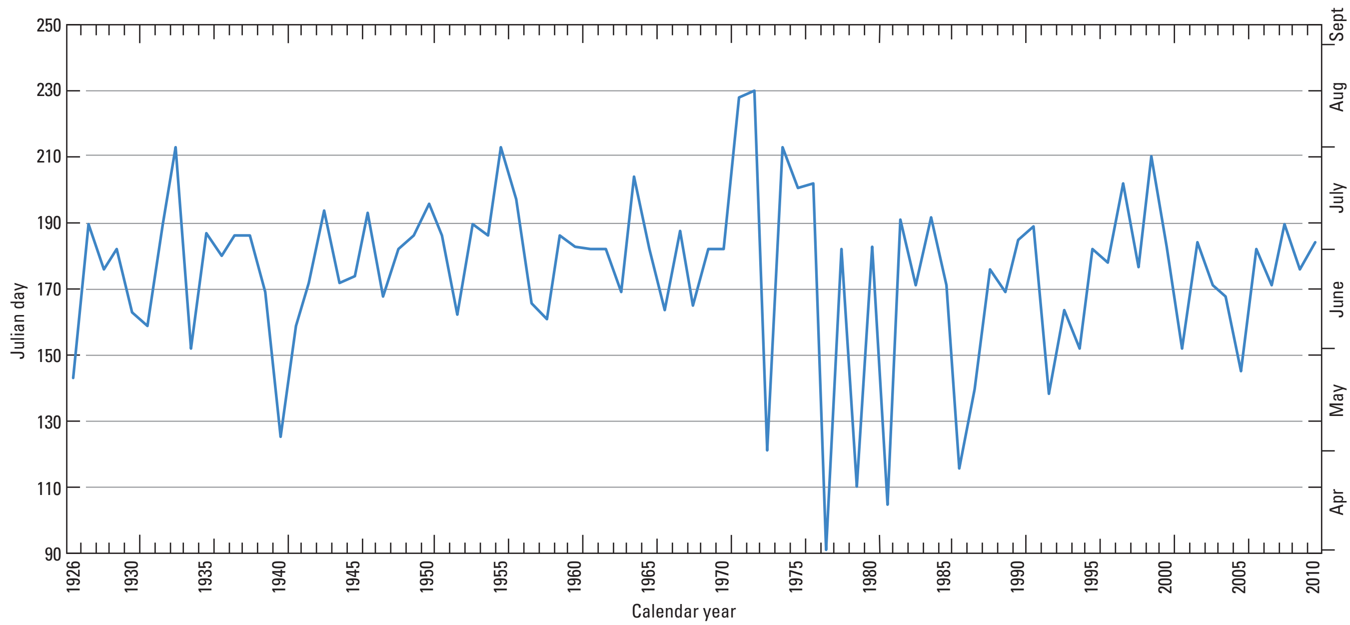


Figure 36. Storage control dates for reservoirs in the Yakima River Basin, Washington, 1926–2010. Data from C. Lynch, Bureau of Reclamation, written commun. (2011).

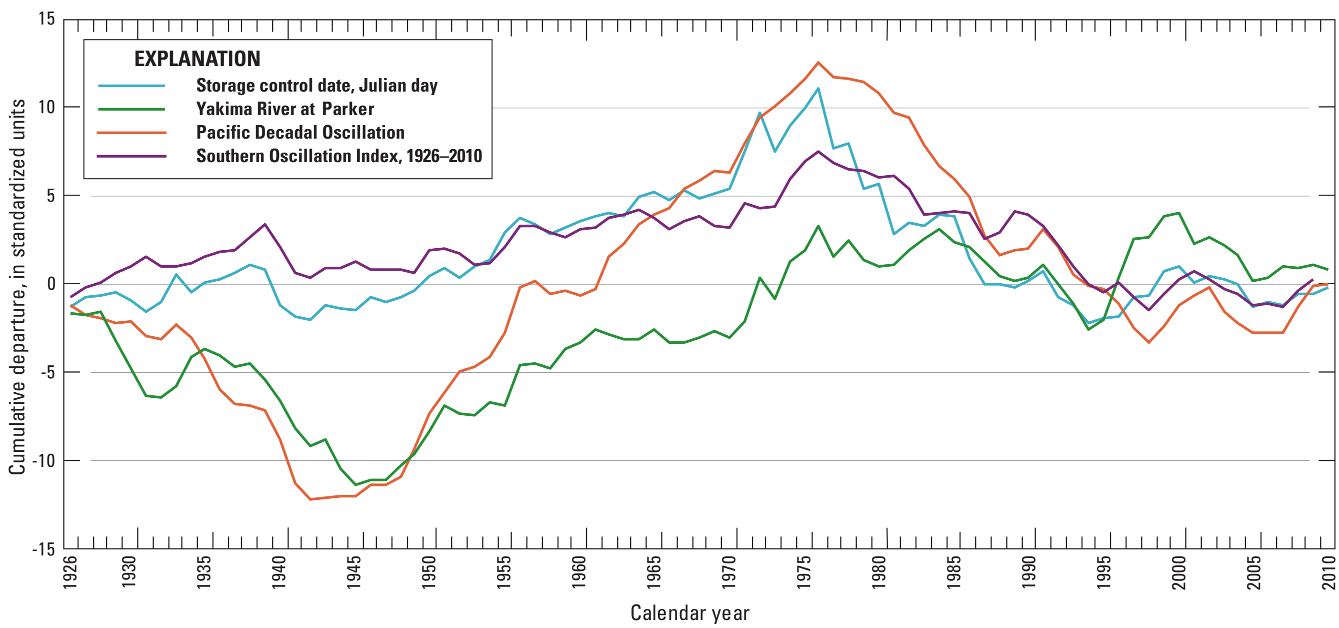


Figure 37. Cumulative departure from 1926–2010 average of standardized values of the storage control date; streamflow at the Yakima River at Parker, Washington; the Pacific Decadal Oscillation; and the Southern Oscillation Index, 1926–2010. Data from C. Lynch, Bureau of Reclamation, written commun. (2011), (http://www.jisao.washington.edu/data/pdo/), and University of East Anglia (2011).

Future Climate Projections

Global Climate Models (GCMs) are ideally suited for analyzing projected climate change because the hydrometeorological regime in the Pacific Northwest is forced by and clearly linked to atmospheric-oceanic circulation. Information suggests that the climate of the Pacific Northwest is already changing (Bureau of Reclamation, 2011) and that the trends are partially owing to human effects (Barnett and others, 2008; Levi, 2008). Results from GCMs indicate that the hydrologic conditions of the study area will continue to shift from historical conditions. Although the exact extent and timing of the long-term changes remain unknown, the projections include increased air temperatures, some changes in precipitation, reductions to the snowpack (more precipitation in the form of rain), earlier snowmelt, possibly larger floods, and other phenomena (Bureau of Reclamation, 2011).

Using GCMs, the Intergovernmental Panel on Climate Change (IPCC) (2001, 2007) analyzed four scenarios, including three future emission scenarios that represented different levels of carbon emission during the 21st century. The future emission scenarios represent different patterns in greenhouse gas emissions and concentrations, from relatively low (B1), to medium (A1B), to high concentrations (A2) during the 21st century (Intergovernmental Panel on Climate Change, 2007). Results from 20 of the 2007 IPCC GCMs for the A1B scenario were used for a climate-change impact assessment for Washington State, and indicate an average increase in air temperature of about 2.2 °F by the 2020s, 3.5 °F by the 2040s, and 5.9 °F by the 2080s (Climate Impacts Group, 2009). According to a 2011 Washington State legislative report (Washington State Department of Ecology, 2011), the 2030 water-demand forecasts using model input forced by the IPCC GCMs indicate that “Water availability will shift away from the irrigation season when demands are highest” and water supply will increase between November and May and decrease by up to 21 percent from June through October. With increased temperatures, ET rates are expected to increase, as would the length of the growing season. As with the Central Valley in California, “other indirect effects of a temperature increase include earlier budding of orchard crops, premature ripening of crops (particularly grapes), the increased ability to grow more than one crop in a season, and reduced milk production from dairy herds” (Faunt, 2009). Together, all these projected changes “undermine a basic assumption that historically has facilitated management of water supplies, demands, and risks” (Milly and others, 2008).

Decreases in snowpack would affect reservoir storage and would be complicated not only by earlier runoff, but by any increased variability in precipitation that would place more stress on the reliability of existing flood management and water-storage systems. Increased ET would result in increased water demands, which would occur with concurrent reductions in late spring and early summer runoff. Less groundwater recharge in the mountain uplands for part of the study area may occur if there is no increase in precipitation (Mastin, 2008; Climate Impacts Group, 2009). Reductions in the amount of water available for recharge and storage during the dry season are likely to occur, and such reductions would affect the amount and timing of groundwater pumpage.

To improve our understanding of the potential effects of climate change on the groundwater system, a simplified analysis was completed for this report. In this analysis, the projected monthly maximum and minimum air temperature changes and percent change in precipitation calculated from six GCMs were down-scaled to the central part of the study area (L. Hay, written commun., U.S. Geological Survey, 2011). The median of the six GCM results (mostly changes in the maximum/minimum air temperature and precipitation) from the A1B medium emission scenario of the IPCC assessment were used in this simplified analysis. It should be noted that as of 2012, the current global emissions are larger than the “high” emission scenario (A2) of the IPCC and, thus, the results likely are conservative in terms of warming. The median projected A1B changes were used to modify, on a monthly basis, historical daily climate at five locations (all of which were existing weather sites). The modified climate series were then used to drive the DPM under various crop types and land covers for each site. Potential changes in recharge and projected increases in irrigation pumpage owing to increased crop potential evapotranspiration were estimated from DPM.

