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Simulation of Groundwater Storage Changes in the Quincy Basin, Washington

Scientific Investigations Report 2018–5162

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

Cover: Photograph showing West Canal flowing west away from Pinto Dam towards Soap Lake, Washington. Photograph by Dave Walsh, Bureau of Reclamation, May 3, 2004.

Inset photographs, clockwise from top left:

Harvest and irrigation activities in the Quincy area, Washington. Photograph by Andy Pernick, Bureau of Reclamation, August 22, 1999.

Concrete-lined head ditch carrying water for gravity-flow irrigation on this farm in Winchester, Washington. Photograph by J.D. Roderick, Bureau of Reclamation, May 30, 1973.

East Low and West canal bifurcation works, Washington. Photograph by Dave Walsh, Bureau of Reclamation, August 22, 1999.

Low-head pivot, wheels irrigation activity in the Ephrata area, Washington. Photograph by Dave Walsh, Bureau of Reclamation, August 22, 1999.

Low-head pivot, wheels irrigation activity in the Ephrata area, Washington. Photograph by Dave Walsh, Bureau of Reclamation, August 22, 1999.

Corn, wheat, and spinach crops in the Royal Slope area, Washington. Photograph by Dave Walsh, Bureau of Reclamation, August 22, 1999.

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

U.S. Department of the Interior
RYAN K. ZINKE, Secretary

U.S. Geological Survey
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Contents

Contents—Continued

Figures

Figures—Continued

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m)
acre	0.4047	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
million acre-foot (million acre-ft)	1,233.48	million cubic meter (million m3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per day (ft^3/d)	0.02832	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)
	Transmissivity and Conductance	
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)

International System of Units to Inch/Pound

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

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

$$°C = (°F - 32) / 1.8.$$

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).

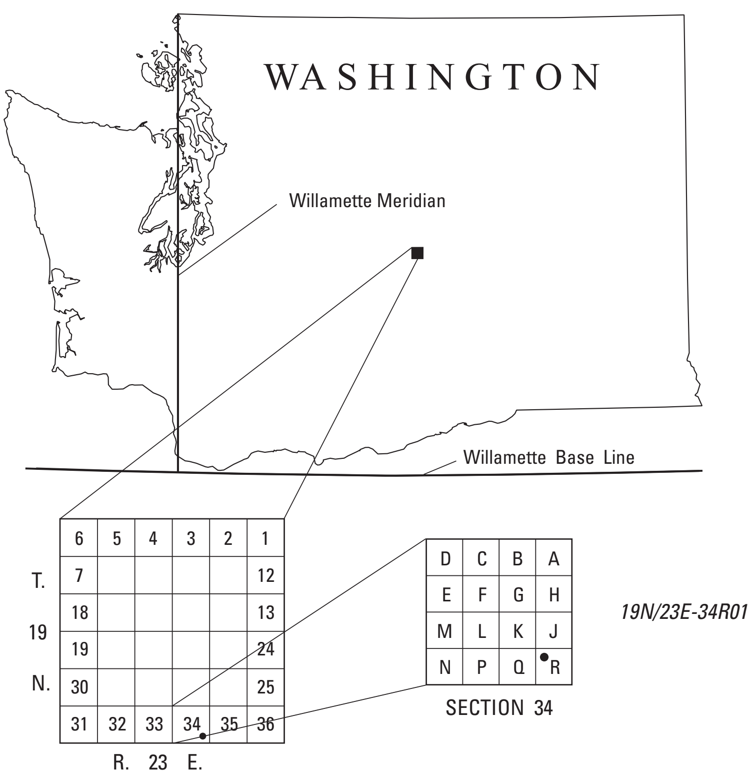
Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations

CBP	Columbia Basin Project
CRBG	Columbia River Basalt Group
DEM	Digital Elevation Model
Ecology	Washington State Department of Ecology
GHB	General Head Boundary package of MODFLOW
GIS	geographic information system
GWMA	Columbia Basin Ground Water Management Area
HFB	Horizontal Flow Barrier
MODFLOW	USGS modular three-dimensional finite-difference groundwater-flow model
NWT	Newton Solver package of MODFLOW
NWIS	National Water Information System
PEST	parameter estimation program
QDEP	Quaternary deposits
Quincy Subarea	Quincy Groundwater Management Subarea
RASA	U.S. Geological Survey Regional Aquifer-System Analysis
Reclamation	Bureau of Reclamation
RING	Ringold Formation
RMSE	root-mean-square error
SFR	Stream Flow Routing package of MODFLOW
SOWAT model	SOil WATer balance model
USGS	U.S. Geological Survey

Well-Numbering System

In Washington, wells are assigned numbers that identify their location in a township, range, section, and 40-acre tract. For example, well number 19N/23E-34R01 indicates that the well is in township 19 north of the Willamette Base Line, and range 23 east of the Willamette Meridian. The numbers immediately following the hyphen indicate the section (34) in the township, and the letter following the section (R) gives the 40-acre tract of the section. The two-digit sequence number (01) following the letter indicates that the well was the first one inventoried in that 40-acre tract.



Well numbering system in Washington.

Simulation of Groundwater Storage Changes in the Quincy Basin, Washington

By Lonna M. Frans, Sue C. Kahle, Alison E. Tecca, and Theresa D. Olsen

Abstract

The Miocene Columbia River Basalt Group and younger sedimentary deposits of lacustrine, fluvial, eolian, and cataclysmic-flood origins compose the aquifer system of the Quincy Basin in eastern Washington. Irrigation return flow and canal leakage from the Columbia Basin Project have caused groundwater levels to rise substantially in some areas. Water resource managers are considering extraction of additional stored groundwater to supply increasing demand. To help address these concerns, the transient groundwater model of the Quincy Basin documented in this report was developed to quantify the changes in groundwater flow and storage.

The model based on the U.S. Geological Survey modular three-dimensional finite-difference numerical code MODFLOW uses a 1-kilometer finite-difference grid and is constrained by logs from 698 wells in the study area. Five model layers represent two sedimentary hydrogeologic units and underlying basalt formations. Head-dependent flux boundaries represent the Columbia River and other streams, lakes and reservoirs, underflow to and (or) from adjacent areas, and discharge to agricultural drains and springs. Specified flux boundaries represent recharge from precipitation and anthropogenic sources, including irrigation return flow and leakage from water-distribution canals and discharge through groundwater withdrawal wells. Transient conditions were simulated from 1920 to 2013 using annual stress periods. The model was calibrated with the parameter-estimation code PEST to a total of 4,064 water levels measured in 710 wells. Increased recharge since predevelopment resulted in an 11.5 million acre-feet increase in storage in the Quincy Groundwater Management Subarea of the Quincy Basin.

Four groundwater-management scenarios were formulated with input from project stakeholders and were simulated using the calibrated model to provide representative examples of how the model could be used to evaluate the effect on groundwater levels as a result of potential changes in recharge, groundwater withdrawals, or increased flow in Crab Creek. Decreased recharge and increased groundwater withdrawals both resulted in declines in groundwater levels over 2013 conditions, whereas increasing the flow in Crab Creek resulted in increased groundwater levels over 2013 conditions.

Introduction

Since 1952, water diverted from the Columbia River has been used to irrigate parts of the Bureau of Reclamation (Reclamation) Columbia Basin Irrigation Project (CBP) in eastern Washington. As a result of the large volumes of surface-water irrigation, groundwater levels in the Quincy Groundwater Management Subarea (Quincy Subarea) sediments and upper basalt generally have risen and caused various problems, such as septic system failures and loss of agricultural lands because of ponding. As demands for water use increase, State and local water resource managers are increasingly looking to the additional groundwater in storage as a potential source of water for development. The development of these groundwater resources not only could provide additional water for claim, but also could potentially mitigate some of the adverse consequences of the increased water levels.

Under Washington State law, subject to existing rights, all natural groundwater and all “artificially stored” groundwater that has been abandoned or forfeited are available for appropriation (Washington State Legislature, 2003; Washington Administrative Code [WAC] 508-14-030). The units in the Quincy Subarea situated between ground surface and the top of the uppermost basalt flow, known as the Quincy unconsolidated zone, have large quantities of groundwater in “artificial” storage. That storage extends into the uppermost basalt flows. Thus, artificially stored groundwater in the Quincy Subarea is believed to be present in the *shallow management unit,* which is defined in a rule to mean that the groundwater is hydraulically continuous between land surface and a depth of 200 ft into the Quincy basalt zone and includes all of the Quincy unconsolidated zone. (Washington State Legislature, 1988; WAC 173-124).

Purpose and Scope

The USGS, in cooperation with Reclamation and the Washington State Department of Ecology (Ecology) conducted this study to quantify natural and artificially stored groundwater in the Quincy Subarea. This report (1) describes the hydrogeologic setting and hydrogeologic units of the study area, (2) documents the groundwater-flow model that was developed to quantify the changes of groundwater storage within the Quincy Subarea, (3) evaluates the applicability and accuracy of the model as a predictive tool for assessing changes in groundwater storage, and (4) discusses limitations of the model.

The four primary objectives of this study are to:

1. Define the hydrogeology of the study area,
2. Determine groundwater flow directions and flows through the aquifer system,
3. Quantify the effect of anthropogenic recharge and groundwater withdrawals on storage in the groundwater system, and
4. Simulate the effects of four groundwater-management scenarios.

Description of Study Area

The Quincy Subarea, described in WAC 173-124-040 (Washington State Legislature, 1988), encompasses 1,100 mi^2 in Grant County and a small part of Adams County, Washington (fig. 1). The Quincy Subarea is located within the structural and topographic Quincy Basin, which is bounded on the north by the Beezley Hills, on the south by the Frenchman Hills, on the west by Evergreen and Babcock Ridges, and on the east by the high land east of Moses Lake (Schwennesen and Meinzer, 1918). Altitudes in the study area range from 570 ft to about 2,500 ft west of Ephrata, with an average altitude of about 1,200 ft. The climate is arid to semi-arid, with mean annual precipitation ranging from 7 to 10 in. and occurring primarily during the winter. Average daily temperatures range from the upper 20s °F in December and January to more than 90 °F in July and August.

The Quincy Basin is drained by Crab Creek. The creek flows westward into the basin and then southeasterly toward Moses Lake. Since the beginning of irrigation in 1952 (Tanaka and others, 1974), perennial flow in Lower Crab Creek is supported by overflow from Potholes Reservoir and discharge from wasteways that primarily are return flows from irrigation.

The 2010 population of the study area was more than 68,000 (Washington State Office of Financial Management, 2017). The largest city in the study area is Moses Lake, with a population of 20,366, followed by Ephrata (7,664) and Quincy (6,750). The dominant land use/land cover in the study area in 2006 (fig. 2) was planted/cultivated crops (49 percent), followed by shrubland (37 percent) and developed areas (3 percent) (Fry and others, 2011). Use of groundwater resources in the Quincy Basin began in the late 1800s, when groundwater was withdrawn for agriculture, stock watering, and domestic use. In the 1950s, the CBP began to deliver water diverted from the Columbia River at Grand Coulee Dam for large-scale agricultural development (Vaccaro and others, 2015). Subsequently, groundwater levels generally have risen in the shallow basin-fill sediments.

Although groundwater withdrawals have increased since the 1950s, surface-water irrigation systems supply most of the agricultural water demand in the study area. Water diverted from the Columbia River is distributed by the CBP through a system of canals and pipes, or buried drains (fig. 3). Irrigation water that is not transpired by crops, evaporated, or discharged to the Columbia River through drains and wasteways recharges the groundwater system.

Previous Investigations

Numerous previous investigations have contributed to the understanding of the hydrogeologic conditions and water resources in or near the Quincy Basin. These studies are discussed here, and the locations of these studies are shown in figure 4. A brief summary of each investigation is provided herein, and the reader is referred to the individual documents for more detailed information provided by the respective investigation.

Early studies of the Quincy Basin focused on generic hydrogeologic unit descriptions and quantifying the available groundwater in the underlying aquifers. One of the earliest published descriptions of the Quincy Basin was completed by Schwennesen and Meinzer (1918) (fig. 4). Based on direct field observations and about 250 groundwater-level measurements, the report detailed various features of the basin including geology, topography, climate, soils, and stream discharge, as well as the feasibility of pumping groundwater for irrigation. Taylor (1948) followed with descriptions of the water-bearing properties of the formations underlying the Quincy Basin, the availability of groundwater in these formations, and the overall changes in the groundwater elevations from 1916 to 1941. Mundorff and others (1952) supplemented the earlier work of Taylor by describing the geology, geologic structure and influence on groundwater, groundwater occurrence and conditions (recharge, discharge, quality, and availability), and a water-level network established in 1940 and expanded with an additional 100 wells during 1949–50.

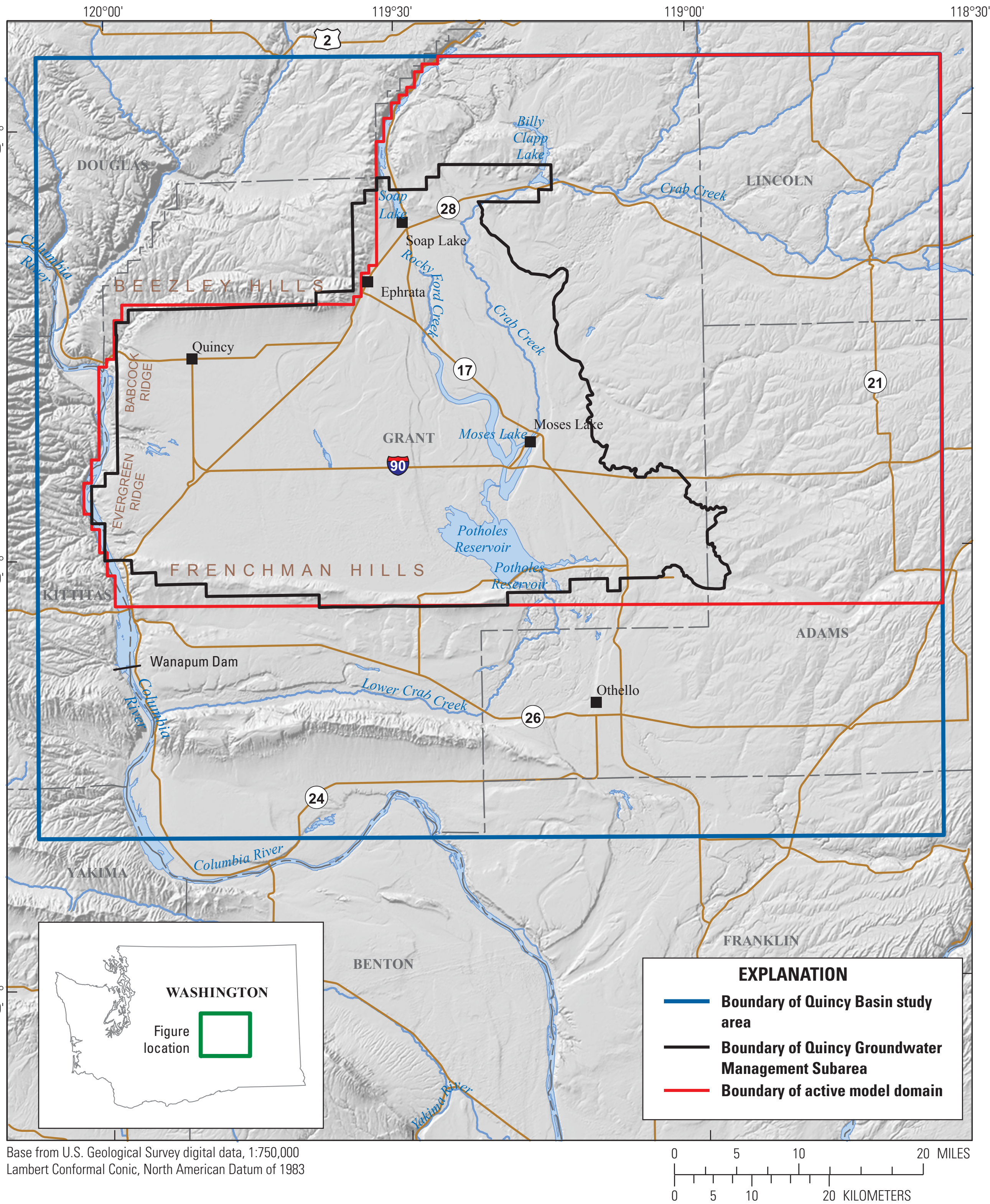


Figure 1. Location of the active model domain and the Quincy Groundwater Management Subarea, Quincy Basin, Washington.

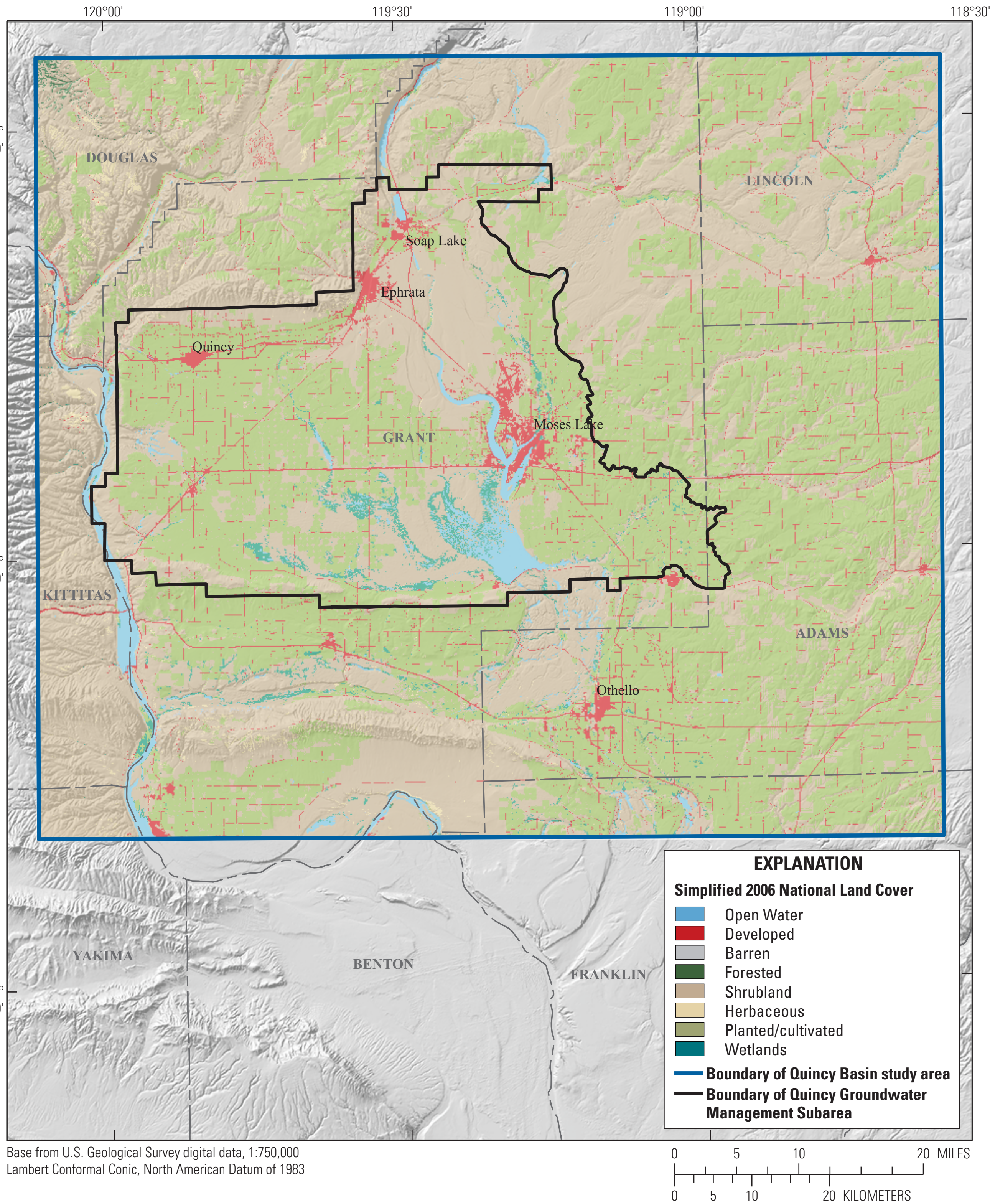


Figure 2. Simplified National Land Cover of the Quincy Basin study area, Washington, 2006.

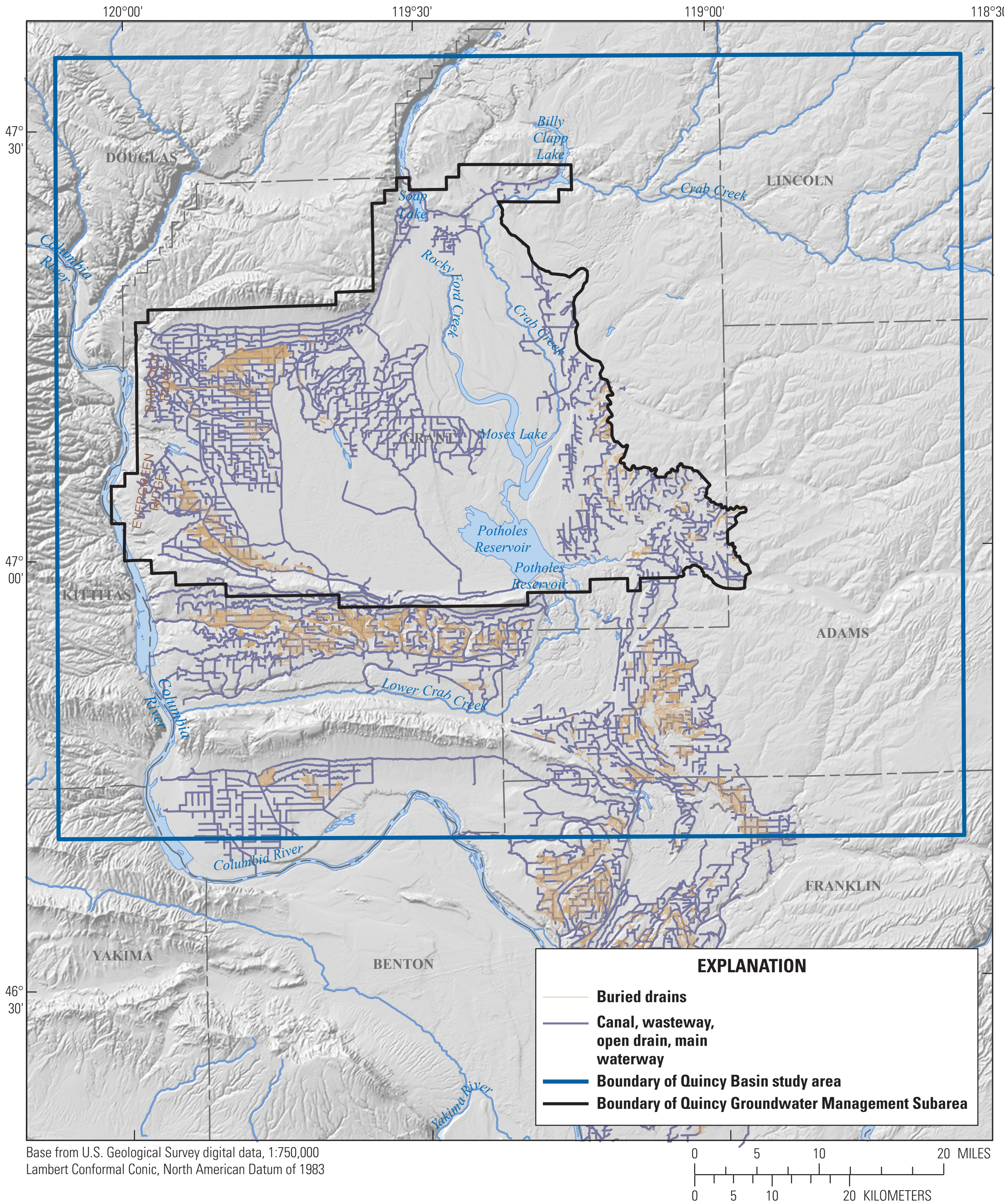


Figure 3. Locations of rivers, water-delivery infrastructure, and buried drains in the Quincy Basin study area, Washington.

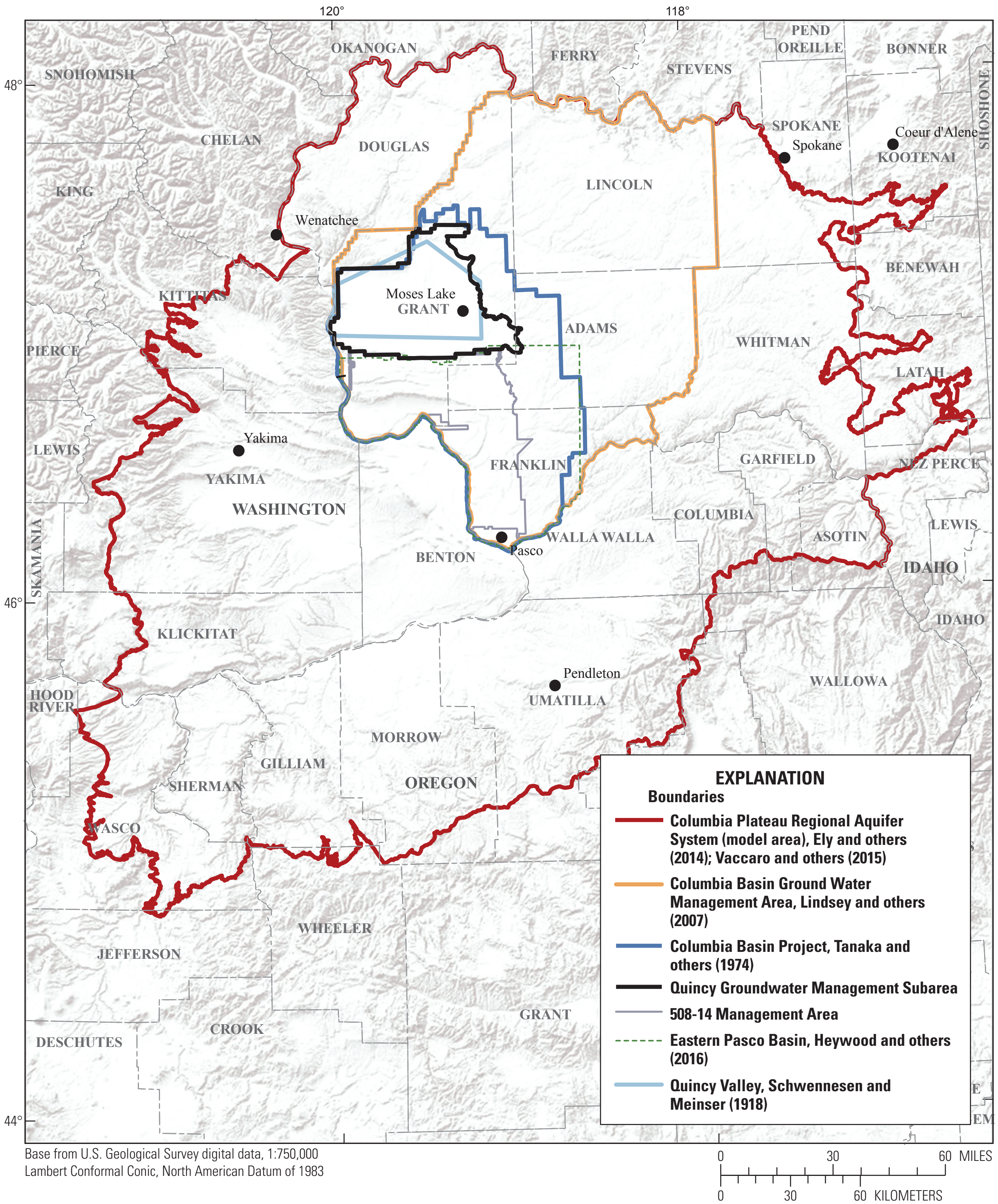


Figure 4. Locations of selected hydrogeologic studies of the Quincy Basin and selected adjacent areas, Washington.