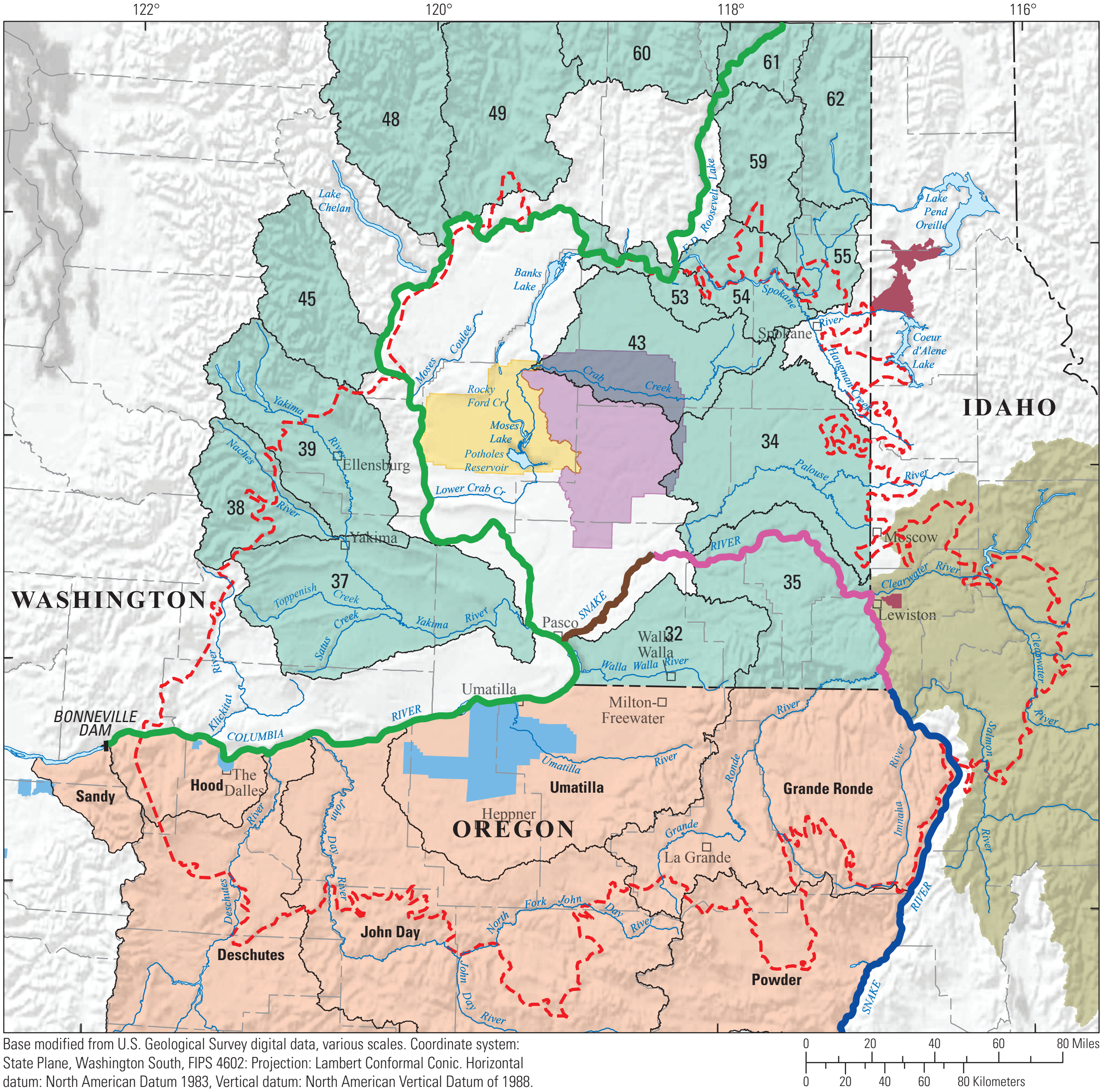
Results from the six GCMs used in this study and the 20 GCMs used in the Washington State impact assessment all show reasonably consistent trends (“consensus”) in warming, but large differences in precipitation changes—from decreases to increases. Results from the operation of DPM under different projected GCM changes in precipitation indicated that any change in precipitation can have a corresponding large effect on recharge and ET. The CPRAS is a transition area between the 20-GCM “consensus” on increasing or decreasing precipitation and, thus, it is unknown as of 2012 what changes may occur in precipitation under the emissions scenarios. This aspect is very important because any changes in precipitation (increases, decreases, and seasonality) will have a large effect on the groundwater system, including water demand. Therefore, the groundwater model was operated with the "current" conditions (2000–2007; Ely and others, 2014) recharge, but with pumpage increasing by 13 percent from 2007 to 2050. The pumpage increase was the average of the increase in crop-water demand for the specific crops types, which included wine grapes, hops, corn, mint, wheat, apples, and row crops, at the locations with irrigation that were modeled with DPM. The largest increase in crop water demand was for wheat, apples, and mint, and the smallest increases were for grapes and hops (the lower increase for those two crops is partly related to them being modeled with DPM using below-canopy/drip irrigation in contrast to above canopy irrigation). The primary result of this analysis is that crop water demand can be expected to increase in the future and add more competitive demands on the available water supply. Some of the results from this analysis are presented in the next section.

Groundwater Availability and Sustainability

Groundwater availability is a function of the quantity and quality of water, and also the laws, rules, regulations, and socioeconomic factors that control its demand and uses (Reilly and others, 2008). Groundwater sustainability can be defined as the achievement of an acceptable tradeoff between groundwater use and the long-term effects of that use (Alley, 2006). Sustainability requires an iterative process of monitoring, analysis, and application of management practices (invariably through State regulations). Groundwater availability and, ultimately, its sustainability in the study area is an issue that is interrelated to groundwater management and the availability and use of surface water. Water management, in turn, generally is intricately related to environmental protection and public health, and availability, thus, is related to conflicts between consumptive use and instream uses (both diversionary and instream flows).

The concept of sustainability is inherently subjective and ambiguous. This is because what is or is not considered sustainable is based partly on social and philosophical issues that change with time (Alley and Leake, 2004). Factors that limit sustainability include physical, chemical, economic, environmental, legal, philosophical, or institutional factors (Faunt, 2009). These issues were discussed as far back as 1958 by Leopold (1958), who also described the importance of the interrelationship between economics and sustainability. Leopold (1990) also stated that the "integrity of the hydrologic continuum is implied in the explicit term 'sustainability' and the dynamic flexibility to adjust constantly through changing circumstances." Like the Central Valley Aquifer study (Faunt, 2009), this study focused on the physical constraints that may affect groundwater sustainability.

An overarching control is the laws, rules, and regulations codified in State law (see appendix 1) that ultimately affect water availability and, thus, sustainability. Limited surface-water and groundwater availability during the "dry" season (when water demand is greatest) in large parts in or near the study area is shown in figure 38; these constraints on availability are defined by existing laws and rules, or are based on recommendations of State, Federal, and Tribal fishery biologists. For the recommendations, there are Water Resource Inventory Areas (WRIAs) not shown on figure 38 that are administratively limited, and water-rights decisions are based on these recommendations. For example, as of 2012 for the Columbia River upstream of Bonneville Dam, there are 379 water-right holders in Washington who are subject to instream flow requirements for salmonids; these interruptible rights total some 309,000 acre-ft of water (Washington State Department of Ecology, 2014). There are numerous added complexities related to legal constraints and water availability. In Washington State, for the Columbia River Basin upstream of The Dalles and downstream of the confluence of the Spokane River with the Columbia River, annual water-right allocations for surface water and groundwater are 9.5 and 3.4 MAF, respectively, and at The Dalles, annual instream flows are on the order of 72.5 MAF (Washington State Department of Ecology, 2011). Even with this large disparity in quantities, the diversions for interruptible rights have been reduced or shut off in dry years, and, at times, instream flows were not met. As a further complicating factor, in Washington, there are an order of magnitude more surface-water and groundwater claims with a listed quantity (many do not list a quantity) than permitted and certificated rights. Many of these claims may not be valid because of non-additive rights—claims that were filed for the same uses authorized through permits and certificates, groundwater claims that may be covered under the exempt statutes (a permit already exists), or spurious claims. For example, Vaccaro and Sumioka (2006) estimated that of 16,605 groundwater claims in the Yakima River Basin, less than about 2,000 may be valid. Until the claims are analyzed through a judicial process (adjudication), they are legal 'paper rights" that must be brought into the mix of managing for water availability. In the overallocated Walla Walla River Basin, there are 45 times more claims than existing rights. If only 3 percent of these claims were valid, there would still be more claims than existing rights, indicating the potential extent of this complicating factor. Sorting out the claims "would probably require a team to look at each water right permit, certificate and claim (both ground and surface water), and compare uses to prevent double-counting, as well as conduct some simplified extent and validity analysis. That effort would be considerable." (M. Shuppe, written commun., Washington State Department of Ecology, 2011.) Entering into this dynamic are a mosaic of rulings from court cases and Federal intervention in State water policy in response to a State request or when State law encroaches on the U.S. Constitution.



EXPLANATION

WASHINGTON

Quincy Groundwater Management area—Limited groundwater availability

Odessa subarea—New groundwater not available for irrigation or M&I

32 **Surface-water basin**—WRIA: over-appropriated, fully-appropriated, or limited appropriable; groundwater availability limited, typically with mitigation

Columbia River—No new irrigation water right during April–August, M&I water is available with mitigation

Snake River—No new irrigation water right during April–August; M&I water is available with mitigation

Snake River—Water may be limited during April–August

OREGON

Critical groundwater and restrictively classified management areas— Groundwater availability limited for most uses

Hood **Basins with limited available surface water**—During low-flow period; groundwater available for selected uses

Columbia and Snake River—No new water rights during April 15–September 30 (limited exceptions)

IDAHO

Water available through appropriation process—However, surface water or groundwater may be limited locally (permit denied or conditioned)

Groundwater-management area

Boundary of study area

Note: Domestic (exempt) groundwater available in most of the study area; Columbia River is for the river upstream of Bonneville Dam; M&I, municipal and industrial; WRIA, Water Resource Inventory Area

Figure 38. Existing "dry"-season water-availability constraints for parts of Washington, Oregon, and Idaho (see appendix 2).

Limited surface water indicates that groundwater would necessarily need to be part of the future water-availability dynamic. However, in overallocated basins such as the Yakima and Walla Walla River Basins, most new, larger (and in some cases even small exempt) groundwater withdrawals need to be mitigated for senior surface-water diversionary rights and instream flows. In Oregon basins, during times of water shortage the junior users are regulated, especially during the summer low-flow season, and by the end of summer for some streams, water is available only for users with water rights established in the late 1800s (Oregon Water Resources Department, 2014). As with the Yakima River Basin in Washington, many of these junior surface-water users switch to groundwater when their surface-water right is unavailable. Most of the junior surface-water rights are senior to groundwater rights in Oregon; thus, "dry" season groundwater availability may be limited in the future. Overall, groundwater availability in the study area is controlled by (1) the problem of variation and timing of precipitation (resulting in the "dry" season legal constraints shown in figure 38), and (2) the relation between pumpage, recharge, and supply of water to wells—that is, the actual and potential for decreases in aquifer storage. For the problem of variation and timing of precipitation, Wolman (1986), in discussing water and human health, identified this aspect in simple terms: "*Water is not and will not always be available at the right place, at the right time, and at a minimum cost.*"

The "dry" season constraints are a result of the need to (1) manage the effects of historical water-development practices (described for the groundwater system in the section, "Changes to the Water Budget between Predevelopment and Existing Conditions") and legal constraints; and (2) manage existing conditions for environmental protection, especially for salmon recovery, including its interrelationship to ESA listings. That is, salmon recovery efforts in the Pacific Northwest greatly influence water availability by the establishment of target or instream flows by the Washington State Department of Fish and Wildlife, Indian Tribes, the National Oceanographic and Atmospheric Administration, or the U.S. Fish and Wildlife Service. Water availability and sustainability can be addressed by estimating the water in storage in the system, fluxes within and through the system, and uses of water, and by describing the legal and ecological framework. This was partly achieved by overlaying the groundwater changes simulated by the CPRAS model for long-term (2050) equilibrium conditions with existing water-management strategies shown in figure 38. The potential future (2050) system under a set of conditions yielding increased pumpage demand estimated to occur with a changing climate is additive to the existing conditions in the future with large water-level declines.

The term "groundwater reserves" is used to emphasize the fact that groundwater, like other limited natural resources, can be depleted (Alley, 2006). Depletion of aquifer-system storage by pumpage has been substantial for many areas in the study area, especially for the Odessa subarea in Washington and the critical groundwater management areas in Oregon. Water-level records and previous studies (Whiteman and others, 1994; Vaccaro, 1999) confirm that large amounts of water were removed from storage in the basalt units prior to 1985. The groundwater-model simulation results for this study also indicate that, since predevelopment times, the basalt storage in areas of groundwater-level declines has been depleted by more than 10 MAF in the Wanapum unit alone. Measured water levels from this study also verified continued declines in the basalt units over large areas and that declines have expanded to other areas (Snyder and Haynes, 2010; Burns and others, 2011). It is unknown if the loss in storage has caused any subsidence or a decrease in pore space, but if so, it may affect the ability to artificially recharge the system in areas of widespread and large water-level declines. The long-term decrease in aquifer-system storage represents a substantial wedge of the water stored in the upper 500 ft of the basalt part of the CPRAS. In comparison, the decrease in storage relative to the storage in the complete system is very small. However, as a practical matter, it is impossible to remove all water from storage by pumpage because many factors limit the amount of water that can be recovered. Important institutional factors (such as use restrictions, basin adjudication, and surface-water rights) limit the availability of water because even small storage changes can have large effects or repercussions because of these institutional factors. Similarly, aquifer-system hydraulic characteristics, well yields, the cost of drilling wells, the cost of energy for lifting water, and the design of the well and pump can limit the availability of water. These hydrologic limitations are amplified by the institutional factors.

Given long-term equilibrium conditions (using 2007 pumpage and average recharge for 2000–2007 simulated through 2050), results of CPRAS model simulations indicated large areas of water-level declines (fig. 39), and these results were consistent with those estimated by the CP-RASA (Bauer and Hansen, 2000). In these areas of declines, groundwater availability may be limited hydrologically or by regulations, or it already is limited (such as in the Odessa subarea, the Walla Walla River Basin, and the critical groundwater and restrictively classified areas in Oregon [fig. 38]). In some areas (especially those with downward vertical gradients), these declines have been aggravated by the draining of upper units owing to numerous large-capacity uncased wells (Ely and others, 2014). Declines may result in changes in surface-water quantity and quality, and (or) reduction of the economic viability of groundwater irrigation because of increased energy costs with the increased pumping lifts. Declines can factor into environmental issues, in turn, by changing and (or) degrading habitats if groundwater discharge to surface-water bodies decreases, and these related effects may constitute the primary constraint to groundwater development. For example, in the Yakima River Basin, Ely and others (2011) determined that groundwater pumping with junior rights is affecting streamflow and, thus, senior surface-water rights, including time-immemorial Tribal rights for sustaining anadromous salmonid populations. In particular, Washington State defines impairment of surface-water rights by groundwater pumping if one molecule of surface water is captured. Under long-term 2043–2050 conditions with 2007 pumpage, groundwater discharge to streams in the model area was estimated to decrease by an additional 623 ft^3/s. Thus, during periods of drought (and perhaps even the normal summer low-flow period), some streams may not have enough groundwater inflow to sustain environmental flows. Surface-water diversions and groundwater pumpage aggravate this problem. Indeed, with the average potential increase of 13 percent in pumpage owing to increased water demand under a changing climate, the model simulated a large decrease in groundwater discharge by 2050. This decrease was owing to groundwater declines resulting in an additional loss in storage in 2050 of more than 713 ft^3/s (this is compared to 2007 and is not cumulative loss, which is much larger); the decrease in basalt storage by 2050 exceeds 5 MAF and declines extend over more than 20,000 mi^2 in the Wanapum unit alone. The 13 percent increase represents an average crop-water demand change for various crop types. However, some crops that are prevalent on the Columbia Plateau, such as orchards and wheat, were estimated to have a more than 20-percent increase in water demand. Thus, the effects of increased pumping owing to warming likely will be larger than estimated. This aspect is especially important because of the total dollar value of perennial crops such as apples, cherries, grapes, and mint. If senior surface-water users have an increased need for irrigation to meet crop-water demand, then both junior surface-water uses and groundwater uses may be limited. This aspect was not addressed in this study but would need to be analyzed for future water-management strategies.

The population in the study area is projected to increase by 150,000 people by 2030, but growth in most of the counties will be less than 1 percent. Although small, this projected growth will add some 27,000 acre-ft to the competing demands for limited water resources (Washington State Department of Ecology, 2011), and the economics of municipal water supply may result in the purchase of agricultural water rights. Even with population growth, however, agriculture will continue to consume substantially more water than public water-supply systems and domestic uses. Although agricultural acreage has stayed relatively constant since about 1992, water deliveries for irrigation have been reduced through greater efficiencies in recognition of environmental needs. Although these trends in efficiencies are projected to continue, there is a forecasted increase in irrigation demand of about 10 percent by 2030 (Washington State Department of Ecology, 2011), as shown by the potential increase in crop-water demand due to climate change. Ongoing negotiations between the United States and Canada on a new Columbia River Treaty also may affect future demand, especially for users of Columbia River water.

Without increased storage, the projected changing surface-water regime with earlier runoff because of less snowpack will lead to larger water demands during the summer low-flow season. If the amount of surface water available during the dry season decreases, the amount and timing of groundwater pumpage ultimately may be affected. These effects are in addition to increased crop-water demand, and also to a potential decrease in summer base flow caused by the earlier snowmelt and recharge period. The projected effects also may decrease the number of years in which water demands for agricultural uses are met, which in some years already are not met. Assuming these climate projections are correct, decreases in groundwater storage likely will continue in some areas, perhaps at an accelerated rate. Additionally, new environmental uses may lead to even larger instream water demands.

The potential effects of global climate change on agricultural water demand are not understood thoroughly. Agricultural water demand is influenced by climate, crop selection, input costs, and farming practices. Crop selection

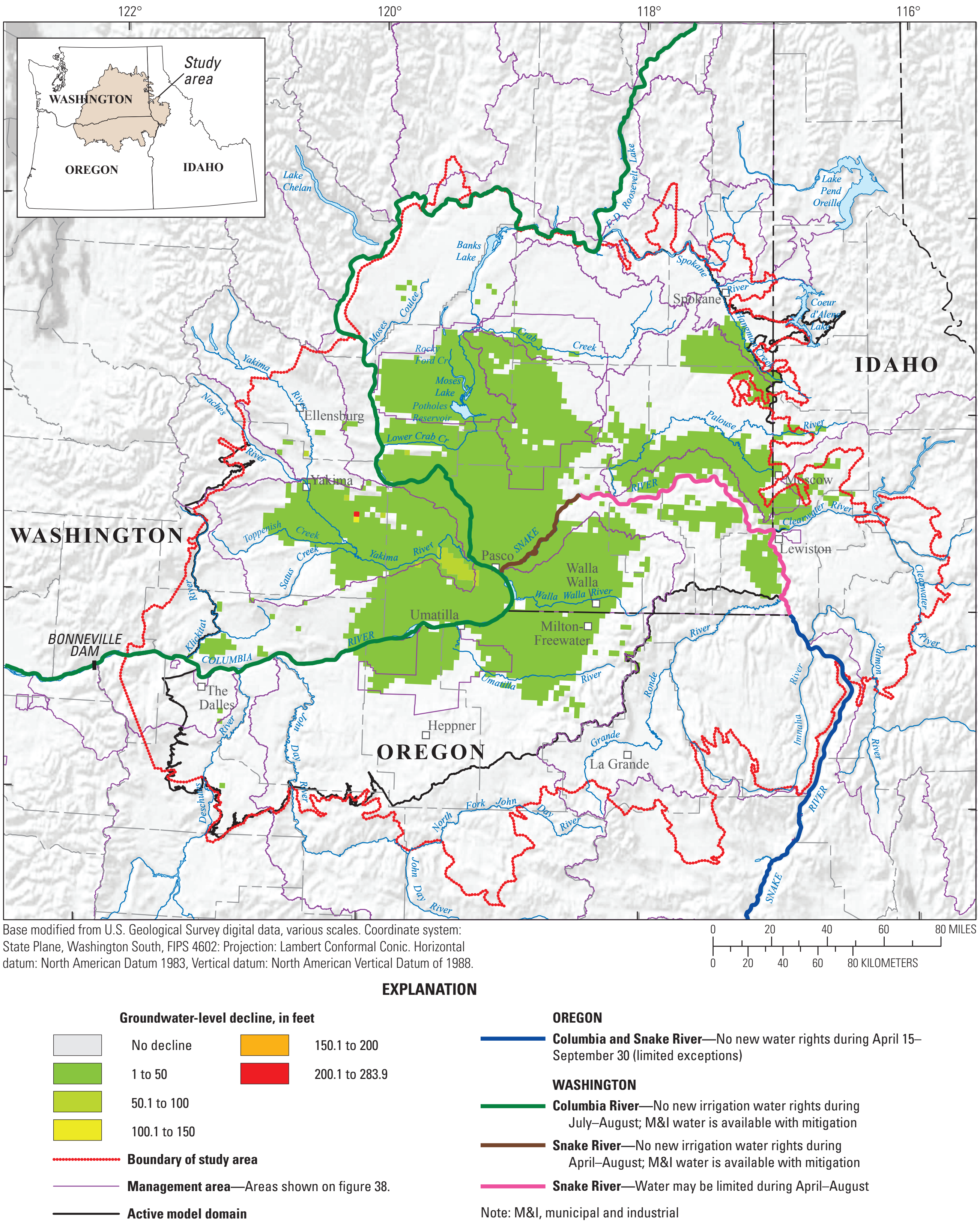


Figure 39. Simulated long-term (2007–2050) water-level declines in the Wanapum unit given average 2000–2007 recharge, and their relation to existing water-availability constraints, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