The establishment of the Columbia Basin Irrigation Project in the mid-20th century renewed interest in the Quincy Basin and the effects of irrigation on local aquifers. A two-volume report compiled by Walters and Grolier (1960) was among the first to document the effects of increased irrigation on groundwater levels by using hydrographs to predict areas of marked water-level rise. Tanaka and others (1974) (fig. 4) produced some of the first digital computer models of groundwater inflow and outflow in the Columbia Basin Irrigation Project area, including a model specific to the Quincy Basin. The analyses were divided into two parts: (1) a steady-state model analyzing conditions before 1952 (pre-irrigation), and (2) a transient model analyzing conditions after 1952 (post-irrigation). Results from these analyses outlined the differences in cumulated water storage amounts from the pre-irrigation to the post-irrigation era.

A series of reports were published in the 1980s and 1990s for the USGS Regional Aquifer-System Analysis (RASA) program for the Columbia Plateau area. Drost and Whiteman (1986) and Drost and others (1990, 1993) characterized the surficial geology, structure, top altitudes and thicknesses of hydrogeologic units, groundwater levels and groundwater quality, and various components of groundwater recharge and discharge for the Columbia Plateau Aquifer System RASA. Bauer and Vaccaro (1990) developed a deep-percolation model using precipitation, temperature, streamflow, soils, land-use, and altitude data to quantify groundwater recharge to this aquifer system for predevelopment and postdevelopment (1956–77) land-use conditions. Whiteman and others (1994) published a paper assessing several components including the hydrogeologic framework of the Columbia Plateau Aquifer System, the area water budget, regional groundwater flow patterns, and the general geochemistry of the aquifer system.

Lindsey and others (2007) described the geologic framework of the sedimentary aquifer system in the Columbia Basin Ground Water Management Area (GWMA) of Adams, Franklin, and Grant Counties (fig. 4). Several years later, a computer groundwater-flow model of the GWMA was completed by Porcello and others (2010).

Recent studies of the hydrogeologic framework, water budget, groundwater conditions, and post-development trends in the Columbia Plateau Regional Aquifer System encompass the current study area and focus on the basalt aquifers (Snyder and Haynes, 2010; Kahle and others, 2011; Burns and others, 2012; Vaccaro and others, 2015) (fig. 4). These studies provided important data used for the construction of a three-dimensional numerical model of groundwater flow in the Columbia Plateau Regional Aquifer System (Ely and others, 2014) (fig. 4). This model was used to evaluate groundwater availability as a result of the combined effects of irrigation-enhanced recharge, natural recharge by precipitation, groundwater withdrawal by pumping, and naturally occurring discharge in the form of streamflow and evapotranspiration.

Most recently, Heywood and others (2016) developed a model for groundwater storage changes in the 508-14 Management Area in the eastern Pasco Basin (fig. 4), just south of the Quincy Basin. The report describes groundwater flow directions and fluxes in the underlying aquifer system and quantifies the effect of anthropogenic inflow and outflow on storage in the system. A large component of the report also is dedicated to the simulation of four different hypothetical pumping scenarios in the 508-14 Management Area in an effort to quantify potential groundwater-level drawdown attributable to an increased demand for withdrawal.

Methods of Investigation

Data compilation and review for the purpose of refining the hydrogeologic framework in the Quincy Basin involved obtaining well driller’s logs for lithologic and hydrologic information, analysis of water-level records, and the construction of hydrogeologic cross sections and hydrogeologic unit maps.

Well Data

Construction, lithologic log, and water-level data from 698 wells in the project area were compiled from 390 sites retrieved from the USGS National Water Information System (NWIS) database and 308 wells from the Ecology well-log database (Washington State Department of Ecology, 2016). The three criteria for selecting wells from the NWIS database were: (1) sites were located in the study area and were previously visited by USGS personnel, (2) complete construction information and well logs were available, and (3) multiple water-level measurements were available.

The 308 additional wells compiled from the Ecology well-log database were used in areas where NWIS well data were not available using the three well-selection criteria. These wells were not field-located and were assigned approximate latitude and longitude coordinates using the public land survey locations (township, range, section, and quarter-quarter section), well addresses, and (or) parcel numbers available on the drillers’ logs for each well. Online maps provided by the Grant County Assessor and Adams County Assessor were used to verify drillers’ locations and tax parcel numbers and to estimate latitudes and longitudes. Selected physical and hydrologic data for the project wells are provided in table 5 (at back of report).

Hydrogeology

The surficial geology of the study area (fig. 5) was simplified by combining similar units from the digital geologic map database of Washington (Washington Division of Geology and Earth Resources, 2005). A map of the surficial hydrogeology of the study area was made by grouping surficial geologic units of similar lithology and extent into hydrogeologic units, refined further by using lithologic information from drillers' logs of project wells (fig. 6). A digital tabulation of borehole hydrogeologic unit assignments facilitated creation of seven hydrogeologic cross sections. Two representative sections are included in this report (fig. 7). Top and extent-of-unit maps of each hydrogeologic unit were manually drawn using information from the hydrogeologic units and the well data.

Raster representations of the top altitudes (surfaces) and extents of the hydrogeologic units described in this report were generated in a geographic information system (GIS) using a grid with square cells 100 ft on a side. These surfaces were used to construct the digital hydrogeologic framework for the USGS modular three-dimensional finite-difference groundwater-flow model (MODFLOW; U.S. Geological Survey, 2018). Unit-top altitudes at project wells were interpolated through the extent of the hydrogeologic units using the Australian National University Digital Elevation Model (ANUDEM) procedure (Hutchinson, 1989). Each hydrogeologic unit surface was constrained where the unit outcropped by the National Elevation Dataset Digital Elevation Model (DEM; U.S. Geological Survey, 2017).

The interpolated hydrogeologic unit surfaces and thicknesses were compared to previous hydrogeologic-unit maps and well interpretations to honor previous data interpretations wherever feasible. Hydrogeologic-framework uncertainties are greatest in areas where the surficial geology changes abruptly, or the project wells do not provide sufficient subsurface lithologic data. These interpolated hydrogeologic unit surfaces were used along with the borehole hydrogeologic unit assignments to create final cross section profiles using the GIS extension CrossView (https://crossviewgis.com/) (fig. 7).

Horizontal Hydraulic Conductivity

Hydraulic conductivity is a measure of the ability of a material to transmit water. Horizontal hydraulic conductivity was estimated for the hydrogeologic units using the drawdown/discharge relation reported on drillers' logs that reported pump testing wells for 1–120 h. Only data from those wells with a driller's log containing discharge rate, duration of pumping, drawdown, static water level, well-construction data, and lithologic log were used.

The modified Theis equation (Ferris and others, 1962) was first used to estimate transmissivity (T) of the pumped interval. To determine transmissivity, the base Theis equation is rearranged and solved for T. Transmissivity is the product of horizontal hydraulic conductivity and thickness of the hydrogeologic unit supplying water to the well.

The modified equation is

$$s = \frac{Q}{4\pi T} \ln \frac{2.25Tt}{r^2 S} \quad (1)$$

where

- s is drawdown in the well, in feet;
- Q is discharge, or pumping rate, of the well, in cubic feet per day;
- T is transmissivity of the hydrogeologic unit, in square feet per day;
- t is length of time the well was pumped, in days;
- r is radius of the well, in feet; and
- S is storage coefficient, a dimensionless number, assumed to be 0.001 for confined units and 0.1 for unconfined units.

Assumptions for using equation 1 are that aquifers are homogeneous, isotropic, and infinite in extent; wells are fully penetrating; flow to the well is horizontal; and water is released from storage instantaneously. Additionally, for unconfined aquifers, drawdown is assumed to be small in relation to the saturated thickness of the aquifer. Although many of the assumptions are not precisely met, the field conditions in the study area approximate most of the assumptions and the calculated hydraulic conductivities are reasonable estimates for the defined hydrogeologic units.

Equation 1 was solved for transmissivity (T) using Newton's iterative method (Carnahan and others, 1969). The calculated transmissivity values were not sensitive to assumed storage coefficient values; the difference in computed transmissivity between using 0.1 and 0.001 for the storage coefficient varies by a factor of 2. The following equation was used to calculate horizontal hydraulic conductivity from the calculated transmissivity:

$$K_h = \frac{T}{b} \quad (2)$$

where

- K_h is horizontal hydraulic conductivity of the geologic material near the well opening, in feet per day; and
- b is thickness, in feet, approximated using the length of the open interval as reported in the driller's report.

The use of the length of a well's open interval for b overestimates values of K_h because the equations assume that all the water flows horizontally within a layer of this thickness. Although some of the flow will be outside this interval, the amount may be relatively small because in most sedimentary deposits, vertical flow is inhibited by layering (Freeze and Cherry, 1979).

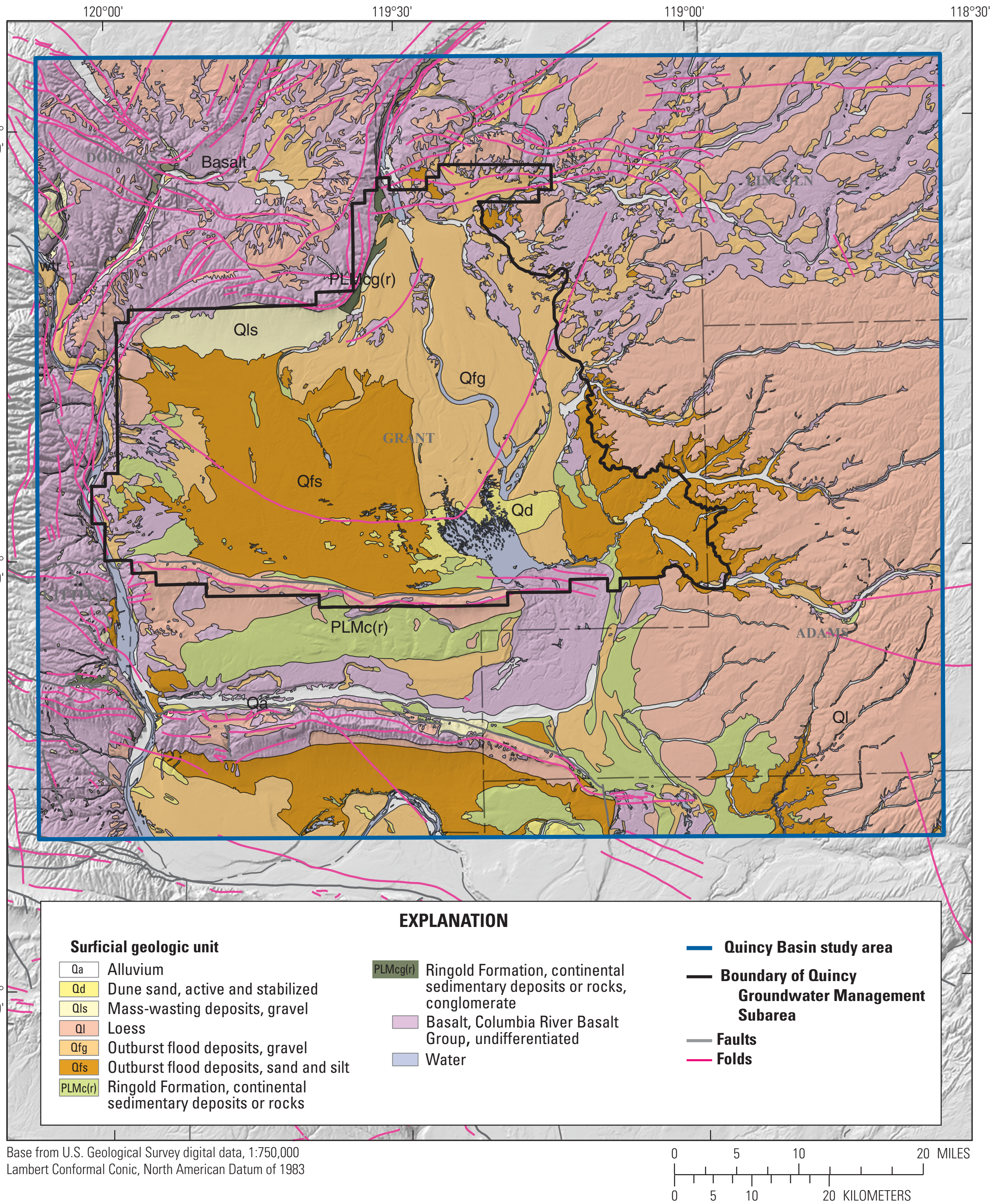


Figure 5. Simplified surficial geology of the Quincy Basin study area, Washington. Simplified from Washington Division of Geology and Earth Resources (2005).

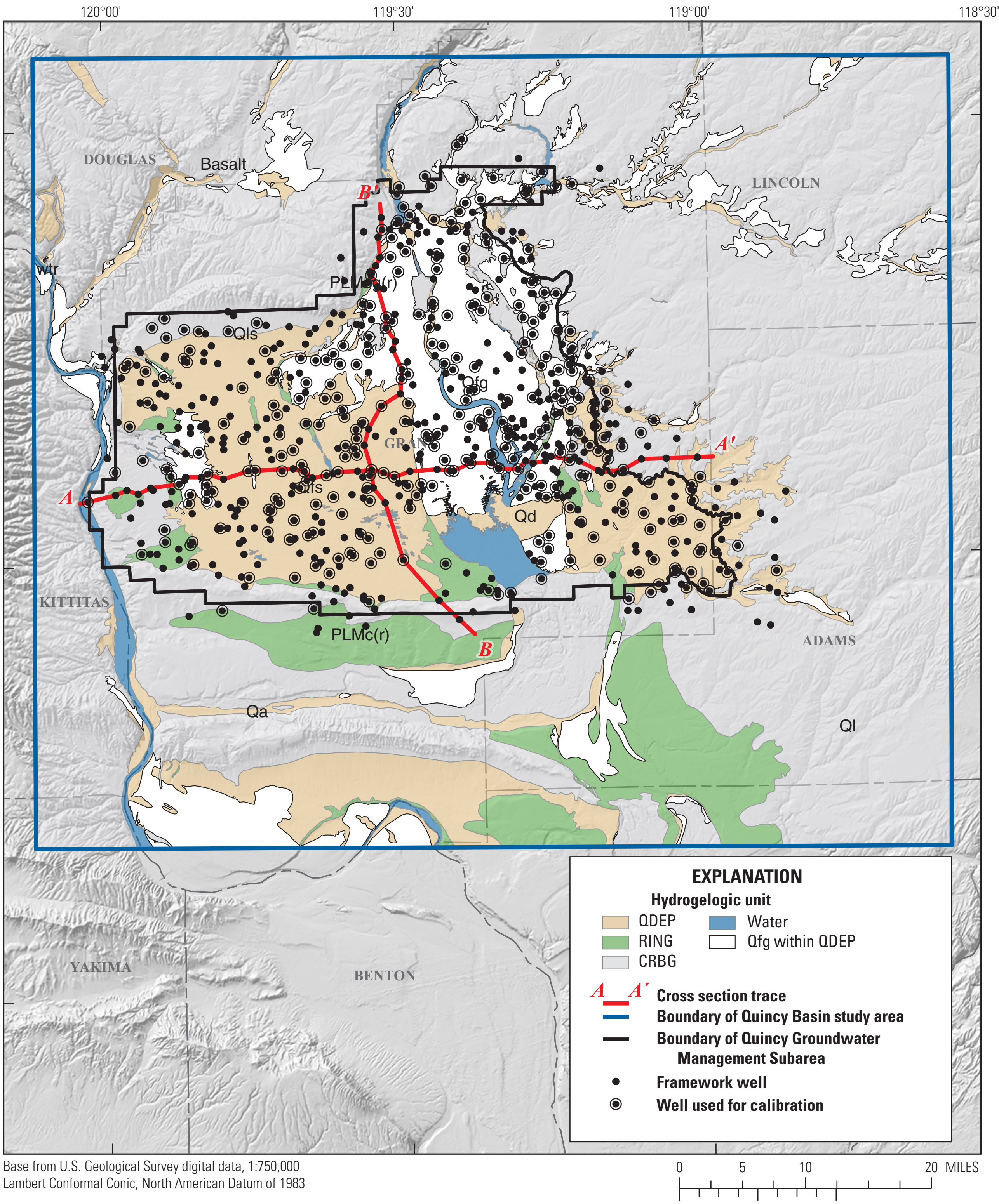


Figure 6. Surficial hydrogeology and locations of project wells of the Quincy Basin study area, Washington. Refer to table 1 for explanation of hydrogeologic units.

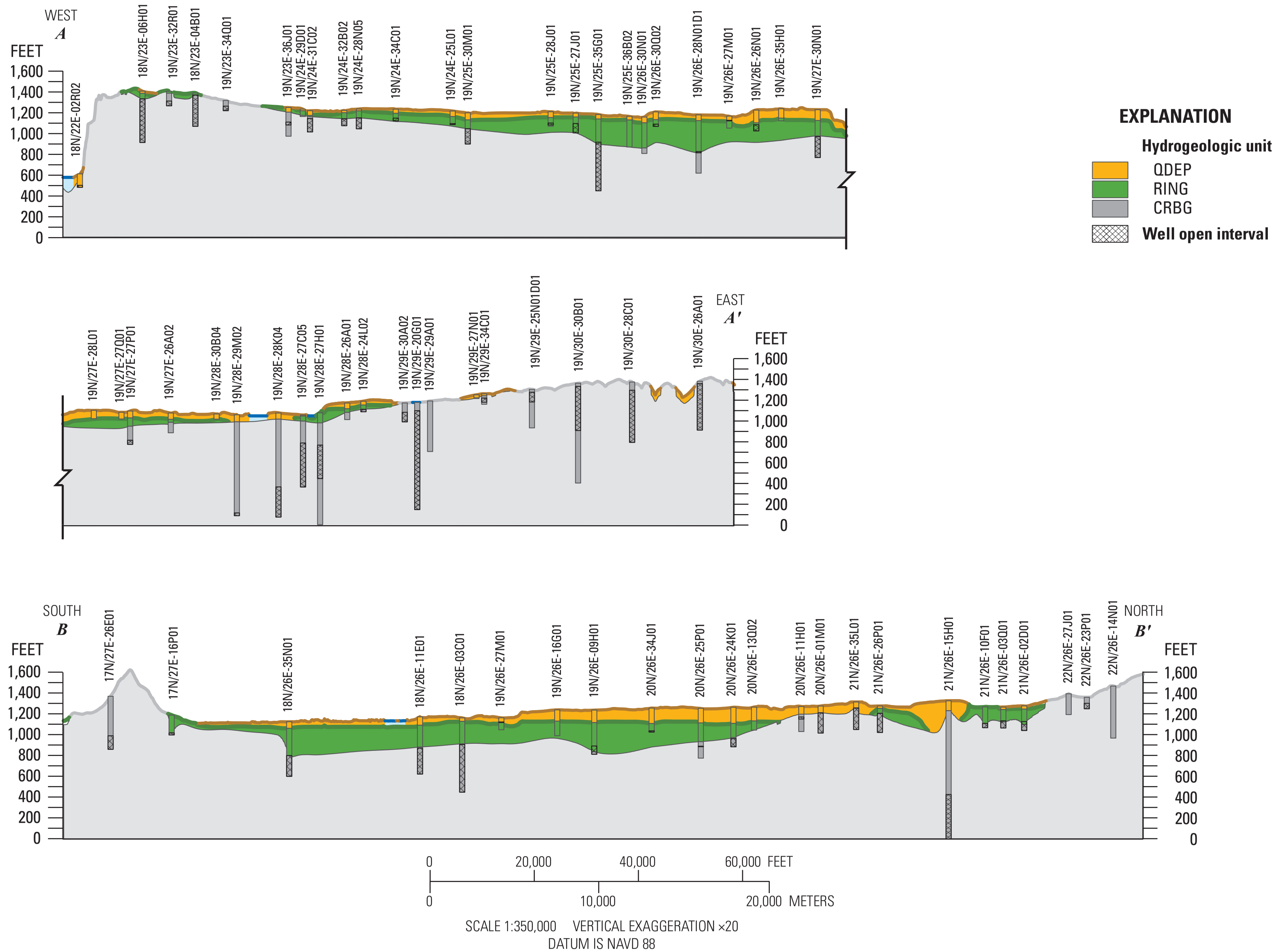


Figure 7. Hydrogeologic cross sections of the Quincy Basin study area, Washington. Refer to table 1 for explanation of hydrogeologic units.

The resulting estimates of hydraulic conductivity using the methods described earlier in this section are presented in section, "Hydrogeologic Setting." The median values of estimated hydraulic conductivities for the aquifers are similar in magnitude to values reported by Freeze and Cherry (1979, p. 29) for similar materials. The estimates are biased toward the more productive zones in these units and may not be representative of the entire unit. The minimum hydraulic conductivities for the hydrogeologic units indicate that there are zones of low hydraulic conductivity in most units. Although many uncertainties are in the estimated values of hydraulic conductivity, these estimates provide an initial assessment of the relative differences in hydraulic conductivity between the different hydrogeologic units.

Hydrogeologic Setting

The Quincy Basin is a structural and topographic low in south-central Washington (fig. 1). The area is underlain by three major stratigraphic units in which most locally significant groundwater occurs. The stratigraphic units are, in ascending order: (1) the Columbia River Basalt Group (CRBG), (2) the Ringold Formation (RING), and (3) the sediments deposited predominantly by catastrophic proglacial flooding (QDEP) (table 1 and figure 6). The surficial geology of the study area is shown in figure 5.

The geologic and hydrogeologic setting was previously described by Tanaka and others (1974) and Drost and others (1990) and is summarized here. During the Tertiary Period, flood basalts flowed intermittently into the region, resulting in a total basalt thickness in excess of 15,000 ft. Between eruptions, particularly those producing the younger flows, minor amounts of sediment (Ellensburg Formation) were interbedded with the basalts. Individual basalt flow tops and bottoms form productive water-bearing zones. Following the emplacement of the basalt flows, deformation took place in the form of northwest- to west-trending folds. The greatest degree of deformation was west of the study area and resulted in a series of folds known as the Yakima fold belt.

Folding and subsidence in the Miocene Epoch resulted in the deposition of fluvial and lacustrine sediments in the Quincy Basin by ancestral rivers and lakes that occupied the region. These sediments formed the Ringold Formation (Pliocene), which consists of sand, silt, and clay. The sandier zones of the Ringold have become saturated since irrigation began and now produce moderate well yields. During the late Pleistocene Epoch, glacial flood and melt water deposited gravels, sands, and silts throughout much of the study area. These floods scoured much of the earlier deposits, down to and into the basalts, and redeposited them in other locations. The resulting sediments form thick, productive aquifers where saturated. During the Quaternary Period, loess, dune sand, and alluvium were deposited on top of the older sediments or basalt. The geologic units were delineated into three generalized hydrogeologic units—QDEP, RING, and CRBG—based primarily on the textures and position of the geologic materials within the study area (table 1).

Columbia River Basalt Group (CRBG) Hydrogeologic Unit

The Columbia River Basalt Group (CRBG) hydrogeologic unit underlies the entire study area and occurs at land surface in the higher-altitude margins (figs. 5, 6). Five hundred fifty-four of the project wells are completed in the CRBG unit (table 1), where overlying sedimentary units (1) do not occur, (2) are insufficiently saturated, or (3) are unable to yield sufficient quantities of water to wells. The top altitude of the CRBG Unit (fig. 8)—which is based on the geologic map, project well logs, and hydrogeologic sections—was used for defining the base of the sedimentary hydrogeologic units. Manually drawn 100-ft contours of the buried basalt surface in the study area extent were combined with DEM land-surface altitudes where the basalt outcrops to generate a digital representation of basalt-surface altitude (fig. 8). The altitude of the basalt ranges from more than 3,000 ft in the Beezley Hills to about 800 ft near the center of the basin. The estimated horizontal hydraulic conductivity for the CRBG unit ranged from 0.3 to 770 ft/d, with a median of 21 ft/d, based on data from 81 wells open to the unit (tables 1 and 5).

The basalts form a complex series of aquifers and confining units at depth in the study area, in which most groundwater movement occurs in zones between basalt flows containing features such as flow breccia, rubble, and vesicles (Kahle and others, 2011). The principal basalt aquifer units in the study area are, from youngest to oldest, (1) the Saddle Mountains Basalt, (2) the Wanapum Basalt, and (3) the Grande Ronde Basalt. The upper surface of the basalts was refined for this study using depth-to-basalt data from the project well set and unit surface altitudes of the principal basalt aquifers mapped previously by Burns and others (2011).

Unconsolidated Sedimentary Hydrogeologic Units

Sedimentary hydrogeologic units, also referred to as overburden, include all the sediment that overlies the basalt, and consist of the Ringold Formation and Quaternary deposits. The thickness of this combined overburden (fig. 9) was calculated by subtracting the basalt-surface altitude (fig. 8) from the land-surface altitude. Overburden thickness is greatest (more than 400 ft thick) in the center of the basin (fig. 9).

Table 1. Geologic and hydrogeologic units of the Quincy Basin study area, Adams, Grant, and Lincoln Counties, Washington.