typically is influenced by market prices of agricultural commodities (both domestic demand and foreign markets, for which Washington State agricultural exports exceeded $10 billion in 2012), but water availability enters into the mix. The large quantity of irrigated lands in the study area dedicated to perennial crops such as apples, cherries, asparagus, grapes, hops, hay, and alfalfa (most of which have a large water demand) makes changing crop types difficult, but water limitations may result in a changing crop mix or a decrease in total acreage planted. As an example, with the dry conditions in 2014 for the Central Valley in California, some almond farmers have pulled at least 20 percent of the trees from their orchards because of the lack of irrigation water (NBC News, 2014). Almonds are one of the most high-value crops in the Central Valley; however, energy costs and poor water quality generally limit additional groundwater pumping. Indeed, in parts of the CPRAS, the deepening of irrigation wells because of declining water levels has led to the need to mix water because of the poor quality of warm, sodium-rich water from the deeper part of the system. Effects of historical usage indicate that in many areas, the groundwater system cannot meet existing demands indefinitely, and any increased groundwater use under a changing climate will only increase the competitive demand for the limited resource. For example, the cities in the Odessa subarea cannot sustainably “chase” declining levels without encountering poor-quality water with higher energy costs and attendant costs of treatment.

Thus far, farmers have adjusted their practices to grow more crops per acre-foot of applied water, especially in drought years such as 2001 and 2005. The increased efficiencies result from changes in crop type, increased efficiency in the delivery and use of irrigation water, improved productivity, and other changes in farming practices. In some areas of groundwater irrigation, less land is being cropped, for example, by irrigating three 160-acre circles instead of four, because of declining water levels and or additional water needs during dry, warm years. Even with improvements or less cropping, groundwater storage loss has continued to occur from 1985 through 2014. Based on the simulated flow system under 2050 conditions, groundwater will continue to be removed from storage (fig. 39) and the availability of groundwater will decrease.

Implications for Groundwater Management

Since the late 1970s, State and Federal water projects have not expanded with growing urbanization and the increased agricultural and environmental uses of water on the Columbia Plateau. Although irrigated agriculture continues to use most of the groundwater, other categories of groundwater use have increased (fig. 23*B*). The study area faces ongoing and projected increases in competing demands for water resources, none of which are likely to be met by improvements in agricultural efficiencies. These demands include providing water for a growing population, agriculture, and environmental uses. The demand for water resources by people directly competes with environmental uses such as maintaining minimum streamflows and preserving fish habitat, and this competition also is expected to increase. The interrelationship between these competing demands and legal constraints is clearly indicated by the spatial distribution of more than 45,000 groundwater (exempt wells not shown) and surface-water rights for Washington and Oregon, and 30,000 claims for Washington (fig. 40). Importantly, figure 40 does not show many of the instream or target flows, nor does is show the thousands of outstanding applications for new water rights.

An integrated water-management approach could help meet competing demands. An analysis of the future conditions for water demand in the Columbia River Basin stated that groundwater dynamics need to be incorporated in the analysis of water supply and agricultural irrigation demand modeling because of its relation to surface water (Washington State Department of Ecology, 2011). Ongoing and increased use of management actions includes enhancements in conjunctive use of surface water and groundwater, artificial recharge, and the use of recycled or reclaimed water. The development of new, off-stream surface-water storage also can be a viable option (Washington State Department of Ecology, 2012b), but finding sites and mitigating environmental consequences is proving to be elusive. Artificial recharge may be approached in two ways. The first way is the use of injected water by major users, which currently is limited to several large municipal systems. The second way includes the spreading of water to recharge larger areas of the groundwater system and taking advantage of irrigation canal losses by running water through the delivery/drain network prior to the irrigation season. The second way would produce the most benefit for long-term sustainability of the resource under existing and future conditions (replacing lost snowpack) within the areas where surface-water networks exist. This method could provide water in the shallow system for both groundwater and surface-water uses, and perhaps delay the release of reservoir water to meet demands. Karlinger and Hansen (1983), however, indicate that an artificial-recharge-irrigation operation may not be an economic alternative to a surface-water irrigation system in groundwater areas. Indeed, the Washington State Department of Ecology and Reclamation have analyzed the expansion of the CBP into the groundwater-irrigated areas in place of artificial recharge (Bureau of Reclamation and Washington State Department of Ecology, 2010; see also Washington State Department of Ecology, 2015).

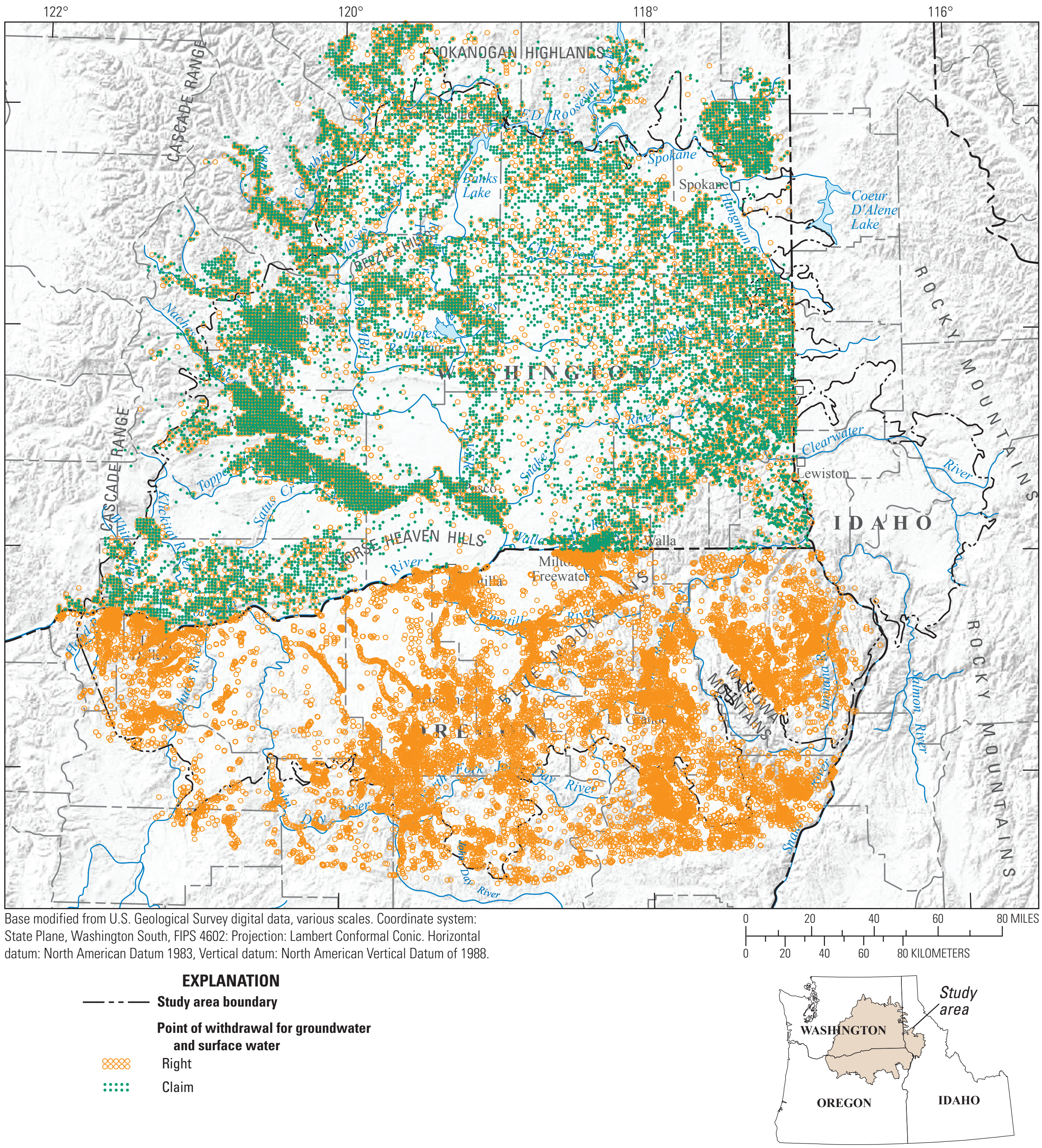


Figure 40. Distribution of points of withdrawal for groundwater and surface-water rights and claims in Washington and Oregon in or near the Columbia Plateau Regional Aquifer System study area, Washington, Oregon, and Idaho.

Monitoring the Hydrologic System

The assessment of water availability, both groundwater and surface water, is dependent on monitored data. Surface-water data are intricately tied to groundwater availability because most senior water rights are for surface water, and these rights may be impaired by groundwater pumping—there is a limit on available water. Monitored data include streamflow, water-level, and water-use. Each of these data components was integral in the assessment of groundwater availability for the CPRAS. The first two categories are discussed in the two subsections that follow. Water use was discussed in depth by the National Research Council (2002); within the study area, the USGS does not directly monitor or estimate water use except as part of individual water-resource investigations such as in the CPRAS study. The USGS compiles water-use information by county and State every 5 years (for example, see Lane, 2009) as part of the National Water-Use Information Program (http://water.usgs.gov/watuse/wunwup.htm). Water quality can affect water availability, and water quality in the CPRAS is monitored by many entities. Water quality has been monitored and described for large parts of the study area as part of the USGS National Water-Quality Assessment Program, and a summary of the studies in the study area and the program is available at http://wa.water.usgs.gov/projects/ccyk/. The potential water-quality effects on availability were beyond the scope of this study, as was a description of the monitoring of quality.

Surface Water

Monitoring of surface water on the Columbia Plateau has a much longer history than groundwater monitoring. Early settlers used the surface waters for irrigation and livestock needs, but the apportioning of water among users (water law) quickly became an issue. Only with measurements of streamflow could water be properly apportioned.

The monitoring of surface water by the USGS in the study area began in 1878 for the Columbia River at The Dalles. After that time, USGS streamgage sites were established on streams in or near the study area starting about 1893, especially in the Yakima River Basin. Many of these early sites were used to monitor streamflow to provide information on the potential for power production and (or) irrigation supply (for example, see Parker and Storey, 1916). Later, some sites were established to:

- Estimate the amount of surface water that was available in a basin for allocation,
- Develop information on peak flows (floods) for flood-control studies,
- Monitor streamflow used for power production/power revenue forecasts (such as along the Columbia and Snake Rivers),
- Conduct hydroregulation studies,
- Analyze environmental effects,
- Plan for operations, or
- Define the contribution of smaller tributary basins to a larger river system.

As of water year 2012, there were 77 active and 131 discontinued streamflow measurement sites in the study area and 28 active sites measuring streamflow entering the study area (fig. 41). Various users rely on water that enters the study area, which is under legal constraints that affect water availability. Thus, measurement of streamflow entering the study area is important for understanding the hydrologic system and its uses. The discontinued streamgages include historical sites that may have operated for numerous years, such as from 1906 to 1948, and sites that were established as part of studies that may have operated for several months to several years. More than 1,800 miscellaneous measurements were made at sites in or near the study area. Data were collected at these sites for various reasons—for example, seepage investigations to estimate gains or losses along a stream, flood studies, low-flow analyses, fish-flow analyses for salmonids, and water-quality studies.

The historical, current, or real-time data for monitoring sites, therefore, are used for many purposes:

- For estimating recurrence intervals for floods,
- For flood warnings,
- For monitoring instream and target-flow quantities,
- For management of irrigation supply, and
- For management of diversions.

The sites with longer periods of record provide a base for calculating descriptive statistics (such as the 1- to 7-day low-flow characteristics) and for assessing trends over time, such as an early runoff owing to changing climate.

Groundwater

Knowledge of current and historical groundwater levels are a key component for the assessment of groundwater availability, including the status and trends evaluation (Burns and others, 2011), groundwater flow modeling (Ely and others, 2014), and availability/sustainability analysis of the CPRAS. Water-level data have been collected in the study area since about 1896, but most measurements in the study area occurred after the 1940s (fig. 42*A*), with about 5,600 water levels measured through 1939, 12,610 measured in the 1940s, and a more than doubling to about 31,100 measured in the 1950s (fig. 42*B*). The largest increase in the number

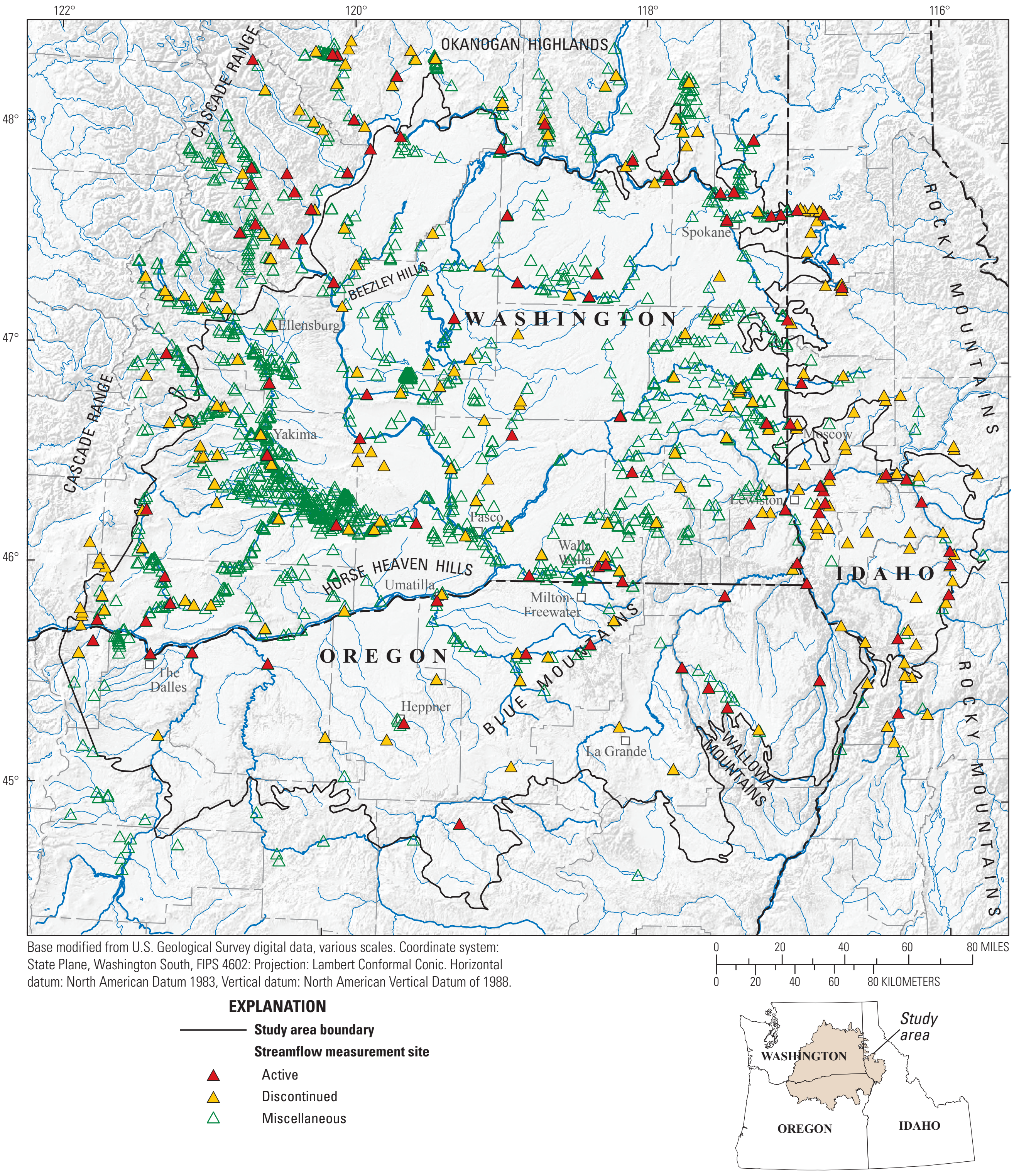


Figure 41. Location of U.S. Geological Survey streamflow measurement sites, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

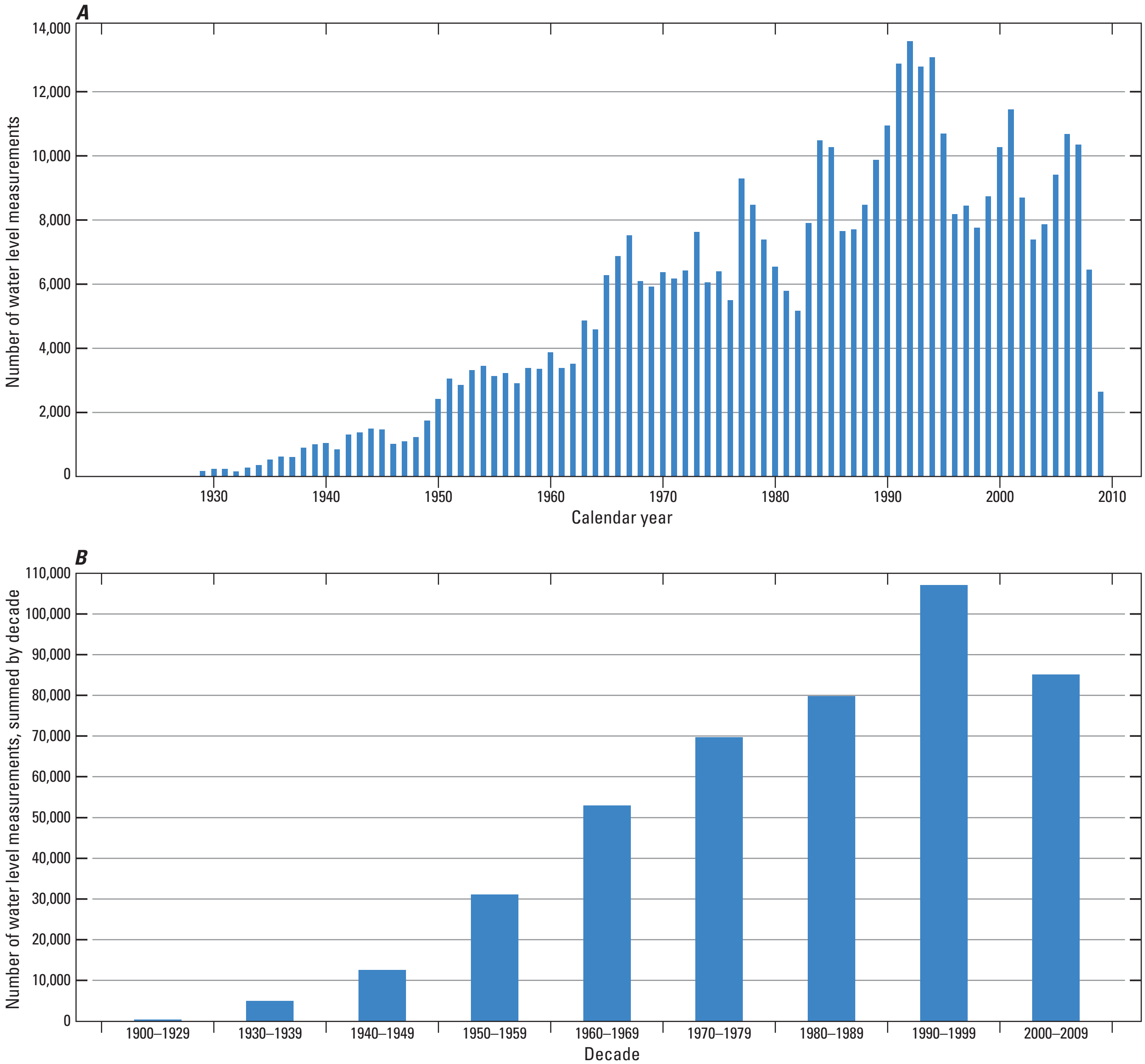


Figure 42. Number of water levels in the National Water Inventory System (*A*) by year, and (*B*) by decade, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

of measurements (27,000) occurred from the 1980s to the 1990s, with the total number of about 108,000 measurements in the 1990s accounting for about 24 percent of the more than 444,000 measurements in the USGS National Water Inventory System (NWIS; fig. 42*B*). The number of measurements ranged widely from year to year and indicated the need for more measurements as a result of population growth, irrigation increases, and environmental needs such as instream flows. The annual number of measurements is strongly related to increased measurements during droughts and the timing of groundwater studies. The distribution of more than 39,000 wells with water levels (fig. 43) indicates that much of the study area has some measurements; the distribution does not include all wells with water levels, but is a subset used by Burns and others (2011) to assess the status and trends of the groundwater system. The high density of data in selected areas corresponds to areas where groundwater sustainability is of particular concern (see fig. 38), and studies were done in these areas many years