[**Surficial geologic units included in hydrogeologic unit:** Qa, alluvium; Qaf, alluvial fan deposits; Qd, dune sand; Qfg, outburst flood deposits, gravel; Qfs, outburst flood deposits, sand and silt; Ql, loess; Qls, mass-wasting deposits; Msdr, continental sedimentary deposits or rocks; Mv(GRB), Grand Ronde Basalt; Mv(SMB), Saddle Mountains Basalt; Mv(WB), Wanapum Basalt; PLMc(r), Ringold Formation, continental sedimentary deposits or rocks; PLMcg(r), Ringold Formation, continental sedimentary deposits or rocks, conglomerate. **Median horizontal hydraulic conductivity:** Brackets indicate number of values. **Abbreviations:** ft, foot; ft/d, foot per day]

Deposit, geologic formation, or group		Hydrogeologic unit	Surficial geologic units included in hydrogeologic unit	Description and occurrence	Median horizontal hydraulic conductivity (ft/d)	Number of project wells open to unit	Groundwater model layer
Quaternary deposits		QDEP	Qfg, Qfs, and Qa; with minor Qd, Ql, and Qls. Thin and discontinuous remnant deposits of PLMc(r) and PLMcg(r) along some coulee walls and the lower slope of Beezley Hills.	Unit consists mostly of cataclysmic flood deposits with minor alluvium, colluvium, and eolian sand, with caliche in places. The unit is coarsest (gravel and boulders) near the mouth of Grand Coulee near Soap Lake and finest to the south and west where the unit is composed mostly of sand. The unit ranges in thickness from about 50 to 150 ft, and nears 300 ft near Ephrata.	250 [1]	45	1
Ringold Formation		RING	PLMc(r), and minor occurences of overlying Qfs and Qd.	Unit is composed predominantly of layered silt, sand (sometimes described as sandstone), massive clay (with occasional gravel), and caliche, and generally is overlain by coarse Quaternary deposits. The unit is underlain everywhere by basalt and in places, has as much as several feet of gravel at the RING-CRBG interface. It occurs at land surface in a few locations, mostly limited to the lower slopes of the southern part of the Quincy Basin and along some flood channels. The unit generally ranges from 100-ft thick to slightly more than 300-ft thick.	48 [10]	62	2
Columbia River Basalt Group	Saddle Mountains Basalt	CRBG	Mv(SMB), Mv(WB), Mv(GRB); some Msdr, Otsdr; and overlying Ql, Qd, Qls, Qfg, Qfs, Qaf, in places.	Basalt and interbedded sediment of the Columbia River Basalt Group, commonly overlain by as much as 50 ft of loess and lesser amounts of other thin and discontinuous Quaternary sediment.	21 [81]	554	3
	Wanapum Basalt						4
	Grande Ronde Basalt						5

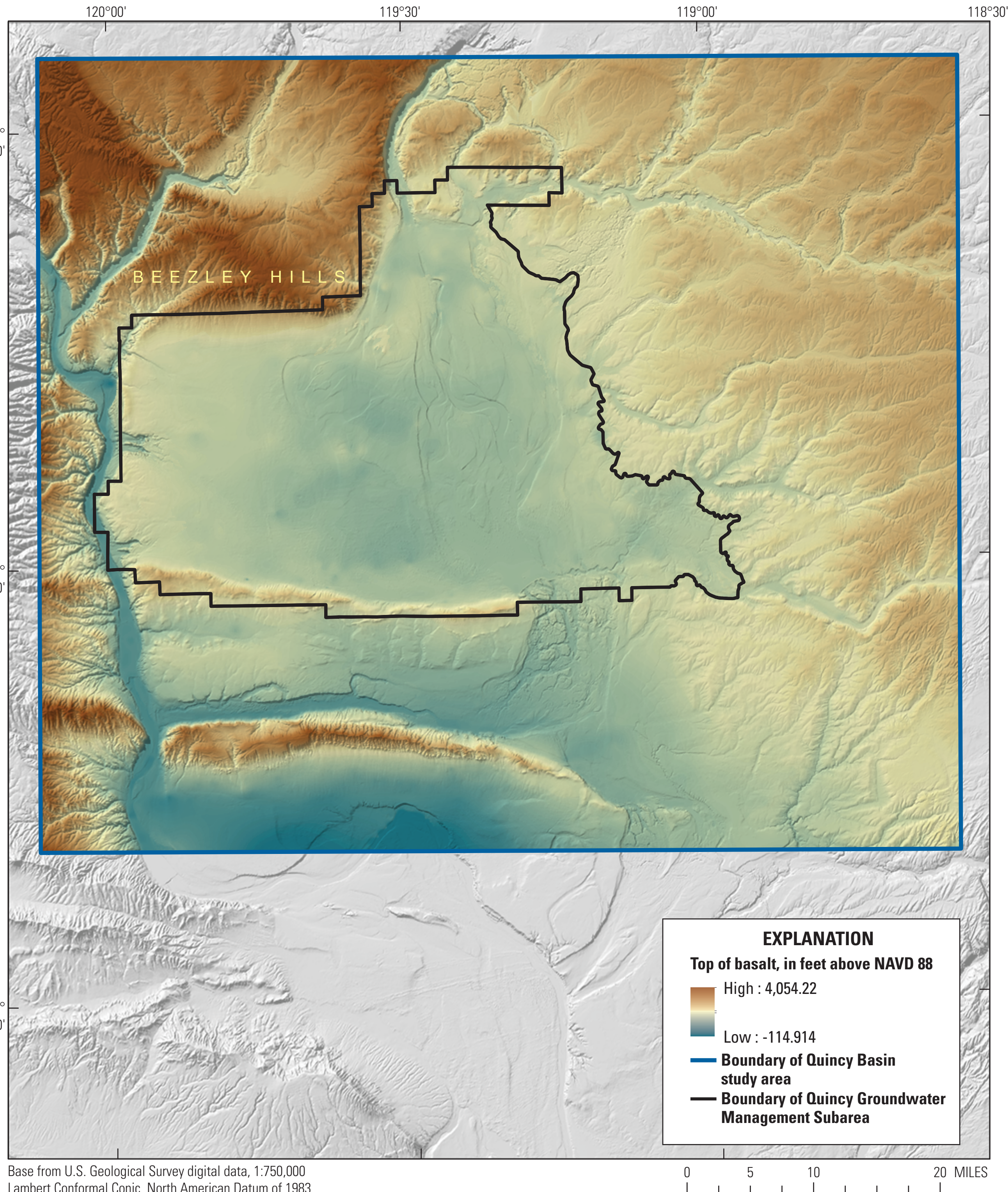


Figure 8. Top altitude of basalt surface in the Quincy Basin study area, Washington.

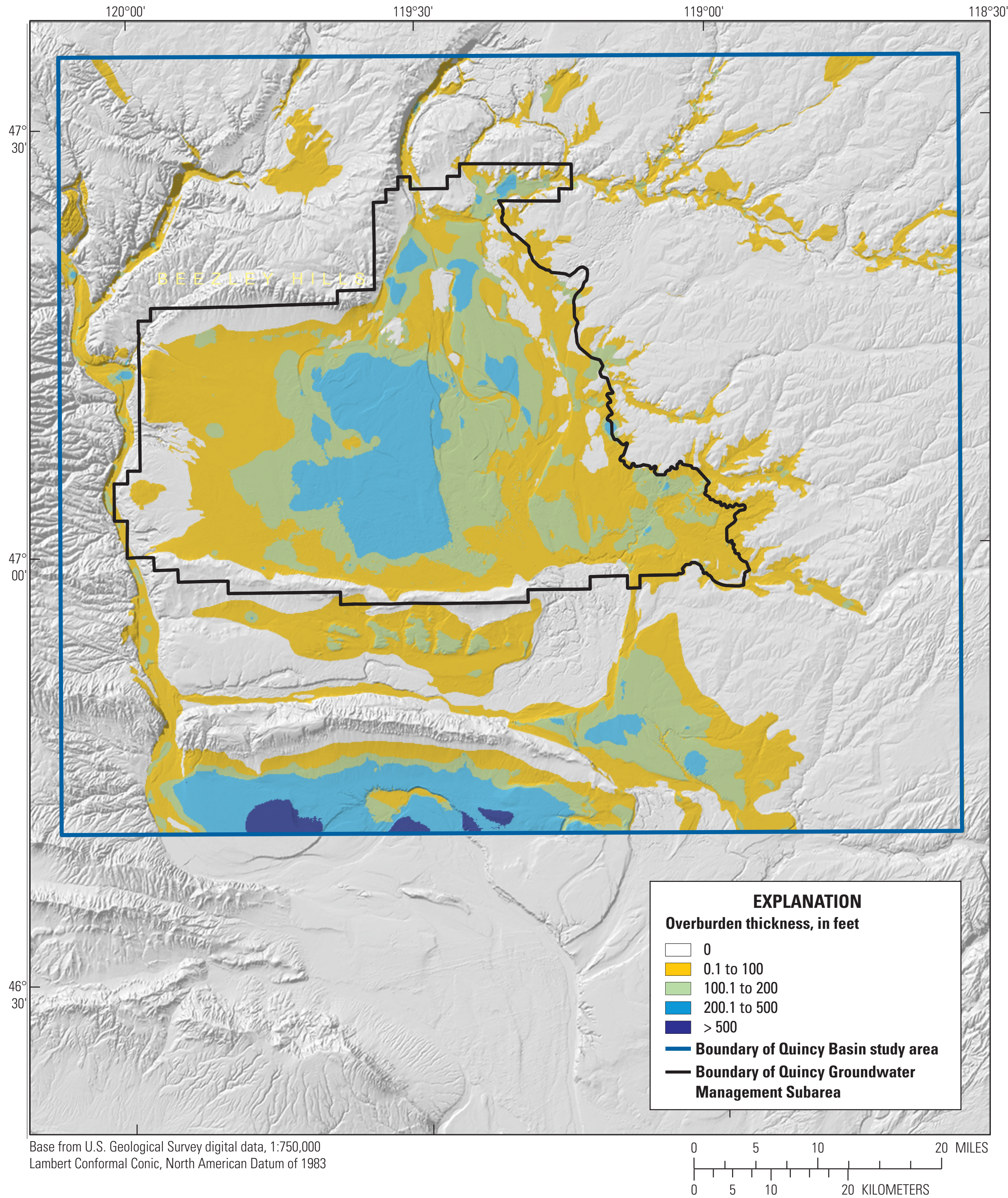


Figure 9. Extent and thickness of combined overburden units in the Quincy Basin study area, Washington.

Quaternary Deposits (QDEP)

The Quaternary deposits (QDEP) consist primarily of cataclysmic flood deposits with minor alluvium, colluvium, and eolian sand, with caliche in places. The unit is coarsest (gravel and boulders) near the mouth of Grand Coulee near Soap Lake and finest to the south and west where the unit is composed primarily of sand. The unit generally ranges in thickness from 50 to 150 ft but nears 300 ft in places near Ephrata (fig. 7, cross section *B-B'*). The QDEP unit occurs at land surface over most of the Quincy Basin (fig. 6). Although most project wells are completed in deeper hydrogeologic units, 45 of the project wells are completed in the QDEP where the unit is sufficiently thick and saturated to yield water to wells. The estimated horizontal hydraulic conductivity for well 18N/22E-02R02 (the only well completed in QDEP with available data to estimate hydraulic conductivity) is 250 ft/d.

Ringold Formation (RING)

The Ringold Formation (RING) is composed predominantly of layered silt, sand (sometimes described as sandstone), massive clay (with occasional gravel), and caliche, and generally is overlain by coarse Quaternary deposits. The unit is underlain everywhere by basalt and, in places, has as much as several feet of gravel at the Ringold-CRBG interface. It occurs at land surface in a few locations, primarily limited to the lower slopes in the southern part of the Quincy Basin and along some flood channels (fig. 6). The RING unit generally ranges from 100 to slightly more than 300 ft thick near the central part of basin (fig. 7). Despite the unit being primarily fine-grained, 62 project wells are completed in the unit (table 1) and provide usable quantities of water. The estimated horizontal hydraulic conductivity for the RING unit ranged from 20 to 290 ft/d , with a median of 48 ft/d, based on data from 10 wells open to the unit (tables 1 and 5).

Hydrologic Setting

Recharge

Prior to the 1950s, infiltration of precipitation was the primary source of groundwater recharge in the study area. Since the construction of the Columbia Basin Irrigation Project starting in the early 1950s, irrigation return flows have become a substantial source of additional groundwater recharge beneath agricultural areas in the Quincy Basin. The spatial distribution and temporal variation of recharge from precipitation and irrigation return flows to the Columbia Plateau Regional Aquifer System have been quantified using a monthly SOil WATer balance (SOWAT) model (Kahle and others, 2011). The SOWAT model uses simple relations among climatic, soils, land cover, and irrigation data to compute irrigation requirements and surplus moisture available for recharge. The SOWAT model incorporated evapotranspiration estimates derived from remotely sensed land-surface temperature data that were combined with other spatially distributed datasets including precipitation, soil moisture storage, and irrigation practices (Kahle and others, 2011). Estimated mean annual groundwater recharge for predevelopment (pre 1920) conditions in the Quincy Basin generally was less than 1.0 in/yr, whereas during current conditions (2000–07), recharge was estimated at as much as 10.0 in/yr within the CBP (Ely and others, 2014).

Historical Groundwater Levels

Water levels measured during 1939–45 in wells screened in both overburden sediments and underlying basalt aquifers (fig. 10*A*) may be considered representative of the predevelopment conditions that were present before the construction of surface-water delivery infrastructure or substantial groundwater withdrawals. Groundwater flowed from the upland areas on the northeastern and northwestern parts of the basin; toward the central part of the basin; and then generally toward Crab Creek, Moses Lake, and what is now the Potholes Reservoir. Groundwater flow direction is determined by connecting a line perpendicular to the water-level contours and going from high to low elevations. Because the water levels mapped in figure 10 are a combination of measurements from both overburden and basalt aquifers, actual water-level gradients could differ between the overburden and basalt aquifers. Therefore, the directions of predevelopment groundwater flow may not be adequately represented in figure 10 for all areas.

Water levels in the basalt and overburden aquifers began to rise substantially in some areas following the development of surface-water delivery infrastructure and associated agricultural irrigation in the early 1950s. A hydrograph depicting a 200-ft increase in water level (well 19N/23E-34R01, fig. 10*B*) from 1957 to 1985 exemplifies the change in water levels measured beneath irrigated areas where both basalt and the overburden occur.

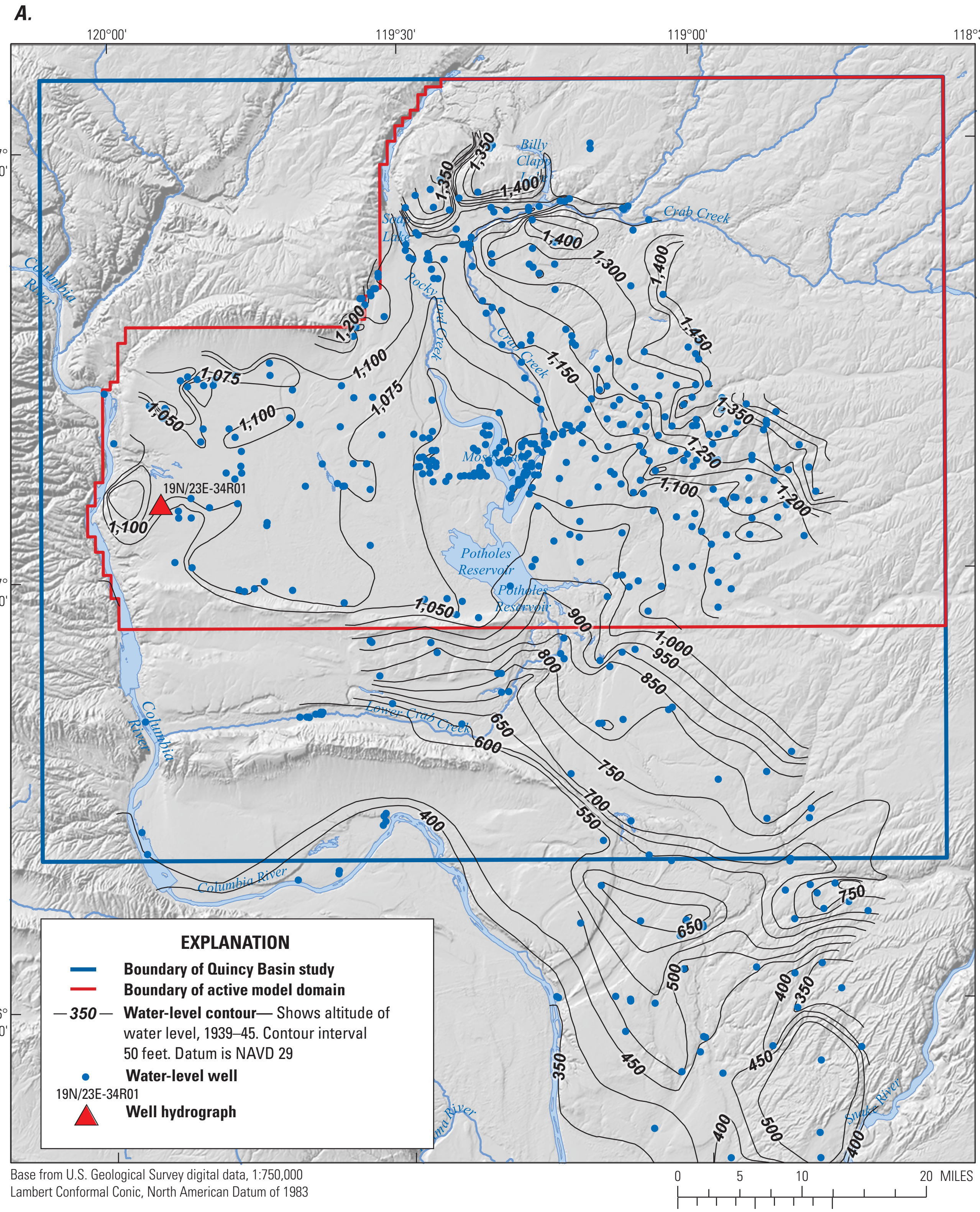


Figure 10. Contours of water levels measured in wells, 1939–45 (*A*); and hydrograph of well at location A (*B*), Quincy Basin, Washington.

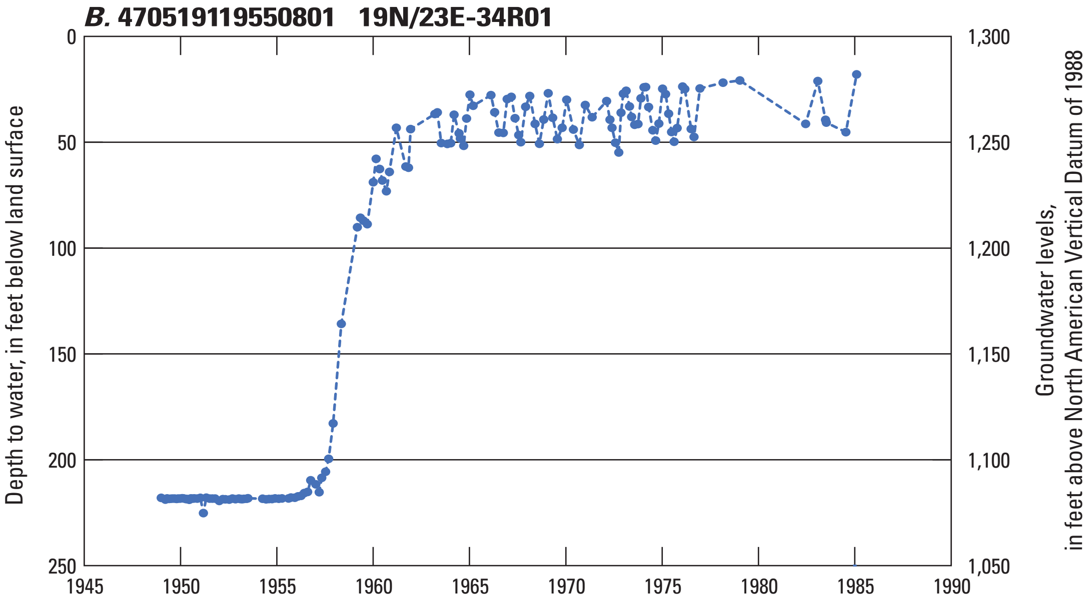


Figure 10.—Continued

Simulation of Groundwater Flow

The groundwater model developed in this study is based on a simple conceptual model in which natural precipitation and irrigation flows recharge the aquifer system by vertical flow through sedimentary overburden (where sediments occur) and into basalt layers. Regional groundwater-flow through basalt-aquifer layers occurs from areas to the north and east of the model domain and generally discharges to the Columbia River, although flow through the deepest basalt layers may discharge farther away. The model was designed to address a primary project objective—quantification of the spatial distribution of additional groundwater in storage resulting from agricultural development. The model also can be used to address secondary project objectives, which include assessments of various pumping and increased irrigation efficiency scenarios on groundwater levels.

Numerical Method

Simulation of a substantially rising water table, such as that which occurred in the Quincy Basin once irrigation of the area began, involves rewetting nonlinearities and associated numerical instabilities. The Newton formulation of the unconfined groundwater-flow equation available in MODFLOW-NWT (Niswonger and others, 2011) facilitates simulation of these systems, and, therefore, was selected to simulate the Quincy Basin.

Spatial Discretization

The model grid contains 101 rows and 117 columns of square finite-difference cells that are 1 km on a side (fig. 11). The grid was positioned so that the model cells correspond with the rasterized SOWAT model recharge and groundwater-withdrawal data to enable the use of the SOWAT data to specify historical flow rates of recharge and groundwater withdrawals into and out of the model domain. The active model domain is east of the Columbia River, and encompasses 2,526 mi^2, or about 55 percent of the area covered by the rectangular finite-difference grid. Five model layers (table 1) represent the two hydrogeologic units in the sedimentary overburden and the three basalt units underlying them. The thicknesses of individual model layers vary spatially to represent the thickness of the Quaternary depositional unit, Ringold Formation, Saddle Mountains Basalt, Wanapum Basalt, and Grande Ronde Basalt. The upper 600 ft of the Grande Ronde Basalt is represented by the lowest model layer. The spatial extents of the CRBG units were taken from Ely and others (2014). Although the five model layers generally correspond to these hydrogeologic units, the hydrogeologic units do not occur in all areas of the model domain. In order to simulate hydraulic connection between hydrogeologic units where a stratigraphically intervening hydrogeologic unit is not present, the absent units were assigned a 1-ft layer thickness and the specified hydraulic properties were changed to represent hydraulic conductivities of the layer below so that all layers are represented everywhere in the active model domain. This results in the simulated flow passing through the "altered" layer as if it were part of an adjacent model layer. Model layers 1–4 were simulated as convertible between confined and unconfined conditions. Layer 5 was simulated as confined.

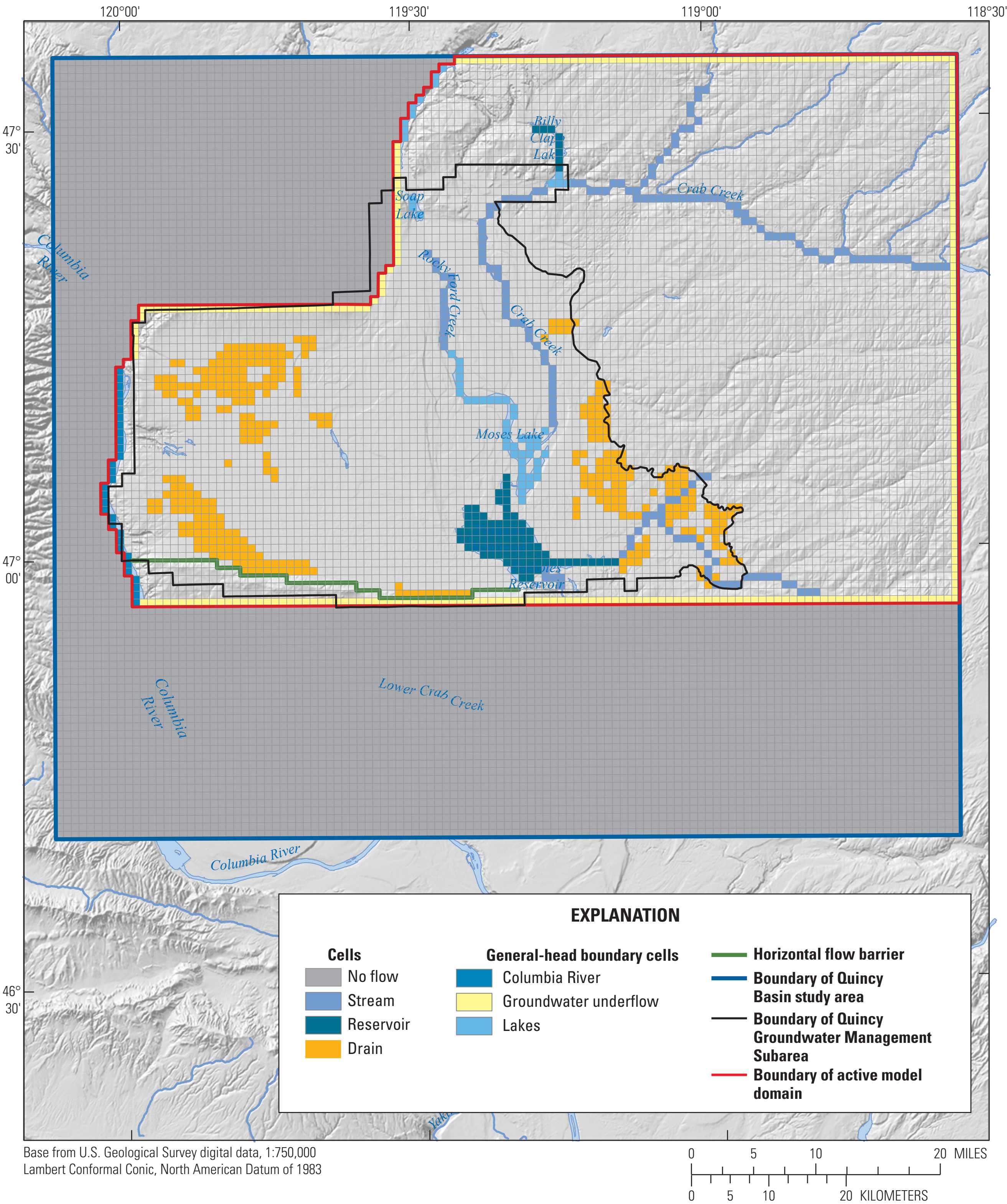


Figure 11. Finite-difference grid for the groundwater model with stream, reservoir, and drain cells; general-head boundary cells; and horizontal-flow barriers, Quincy Basin, Washington.

Time Discretization

A steady-state stress period was used to simulate groundwater conditions in the Quincy Basin prior to 1920. Ninety-four annual stress periods encompass the time interval of January 1, 1920–December 31, 2013, that was used for calibration to observed water levels. These annual stress periods were selected to correspond to the temporal discretization of Ely and others (2014) from which the recharge and groundwater withdrawals of this model are specified. For the scenarios described in this report, the final transient stress period (2013) was run to steady-state conditions and model input was modified for the steady-state scenarios.

Boundary Conditions

Boundary conditions define the locations and manner in which water enters and exits the active model domain. Conceptually, water enters the aquifer system as recharge from precipitation and irrigation and through lateral groundwater flow and exits the system as discharge to the Columbia River and other streams, lateral groundwater flow, and groundwater pumpage. Three types of model boundaries were used: (1) no-flow boundaries (bottom and edges of the model), (2) head-dependent flux boundaries (streams, drains, and general-head boundaries), and (3) specified-flux boundaries (pumpage and recharge).

No-Flow Boundaries

The lateral and bottom surfaces of the model domain are no-flow boundaries except for those lateral parts of the model domain that simulate groundwater underflow with head-dependent flow boundaries (see section, "Head-Dependent Flux Boundaries").

Specified Flux Boundaries

Two types of specified fluxes were simulated in the model: (1) recharge and (2) groundwater withdrawals (pumpage).

Recharge

The annual recharge rates specified for the Quincy Basin model documented in this report came from the regional model of Ely and others (2014), which includes both natural and anthropogenic (for example, irrigation flows) components. Although the regional model of Ely and others (2014) uses larger (3-km^2) finite-difference cells, recharge for that model was computed with 1-km^2 raster arrays that are compatible with the 1-km^2 finite-difference cells of this model. Ely and others (2014) estimated natural recharge using gridded historical estimates of annual precipitation for the period 1895–2007; predevelopment recharge was estimated as the average natural recharge for this period, irrigation recharge and irrigation pumping were estimated using a remote-sensing based SOWAT model for 1985–2007 (Kahle and others, 2011), and pre-1985 irrigation recharge and pumping were estimated using previously published compilation maps and the history of large-scale irrigation projects. The recharge estimated for 2007 (fig. 12) was specified for all subsequent years of the simulation (2008–13). Because 2007 precipitation was similar to the mean annual precipitation (Kahle and others, 2011), extrapolation of the 2007 simulated recharge was a reasonable representation for subsequent years.

Groundwater Withdrawals

The groundwater withdrawals estimated with the SOWAT model used by Ely and others (2014) were used for this model and were simulated with the WELL package (McDonald and Harbaugh, 1988). Assignment of the SOWAT model-estimated groundwater withdrawals to appropriate depths likely introduces the greatest errors in the model because records of the actual location and magnitude of withdrawals are not available. For each stress period, the groundwater withdrawal estimated by the SOWAT model for each model cell was assigned to one or more wells (fig. 13). Well locations were obtained from the Washington State Department of Ecology well database. The total amount of pumping in each cell was split equally among the number of wells in the cell. If no well was in a cell with groundwater withdrawals, the groundwater withdrawals were distributed between layers based on the well depths from the next nearest cell that contained a well. Some structural model error was a byproduct of the specification of these specified groundwater withdrawals.

The magnitude of groundwater withdrawals from the study area was negligible until the 1930s, when it began to increase to about 10,000 acre-ft/yr by the early 1940s (fig. 14). Withdrawal rates increased rapidly from the mid-1960s through the mid-1980s—from about 50,000 acre-ft/yr in 1965 to more than 275,000 acre-ft/yr by 1985.

Head-Dependent Flux Boundaries

Groundwater flows to rivers, streams and lakes, agricultural drains, reservoirs, and flow across the model perimeter depend on the hydraulic heads of those features and the aquifer groundwater levels, and, therefore, are simulated as head-dependent boundaries.

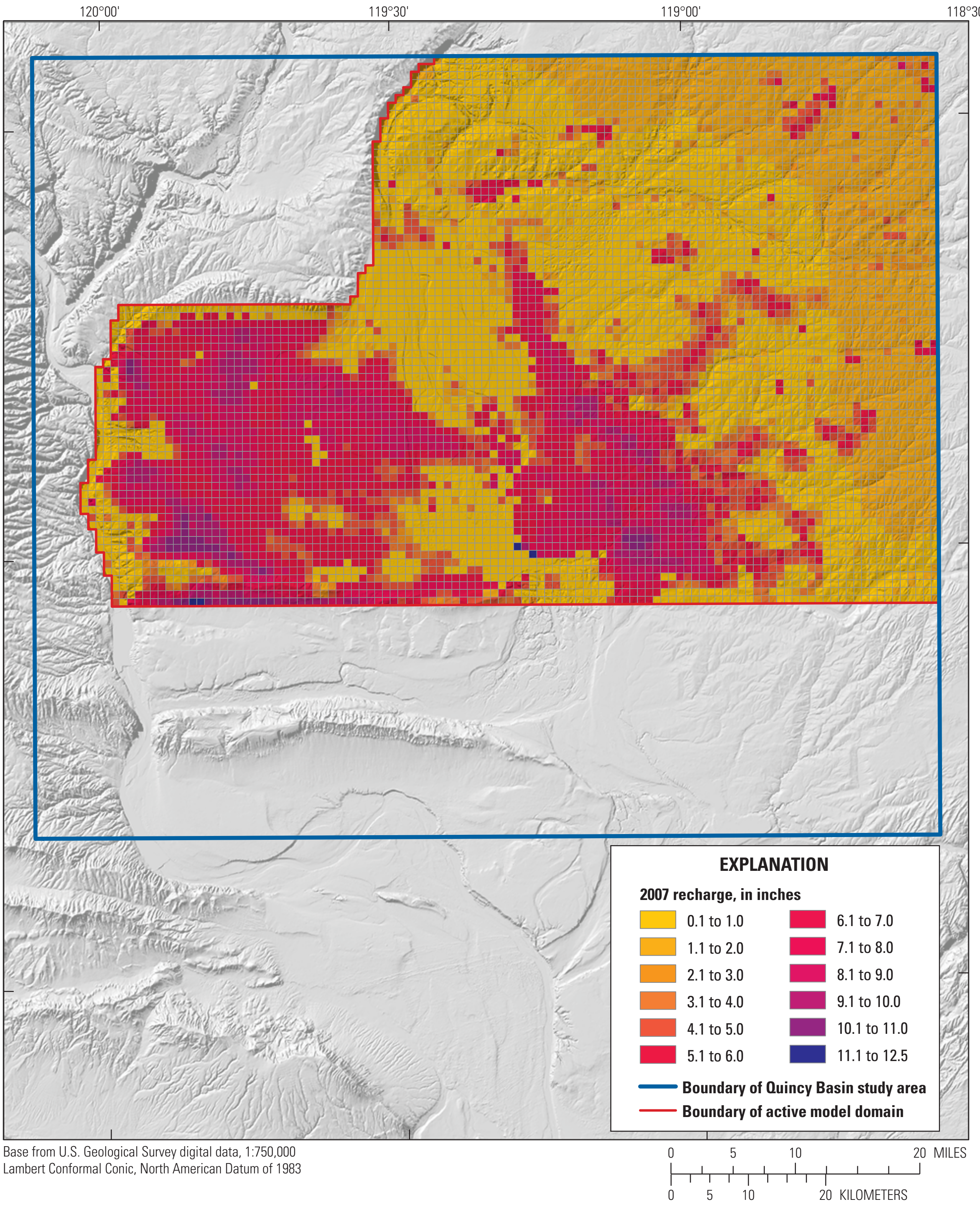


Figure 12. Distribution of recharge specified in the Quincy Basin model domain, Quincy Basin, Washington, 2007.

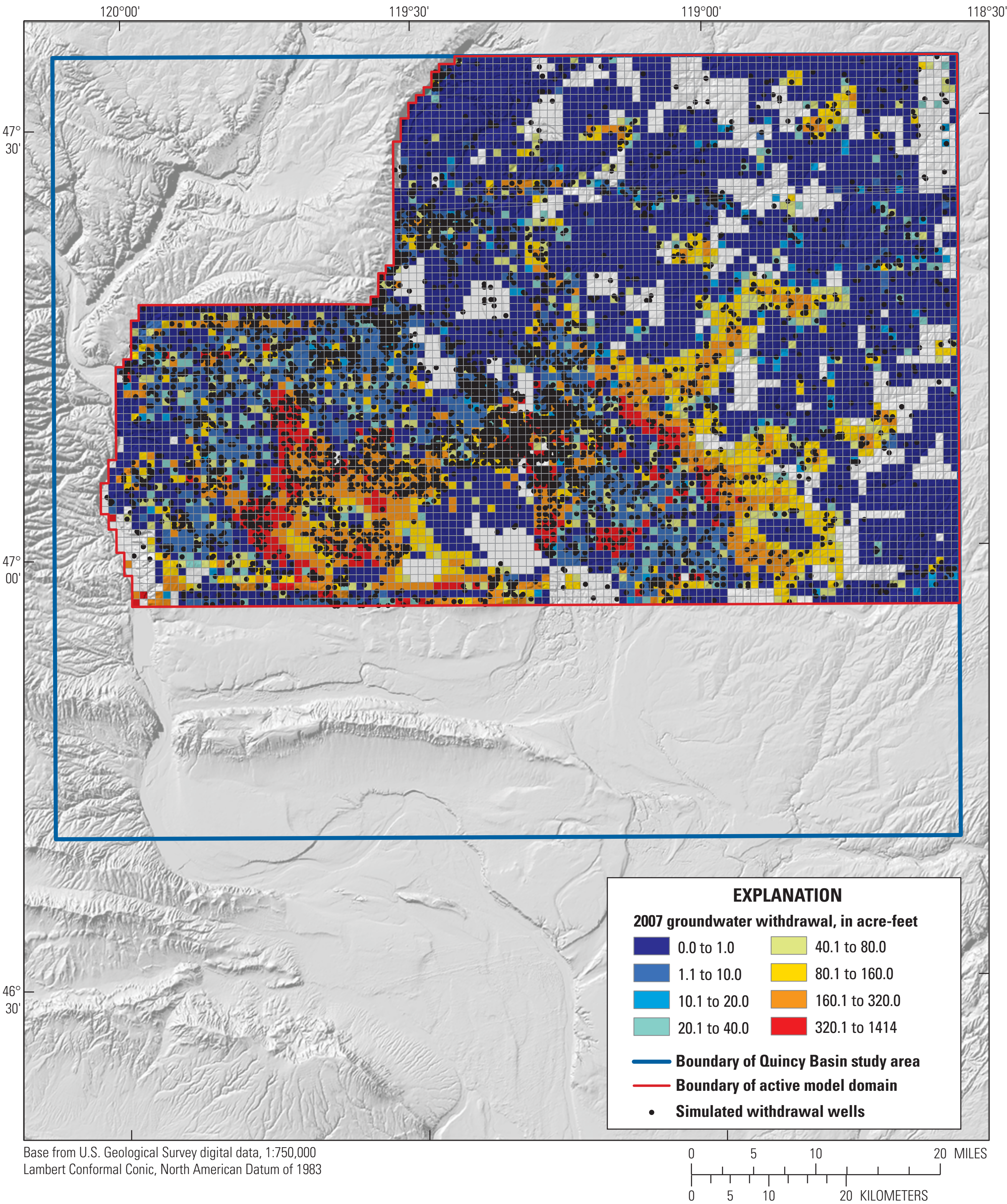


Figure 13. Locations of simulated withdrawal wells and SOil WATer balance (SOWAT) model-estimated groundwater withdrawals, Quincy Basin, Washington, 2007.

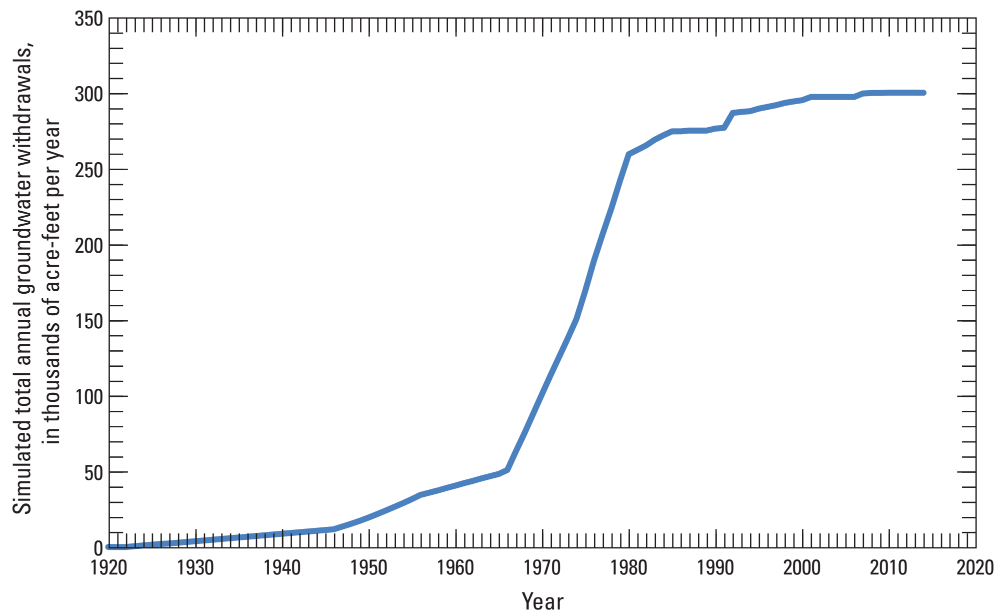


Figure 14. Total annual groundwater withdrawals simulated from the Quincy Basin, Washington, 1920–2014.

General Head Boundaries

The Columbia River bounds the western side of the model domain and was simulated with the General Head Boundary (GHB) package of MODFLOW (McDonald and Harbaugh, 1988) (fig. 11). The part of the Columbia River that borders the model domain was simulated without dams prior to 1963. For simplicity, the stage change due to construction of the Wanapum Dam (fig. 1) was simulated to occur in 1963. River stages were set to 520 ft prior to dam construction and 570 ft afterwards based on topographical map information.

The underflow of groundwater in the CRBG through the northern, eastern, and southern perimeter of the study area was simulated at the locations in figure 11 with the GHB package. The GHB cells were connected to model layer 5, which represents the top of the Grande Ronde Basalt. Water levels specified for each of the groundwater underflow GHB cells in this model were taken from corresponding locations simulated in layer 36 (which represents the top of the Grand Ronde Basalt) during the steady-state, predevelopment stress period of the revised Columbia Plateau Regional Aquifer System (CPRAS) model (Ely and others, 2014).

The GHB package also was used to simulate subsurface exchange of water from certain naturally occurring lakes with the underlying aquifers (fig. 11). Representation of the lakes in this way allows flow into and out of a lake cell in proportion to the difference between the head in the cell and the specified head of the lake. The specified lake stages were determined from USGS 1:24,000-scale topographic maps because no data about changes in lake stages were available with the exception of Moses Lake. Stage data for Moses Lake was provided by Reclamation (Alexis Mills and Karl Williams, Bureau of Reclamation, written commun., 2017).

Drains

Agricultural drains (fig. 11) were simulated with the Drain (DRN) package of MODFLOW (McDonald and Harbaugh, 1988). The drain-boundary altitudes were specified as the minimum DEM land-surface altitude in the model cell containing the drain. Drain locations were obtained from Reclamation (Karl Williams, Bureau of Reclamation, written commun., 2017).

Streams

The part of Crab Creek within the model domain was simulated with the Streamflow-Routing (SFR) package of MODFLOW, as were other smaller naturally occurring streams in the model (fig. 11), to route streamflow and calculate stream-aquifer exchanges (Niswonger and Prudic, 2005). The model has 14 simulated stream segments that are coincident with the underlying MODFLOW cells (U.S. Geological Survey, 2014).

The exchange of water between streams and groundwater is controlled by the difference in the groundwater level and stream stage in each cell, and by the hydraulic properties of the streambed at the river-aquifer boundary in each cell, which is represented in the model by a streambed conductance term. The depth of each stream within each reach was computed by SFR using Manning's equation for open channel flow assuming a wide rectangular channel, which is a reasonable approximation of channel geometry. For routing streamflow, a constant value of 0.04 was used for Manning's coefficient (Ely and Kahle, 2012).

Reservoirs

Two reservoirs, Potholes Reservoir and Billy Clapp Lake, were included in the model using the Reservoir (RES) package of MODFLOW (Fenske and others, 1996). The exchange of water between the reservoirs and groundwater is controlled by the difference in the groundwater level and reservoir stage in each cell, and by the hydraulic properties of the reservoir-aquifer boundary in each cell, which is represented in the model by the conductance term of 0.01 ft^2/d. Stage data for the two reservoirs was provided by Reclamation (Alexis Mills and Karl Williams, Bureau of Reclamation, written commun., 2017).

Horizontal Flow Barriers

The Frenchman Hills Fault (Lidke, 2003) acts as a barrier to groundwater flow and was simulated as a horizontal flow barrier (HFB; Hsieh and Freckleton, 1993) in model layers 1–4 at the locations shown in figure 11. The decreased hydraulic conductance between adjacent model cells is specified with a hydraulic characteristic for each HFB that is dimensionally equivalent to the hydraulic conductivity of the fault zone (in the direction perpendicular to the fault plane) divided by the width of the fault zone. A single hydraulic characteristic for HFBs representing the Frenchman Hill Fault barrier was parameterized and estimated during model calibration.

Model Calibration

Model calibration is the adjustment of model parameters within reasonable limits so that the differences (residuals) between measured and simulated groundwater levels are minimized with respect to an objective function. The calibration is assessed by examining how well the simulated quantities fit the measured quantities.

Calibration Procedure

The model was calibrated using a combination of traditional trial-and-error adjustments of parameters and the parameter estimation program (PEST; Doherty, 2005, 2006), enhanced with Pilot-Point Parameterization (Doherty, 2003; Doherty and others, 2010), Tikhonov Regularization (Doherty, 2003; Fienen and others, 2009), and Singular Value Decomposition (Doherty and Hunt, 2010). PEST automatically adjusted model parameters (horizontal and vertical hydraulic conductivity; specific storage; specific yield; and stream, drain, HFB, and general head boundary conductance) within specified limits through a series of model runs. After each model run, simulated groundwater levels were compared to measured values. Model runs continued until the differences (residuals) between simulated and measured values were minimized.

Pilot-point parameterization was used to represent spatial heterogeneity in horizontal and vertical hydraulic conductivity, specific yield, and specific storage. Pilot points were evenly distributed over the entire model domain by hydrogeologic unit and were used as surrogate parameters at which values for horizontal and vertical hydraulic conductivity were estimated during calibration. Estimated values of horizontal and vertical hydraulic conductivity and storage coefficients at pilot points were interpolated throughout the active model domain using kriging (a geostatistical algorithm) procedures in PEST. The result is a smooth variation of the hydraulic property over the model domain. Numerous studies have used pilot points for groundwater model calibration (de Marsily and others, 1984; LaVenue and Pickens, 1992; Petkewich and Campbell, 2007) and have proven them to be powerful, flexible tools for representing spatial heterogeneity in various types of aquifer-hydraulic properties.

Pilot points generally were spread in a regular grid pattern where possible. The pilot points were distributed vertically so that each hydrogeologic unit contained pilot points. If a pilot point for any given hydrogeologic unit occupied a location where that unit was absent, it was deleted from that location for that unit to ensure that the pilot points for each hydrogeologic unit were kriged only to other points within that unit.

Water-Level Observations

The model-calibration dataset included a total of 4,064 water levels measured in 710 wells with screen interval information. Although only a single measurement was recorded from some wells, multiple measurements from many of the wells constituted water-level hydrographs of as much as 68 years in duration. The calibration data set included 377 water-level measurements that were used to construct the map of predevelopment water levels (fig. 10*A*) that were located within the active model domain to represent the 1939 water-table altitude. No depths were available for wells shown in figure 10*A*, so the water levels were assigned to the whichever hydrogeologic unit was at the surface where the well was located.

The weight (ω) assigned to observations should represent the measurement error, and typically is computed as the inverse of the total observation-error variance. Substantial differences in measurement errors of the water levels were unable to be determined, and, therefore, were assumed to be equivalent, which resulted in uniform weighting among the water-level observations.

Final Parameter Values and Sensitivities

The ability to estimate a parameter value during the calibration process is related to the sensitivity of the model-simulated output to changes in the parameter value. For example, if a parameter has a high sensitivity, the observation data effectively estimate the value. For parameters with low sensitivity, changes in the value have little effect on the model-calibration process. Insensitive parameters may or may not be close to their corresponding field values and are not likely to be estimated accurately during the parameter-estimation process.

Relative composite sensitivities are a measure of composite changes in model outputs that are caused by small changes in the value of a modeled parameter (Doherty, 2005). For a given modeled parameter, the larger the value of the associated relative composite sensitivity, the more sensitive the model is to that parameter. Relative composite sensitivities were calculated and analyzed for the parameters used in the model-calibration process (table 2). Median sensitivities are presented for each hydrogeologic unit for the horizontal and vertical hydraulic conductivities, the storage coefficients, and other parameters.

The simulated water levels were most sensitive to parameters representing the groundwater flow to the Columbia River and groundwater underflow across the southern and northwestern model perimeter (GHB conductances). The simulated groundwater levels were most insensitive to the vertical hydraulic conductivity of the Quaternary deposits, the storage coefficients of the three basalt layers, and the GHB conductances of some of the lakes.

The calibrated values of the model parameters representing aquifer hydraulic conductivity, storage, and boundary and fault conductances are tabulated in table 2. The median calibrated values of hydraulic conductivities and storage coefficients are similar to corresponding values in other studies (Ely and others, 2014; Heywood and others, 2016).

Table 2. Parameter sensitivities and final values for all parameters used in calibration of groundwater model for Quincy Basin, Washington.

[**Specific yield pilot points:** Specific yield numbers are not adjusted by parameter estimate code PEST. **Abbreviation and symbol:** GHB, General Head Boundary; –. not computed]

Hydrogeologic unit	Model layer	Number of parameters	Median sensitivity	Estimated value		
				Minimum	Median	Maximum
Horizontal aquifer hydraulic conductivity pilot points, in feet per day						
Quaternary deposits	1	26	0.005774187	16.69	46.55	858.67
Ringold Formation	2	16	0.014776585	5.47	57.40	309.16
Saddle Mountain Basalt	3	24	0.000903991	2.46	4.80	7.21
Wanapum Basalt	4	22	0.018148775	1.00	4.29	227.79
Grande Ronde Basalt	5	129	0.007902205	0.06	4.58	5,400.74
Vertical aquifer hydraulic conductivity pilot points, in feet per day						
Quaternary deposits	1	26	7.72428×10^{-5}	4.74	5.01	5.73
Ringold Formation	2	16	0.000103905	4.10	4.96	6.00
Saddle Mountain Basalt	3	24	0.000288208	0.03	0.05	0.06
Wanapum Basalt	4	23	0.005611046	0.00	0.05	0.15
Grande Ronde Basalt	5	129	0.000502951	0.02	0.05	0.17
Specific storage pilot points						
Ringold Formation	2	16	0.001875517	0.10	0.15	0.34
Saddle Mountain Basalt	3	24	7.72428×10^{-5}	9.98×10^{-7}	1×10^{-6}	1.01×10^{-6}
Wanapum Basalt	4	23	6.71547×10^{-5}	9.559×10^{-7}	1×10^{-6}	1.06×10^{-6}
Grande Ronde Basalt	5	24	9.16492×10^{-5}	9.43×10^{-7}	1×10^{-6}	1.05×10^{-6}
Specific yield pilot points						
Quaternary deposits	1		1.38471×10^{-5}	0.2	0.2	0.2
Ringold Formation	2		2.25016×10^{-5}	0.2	0.2	0.2
Saddle Mountain Basalt	3		1.50011×10^{-5}	0.2	0.2	0.2
Wanapum Basalt	4		1.56533×10^{-5}	0.2	0.2	0.2
Grande Ronde Basalt	5		1.50011×10^{-5}	0.2	0.2	0.2
Other calibration parameters						
Stream conductance		14	5.62×10^{-3}	0.094923395	14.1745005	39,868.92
Drain conductance (feet per day)		1	1.33×10^{-2}	–	52,089.03	–
GHB conductance (Columbia River)		1	0.132533	–	25.27162	–
GHB conductance (northwestern boundaries)		1	0.107717	–	1,209.831	–
GHB conductance (southern boundary)		1	0.563673	–	17,876.23	–
GHB conductance (northeastern boundaries)		1	2.16×10^{-3}	–	3.55451	–
GHB conductance (Soap Lake)		1	3.50×10^{-4}	–	3.07262	–
GHB conductance (Lenore Lake)		1	8.34×10^{-4}	–	2.337191	–
GHB conductance (Alkali Lake)		1	5.98×10^{-5}	–	1.118948	–
GHB conductance (Blue Lake)		1	2.32×10^{-4}	–	1.497946	–
GHB conductance (Moses Lake)		1	2.68×10^{-3}	–	2.778726	–
GHB conductance (Brook Lake)		1	1.72×10^{-4}	–	5.083055	–
Hydrologic flow barrier conductance		1	1.87×10^{-3}	–	1.64×10^{-5}	–

Assessment of Model Fit

A graphical and descriptive comparison of simulated and measured groundwater levels provides a clear insight into the model fit and complements the statistical measures of model fit. Such a comparison indicates how well the model replicates the flow system. It is important to determine that the model accurately simulates the regional direction and amounts of flow in the groundwater-flow system.

Comparison of Measured and Simulated Hydraulic Heads

The results of the calibration were assessed by comparing measured and simulated groundwater levels and by examining the mean and standard deviation of residuals (unweighted) and the root mean-square error (RMSE) of residuals for the groundwater levels. The mean of residuals represents the average difference between all measured and simulated values (residuals), and the sign of the mean of residuals (bias) indicates whether the model is overpredicting or underpredicting values (negative and positive mean of residuals, respectively). The standard deviation of residuals is a measure of how much variation there is in residual values greater than and less than the mean residual value. A low standard deviation indicates that the residuals tend to be close to the mean, whereas a high standard deviation indicates that residuals are spread out over a large range of values around the mean. The RMSE of weighted residuals provides a measure of variation that considers measurement accuracy. The RMSE of the difference between simulated and measured hydraulic heads in the observation wells, divided by the total range in water levels in the groundwater system (Anderson and Woessner, 1992, p. 241), also should be less than 10 percent to be acceptable (Drost and others, 1999).

The RMSE and the standard deviation of the residuals were 47.61 and 47.59 ft, respectively. The scaled RMSE was 0.048 (4.8 percent) and was obtained by dividing the RMSE of the residuals by the 1,001-ft range of observed water levels. Overall, because the groundwater levels have a RMSE divided by the total range of values of less than 10 percent, the model has a good fit (Drost and others, 1999). The mean error, calculated as the mean of the residuals (measured minus simulated water levels), was -1.38 ft, indicating that overall simulated water levels are slightly higher than observed water levels. The mean absolute error (the mean of the absolute value of the residuals) was 36.02 ft.

A plot of measured compared to simulated groundwater-level altitudes provides a useful graphical assessment of model calibration (fig. 15). Measured compared to simulated values should plot close to a line with a slope of 1.0 and an intercept of zero. This diagonal line represents perfect agreement between measured and simulated values (the line of equal measured and simulated values), and the magnitude of the residual (difference between measured and simulated values) is indicated in the distance of the value above or below the line. Positive residuals (measured value is greater than simulated) and negative residuals (measured value is less than simulated) plot above and below the line, respectively.