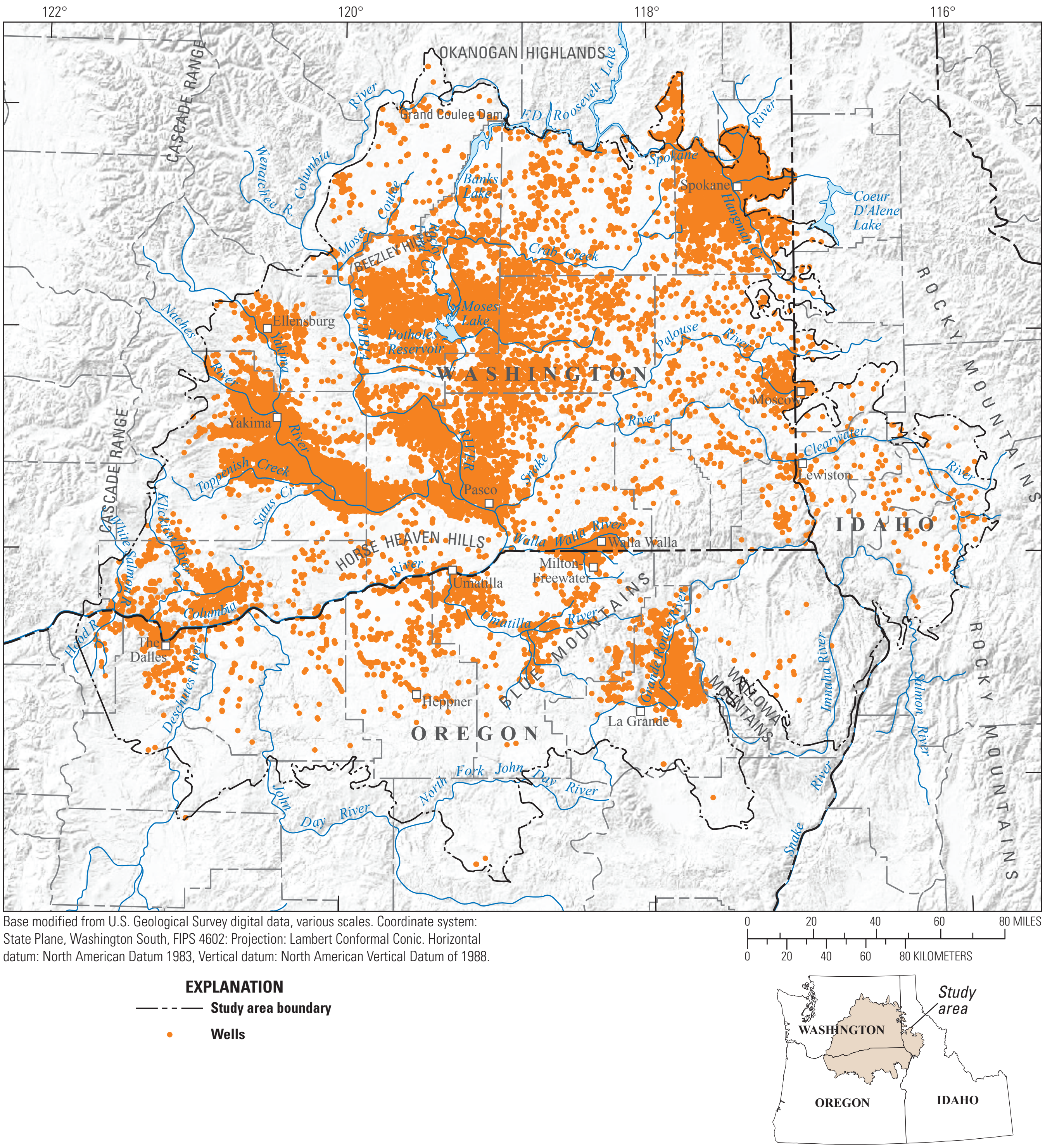


Figure 43. Distribution of wells with water levels in the National Water Inventory System, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.

ago (for example, Newcomb, 1965). Such areas of concern have expanded, as shown by the high density of data in the northeastern part of the study area. In the areas with a high density of data, the groundwater resources have been studied intensively over time, with concomitant measurements of water levels.

There are two categories of water-level monitoring. The first category includes wells that are monitored from over the course of a season to as many as several years for a specific purpose (these represent most of the water levels in NWIS), typically in support of area-specific groundwater investigations. The second category consists of networks of wells for systematically collecting long-term water-level data. Such networks were established in about the 1980s in Washington, the 1960s in Oregon, and the 1950s in Idaho by the respective State water agencies (for Idaho, USGS initiated measuring water levels in the 1950s). These long-term networks include about 905 wells that withdraw water from various hydrogeologic units; these wells are included in the distribution shown in figure 43. Many of these network-monitoring wells are in areas of declining water levels. The Washington network also includes more than 10 deep wells that contain multiple piezometers. The Yakama Nation monitors about 113 wells on Tribal lands, and hundreds of wells are monitored on the Hanford Site as part of historical and ongoing nuclear waste restoration activities. As of 2014, the USGS monitors about 110 wells in the study area.

Use of Water-Level Data

The two categories of water-level monitoring are complementary. For example, the CP-RASA monitoring of water levels over a 3-year period (1983–85) provided information to:

- Map groundwater levels by hydrogeologic units;
- Assess water-level changes over this period and compare these changes to those mapped for 1967–81 (Cline, 1981);
- Calibrate the CP-RASA regional-flow model; and
- Describe the flow system in a detailed manner, including lateral and vertical hydraulic gradients, and possible effects of geologic structure on the flow system.

Afterward, State monitoring networks (which included many of the CP-RASA monitored wells) provided information on the status and trends of the mapped groundwater levels. The CPRAS monitoring (Snyder and Haynes, 2010) incorporated the previous data to estimate the spatial changes in water levels from 1984 to 2009, and described local changes based on the information from State networks.

Hydrographs from several wells (fig. 44*A–D*) show the complementary nature of the monitoring. Early measurements were made to improve the understanding of the flow system as part of groundwater-resource investigations. Wells were then added to a monitoring network, resulting in long-term records that indicate the trends or lack of trends in water levels and potential effects on sustainability. For example, the 1,510-ft-deep well (fig. 44*A*) in the Toppenish Creek Basin in the Yakima River Basin, was measured during three groundwater investigations (the CP-RASA measurements were made in the mid-1980s), and was then added to the Yakama Nation network in 1992; additional

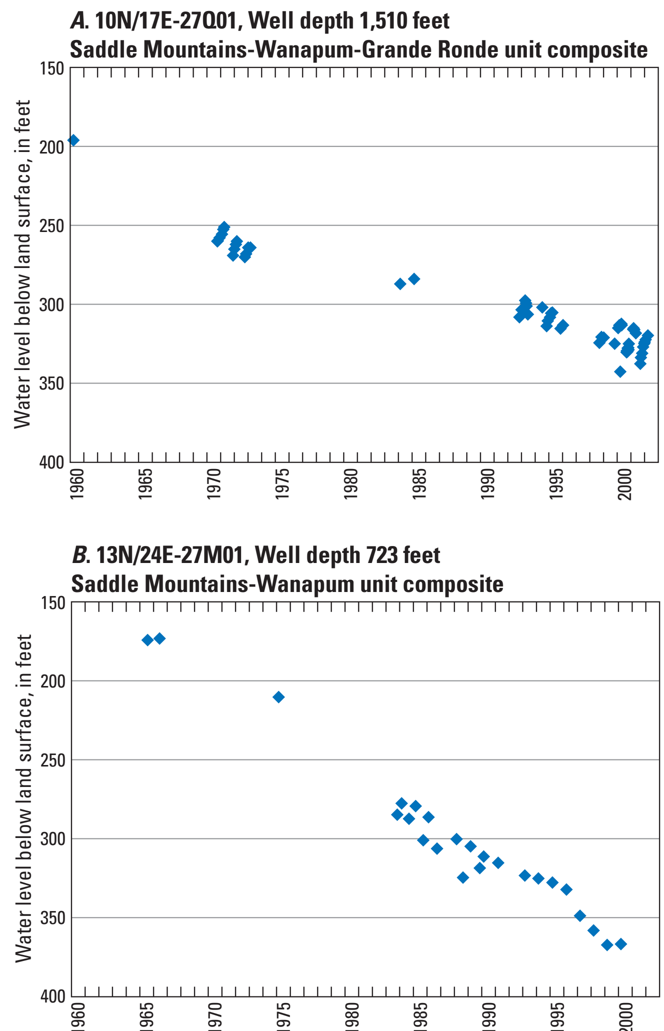
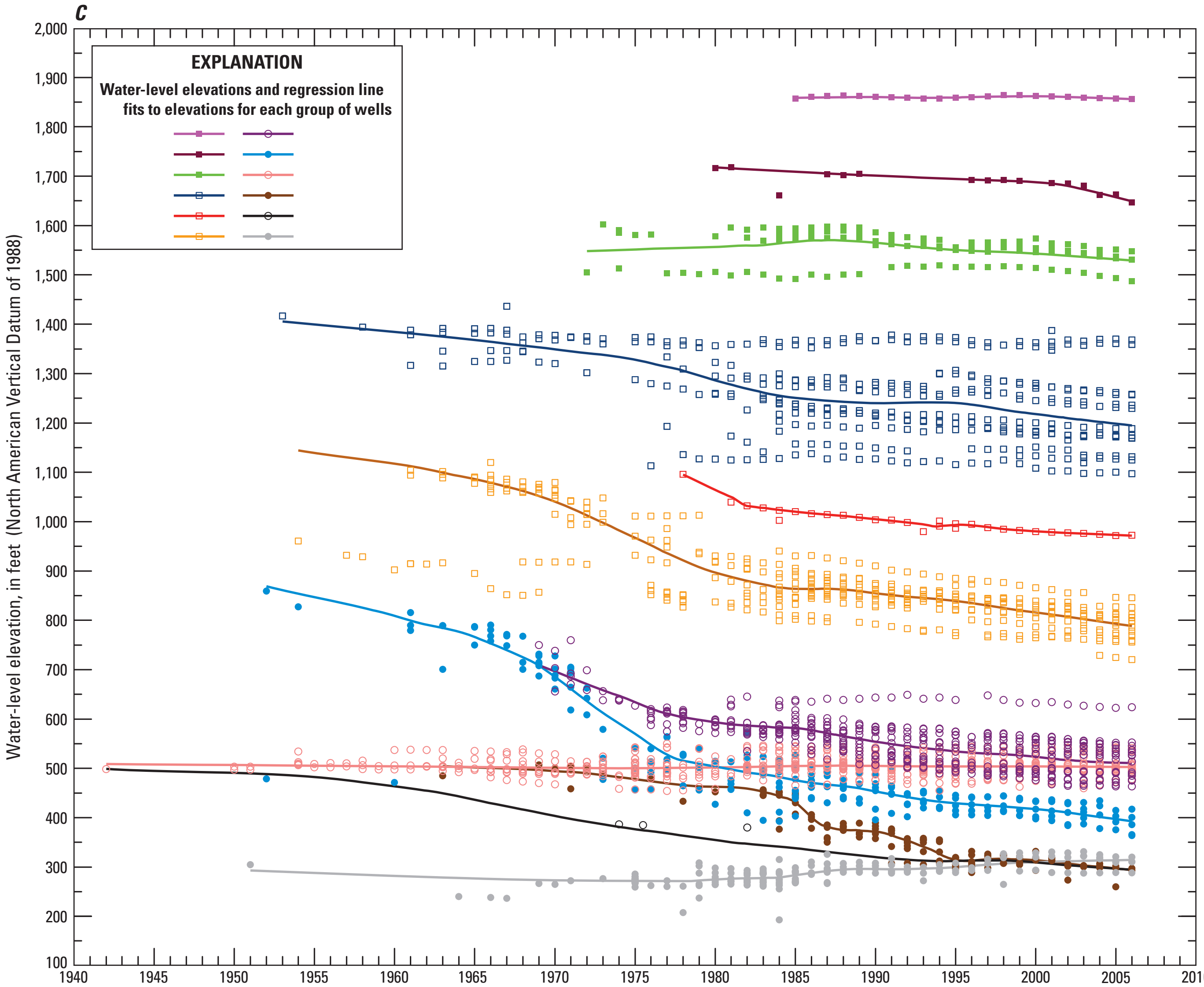


Figure 44. Water levels for selected wells in the (*A*) Toppenish Creek Basin, (*B*) Cold Creek drainage, (*C*) Umatilla Basin, and (*D*) Toppenish Basin, Columbia Plateau Regional Aquifer System, Washington, Oregon, and Idaho.



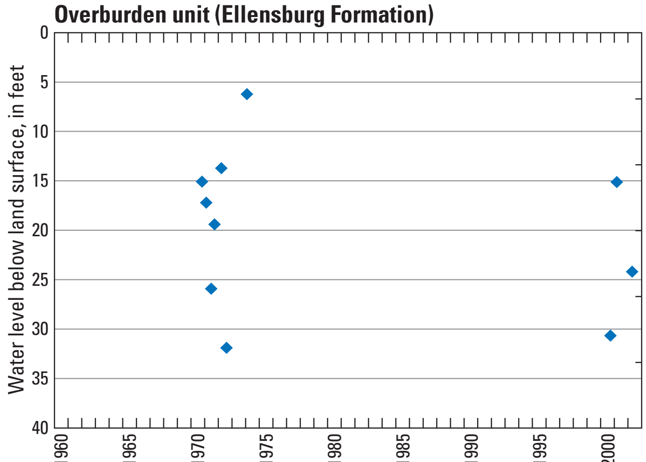


Figure 44.—Continued.

measurements were made in the earlier 2000s as part of the YRBAS study. The hydrograph of the well clearly shows a trend of decreasing water levels that are consistent with measurements from nearby deep basalt wells. Similarly, the 723-ft-deep basalt well (fig. 44*B*) north of the Hanford Site near the Cold Creek drainage was measured as part of past investigations, with Washington State adding it to their monitoring network after the CP-RASA ended. The hydrographs for wells in the Umatilla Basin (fig. 44*C*, from Burns and others, 2011) are primarily based on measurements from the Oregon Water Resources Department network, but also include measurements made during USGS groundwater investigations. These wells are in critical groundwater and restrictively classified management areas of Oregon (fig. 38), and the water levels provide information for managing the resources and understanding the complex flow system in this area (Burns and others, 2012). The complexity of the response in the aquifer system to pumping is clearly shown by the variations in water levels between these groups of wells. Even without a monitoring network, water levels measured as part of investigations at different time periods provide valuable information. For example, the 765-ft-deep well (fig. 44*D*) in the Toppenish Basin was measured during the 1970s and later during the YRBAS, and the water levels over this 30-year period indicate that there are only seasonal but no long-term trends—groundwater use seems sustainable at this location.

Future Uses of Model and Challenges to Assessing Groundwater Availability

The CPRAS hydrologic model uses a set of mathematical equations to represent an extremely complex natural system that has been perturbed by human activities. The model was constructed to simulate regional-scale groundwater flow; therefore, it can be used to address questions regarding issues at that scale that are relevant to water management. For example, on a regional scale, interactions can be considered between hydraulic heads, groundwater discharge, pumping, and flow direction and magnitude. The annual time step used in the model was selected to provide adequate temporal resolution for analyses of variations in pumping and recharge rates corresponding to numerous years of changes in recharge, irrigation practices, and pumpage. Effects of management decisions on time scales of less than a year are unlikely to be adequately simulated, but the model can appropriately be used to simulate annual changes to water-use practices, crop types, or potential future climate.

As shown by this study, groundwater availability can be evaluated with the model by examining the effects of human and climatic temporal changes on the groundwater-budget components provided by the model. An additional benefit is the ability to forecast system response to these same effects (including potential management scenarios), thus providing insights into the longer-term sustainability of the groundwater-flow system. Alternative conceptualizations of the flow system that are likely to have a regional effect also can be evaluated. These conceptualizations might include the effects of changes in recharge caused by climate change, different interpretations of the extent of geologic structure, or other conceptual models (Faunt and others, 2004). Flow direction and magnitude also may be appropriately represented using particle tracking methods, as long as the particle paths are interpreted to represent advective-transport flow paths that are at least several times longer than the length of a model cell (Tiedeman and others, 2003).

Future uses of the flow model could include optimization techniques to assist in the management of local or sub-regional groundwater problems such as substantial water-level declines at concentrated pumping centers. The potential effects of new wells on streamflow and existing groundwater users could be simulated and evaluated by using the local grid refinement package available for MODFLOW-2000.

The model cannot represent completely, or “capture,” all the physical processes within the hydrologic system. Determining if a model weakness is attributable to input data error or model shortcomings is almost impossible, but the simplifying assumptions and generalizations that are incorporated into a model undoubtedly affect the results of the simulation. The model in this study was not designed to represent every detail of the hydrologic system (a task beyond the scope of the investigation). Model results will vary based on which details were and were not included.

Acknowledgments

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Appendix 1. An Overview of Water Law in Washington, Oregon, and Idaho

The development of water resources with the concomitant economic growth in Washington, Oregon, and Idaho has been, is, and will be controlled by State water law, which, as in most of the Western United States, is the doctrine of "prior appropriation" for both surface water and groundwater. As early as 1873, the Washington territorial legislature approved the principle of appropriative water rights—the first in time is the first in right. The priority date, common to all the State water codes in the study area, establishes the temporal relation between water rights, with the oldest or most senior rights receiving water first, before later, more junior rights. This concept is important in overallocated basins or in drought years when there may not be enough water available to meet all appropriated rights and, thus, there may be no water remaining for the junior water-right holders after the more senior water-right holders receive their water. With respect to groundwater availability, the potential impairment of more senior surface-water rights by junior groundwater rights is an issue in all three states. An important aspect of the priority date is the "Winters Doctrine." This 1908 U.S. Supreme Court ruling established the principle of reserved water rights for Indian Tribes with reservations in sufficient quantities under the terms of the establishment of the reservations; the priority date of each reserved right is the date of the treaty. These rights, many of which have not been quantified, generally have much earlier priority dates than non-Indian rights. Additionally, some tribal rights associated with treaty rights in the study area are considered to have a priority date of "time immemorial." Laws of each of the three States also include a beneficial use and a "use-it-or-lose-it" provision. Beneficial uses include irrigation, municipal, livestock, domestic, and industrial uses. Use-it-or-lose-it means that if a water right is not used for beneficial use for 5 consecutive years, it may be forfeited; however, the Indian reserved rights are not bound by this provision. The creation and implementation of the water laws for the three States in the study area has directly affected the development of water resources and, thus, the economic development of the region. A brief overview of the creation of the water codes for each of the three States is provided in this appendix; a more detailed summary is available at https://archive.org/details/westernstateswat4002heco for the three States, and at http://www.idwr.idaho.gov/WaterManagement/default.htm for Idaho, http://egov.oregon.gov/OWRD/LAW/index.shtml for Oregon, and http://www.ecy.wa.gov/programs/wr/rights/water-right-home.html for Washington. The constitutions and statutes of all three States define all waters within the State as public waters administered by the State, and these definitions underlie the water codes of these States. Note that the brief description of State water law captures the essence of the law, but it does not capture the true complexity and nuances inherent in State water law.

Although prior appropriation was established as the general principle of water law in the study area, many of the settlers came from States with riparian water rights and assumed that similar rights prevailed in the territories and, later, in the three States. The riparian doctrine allows landowners with property bordering a stream to use the water as long as that use does not unreasonably affect downstream water uses or earlier rights. For example, as late as 1912, Parker and Storey (1916) state that in the Yakima River Basin "the scarcity of water resulting from overappropriation has led to much litigation and adjudication of water rights, and the rights of the valley are in a condition of chaos, owing to the absence of a water code in the State of Washington, to conflicting claims of riparian owners and prior appropriators, and to the exorbitant filings made for many canals." They further state that the water-appropriation filings in the basin were enough to irrigate several States as large as Washington. It was not until 1917 that Washington passed a water code for surface water (8 years after Oregon) that in effect established the prior appropriation principle, but also included remnants of the riparian doctrine. Note that Idaho does not recognize riparian water rights but Oregon does for rights with priority dates prior to 1909.