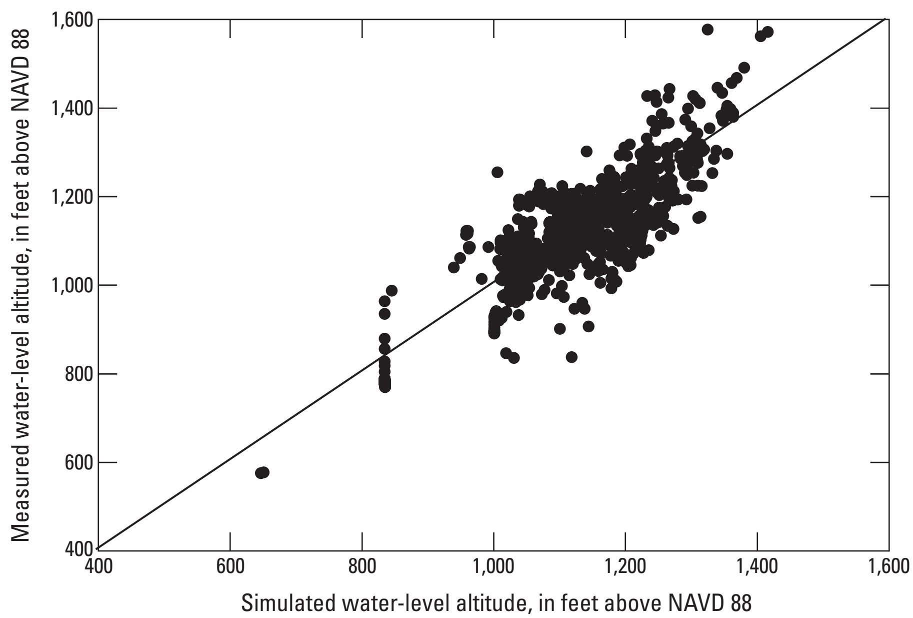


Figure 15. Measured compared to simulated water levels in the Quincy Basin, Washington.

Measured compared to simulated values shown in figure 15 generally are along the line of equal measured and simulated values, indicating a good model fit; groundwater-level altitudes above 1,300 ft tend to be underpredicted in some areas with high water levels. Some model bias is indicated by this deviation from a random residual distribution.

A spatial comparison of simulated and measured hydraulic heads indicates that the model reasonably simulates the measured groundwater levels (fig. 16). The residuals are calculated by subtracting the simulated heads from the measured heads, so positive residuals are at sites where the model predicts heads that are lower than measured (underprediction), and negative residuals are at sites where the model predicts heads that are higher than measured (overprediction). The smaller the residuals, the better the model is at predicting the water levels. The spatial distribution of the hydraulic-head residuals does not indicate any major patterns of bias, with the exception of the Moses Lake area and north along Crab Creek where the values tend to be overpredicted.

Simulated Water Levels

The general directions of simulated groundwater flow during 2013 may be inferred from contours of water-level altitudes simulated for 2013 (fig. 17). Groundwater generally flows either towards Crab Creek, Moses Lake, and Potholes Reservoir or towards the Columbia River, as the main discharge areas of the model. The highest water levels occur in the northeastern corner of the model.

The simulated rise in groundwater levels since 1920 in areas of the Quincy Basin primarily is a function of the magnitude of groundwater recharge and groundwater withdrawals in the area. Groundwater levels have risen substantially (generally from 50 ft to as much as 250 ft) in the western part of the study area (fig. 18), where simulated recharge is primarily 5–10 in/yr (fig. 12). The unconsolidated sediments in these areas generally were unsaturated prior to irrigation occurring in the area. Water levels also have risen 25–100 ft in the central part of the study area and occur where simulated recharge primarily is 5–10 in/yr. The highest water-level increases occur south of the hydrologic flow barrier that represents the Frenchman Hills Fault along the southern edge of the model. Simulated water levels have increased in that region by 250 ft to more than 400 ft in an area that receives as much as 12.5 in/yr of simulated recharge. The water levels in that area may be subject to larger uncertainties as there is only a small sliver of land between the horizontal flow barrier and the southern boundary of the model. Little calibration data are available to verify the water-level increases in that area. Some areas of the model (particularly a large swath in the eastern half) have had slight simulated water-level declines of less than 20 ft, with a small region having simulated declines of 20–40 ft presumably due to increased groundwater pumping. The largest simulated declines of more than 40 ft occur in the model cells that contain Billy Clapp Lake (fig. 18) and are due to structural model error and are not considered to be realistic. Further spatial refinement of the model grid and hydraulic parameters would be needed to more accurately simulate changes in water levels near Billy Clapp Lake.

Simulated Groundwater Budgets

The net flows (inflow minus outflow from the model domain) of groundwater-model components were calculated for each model stress period (fig. 19). Prior to the mid-1940s, variations in annual precipitation resulted in small amounts of recharge (generally less than 2 in/yr) and relatively modest changes in storage. Note that increased groundwater storage is an outflow from the groundwater-flow system and is negatively signed; increasing negatively signed absolute values of storage in figure 19 indicate increases in the quantity of stored groundwater. From the late 1940s through the mid-1960s, increased anthropogenic recharge due to irrigation and the leakage of water from Potholes Reservoir substantially increased groundwater storage in the aquifer system. Increasing groundwater withdrawals (pumpage) since the mid-1960s have abated further contributions to storage, with changes in storage stabilizing since about 1980. Net changes to groundwater storage since 1980 have resulted primarily from variations in groundwater recharge caused by changes in annual precipitation.

The simulated groundwater budgets in the Quincy Subarea calculated for the initial steady-state stress period (which represents average “predevelopment” conditions prior to 1920) and the last transient stress period (which represents the year 2013) are summarized in table 3. During the initial steady-state conditions, vertical recharge, lateral groundwater flow from the surrounding area, and some seepage from streams into the subarea were balanced by discharge to streams, and lateral groundwater flow out through the downgradient Quincy Subarea boundary (fig. 11). By 2013, substantially more recharge into the area compared to the initial conditions (as well as inflow from the reservoirs) resulted in increased discharge to streams, lakes, and drains, and increased lateral groundwater flow out of the subarea. Groundwater withdrawals from wells were the largest outflow from the subarea. The distribution of both recharge and groundwater withdrawals causes increases and decreases in groundwater storage in different areas, which are summarized as outflows to and inflows from storage, respectively, in table 3. During 2013, the simulation showed a 27,000 acre-ft net increase in groundwater storage for the Quincy Subarea.

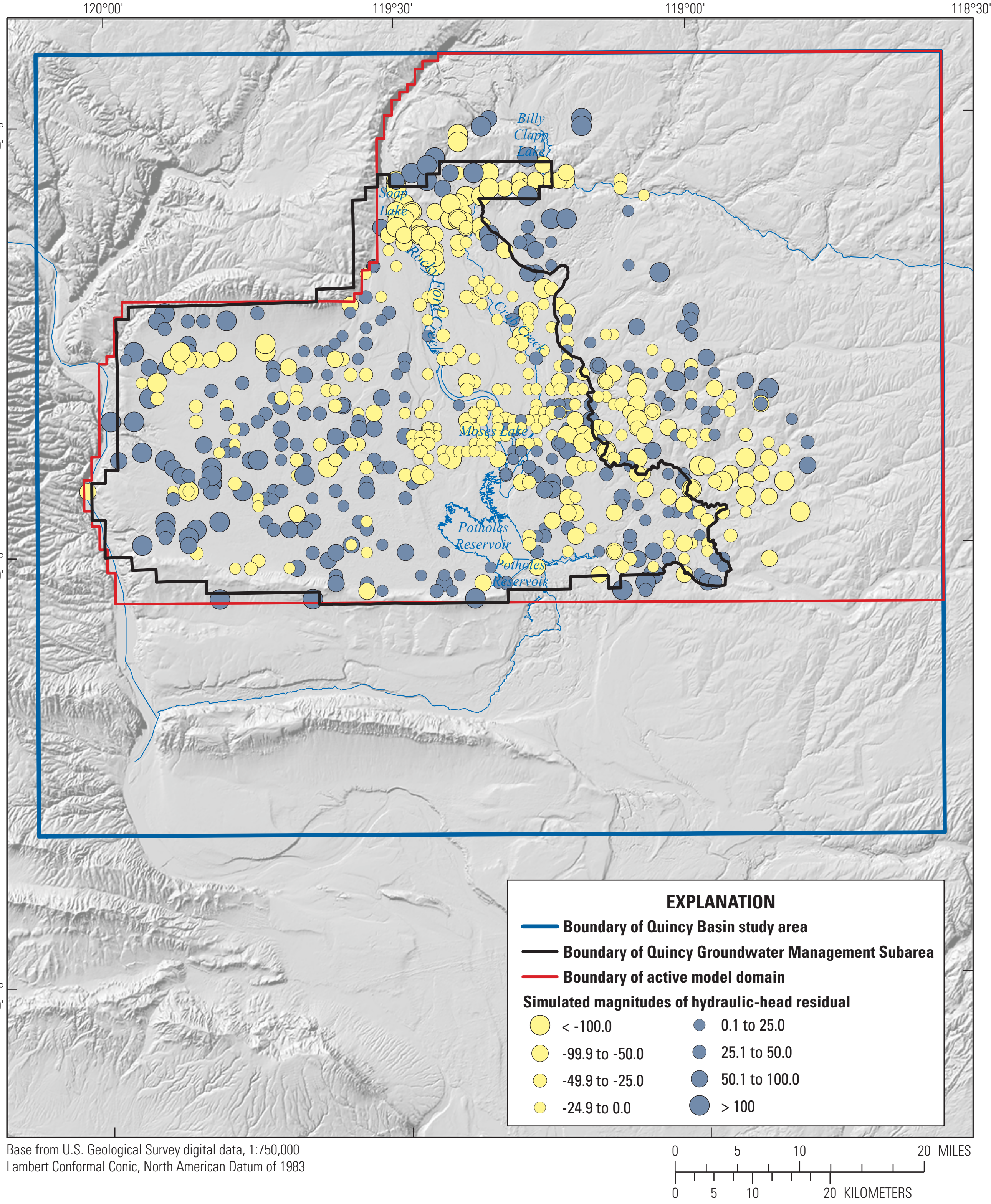


Figure 16. Simulated magnitudes of hydraulic-head residuals in the Quincy Basin, Washington.

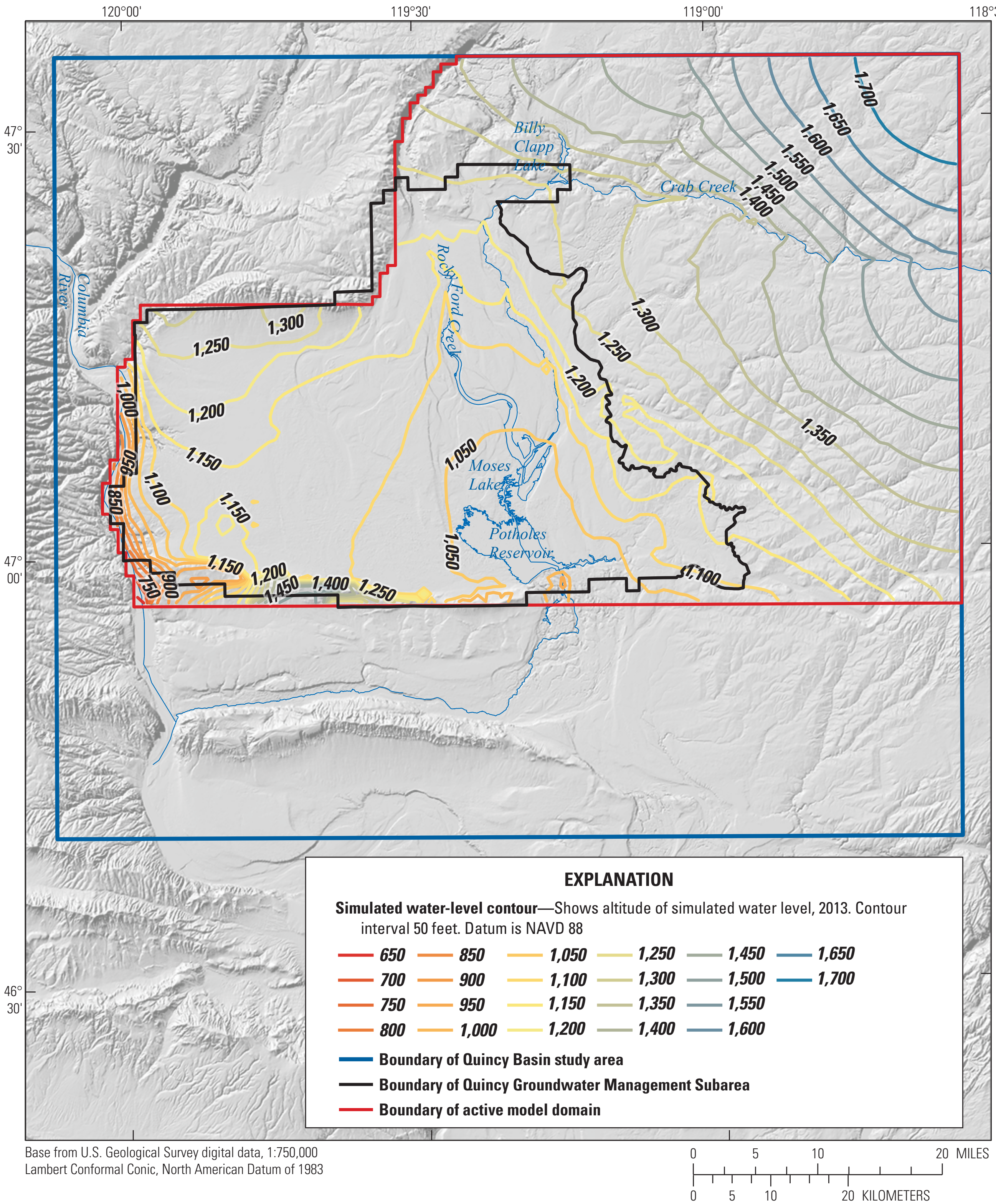


Figure 17. Contours of simulated water-level altitudes, Quincy Basin, Washington, 2013.

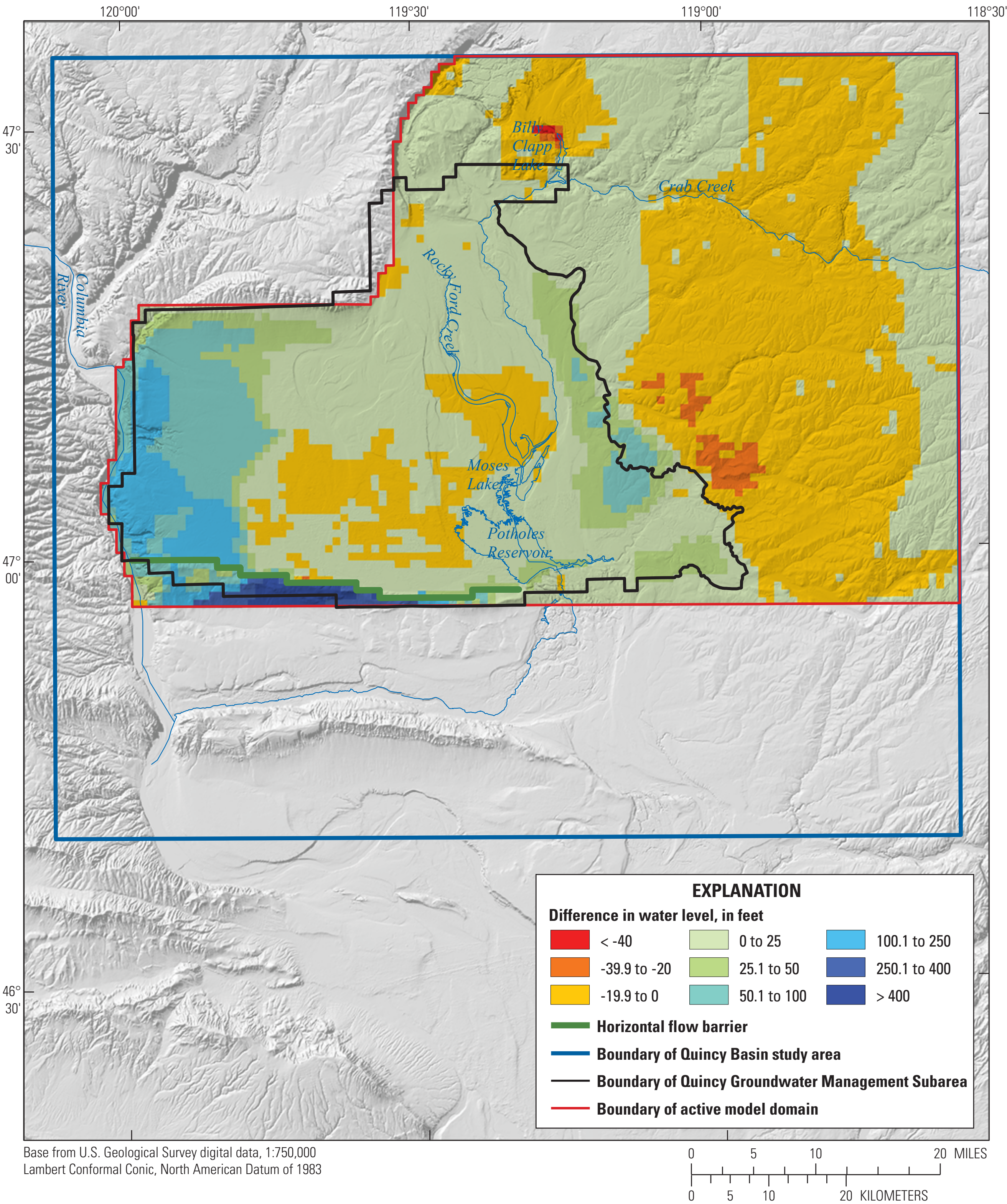


Figure 18. Simulated changes in water-level altitude, Quincy Basin, Washington, 1920–2013.

Table 3. Groundwater budget of the Quincy Groundwater Management Subarea, Quincy Basin, Washington, pre-1920 and 2013.

[Values in thousands of acre-feet per year]

	Pre-1920 (steady state)	2013
Inflows		
Recharge	28	273
Groundwater flow from surrounding model domain	37	27
Lakes and groundwater flow from model boundary	27	25
Streams	1	0
Reservoirs	0	22
Storage	0	38
Total	93	385
Outflows		
Groundwater flow to surrounding model domain	44	55
Lakes and groundwater flow from model boundary	20	23
Streams	28	35
Reservoirs	0	1
Groundwater withdrawals	0	200
Drains	1	6
Storage	0	65
Total	93	385

Water budgets for 2013 also were calculated for three other areas of interest within the Quincy Subarea: (1) High Hills Irrigation development area, (2) Moses Lake Irrigation Rehabilitation District, and (3) the City of Quincy (fig. 20 and table 4). In the High Hills area, inflows primarily are the result of groundwater flow from the surrounding area and recharge from the surface. Groundwater withdrawals of 974 acre-ft account for 22 percent of the total outflow, with the remainder flowing out to Soap Lake and the surrounding area. There was a net increase in the amount of water stored in the area of 59 acre-ft for 2013. In the Moses Lake area, inflows primarily are the result of groundwater flow from the surrounding area, recharge from the surface, and from storage. Groundwater withdrawals of 19,242 acre-ft account for almost 67 percent of the total outflow, with most of the rest of the groundwater flowing out to the surrounding area. In 2013, there was a net decrease of 4,614 acre-ft in the amount of water stored in the area. For the area around the City of Quincy, inflows primarily are the result of groundwater flow from the surrounding area and recharge from the surface, with a minor amount coming from storage. Groundwater withdrawals of 3,017 acre-ft account for 43 percent of the total outflow, with the remainder flowing out through the groundwater system to the surrounding area. In 2013. there was a net decrease of 85 acre-ft in the amount of water stored in the area.

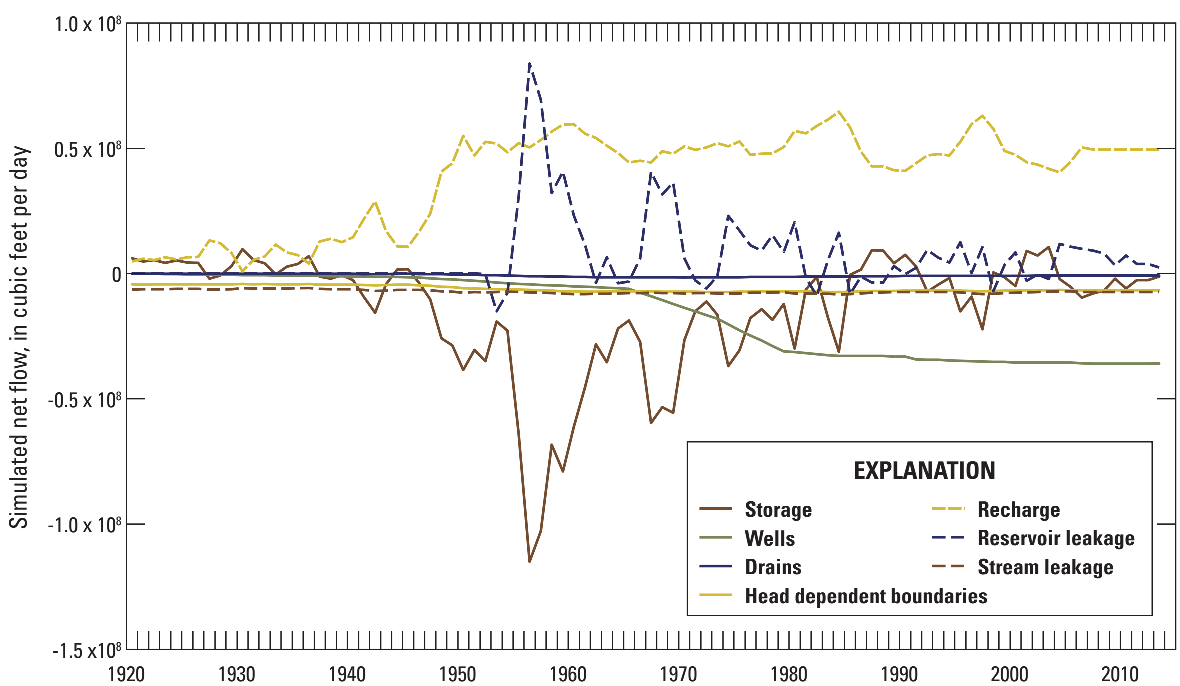


Figure 19. Simulated net flows into the groundwater model domain, Quincy Basin, Washington, 1920–2013.

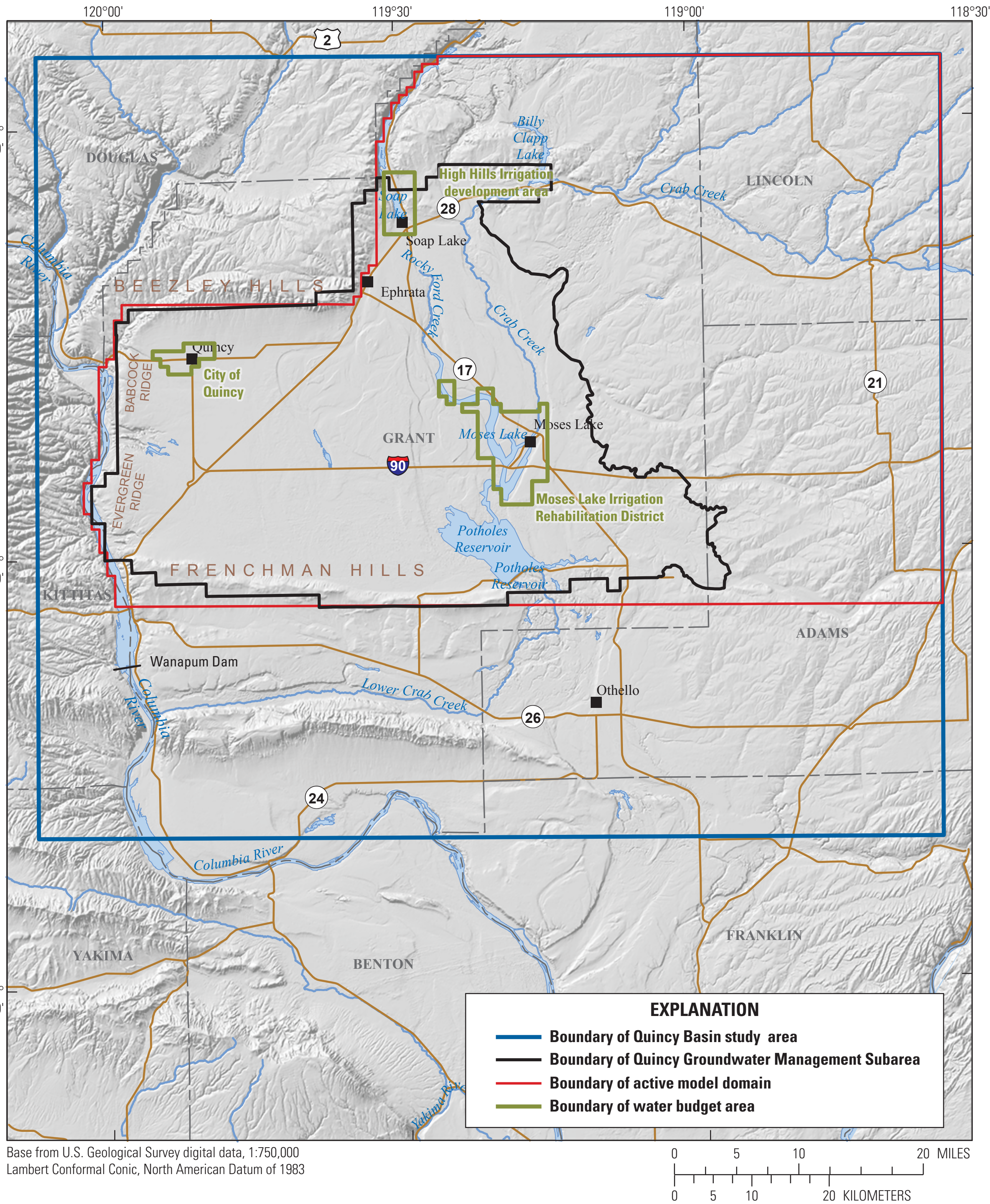


Figure 20. Water budget areas, Quincy Basin, Washington, 1920–2013.

Table 4. Groundwater budget of the High Hills Irrigation development area, Moses Lake Irrigation Rehabilitation District, and the City of Quincy, Washington, 2013.