Some laws were passed by the Washington legislature for groundwater, such as capping artesian wells when not in use, but a State groundwater code (modeled after the surface-water code) was not implemented until 1945. This code has an exemption in the permitting process for single wells producing up to 5,000 gallons per day (gal/d) (referred to as "exempt wells"), and an unlimited exemption for livestock wells. As in Idaho and Oregon, there is an exemption for irrigating as much as one-half acre. The Washington groundwater code also explicitly states that surface-water rights cannot be impaired by groundwater rights. Surface-water and groundwater rights applied for after 1917 and 1945, respectively, are based on first in time. Beneficial use of surface water put to use prior to 1917 is acceptable, but the use occurs without a permit or certificate; the actual water right is only clearly defined by adjudication. To date (2014), 82 drainage basins (mostly small streams) have been adjudicated. More than 165,000 Statements of Water Right Claims were filed in the Washington State during the four claims registry periods. Only a small number (about 4,500) of these claims has been adjudicated. There is no current timeframe for adjudicating the remaining claims. As of 2014, only one adjudication is active in the State. Adjudication of the Yakima River Basin is nearly complete. This adjudication has been ongoing for more than 30 years at a cost of tens of millions of dollars.

Similarly, users of groundwater prior to 1945 would need to file a claim for the water, and the claims and post-1945 water rights would need to be adjudicated to clearly define the purpose, quantity, and location of use of the claims. As in Oregon and Idaho, groundwater claims provide a means for identifying water rights with no previous records, but importantly, claims are not confirmations of water rights. As of 2011, only 400 groundwater claims have been adjudicated in Washington.

In 1909, Oregon created its surface-water code based on the prior appropriation doctrine. However, prior to the code, Oregon recognized riparian water rights; thus, Oregon has a dual system. The groundwater code initially was established for the area east of the Cascade Range in 1927 and was modeled after the surface-water code. Applications for groundwater use are assessed for their potential effect on other wells and surface-water rights/claims. Oregon also has an exempt well provision for wells that are not required to go through the permitting process. These provisions allow for single or group domestic uses not exceeding 15,000 gal/d, lawn watering of less than one-half acre, stock watering (as in Washington and Idaho), and single industrial/commercial uses not exceeding 5,000 gal/d. For surface-water uses prior to 1909, adjudications are used to determine water rights. As in Washington, a claim needs to be filed. The State reviews these claims and makes a determination of their validity. If there is an appeal of the State determination, a circuit court would then agree with the State or modify the State determination, generally resulting in a water right with a certificate. Most of the pre-1909 claims in the study area in Oregon have been adjudicated.

Idaho established a groundwater code in 1963 and a surface-water code in 1971. As in Washington and Oregon, the Idaho codes allow water rights to be granted only under an application and permitting procedure and the priority date for the rights is the date of filing of the application. Prior to the establishment of codes for groundwater (1963) and surface water (1971), there were two methods to obtain water rights. The first method was simply to put water to beneficial use. These rights, referred to as "historic" or "beneficial" use rights, have a priority date of when the water was first put to use. However, until adjudication is completed, these rights are not associated with a permit/certificate/decree. The second method made use of the posted-notice statute that was in effect in Idaho prior to 1903. Under this statute, people would post a notice at the point of diversion and record the notice with the county where the diversion occurred. These rights would have a priority date of when the notice was posted, and are essentially the same as beneficial rights. Idaho also has an exempt well exclusion where domestic uses do not have to go through the permitting process. Idaho allows one-half acre of land to be irrigated under this exemption (the same as Washington and Oregon) and to use as much as 13,000 gal/d or 0.04 ft^3/s. Instream livestock water use also is a defined exempt use in Idaho. The water-rights adjudication process in Idaho is similar to the process in Washington. To date (2011), the only major adjudication has been completed for the Snake River Basin.

Various other statutes, laws, and rules have been implemented by the three States that also affect water availability in the study area. For example, each State now (2014) considers instream flows a beneficial use and has passed legislation to protect instream flows that can reduce the quantity of surface water available for future appropriation. As part of a 1955 groundwater law, Oregon can regulate water by designating "Critical Groundwater Areas." As of 2011, there were four such areas on the Columbia Plateau in Oregon and two other areas are designated "restrictively classified." In one area, the Moiser area, new appropriation of groundwater mostly has been stopped. Oregon also manages groundwater and surface water conjunctively by basin; within a basin, further appropriation of water for parts or the entire basin can be restricted. Idaho also manages water by basin and has about 50 administrative units or basins under this management strategy. In several areas, parts or all of these units have a moratorium on some uses. For groundwater, Idaho has legislation that allows for the creation of water-measurement districts and groundwater districts, and has authority for establishing Ground Water Management and Critical Ground Water Areas; there are two Ground Water Management Areas in the study area. Washington legislation allows for the development of groundwater-management areas, and for declaring critical areas where groundwater levels are declining and no new appropriations are allowed. Other laws in Washington established a watershed-management program in which the water resources in a basin, including water rights, are analyzed. In some cases, such analyses have resulted in limiting future appropriations, including limiting exempt wells. For basins considered fully or over-appropriated, the three States generally require the retiring (purchase) of a surface-water right (based on its estimated consumptive use) in exchange for allowing new groundwater withdrawals; this process typically is referred to as "mitigation." Finally, a major issue in the study area and the West generally is the status of exempt-well statutes (http://www.lclark.edu/live/files/4541-401bracken.html) because it is recognized that exempt wells affect water-management strategies and may affect senior surface-water and groundwater rights.

Appendix 2. Sources of Information for “Dry” Season Water-Availability Map

The information presented in figure 38 is from John Covert (Washington State Department of Ecology, written commun., 2011); Kenneth Lite, Jon La Marche, and Dwight French (Oregon Water Resources Department, written commun., 2011); and Shelley Keen, Pamela Skaggs, and Sean Vincent (Idaho Water Resources Department, written commun., 2011). Water-availability information for Water Resource Inventory Areas in Washington is available at http://www.ecy.wa.gov/programs/wr/rights/wrpenapp_avail.html, Washington State digital archives contain a map of over-appropriated basins in Washington presented in the Statewide Strategy to Recover Salmon (http://www.digitalarchives.wa.gov/GovernorLocke/gsro/strategy/summary/background.htm), various maps for Oregon are available at http://egov.oregon.gov/OWRD/MAPS/index.shtml, and Groundwater Management Areas in Idaho are available at http://www.idwr.idaho.gov/WaterInformation/GroundWaterManagement/designated_areas.htm.

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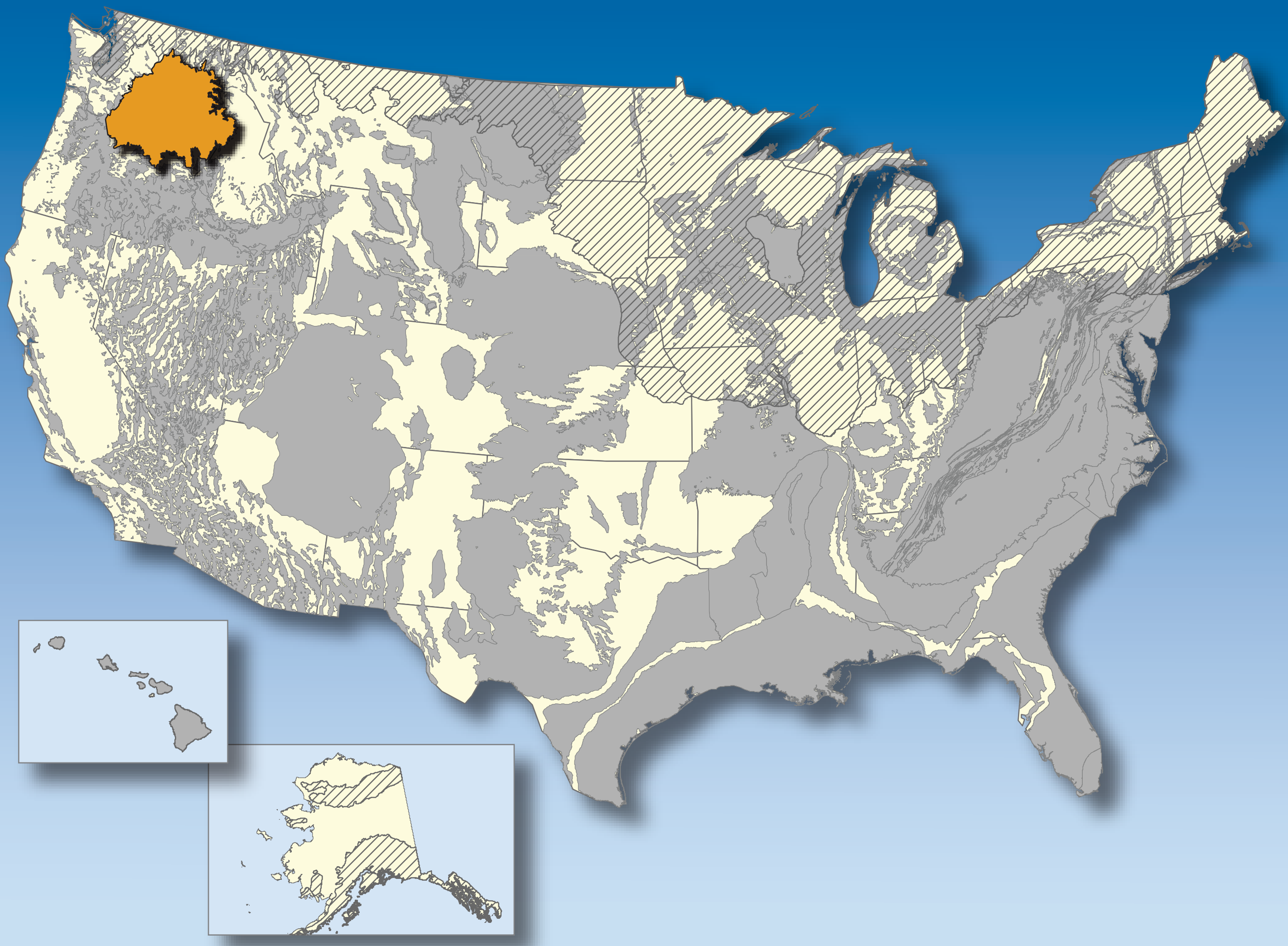
Director, Washington Water Science Center
U.S. Geological Survey
934 Broadway, Suite 300
Tacoma, Washington 98402
http://wa.water.usgs.gov

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

Vaccaro and others—**Groundwater Availability of the Columbia Plateau Regional Aquifer System**—Professional Paper 1817



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