[Values in acre-feet per year]

	High Hills	Moses Lake	City of Quincy
	Inflows		
Recharge	980	8,467	2,231
Groundwater flow from surrounding model domain	3,432	15,062	4,622
Lakes	0	3	0
Streams	0	204	0
Storage	6	5,106	85
Total	4,417	28,841	6,938
	Outflows		
Groundwater flow to surrounding model domain	3,367	8,916	3,921
Lakes	11	4	0
Streams	0	186	0
Groundwater withdrawals	974	19,242	3,017
Storage	65	492	0
Total	4,417	28,841	6,938

Simulated Storage Changes in the Quincy Subarea

The cumulative simulated change in storage through 2013 was summarized for the entire model domain as well as the Quincy Subarea within the model domain (fig. 1) for all model layers as well as just the unconsolidated layers (fig. 21) in which Ecology regulates groundwater withdrawals. Note that *cumulative* increases in groundwater storage are shown as a positive quantity in figure 21 (in contrast to the negative *rates* of flow from the groundwater system into storage shown in figure 19). To evaluate the effect of approving pending applications for groundwater-withdrawal permits, anthropogenic additions to storage (referred to as “artificially-stored” groundwater by Ecology) must be quantified. The changes to groundwater storage in the Quincy Subarea for all model layers, as well as just for the unconsolidated layers, are shown with the total for the model domain (fig. 21). The additional groundwater in storage since the predevelopment period in the Quincy Subarea rapidly reached about 10 million acre-ft by 1980 and has slowly increased since then to about 11.5 million acre-ft in 2013. The storage increase for just the unconsolidated units in the Quincy Subarea totaled about 9.5 million acre-ft by 2013. A small sliver of the Quincy Subarea south of the Frenchman Hills Fault is isolated from the remainder of the Subarea and had an increase in storage of 0.31 million acre-ft by 2013. Virtually all of the increase in storage for the model domain occurs in the Quincy Subarea.

A larger change in storage was noted in this study than in Tanaka and others (1974). Tanaka and others (1974) reported an increase in storage in their upper aquifer, which equates to the unconsolidated units, of 2.7 million acre-ft from 1952 to 1968, whereas this study simulated an increase of about 4.9 million acre-ft of increased storage for the same period.

Limitations and Appropriate Use of the Model

A groundwater-flow model represents a complex, natural system with a set of mathematical equations that describe the groundwater-flow system. Intrinsic to the model is the error and uncertainty associated with the approximations, assumptions, and simplifications that must be made. Hydrologic-modeling errors typically are the consequence of a combination of (1) input data, (2) representation of the physical processes by the algorithms of the model, and (3) parameter estimation during the calibration procedure (Troutman, 1985). Examples of the three types of model errors and how those errors limit application of the model follow.

Examples of Errors in Model Input Data

Input data on types and thicknesses of hydrogeologic units, water levels, recharge and groundwater withdrawal amounts, and hydraulic properties represent only approximations of actual values. Parts of the model domain include areas that are poorly characterized. In areas without lithologic well logs, variability in hydrogeologic properties or depths of contacts may be outside the range of values in areas that have been better characterized, and the errors associated with this variability would remain unrepresented. Specific conclusions drawn from regions of the model with sparse observations should be limited to general flow directions and relative magnitudes.

The absence of historical withdrawal data from wells results in the greatest limitation of the groundwater model. Although the best available land- and water-use data were used, the method that specified the spatial distribution of withdrawals both by area and aquifer (that is, assigned model layer) is uncertain and introduces error in the simulated withdrawal wells because the actual historical withdrawals are unknown. The observed water levels used for model calibration respond to actual groundwater withdrawals, but because the location and magnitude of withdrawals specified in the model is at best an approximation of the actual withdrawals, water levels simulated at observation-well locations cannot reproduce measured water levels with high accuracy. Although the model may not simulate water levels measured at a particular location with high accuracy, average simulated changes in water levels, such as those resulting from increased recharge over many years, are more reliable. Changes in water levels resulting from an additional simulated stress also may be simulated more accurately than the altitudes of the water levels.

Recharge values for 2008–13 used the 2007 recharge rates, as no data for 2008 and later were available. Because 2007 precipitation was similar to the mean annual precipitation (Kahle and others, 2011), extrapolation of the 2007 simulated recharge was considered a reasonable representation for subsequent years. However, this estimation could result in different results if actual values of recharge were known for that period.

The calibration bounds for hydraulic-property data generally came from specific-capacity tests, which typically measure drawdown at one time and at one pumping rate, and typically are not as accurate as aquifer tests. Thus, broad ranges of hydraulic-property parameter values are possible. Additionally, lack of information on streambed hydraulic conductivity values resulted in these values being poorly constrained, which limit the accuracy of groundwater/surface-water exchanges.

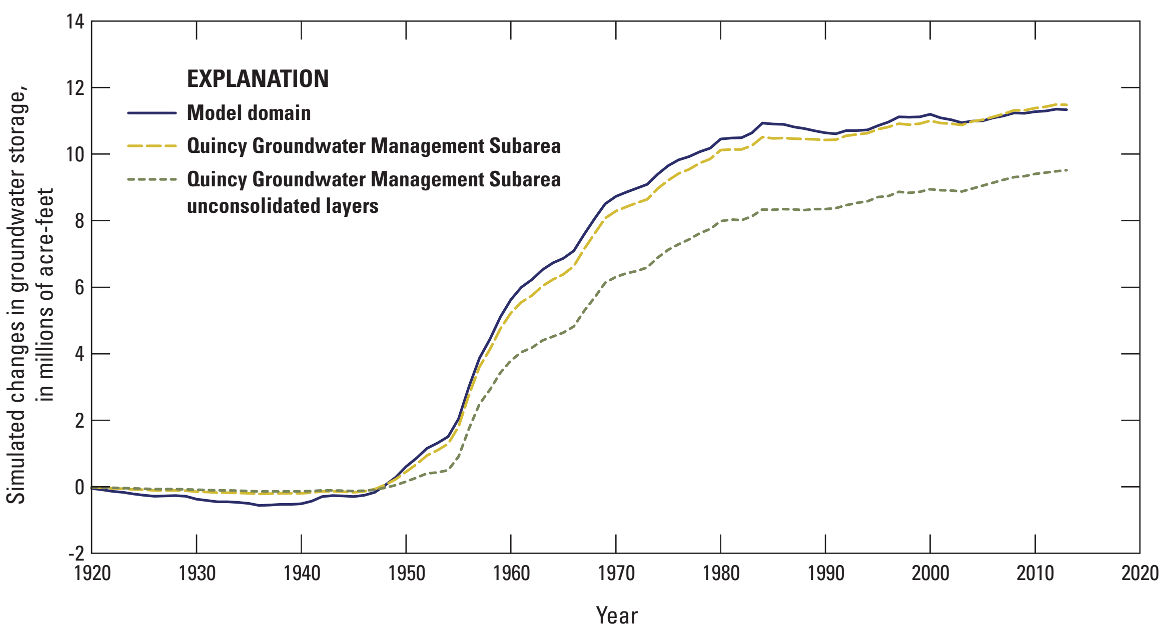


Figure 21. Cumulative simulated changes in groundwater storage in the model domain and areas in the Quincy Groundwater Management Subarea, Quincy Basin, Washington, 1920–2013.

Examples of Errors in Representation of the Physical Processes by the Algorithms of the Model

All the physical processes within a watershed cannot be represented completely or “captured” in a numerical model. Determining if a weakness in a simulation is attributable to input data error or model shortcomings is almost impossible, but the simplifying assumptions and generalizations that are incorporated in a model undoubtedly affect the results of the simulation.

Model-discretization errors (including effects of averaging elevation information over the model cell size) result from inaccuracies in the geometric representation of hydrogeologic units, in the representation of the bedrock areas and their contact with unconsolidated units, and in the location of the Frenchman Hills Fault zone. For this reason, interpretations of simulation results should be limited to scales several times greater than the model spatial and temporal resolutions of 1 km and 1 year.

Examples of Errors in Parameter Estimation During the Model Calibration Procedure

Errors in parameter estimates occur when improper values are selected during the calibration process. Various combinations of parameter values may result in low residual error yet may improperly represent the actual system. An acceptable degree of agreement between simulated and measured values does not guarantee that the estimated model-parameter values uniquely and reasonably represent the actual parameter values. The use of automatic parameter estimation techniques and associated statistics, such as composite scaled sensitivities and correlation coefficients, removes some of the effects of non-uniqueness, but does not eliminate the problem entirely. The comparison of calibrated values to literature values also can reduce error caused by parameter estimation if the model simulation results are within previously accepted ranges. Limitations of the observation weighting scheme used in this study include non-varying weights for heads that did not account for measurement errors within each group of measurements.

Appropriate Use of the Model

If the regional groundwater-flow model is used appropriately, the effects of the simplifications and other potential errors can be limited. If the model is used for simulations beyond which it was designed, however, the generalizations and assumptions used could significantly affect the results. Because of the model scale and level of detail, the model generally is most applicable to analysis of regional-scale groundwater problems. Local-scale (anything less than an area 3 × 3 km) heterogeneity in hydrologic properties, recharge, and discharge is not represented adequately by the regional-scale, groundwater-flow model constructed for this study.

Scenarios

The groundwater-flow model was used to simulate possible effects on water levels caused by potential changes in recharge, well withdrawals, and streamflow. A simulation with the calibrated transient model with a final stress period of the model (representing year 2013) run to steady-state conditions was done to provide a “base simulation” for scenario comparison. Four scenarios were formulated and simulated using the steady-state 2013-simulation conditions to show how the model could be used to investigate water-resource issues. Results from the scenario model simulations were compared to base simulation results and resultant changes in water-level altitudes were evaluated. The change in storage over time was not evaluated as the scenarios are run to steady-state. Model scenarios were developed to evaluate the following conditions:

- **Scenario 1.** Reduce recharge in irrigated areas by 10 percent from 2013 amounts to assess the effects of increased irrigation efficiency.
- **Scenario 2.** Increase current withdrawals from 2013 amounts by 2,000 acre-ft/yr to access future increases in permitted withdrawals.
- **Scenario 3.** Increase streamflow in Crab Creek downstream of Billy Clapp Lake by 100 ft^3/s to assess the effect of routing additional flow down Crab Creek.
- **Scenario 4.** Increase streamflow in Crab Creek downstream of Billy Clapp Lake by 500 ft^3/s to assess the effect of routing additional flow down Crab Creek.

Scenario 1—Reduce Recharge

Scenario 1 uses the conditions for the 2013 stress period run to steady-state with the exception of reducing recharge by 10 percent in all irrigated areas, which were determined as being those cells with recharge greater than the background rate of 2 in/yr. The purpose of this scenario is to simulate the effects of increasing irrigation efficiency. All other boundary conditions were left unchanged.

Reducing recharge amounts by 10 percent in irrigated areas reduces water-level altitudes throughout the model domain compared to the conditions for the 2013 stress period run to steady-state (fig. 22). Most of the model domain shows simulated declines of about 0–15 ft, particularly in areas that did not have much irrigation. Areas of the model with higher irrigation amounts have larger declines, with areas east of Moses Lake having declines of as much as 50 ft and areas west of Potholes Reservoir also having declines of as much as 50 ft with isolated pockets exceeding 50 ft.

Scenario 2—Increase Withdrawal Amounts

Scenario 2 uses the conditions for the 2013 stress period run to steady-state, with the exception of increasing groundwater withdrawals in the Quincy Subarea. The total withdrawals in the Quincy Subarea were increased by about 2,000 acre-ft/yr to represent the additional permitting capacity available in the subarea. Because the location of future withdrawals is unknown, withdrawals for all wells that are screened in the unconsolidated sediments or the upper two basalt layers within the subarea were increased in proportion (about 1.2 percent) to their original withdrawal amount. Wells that were open to the Grande Ronde Basalt were not increased. All other boundary conditions were left unchanged.

Simulated increases in groundwater withdrawal rates result in decreased water-level elevations. Simulated water levels decline by as much as about 5 ft compared to the conditions for the 2013 stress period run to steady-state (fig. 23). Groundwater levels decline by about 0–2 ft in most of the model domain. The largest declines (from about 2 to more than 5 ft) occur to the west of Potholes Reservoir. Because the increased groundwater withdrawals are spread throughout the Quincy Subarea, actual changes in water levels are different depending on where the additional withdrawals actually occur.

Scenario 3—Increase Flow in Crab Creek Downstream of Billy Clapp Lake by 100 Cubic Feet Per Second

Reclamation is interested in establishing a supplemental route to route water into Potholes Reservoir from Billy Clapp Lake using the natural channel of Crab Creek. To simulate the effects of adding additional water in this steady-state simulation, 100 ft^3/s was added to the flow in Crab Creek where it passes Billy Clapp Lake and compared to the conditions for the 2013 stress period run to steady-state. No other boundary conditions were changed.

In this scenario, the simulated groundwater levels rise near Crab Creek between Billy Clapp Lake and Moses Lake as the stage of the creek rises with the additional flow (fig. 24). Groundwater levels generally rise by about 5–10 ft alongside the creek, with a few areas rising by more than 10 ft. Farther away from the stream, groundwater levels rise by about 2.5–5 ft, with areas farthest from the stream having a minimal rise of about 0–2.5 ft.

Scenario 4—Increase Flow in Crab Creek Downstream of Billy Clapp Lake By 500 Cubic Feet Per Second

Scenario 4 is identical to scenario 3, with the exception of 500 ft^3/s of additional water being added to Crab Creek downstream of Billy Clapp Lake rather than 100 ft^3/s. No other boundary conditions were changed.

With the addition of 500 ft^3/s to Crab Creek, the simulated groundwater levels rise near Crab Creek between Billy Clapp Lake and Moses Lake as the stage of the creek rises with the additional flow (fig. 25). The groundwater levels rise higher and over a larger area than with the addition of 100 ft^3/s. Groundwater levels generally rise by about 20–30 ft alongside the creek, with a few areas rising by more than 30 ft. Farther away from the stream, the effect of the additional water in the stream diminishes as groundwater levels rise by about 2.5–20 ft, with areas farthest from the stream having a minimal rise of about 0–2.5 ft.

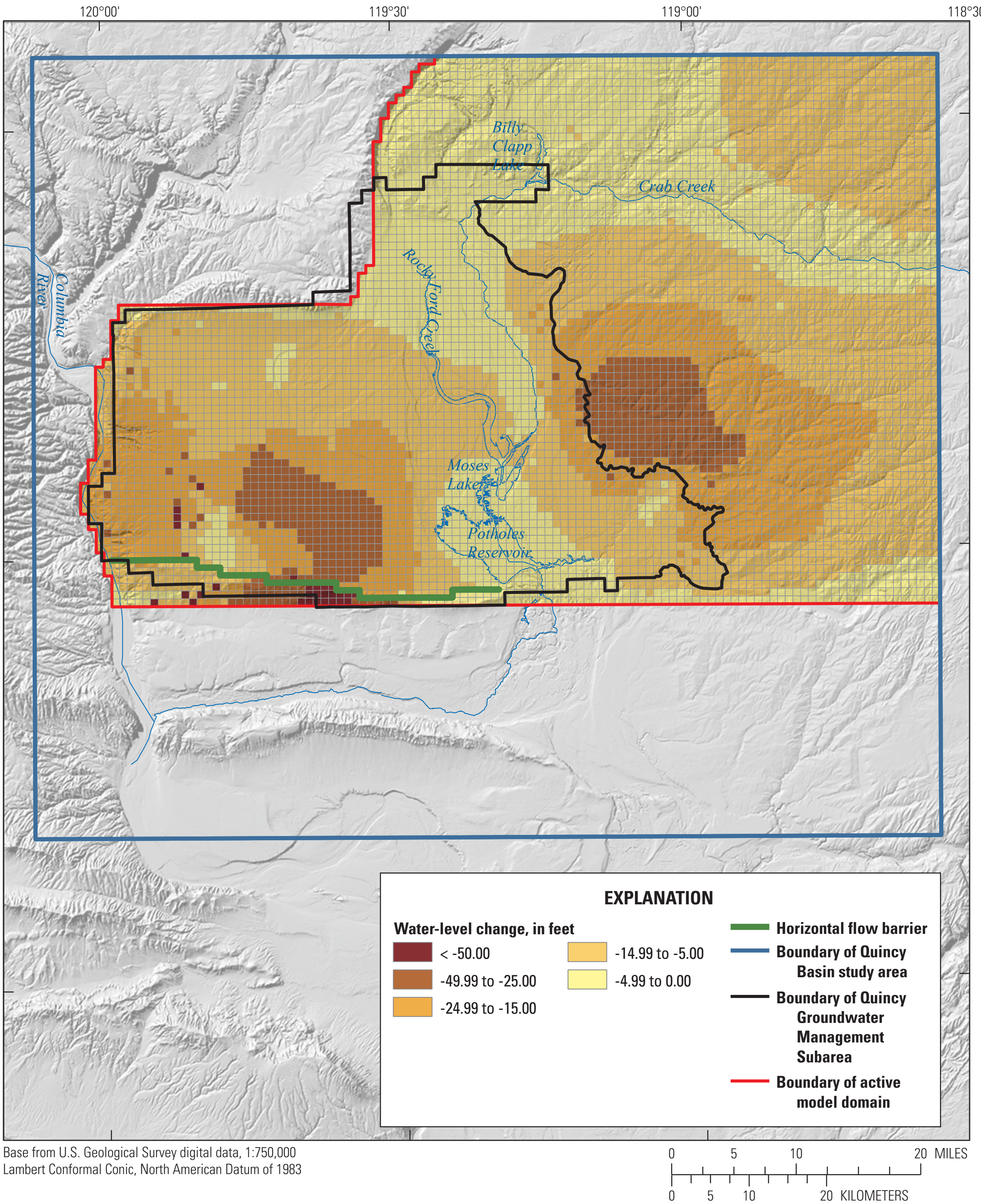


Figure 22. Simulated water-level changes after reducing 2013 irrigation amounts by 10 percent, Quincy Basin, Washington.

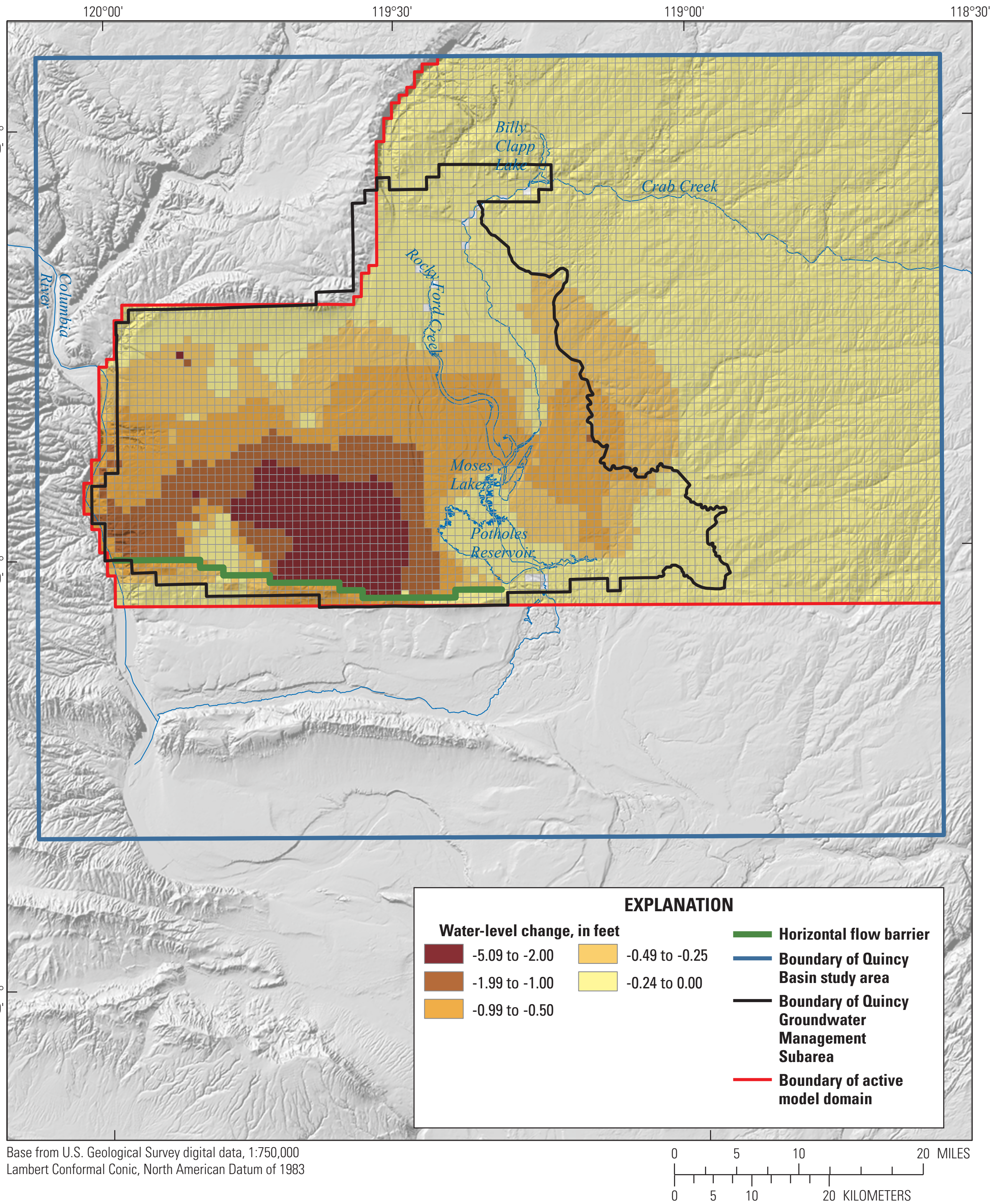


Figure 23. Simulated water-level changes after increasing groundwater withdrawal amounts by 2,000 acre-feet per year, Quincy Basin, Washington.

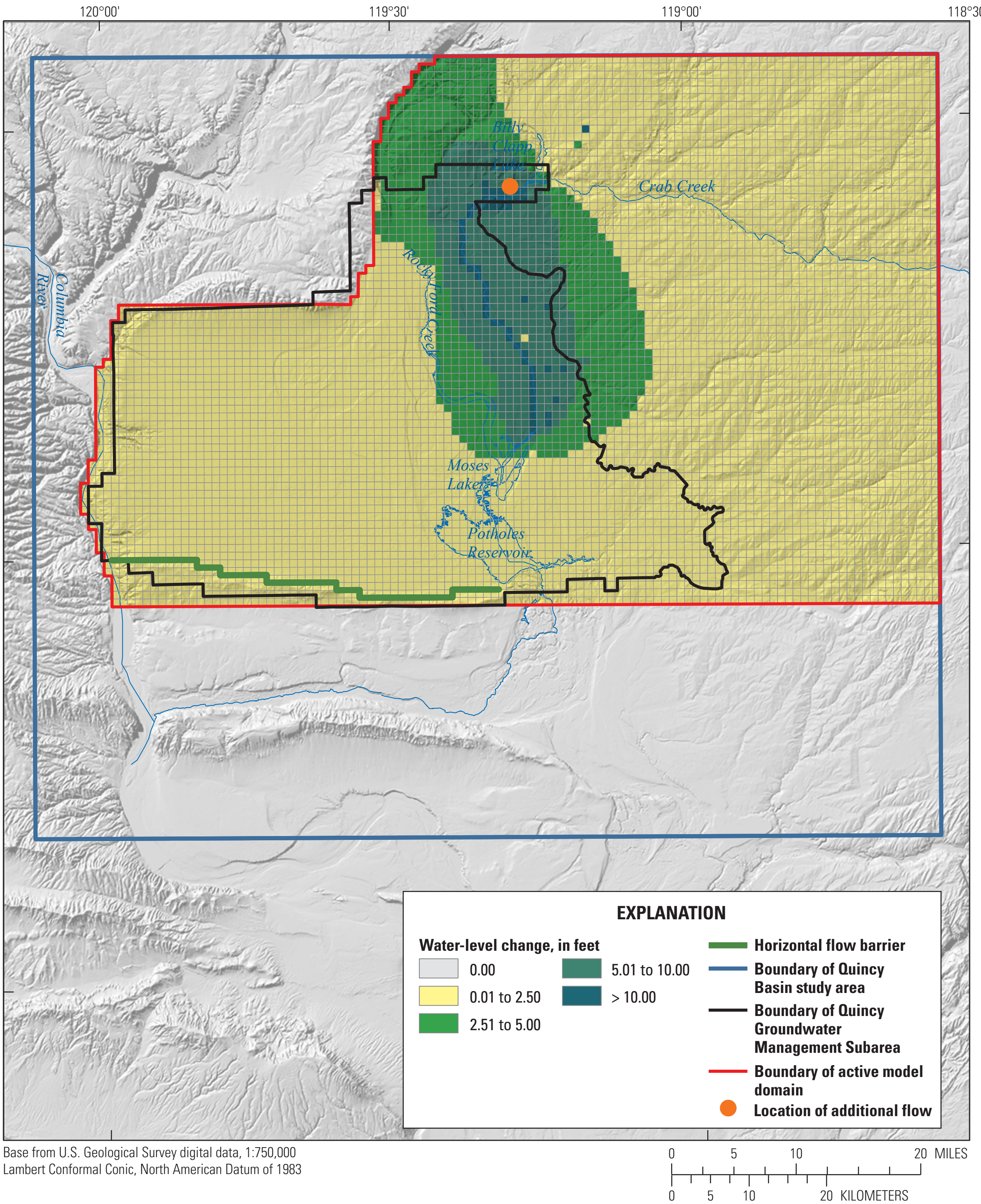


Figure 24. Simulated water-level changes after increasing flow in Crab Creek downstream of Billy Clapp Lake by 100 cubic feet per second, Quincy Basin, Washington.

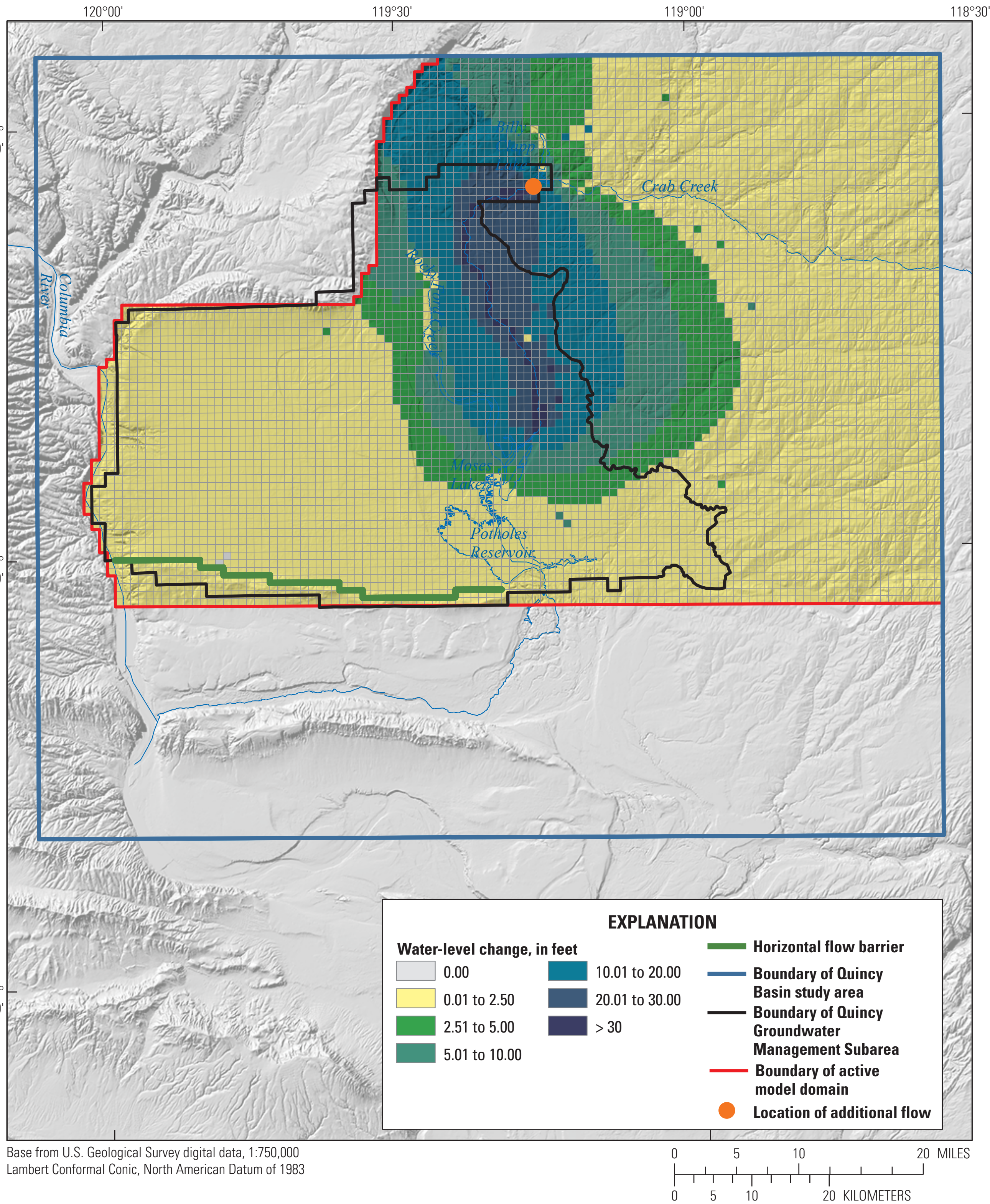


Figure 25. Simulated water-level changes after increasing flow in Crab Creek downstream of Billy Clapp Lake by 500 cubic feet per second, Quincy Basin, Washington.

Summary

The Miocene Columbia River Basalt Group and younger sedimentary deposits of lacustrine, fluvial, eolian, and cataclysmic-flood origin compose the aquifer system of the Quincy Basin in eastern Washington. Irrigation return flow and canal leakage from the Columbia Basin Project have recharged this aquifer system under parts of the Quincy Basin since 1952. Groundwater levels in the sedimentary overburden have risen substantially in some areas of the Quincy Basin. State and local water resource managers are considering extracting the additional stored groundwater to supply increasing demand. The objectives of this study were to (1) define the area hydrogeology, (2) determine rates and directions of groundwater flow through the aquifer system, (3) quantify the effect of anthropogenic recharge and groundwater withdrawals on groundwater storage, and (4) simulate the effects of certain groundwater-management scenarios.

To address the objectives of this study, the U.S. Geological Survey developed a transient groundwater model of the Quincy Basin that quantifies changes in groundwater flow and storage. The model uses a 1-kilometer finite difference grid with MODFLOW-NWT (the Newton Solver package in the U.S. Geological Survey modular three-dimensional finite-difference groundwater-flow model) and is constrained by 698 well logs in the study area. Five model layers represent two sedimentary hydrogeologic units and the underlying basalt formations. Head-dependent flux boundaries represent the Columbia River and other streams, lakes and reservoirs, underflow to and (or) from adjacent areas, and discharge to agricultural drains and springs. Specified flux boundaries represent recharge from precipitation and anthropogenic sources, including irrigation flows and leakage from water-distribution canals and discharge through groundwater withdrawal wells. The model was calibrated with the parameter-estimation code PEST to a total of 4,064 water levels measured in 710 wells.

A simulated increase of about 11.5 million acre-feet in groundwater storage in the Quincy Subarea since predevelopment results from Columbia Basin Irrigation Project operations increasing the recharge into the aquifer system. Four hypothetical groundwater-management scenarios were simulated to estimate potential changes in groundwater levels due to changed conditions. Scenario 1 simulates a reduction in recharge of 10 percent in all irrigated areas to simulate increase irrigation efficiency. Most of the model domain would have groundwater-level declines of about 0–15 feet, with areas east of Moses Lake and west of Potholes Reservoir having declines of as much as 50 feet. Scenario 2 simulates an increase in groundwater withdrawal amounts by 2,000 acre-feet per year in the Quincy Subarea. Increasing groundwater withdrawals decreases groundwater levels by as much as about 5 feet. Groundwater levels would decline in most of the model domain by only about 0–2 feet. The largest declines occur west of Potholes Reservoir. Scenarios 3 and 4 simulate an increase in flow in Crab Creek downstream of Billy Clapp Lake of 100 and 500 cubic feet per second (ft^3/s), respectively. Groundwater levels increase over 2013 steady-state levels with the increased streamflow. Areas closer to the stream rise more than those areas farther away, with groundwater levels rising by about 5–10 feet along the stream with the addition of 100 ft^3/s of streamflow and by about 20–30 feet along the stream with the addition of 500 ft^3/s of streamflow. Groundwater levels increase more and over a larger area with the addition of 500 ft^3/s of streamflow compared to the addition of 100 ft^3/s of streamflow.

Acknowledgments

The authors would like to thank the many people who have contributed to our understanding of the hydrogeology of the Quincy Basin, and the personnel of the Bureau of Reclamation and Washington State Department of Ecology involved in the Quincy Groundwater Management Area Program.

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Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington.

[**Well No.:** See well-numbering diagram for explanation of well-numbering system. **USGS site identification No.:** Unique identification number for sites in the U.S. Geological Survey National Water Information System. **Latitude** and **Longitude** are given in decimal degrees, referenced to the North American Datum of 1983 (NAD 83). **LSA:** Land-surface altitude, referenced to the North American Vertical Datum of 1988 (NAVD 88). **Hydrogeologic unit:** QDEP, Quaternary deposits; RING, Ringold Formation; CRBG, Columbia River Basalt Group. **K**: Horizontal hydrologic conductivity. **Abbreviations and symbol:** ft/d, foot per day; NP, not present; UK, unknown; –, no data available]

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
17N/23E-02B01	465948119542001	46.9990	-119.9048	1,510	364	NP	0	93	CRBG	–
17N/24E-01Q01	465912119453401	46.9865	-119.7606	1,216	50	0	NP	UK	QDEP	–
17N/24E-02R01	465915119462401	46.9875	-119.7731	1,221	852	0	41	637	CRBG	11
17N/24E-03N01	465925119484301	46.9903	-119.8119	1,289	183	NP	NP	0	CRBG	120
17N/24E-12M01	465837119460101	46.9768	-119.7681	1,470	805	0	NP	60	CRBG	–
17N/24E-19R01 OE04	465649119513901	46.9432	-119.8621	1,105	90.5	NP	0	63	CRBG	26
17N/24E-22L01	465657119483501	46.9490	-119.8064	1,234	280	NP	0	90	CRBG	–
17N/25E-01J01	465924119373001	46.9901	-119.6259	1,143	787	0	50	230	CRBG	21
17N/25E-02B01	465950119384501	46.9993	-119.6486	1,144	450	0	58	175	CRBG	5.8
17N/25E-10D02	465909119405701	46.9857	-119.6837	1,169	157	0	8	UK	RING	290
17N/25E-12M01	465838119382401	46.9772	-119.64	1,150	300	NP	0	287	CRBG	–
17N/25E-14F01	465753119391501	46.9646	-119.6553	1,595	420	NP	NP	0	CRBG	–
17N/25E-23F01	465700119390601	46.9499	-119.6528	1,246	280	NP	0	65	CRBG	–
17N/25E-35A01	465539119384201	46.9274	-119.6461	1,066	50	NP	0	UK	RING	–
17N/25E-35H01 ON07	465522119384901	46.9226	-119.6486	1,092	47.5	NP	0	UK	RING	–
17N/26E-06B01	465954119363101	46.9983	-119.6086	1,131	160	0	150	UK	QDEP	–
17N/26E-08P01	464728119352501	46.9735	-119.5914	1,127	427	0	UK	UK	CRBG	–
17N/26E-15R01 ON62	465738119322001	46.9607	-119.5390	1,132	29.5	0	UK	UK	QDEP	–
17N/26E-16K01 ON104	465748119340601	46.9634	-119.5684	1,130	15	0	15	UK	QDEP	–
17N/26E-18C01 PN102	465821119365401	46.9724	-119.615	1,158	45	0	UK	UK	QDEP	–
17N/26E-18H01	465800119360801	46.9674	-119.6011	1,202	310	NP	0	146	CRBG	–
17N/26E-19D01	465728119370501	46.9576	-119.6192	1,426	505	NP	NP	0	CRBG	–
17N/26E-21A01	465726119333601	46.9572	-119.56	1,246	296	NP	0	70	CRBG	–
17N/26E-22L01	465655119325901	46.9485	-119.5509	1,308	314	NP	0	100	CRBG	–
17N/26E-28Q01	465545119335301	46.9290	-119.5659	1,130	404	NP	0	125	CRBG	–
17N/26E-29C01 PE10	465648119353901	46.9413	-119.5934	1,217	157	NP	0	21	CRBG	1.1
17N/27E-02Q01	465918119234001	46.9882	-119.3956	1,093	328	NP	0	83	CRBG	–
17N/27E-04A01	465957119254501	46.9990	-119.4303	1,103	60	NP	0	UK	RING	–
17N/27E-12R01	465820119221001	46.9721	-119.3670	1,091	130	NP	0	97	CRBG	–
17N/27E-13B01	465804119222201	46.9678	-119.3728	1,124	155	NP	0	37	CRBG	–
17N/27E-16J01 PN104	465755119254901	46.9652	-119.4315	1,132	29	NP	0	UK	RING	–
17N/27E-16P01 PE15	465736119262701	46.9573	-119.4424	1,187	190	NP	0	170	CRBG	–
17N/27E-23R01	465636119230501	46.9432	-119.3859	1,620	490	NP	NP	0	CRBG	–
17N/27E-26E01	465604119242901	46.9348	-119.4088	1,369	510	NP	NP	0	CRBG	–
17N/28E-02C01	465956119161201	46.9989	-119.27	1,073	142	0	NP	93	CRBG	15
17N/28E-07G01 SU109	465852119210801	46.9813	-119.3535	1,063	180	NP	0	64	CRBG	12
17N/28E-11F01	465851119161601	46.9796	-119.2700	1,032	168	NP	NP	0	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet) QDEP	RING	CRBG	Hydrogeologic unit of open interval	K (ft/d)
17N/28E-16E03	465752119191901	46.9644	-119.3219	1,077	56	NP	NP	0	CRBG	–
17N/28E-16M02	465742119190821	46.9615	-119.3200	1,172	95	NP	NP	0	CRBG	–
17N/28E-17M01	465746119203301	46.9624	-119.3434	1,226	515	NP	NP	0	CRBG	–
17N/28E-18A01 SU111	465809119204101	46.9674	-119.3442	1,092	98	NP	NP	0	CRBG	–
17N/28E-18D01	465803119213201	46.9675	-119.3589	1,116	537	NP	0	55	CRBG	–
17N/28E-21P01	465638119185201	46.9438	-119.3156	1,304	498	0	NP	55	CRBG	0.5
17N/29E-11D01	465858119085701	46.9826	-119.1503	1,124	50	NP	0	UK	RING	–
17N/29E-12C01	465903119070901	46.9843	-119.1197	1,224	315	0	UK	UK	CRBG	–
17N/29E-16K01 ON55	465736119340401	46.9599	-119.5689	1,192	89	0	55	UK	RING	–
17N/29E-24C01	465717119064201	46.9546	-119.1242	1,274	210	NP	NP	0	CRBG	–
17N/29E-24N02	465630119074301	46.9413	-119.1261	1,266	250	NP	NP	0	CRBG	–
17N/30E-03N01	465910119023801	46.9860	-119.0439	1,262	162	NP	NP	0	CRBG	–
17N/30E-04J01	465918119024301	46.9884	-119.0453	1,267	242	0	9	121	CRBG	–
17N/30E-07D01	465905119062301	46.9847	-119.1064	1,234	102	0	20	80	CRBG	–
17N/30E-08Q01	465817119042401	46.9707	-119.0732	1,266	78	0	NP	26	CRBG	–
17N/30E-09A01	465903119024401	46.9841	-119.0456	1,234	220	0	28	97	CRBG	–
17N/30E-11D01	465900119010701	46.9835	-119.0185	1,251	220	NP	NP	0	CRBG	–
17N/30E-12P01D1	465813118595401	46.9703	-118.9984	1,212	290	0	NP	91	CRBG	–
17N/30E-13K01	465741118591901	46.9614	-118.9885	1,198	205	NP	NP	0	CRBG	–
17N/30E-15H01	465757119013701	46.9658	-119.0269	1,285	857	0	NP	81	CRBG	110
17N/30E-16E01	465752119035301	46.9644	-119.0647	1,259	355	NP	NP	0	CRBG	50
17N/30E-17M01	465742119051301	46.9617	-119.0868	1,275	220	NP	NP	0	CRBG	–
17N/30E-21K01	465657119031901	46.9491	-119.0554	1,316	269	NP	NP	0	CRBG	–
17N/30E-26C01	465626119010601	46.9404	-119.0195	1,407	400	NP	NP	0	CRBG	–
17N/30E-29P01R1	465540119045501	46.9699	-119.0353	1,281	780	NP	NP	0	CRBG	–
17N/30E-30D01	465627119063201	46.9409	-119.109	1,285	300	NP	NP	0	CRBG	–
17N/31E-02A01	465950118525001	46.9979	-118.8775	1,470	1,410	NP	NP	0	CRBG	–
17N/31E-04M01	465925118561301	46.9901	-118.9381	1,354	1,310	NP	NP	0	CRBG	–
17N/31E-06P01	465910118581001	46.9860	-118.9706	1,210	220	0	UK	UK	CRBG	–
17N/31E-08D01	465858118572401	46.9826	-118.9578	1,224	125	0	UK	UK	CRBG	–
17N/31E-12D01	465900118522701	46.9832	-118.8750	1,265	1950	0	NP	50	CRBG	–
17N/31E-13N03	465727118521801	46.9579	-118.8742	1,204	1,164	NP	NP	0	CRBG	–
17N/31E-14F02	465718118531101	46.9632	-118.8880	1,201	770	0	NP	48	CRBG	–
17N/31E-34C02	465532118542501	46.9246	-118.9094	1,418	1,100	NP	NP	0	CRBG	–
17N/31E-35G01D1	465515118531001	46.9207	-118.8872	1,394	1,310	NP	NP	0	CRBG	–
18N/22E-02R02	470433120014401	47.0757	-120.0301	607	131	0	NP	UK	QDEP	250
18N/23E-01C01	470513119531501	47.0868	-119.8887	1,248	185	NP	0	UK	CRBG	–
18N/23E-04B01	470503119564201	47.0842	-119.945	1,384	320	NP	0	18	CRBG	–
18N/23E-04R01	470427119562601	47.0740	-119.9417	1,341	50	NP	NP	0	CRBG	–
18N/23E-06H01	470500119585501	47.0832	-119.9831	1,402	493	0	20	75	CRBG	–
18N/23E-11A01	470420119535201	47.0721	-119.8989	1,253	32.5	NP	NP	0	CRBG	–
18N/23E-12C02	470422119032301	47.0729	-119.8923	1,248	275	NP	0	22	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
18N/23E-16D01	470325119572501	47.0568	-119.9581	1,326	50	NP	NP	0	CRBG	–
18N/23E-23A01	470234119540601	47.0428	-119.9017	1,220	80	NP	NP	0	CRBG	–
18N/23E-25A01	470144119535801	47.0287	-119.9006	1,239	200	NP	0	18	CRBG	–
18N/23E-25J02	470115119523701	47.0207	-119.8781	1,255	50	NP	0	UK	RING	–
18N/23E-26A01	470141119562401	47.0279	-119.9412	1,184	32	NP	NP	0	CRBG	–
18N/23E-27N01	470054119562101	47.0149	-119.9403	1,342	145	NP	0	84	CRBG	–
18N/23E-27Q01	470055119553501	47.0153	-119.9264	1,328	318	NP	0	86	CRBG	–
18N/23E-35D01	470054119544801	47.0149	-119.9145	1,322	125	NP	0	83	CRBG	40
18N/23E-36H01	470031119523501	47.0082	-119.8778	1,306	669	NP	0	70	CRBG	47
18N/24E-02R01	470430119461701	47.0749	-119.7725	1,209	154	0	UK	150	QDEP	–
18N/24E-04B01	470505119490601	47.0860	-119.8200	1,218	318	0	31	118	CRBG	16
18N/24E-04D02	470510119494801	47.0849	-119.8295	1,204	280	0	8	54	CRBG	15
18N/24E-04N01	470433119494401	47.0757	-119.8300	1,195	255	0	33	69	CRBG	–
18N/24E-06H01	470157119512701	47.0826	-119.8573	1,228	330	0	NP	37	CRBG	5.4
18N/24E-07A01	470423119513501	47.0728	-119.8597	1,223	416	0	NP	68	CRBG	340
18N/24E-08N01	470341119511301	47.0612	-119.8548	1,222	50	0	NP	UK	QDEP	–
18N/24E-10D01	470418119483501	47.0715	-119.8109	1,212	96	0	35	93	RING, CRBG	–
18N/24E-11E01	470404119471901	47.0676	-119.7898	1,219	146	0	43	127	RING, CRBG	36
18N/24E-11K01	470418119465901	47.0646	-119.7800	1,204	810	0	33	98	CRBG	–
18N/24E-11K02	470353119463901	47.0646	-119.7787	1,203	133	0	52	127	QDEP, RING, CRBG	15
18N/24E-12D02	470423119461101	47.0731	-119.7697	1,209	310	0	37	155	CRBG	–
18N/24E-14C02	470328119465401	47.0576	-119.7828	1,199	99	0	39	92	RING, CRBG	–
18N/24E-22A02	470239119474001	47.0440	-119.7956	1,193	78	0	33	75	QDEP, RING, CRBG	640
18N/24E-22C01	470238119482701	47.0439	-119.8075	1,199	90	0	47	73	CRBG	–
18N/24E-22D01	470236119484001	47.0432	-119.8123	1,202	193	0	NP	32	CRBG	–
18N/24E-23A01	470235119462401	47.0429	-119.7745	1,193	113	0	82	100	QDEP, RING, CRBG	–
18N/24E-24A01	470238119450201	47.0439	-119.7506	1,182	125	0	25	UK	RING	–
18N/24E-25D02	470146119461201	47.0294	-119.77	1,184	220	0	50	81	CRBG	–
18N/24E-26A01	460134119464001	47.0262	-119.7762	1,187	732	0	NP	81	CRBG	1.9
18N/24E-29D02	470143119511801	47.0286	-119.855	1,219	100	NP	0	16	CRBG	–
18N/24E-30H02	470130119513001	47.025	-119.8583	1,226	120	NP	0	43	CRBG	–
18N/24E-31R01	470004119513101	47.0011	-119.8586	1,339	350	0	54	128	CRBG	0.3
18N/24E-32N02	470009119510901	47.0024	-119.8537	1,306	425	0	75	135	CRBG	75
18N/24E-33Q01	470008119491301	47.0021	-119.8214	1,231	168	0	20	60	CRBG	–
18N/24E-36D01	470050119460301	47.0137	-119.7687	1,159	92	0	24	91	RING, CRBG	–
18N/25E-03B02	470520119402501	47.0889	-119.6736	1,187	390	0	70	290	CRBG	–
18N/25E-04H01	470500119423001	47.0824	-119.6873	1,182	740	0	67	291	CRBG	–
18N/25E-05K01	470438119424501	47.0771	-119.7137	1,165	136	0	28	UK	RING	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
18N/25E-08M01	470352119433201	47.0643	-119.7256	1,174	101	0	UK	UK	RING	–
18N/25E-08M02	470354119432802	47.0649	-119.7256	1,173	147	0	21	UK	RING	–
18N/25E-08N01	470339119433001	47.0629	-119.7214	1,170	323	0	31	UK	RING	–
18N/25E-09D01	470419119422401	47.0718	-119.7078	1,172	140	0	33	UK	RING	–
18N/25E-11H01	470139119375001	47.0699	-119.6464	1,152	202	0	60	UK	RING	20
18N/25E-13N02	470255119381301	47.0486	-119.6369	1,157	420	0	80	230	CRBG	–
18N/25E-14G01	470321119385101	47.0556	-119.6475	1,154	765	0	31	191	CRBG	–
18N/25E-15E01	470307119405101	47.0518	-119.6839	1,156	976	0	UK	180	CRBG	71
18N/25E-15E06	470307119405102	47.0521	-119.6839	1,154	1,170	0	UK	180	CRBG	–
18N/25E-15E07	470307119405103	47.0521	-119.6839	1,154	1,410	0	UK	180	CRBG	–
18N/25E-15E08	470307119405104	47.0521	-119.6839	1,154	1,550	0	UK	180	CRBG	–
18N/25E-17E01	470310119432201	47.0526	-119.7239	1,167	152	0	34	UK	RING	–
18N/25E-19H01	470219119434201	47.0386	-119.7283	1,169	110	0	20	76	CRBG	–
18N/25E-20N01 PN53	470152119432301	47.0305	-119.7236	1,164	36	0	UK	UK	QDEP	–
18N/25E-22N01	470150119410001	47.0311	-119.6828	1,152	84.5	0	60	UK	QDEP, RING	–
18N/25E-23K01	470215119390201	47.0374	-119.6517	1,152	714	0	50	148	CRBG	–
18N/25E-23M01	470203119393801	47.0342	-119.6606	1,151	225	0	62	115	CRBG	–
18N/25E-24E01	470216119381501	47.0378	-119.6375	1,153	367	0	50	197	RING, CRBG	–
18N/25E-25Q02D1	470100119375002	47.0168	-119.6303	1,134	790	0	36	174	CRBG	–
18N/25E-28A02	470147119410701	47.0297	-119.6853	1,156	150	0	60	88	CRBG	–
18N/25E-28B01	470148119412601	47.0299	-119.6917	1,158	694	0	38	101	CRBG	–
18N/25E-31N01	470006119444101	47.0015	-119.7459	1,158	230	0	15	140	CRBG	–
18N/25E-34C01	470055119403501	47.0140	-119.6748	1,144	102	0	30	98	RING, CRBG	49
18N/25E-35K01D1	470030119390302	47.0082	-119.6503	1,144	960	0	28	165	CRBG	42
18N/25E-36N01D1	470012119381801	47.0032	-119.6395	1,133	975	0	30	170	CRBG	–
18N/26E-01L01	470442119302201	47.0781	-119.5061	1,173	530	0	60	320	CRBG	–
18N/26E-03C01	470517119325501	47.0879	-119.5498	1,161	714	0	33	249	CRBG	15
18N/26E-04A01	470516119333001	47.0876	-119.5595	1,170	103	0	UK	UK	RING	–
18N/26E-04A02	470508119334601	47.0854	-119.5639	1,172	264	0	58	260	RING, CRBG	49
18N/26E-04Q01 PN90	470430119334801	47.0763	-119.5667	1,160	54	0	UK	UK	QDEP	–
18N/26E-05K01D1	470450119350401	47.0804	-119.5856	1,144	951	0	40	254	CRBG	–
18N/26E-06L01	470441119365701	47.0779	-119.6170	1,162	182	0	59	UK	RING	–
18N/26E-10D01	470423119331701	47.0729	-119.5559	1,162	20	0	UK	UK	QDEP	–
18N/26E-11E01	470413119314801	47.0703	-119.53	1,171	550	0	80	290	CRBG	–
18N/26E-18F01	470330119360601	47.0582	-119.6028	1,144	211	0	43	UK	RING	–
18N/26E-19R01	470152119355901	47.0311	-119.5997	1,142	163	0	36	UK	RING	44
18N/26E-21E02	470217119343201	47.0381	-119.5756	1,152	1,050	0	47	273	CRBG	–
18N/26E-21L01	470228119342801	47.0346	-119.5720	1,150	175	0	57	UK	RING	67
18N/26E-28A01	470148119333001	47.0299	-119.5595	1,134	160	0	42	UK	RING	37
18N/26E-31K01	470028119363301	47.0071	-119.6100	1,134	715	0	70	240	CRBG	–
18N/26E-32C01	470050119352301	47.0135	-119.5903	1,131	450	0	43	250	CRBG	9.9

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
18N/26E-32G01	470037119350401	47.0101	-119.5856	1,131	158	0	56	UK	RING	45
18N/26E-34A01	470045119322001	47.0124	-119.5400	1,128	742	0	55	291	CRBG	–
18N/26E-34N01	470005119331601	47.0013	-119.5556	1,134	65	0	UK	UK	QDEP	–
18N/26E-35N01	470016119300001	47.0043	-119.5011	1,124	525	0	63	325	CRBG	34
18N/27E-05E02	470504119275701	47.0843	-119.4670	1,105	199	0	13	183	CRBG	–
18N/27E-06K02	470442119283601	47.0783	-119.4767	1,183	600	0	53	242	CRBG	–
18N/27E-07D01D1	470419119282102	47.0704	-119.4889	1,195	489	0	79	284	CRBG	28
18N/27E-07M01D1	470338119290402	47.0635	-119.4886	1,185	503	0	51	298	CRBG	96
18N/28E-01B01	470505119143501	47.0847	-119.2431	1,194	246	0	NP	22	CRBG	–
18N/28E-01R01	470430119142201	47.0749	-119.2406	1,171	456	0	NP	10	CRBG	3.1
18N/28E-02B01	470513119155701	47.0868	-119.2670	1,143	88	0	40	65	CRBG	–
18N/28E-02D03	470509119163401	47.0857	-119.2772	1,145	660	0	42	64	CRBG	1.0
18N/28E-02P01	470445119160301	47.0754	-119.2717	1,143	184	0	UK	UK	CRBG	–
18N/28E-02R01	470423119153201	47.0731	-119.2589	1,163	145	0	47	102	CRBG	–
18N/28E-03F01	470500119173001	47.0832	-119.2928	1,147	468	0	45	65	CRBG	–
18N/28E-04R01	470425119181301	47.0736	-119.3036	1,146	239	0	6	55	CRBG	–
18N/28E-24N01	470148119175401	47.0293	-119.2559	1,154	590	0	81	161	CRBG	–
18N/28E-25N01	470051119152701	47.0142	-119.2575	1,144	180	0	94	150	CRBG	–
18N/28E-26F01	470140119161901	47.0221	-119.2731	1,114	801	0	70	141	CRBG	–
18N/28E-34G01	470032119171901	47.0088	-119.2897	1,106	479	0	132	158	QDEP, RING, CRBG	–
18N/28E-34R01	470004119164901	47.0010	-119.2814	1,087	268	0	NP	128	CRBG	–
18N/28E-36D01	470046119152201	47.0126	-119.2572	1,136	218	0	83	133	CRBG	–
18N/29E-01F01	470447119070701	47.0796	-119.1195	1,267	604	0	NP	13	CRBG	–
18N/29E-01M01	470437119071901	47.0763	-119.1250	1,260	616	0	NP	12	CRBG	–
18N/29E-03A01	470505119090601	47.0847	-119.1517	1,237	107	0	NP	27	CRBG	–
18N/29E-05E01	470448119125101	47.08	-119.2139	1,174	236	NP	0	32	CRBG	–
18N/29E-06N01	470422119135101	47.0728	-119.2308	1,148	50	0	NP	20	QDEP, CRBG	–
18N/29E-06Q01	470429119131601	47.0746	-119.2222	1,166	700	NP	0	11	CRBG	–
18N/29E-07R01	470335119125301	47.0610	-119.2192	1,174	521	0	NP	70	CRBG	–
18N/29E-08P01	470330119121901	47.0582	-119.2064	1,167	190	0	NP	38	CRBG	–
18N/29E-11J02	470350119075001	47.0639	-119.1306	1,237	174	0	NP	31	CRBG	–
18N/29E-14A02	470315119074901	47.0544	-119.1306	1,194	165	0	NP	30	CRBG	–
18N/29E-15B01	470326119083301	47.0571	-119.1436	1,211	176	0	NP	55	CRBG	–
18N/29E-17P01	470237119121901	47.0435	-119.2064	1,165	342	0	42	90	CRBG	–
18N/29E-17Q02	470239119120401	47.0442	-119.2011	1,178	178	0	47	93	CRBG	–
18N/29E-19R01 PN25	470145119131101	47.0287	-119.2212	1,117	38.5	0	UK	UK	QDEP	–
18N/29E-20B01	470233119115601	47.0424	-119.2000	1,181	219	0	UK	UK	CRBG	–
18N/29E-22B01	470235119093401	47.0429	-119.1606	1,157	268	0	NP	12	CRBG	–
18N/29E-28B01	470135119104801	47.0263	-119.1811	1,175	321	0	NP	96	CRBG	710
18N/29E-31R01	470001119131501	47.0003	-119.2208	1,110	160	0	71	140	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
18N/29E-34N01	470000119101301	46.9999	-119.1714	1,142	455	0	13	103	CRBG	–
18N/29E-36H01 PE15A	470032119063301	47.0085	-119.1102	1,174	114	0	18	UK	RING	–
18N/29E-36R01 PN107	470056119063801	47.0156	-119.1106	1,144	31	0	UK	UK	QDEP	–
18N/30E-02C02	470504119004702	47.0838	-119.0139	1,161	94	0	NP	43	CRBG	–
18N/30E-02L01	470438119005501	47.0785	-119.0153	1,249	125	0	NP	52	CRBG	65
18N/30E-03N01	470417119023002	47.0713	-119.0428	1,127	50	0	NP	UK	QDEP	–
18N/30E-08C01	470417119043401	47.0713	-119.0772	1,229	228	0	UK	UK	CRBG	–
18N/30E-09R01	470327119025501	47.0575	-119.0486	1,165	330	0	30	120	CRBG	–
18N/30E-11G01	470359119004201	47.0663	-119.0128	1,273	433	0	NP	18	CRBG	–
18N/30E-15Q01	470240119020101	47.0444	-119.0336	1,184	120	0	6	95	CRBG	–
18N/30E-16R01	470236119024101	47.0426	-119.0461	1,207	185	0	20	113	CRBG	34
18N/30E-17R01	470236119035701	47.0432	-119.0670	1,180	50	0	36	UK	QDEP, RING	–
18N/30E-18G01	470309119054501	47.0525	-119.0958	1,166	178	0	40	78	CRBG	–
18N/30E-20N01	470202119050301	47.0338	-119.0853	1,131	50	0	UK	UK	QDEP	–
18N/30E-24E01	470215119000801	47.0375	-119.0022	1,241	202	0	30	127	CRBG	–
18N/30E-26M01	470109119012101	47.0190	-119.0236	1,185	106	0	22	42	CRBG	–
18N/30E-28J02	470108119024801	47.0189	-119.0467	1,136	100	0	6	25	CRBG	–
18N/30E-31J01	470021119051901	47.0058	-119.0886	1,194	199	0	25	190	CRBG	–
18N/30E-32N01	465957119044701	46.9990	-119.0808	1,195	205	0	17	172	CRBG	–
18N/30E-34M01	470022119023801	47.0060	-119.0450	1,177	147	0	UK	UK	CRBG	–
18N/30E-35H01	470023119001601	47.0064	-119.0044	1,180	68	0	UK	UK	QDEP	–
18N/30E-36D02	470036119000201	47.01	-119.0006	1,204	142	0	56	88	CRBG	–
18N/31E-01R01	470424118585401	47.0740	-118.8561	1,238	496	0	UK	UK	CRBG	–
18N/31E-05A04D1	470510118562801	47.0860	-118.9422	1,247	655	0	NP	96	CRBG	55
18N/31E-06F01D2	470451118582002	47.0793	-118.9711	1,173	626	0	NP	44	CRBG	–
18N/31E-15J01	470258118535401	47.0493	-118.8994	1,371	697	0	NP	27	CRBG	–
18N/31E-16M01	470250118561501	47.0471	-118.9386	1,260	509	0	NP	35	CRBG	–
18N/31E-18C01	470327118582601	47.0571	-118.9753	1,324	787	0	NP	17	CRBG	–
18N/31E-20D01	470232118572901	47.0421	-118.9592	1,259	150	0	UK	UK	CRBG	–
18N/31E-23A01D1	470229118534402	47.0413	-118.8764	1,440	680	NP	NP	0	CRBG	–
18N/31E-30K01	470457118501101	47.0204	-118.9660	1,309	616	0	NP	38	CRBG	21
18N/31E-31E01	470021118583301	47.0057	-118.9769	1,236	125	0	NP	35	CRBG	–
18N/31E-33D01	470048118561701	47.0126	-118.9389	1,424	2400	NP	NP	0	CRBG	–
19N/23E-01R01	470937119523601	47.1603	-119.8767	1,272	88	NP	0	9	CRBG	–
19N/23E-02Q01	470942119542501	47.1617	-119.9069	1,291	139	NP	0	34	CRBG	–
19N/23E-04N01	470943119572601	47.1618	-119.9584	1,367	178	0	NP	25	CRBG	–
19N/23E-05K01	471002119583601	47.1671	-119.9778	1,376	425	NP	NP	0	CRBG	–
19N/23E-13A01	470835119524601	47.1431	-119.8794	1,245	137	0	34	48	CRBG	–
19N/23E-19F02	470733119594221	47.1257	-119.9962	932	80	NP	NP	0	CRBG	–
19N/23E-22M01	470720119561901	47.1226	-119.9367	1,274	111	NP	NP	0	CRBG	–
19N/23E-25E01	470645119534501	47.1124	-119.8970	1,234	115	0	NP	17	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
19N/23E-25P01	470615119531801	47.1040	-119.8895	1,250	241	NP	0	40	CRBG	–
19N/23E-30H01	470634119590101	47.1094	-119.9836	1,367	320	NP	NP	0	CRBG	–
19N/23E-32R01	470519119575101	47.0886	-119.9642	1,401	140	NP	0	19	CRBG	–
19N/23E-34Q01	470528119552601	47.0911	-119.9239	1,313	100	NP	NP	0	CRBG	–
19N/23E-34R01	470519119550801	47.0885	-119.9201	1,304	243	NP	NP	0	CRBG	–
19N/23E-36J01	470542119520101	47.0951	-119.8759	1,245	276	0	NP	45	CRBG	26
19N/24E-02D01	471022119471501	47.1726	-119.7887	1,231	200	0	UK	50	CRBG	–
19N/24E-03Q01	470951119475501	47.1640	-119.7998	1,234	50	0	UK	UK	QDEP	–
19N/24E-04N01	470952119494501	47.1643	-119.8303	1,242	45.1	0	29	UK	QDEP, RING	–
19N/24E-07A01	470936119512201	47.16	-119.8558	1,261	94.5	0	16	46	CRBG	–
19N/24E-07J01	470913119511701	47.1535	-119.8559	1,255	502	0	UK	167	CRBG	–
19N/24E-08B01	470940119501701	47.1611	-119.8381	1,247	193	0	35	53	CRBG	–
19N/24E-09D01	470929119494301	47.1581	-119.8286	1,243	177	0	17	57	CRBG	–
19N/24E-10Q01	470852119475501	47.1476	-119.7998	1,234	190	0	UK	UK	CRBG	–
19N/24E-12L01	470904119453701	47.1511	-119.7603	1,214	176	0	54	88	CRBG	–
19N/24E-13D02	470845119460001	47.1458	-119.7669	1,219	45	0	40	UK	QDEP	–
19N/24E-15L01 PE05C	470820119480201	47.1416	-119.8013	1,231	196	0	UK	83	CRBG	–
19N/24E-15Q02 PN37R	470803119480001	47.1341	-119.8002	1,229	21	0	UK	UK	QDEP	–
19N/24E-16B01	470845119491201	47.1457	-119.8212	1,239	105	0	UK	76	CRBG	–
19N/24E-19B01	470748119515201	47.13	-119.8644	1,223	100	0	NP	24	CRBG	–
19N/24E-20B01	470752119503301	47.1311	-119.8425	1,233	140	0	40	70	CRBG	–
19N/24E-25L01	470633119453401	47.1092	-119.7594	1,211	130	0	53	UK	RING	–
19N/24E-28N05	470623119494201	47.1064	-119.8283	1,230	190	0	17	85	CRBG	–
19N/24E-29D01	470559119515701	47.0996	-119.8670	1,229	71	0	15	60	CRBG	–
19N/24E-31C02	470611119515301	47.1031	-119.8647	1,214	204	0	45	56	CRBG	400
19N/24E-32B02	470610119501801	47.1028	-119.8383	1,217	147	0	22	80	CRBG	–
19N/24E-33M01	470537119493901	47.0935	-119.8298	1,206	283	0	31	84	CRBG	54
19N/24E-34C01	470601119480501	47.1003	-119.8014	1,229	113	0	40	UK	RING	–
19N/25E-02N02	470946119393701	47.1626	-119.6614	1,159	184	0	18	UK	RING	–
19N/25E-02N03 PE07	470947119392901	47.1632	-119.6601	1,160	70	0	25	UK	RING	–
19N/25E-05A01	471024119423001	47.1732	-119.7095	1,231	364	0	38	132	CRBG	34
19N/25E-06H01 PN49	471013119433401	47.1692	-119.7276	1,224	67	0	23	UK	RING	–
19N/25E-07D01 PE07A	470940119443901	47.1596	-119.7438	1,209	106	NP	0	80	CRBG	–
19N/25E-08A01	470930119423001	47.1582	-119.7045	1,230	722	0	54	154	CRBG	–
19N/25E-08R03	470903119422601	47.1507	-119.7062	1,221	145	0	66	143	RING	130
19N/25E-12D01	470941119382101	47.1614	-119.6392	1,175	120	0	36	UK	RING	–
19N/25E-15F01	470835119402001	47.1431	-119.6722	1,206	450	0	100	240	CRBG	–
19N/25E-17N01	470759119432801	47.1331	-119.7244	1,205	120	0	46	UK	QDEP, RING	–
19N/25E-18A01	470844119433801	47.1454	-119.7284	1,213	697	0	25	45	CRBG	–
19N/25E-20M01	470720119373001	47.1221	-119.7198	1,195	306	0	68	154	CRBG	9.9
19N/25E-21E01	470734119421101	47.1261	-119.7031	1,194	140	0	32	UK	RING	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
19N/25E-22D01	470757119405701	47.1324	-119.6837	1,208	192	0	44	189	RING	–
19N/25E-27A01	470655119400601	47.1151	-119.6695	1,200	180	0	52	UK	RING	31
19N/25E-27J01	470628119395101	47.1076	-119.6653	1,191	190	0	37	UK	RING	58
19N/25E-28J01 PE08A	470317119405701	47.1111	-119.6839	1,204	139	0	55	UK	RING	–
19N/25E-28M01	470631119420501	47.1085	-119.7025	1,194	115	0	UK	UK	RING	–
19N/25E-30M01	460635119444801	47.1096	-119.7478	1,194	300	0	68	154	CRBG	10
19N/25E-33R01	470529119410401	47.0914	-119.6844	1,198	300	0	64	254	CRBG	–
19N/25E-35E01	470550119394001	47.0972	-119.6611	1,181	355	0	27	261	CRBG	–
19N/25E-35G01	470601119390201	47.1001	-119.6517	1,177	733	0	42	282	RING, CRBG	2.9
19N/25E-36B02	470610119374101	47.1028	-119.6281	1,160	295	0	35	UK	RING	–
19N/26E-01R01	470948119293801	47.1635	-119.4942	1,261	459	0	140	385	CRBG	–
19N/26E-04Q01	470955119334201	47.1629	-119.5653	1,245	436	0	102	412	CRBG	11
19N/26E-05M01	471011119354701	47.1697	-119.5964	1,217	172	0	72	UK	RING	–
19N/26E-08J01	470918119343801	47.155	-119.5772	1,234	160	0	84	UK	RING	–
19N/26E-09C01	470943119340001	47.1618	-119.5678	1,240	429	0	UK	UK	CRBG	–
19N/26E-09H01	470920119332101	47.1556	-119.5558	1,236	425	0	120	400	RING, CRBG	–
19N/26E-11J01	470909119304501	47.1524	-119.5136	1,254	705	0	147	400	RING, CRBG	1.0
19N/26E-13R01 PN45	470801119293601	47.1333	-119.4932	1,236	112	0	UK	UK	QDEP	–
19N/26E-15B01 PN57	470850119323501	47.1472	-119.5443	1,239	79.5	0	UK	UK	QDEP	–
19N/26E-16D04	470841119343101	47.1446	-119.5764	1,233	252	0	92	UK	RING	–
19N/26E-16G01	470813119334501	47.1368	-119.5636	1,238	248	0	108	UK	QDEP, RING	–
19N/26E-17L01	470812119353901	47.1365	-119.5953	1,206	437	0	70	300	CRBG	7.8
19N/26E-18Q02 PE08	470803119362401	47.1340	-119.6079	1,189	65	0	45	52	CRBG	–
19N/26E-20A01	470759119344501	47.1329	-119.5803	1,226	153	0	UK	UK	RING	–
19N/26E-20M01	470727119354101	47.1240	-119.5959	1,184	180	0	40	UK	RING	52
19N/26E-21M02	470733119343501	47.1258	-119.5764	1,213	228	0	78	UK	RING	–
19N/26E-26N01	470617119315501	47.1047	-119.5319	1,220	200	0	122	UK	RING	–
19N/26E-27M01	470631119330301	47.1085	-119.5520	1,162	115	0	46	UK	RING	–
19N/26E-28N01D1	470637119341702	47.1071	-119.5756	1,174	560	0	55	364	RING, CRBG	–
19N/26E-30N01	470618119365701	47.1049	-119.6170	1,153	350	0	55	297	CRBG	17
19N/26E-30Q02	470624119363101	47.1067	-119.6086	1,203	140	0	75	UK	RING	–
19N/26E-33B01	470602119335701	47.1004	-119.5670	1,174	480	0	48	270	RING, CRBG	–
19N/26E-34D01D1	470608119331502	47.1021	-119.5553	1,173	112	0	UK	UK	RING	–
19N/26E-35H01	470559119305101	47.0997	-119.5142	1,233	116	0	90	UK	RING	–
19N/26E-36J01D01	470534119294501	47.0926	-119.4970	1,227	960	0	123	300	CRBG	1.5
19N/27E-01Q01	470950119220801	47.1639	-119.3689	1,128	220	0	107	174	CRBG	–
19N/27E-01R01	470545119215001	47.1624	-119.3650	1,128	100	0	UK	UK	QDEP	–
19N/27E-02E01	471013119240701	47.1701	-119.4031	1,144	270	0	95	104	CRBG	–
19N/27E-04L01	471005119262501	47.1679	-119.4414	1,127	207	0	71	152	CRBG	–
19N/27E-07A01	470936119281801	47.1599	-119.4728	1,177	570	0	100	236	CRBG	–
19N/27E-07C01	470945119290801	47.1625	-119.4856	1,246	581	0	61	205	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
19N/27E-08C01	470942119273501	47.1615	-119.4609	1,112	201	0	30	140	RING, CRBG	–
19N/27E-08Q01	470852119273101	47.1478	-119.4586	1,126	76	0	39	UK	RING	–
19N/27E-09H01	470917119254001	47.1547	-119.4278	1,170	305	0	120	202	CRBG	–
19N/27E-09P01	470855119262001	47.1485	-119.4400	1,091	64	0	57	UK	QDEP	–
19N/27E-11H01	470922119230701	47.1561	-119.3853	1,127	232	0	121	164	CRBG	–
19N/27E-12H01	470917119215101	47.1547	-119.3642	1,124	220	0	89	138	CRBG	–
19N/27E-13P01	470756119223401	47.1322	-119.3761	1,099	220	0	102	144	CRBG	–
19N/27E-14H02	470829119232301	47.1414	-119.3897	1,127	200	0	102	157	CRBG	–
19N/27E-16D02	470847119263401	47.1463	-119.4439	1,094	205	0	40	142	RING, CRBG	–
19N/27E-16N01	470805119263801	47.1346	-119.4459	1,100	74	0	UK	UK	QDEP	–
19N/27E-17G01	470835119275501	47.1429	-119.4553	1,118	355	0	55	237	CRBG	–
19N/27E-19R01	470711119281401	47.1196	-119.4717	1,116	225	0	20	167	CRBG	–
19N/27E-20E02	470732119281101	47.1256	-119.4697	1,118	316	NP	0	220	CRBG	–
19N/27E-21R01	470706119254301	47.1183	-119.4286	1,087	150	0	60	110	CRBG	–
19N/27E-23Q01	470705119232801	47.1179	-119.3922	1,109	105	0	UK	UK	RING	–
19N/27E-24M01	470721119225001	47.1225	-119.3806	1,085	160	0	57	116	CRBG	–
19N/27E-26A01	470652119230301	47.1143	-119.3853	1,076	52	0	UK	UK	QDEP	–
19N/27E-26A02	470654119230701	47.115	-119.3853	1,077	190	0	60	90	CRBG	–
19N/27E-27P01	470621119251401	47.1058	-119.4206	1,084	64	0	UK	UK	QDEP	–
19N/27E-27Q01	470620119245001	47.1056	-119.4139	1,096	320	0	66	146	CRBG	–
19N/27E-28L01	470628119263001	47.1078	-119.4417	1,103	78	0	UK	UK	QDEP	–
19N/27E-30N01	470620119292001	47.1060	-119.4875	1,224	460	0	104	252	CRBG	9.5
19N/27E-31N01	470522119223001	47.0893	-119.4917	1,224	535	0	115	306	CRBG	9.4
19N/27E-32N01	470528119280901	47.0911	-119.4692	1,114	420	0	14	209	CRBG	–
19N/27E-32R01	470520119270201	47.0889	-119.4506	1,097	124	0	124	UK	QDEP	–
19N/28E-01H01	471006119142601	47.1683	-119.2406	1,216	220	0	65	108	CRBG	–
19N/28E-02J01	470952119152601	47.1644	-119.2572	1,088	140	0	26	48	CRBG	–
19N/28E-03N01	470943119174301	47.1619	-119.2953	1,116	360	0	65	81	CRBG	–
19N/28E-04L01R1 SU119	470945119181401	47.1644	-119.3139	1,185	750	0	127	199	CRBG	–
19N/28E-05Q01	470939119194901	47.1608	-119.3303	1,096	180	0	58	113	CRBG	–
19N/28E-06C01	471020119210701	47.1721	-119.3531	1,081	37	0	UK	UK	QDEP	–
19N/28E-07E01	470925119213501	47.1568	-119.3609	1,125	208	0	101	155	CRBG	–
19N/28E-07E02	470915119214201	47.1542	-119.3617	1,124	755	0	131	142	CRBG	11
19N/28E-08H02	470913119192401	47.1535	-119.3245	1,093	48	0	UK	UK	QDEP	–
19N/28E-09G02 PAS18	470915119182601	47.1542	-119.3072	1,174	743	0	NP	161	CRBG	–
19N/28E-09L01	470903119190201	47.1507	-119.3184	1,123	338	0	142	175	CRBG	–
19N/28E-09P02 MW-SU-123	470847119184101	47.1463	-119.3125	1,177	148	0	UK	UK	QDEP	–
19N/28E-10D02	470927119173701	47.1574	-119.2947	1,114	448	0	59	88	CRBG	–
19N/28E-11Q01	470856119160101	47.1489	-119.2669	1,075	140	0	NP	45	CRBG	–
19N/28E-12E02	470912119152001	47.1533	-119.2556	1,074	157	0	NP	20	CRBG	–
19N/28E-13R01 SU126	470805119140501	47.1343	-119.2367	1,201	568	0	24	72	CRBG	14

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
19N/28E-14R01 SU127	470758119152501	47.1325	-119.2573	1,154	796	0	UK	64	CRBG	25
19N/28E-15A04R1	470836119165101	47.1433	-119.2808	1,088	1,027	0	51	68	CRBG	27
19N/28E-15D01R2	470833119174701	47.1422	-119.2944	1,111	705	0	52	134	CRBG	60
19N/28E-15Q01	470858119171001	47.1340	-119.2859	1,076	909	0	NP	74	CRBG	–
19N/28E-16B01 SU129	470844119182501	47.1427	-119.3077	1,167	132	0	UK	UK	QDEP	–
19N/28E-17A01	470836119191901	47.1433	-119.3219	1,074	120	0	43	118	CRBG	–
19N/28E-19K02	470726119205101	47.1238	-119.3474	1,050	171	0	74	124	CRBG	–
19N/28E-19K03	470720119210601	47.1222	-119.3517	1,066	170	0	80	120	CRBG	–
19N/28E-20A01	470753119192402	47.1313	-119.3259	1,084	45	0	UK	UK	QDEP	–
19N/28E-21P02	470706119184501	47.1183	-119.3125	1,052	102	0	42	53	CRBG	–
19N/28E-22B02	470751119172501	47.1307	-119.2914	1,066	763	0	NP	40	CRBG	–
19N/28E-23D08	470720119161601	47.1304	-119.2770	1,070	950	0	26	71	CRBG	–
19N/28E-23J01	470720119153201	47.1221	-119.2600	1,176	950	0	53	99	CRBG	3.3
19N/28E-24L02	470713119145801	47.1203	-119.2494	1,190	101	0	36	77	CRBG	–
19N/28E-25L01	470621119144401	47.1057	-119.2467	1,194	492	0	65	135	CRBG	–
19N/28E-25R01	470607119142401	47.1019	-119.24	1,193	240	0	32	64	CRBG	–
19N/28E-26A01	470655119153001	47.1151	-119.2595	1,173	159	0	55	90	CRBG	–
19N/28E-27C05	470650119174001	47.1156	-119.2925	1,058	692	0	10	59	CRBG	9.3
19N/28E-27H01	470638119164001	47.1126	-119.2800	1,079	1,045	NP	0	97	CRBG	4.6
19N/28E-28K04	470627119182501	47.1061	-119.3055	1,077	1,000	0	NP	59	CRBG	48
19N/28E-29M01	470635119202001	47.1071	-119.3381	1,064	696	0	NP	74	CRBG	–
19N/28E-29M02	470627119201501	47.1075	-119.3375	1,060	970	0	NP	67	CRBG	77
19N/28E-30B04	470650119210001	47.1139	-119.35	1,068	50	0	UK	UK	QDEP	–
19N/28E-34G01	470553119165901	47.0979	-119.2842	1,154	419	0	40	90	CRBG	–
19N/29E-01B01	471020119070202	47.1721	-119.1183	1,235	490	0	NP	24	CRBG	–
19N/29E-03B01	471023119092501	47.1732	-119.1572	1,338	1,200	NP	NP	0	CRBG	–
19N/29E-04B01	471026119103901	47.1739	-119.1775	1,269	104	0	NP	6	CRBG	–
19N/29E-04H02	471011119101801	47.1676	-119.1722	1,312	930	0	NP	10	CRBG	–
19N/29E-06A01	471027119124902	47.1740	-119.2147	1,194	48.5	0	NP	100	QDEP	–
19N/29E-06E01	471013119140001	47.1703	-119.2333	1,227	216	0	NP	167	CRBG	–
19N/29E-07A01 SU131	470759119143101	47.1581	-119.2170	1,202	170	NP	NP	0	CRBG	–
19N/29E-07R03 PE16A	470848119125501	47.1472	-119.2172	1,186	62	NP	NP	0	CRBG	–
19N/29E-08L01	470857119122001	47.1490	-119.2061	1,224	273	NP	NP	0	CRBG	2.5
19N/29E-08Q01	470845119120201	47.1458	-119.2006	1,216	165	NP	NP	0	CRBG	–
19N/29E-09H02	470917119101701	47.1540	-119.1733	1,300	592	0	NP	21	CRBG	–
19N/29E-09H03	470914119102101	47.1539	-119.1725	1,303	180	0	NP	44	CRBG	–
19N/29E-10A01	470922119085601	47.1560	-119.1500	1,336	644	NP	NP	0	CRBG	–
19N/29E-11C01	470921119081901	47.1557	-119.1397	1,363	687	NP	NP	0	CRBG	13
19N/29E-14J01	470811119074301	47.1363	-119.1297	1,359	368	NP	NP	0	CRBG	–
19N/29E-15A01	470839119090601	47.1440	-119.1528	1,365	685	NP	NP	0	CRBG	–
19N/29E-15G01	470826119093001	47.1404	-119.1595	1,353	620	NP	NP	0	CRBG	98

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
19N/29E-16E01	470624119132301	47.1382	-119.1928	1,228	288	0	NP	31	CRBG	–
19N/29E-16P02	470754119110301	47.1317	-119.1842	1,255	608	0	NP	22	CRBG	310
19N/29E-19D02	470749119135501	47.1303	-119.2319	1,194	210	0	17	74	CRBG	–
19N/29E-19E01	470728119140201	47.1244	-119.2339	1,196	100	0	36	78	CRBG	–
19N/29E-20D01	470753119124601	47.1313	-119.2139	1,176	525	0	NP	25	CRBG	14
19N/29E-20G01	470707119123101	47.1185	-119.2097	1,179	1,030	NP	NP	0	CRBG	–
19N/29E-21E01 PAS03	470727119113401	47.1240	-119.1939	1,210	1,240	NP	NP	0	CRBG	12
19N/29E-22E04	470731119101201	47.1253	-119.17	1,285	180	0	NP	16	CRBG	–
19N/29E-22R01	470700119090501	47.1160	-119.1539	1,284	560	0	NP	50	CRBG	–
19N/29E-23A01	470747119074701	47.1297	-119.1297	1,342	200	NP	NP	0	CRBG	–
19N/29E-25N01D01	470611119074301	47.1031	-119.1286	1,304	370	NP	NP	0	CRBG	–
19N/29E-27N01	470509119110901	47.1026	-119.1706	1,252	34	0	NP	29.5	QDEP, CRBG	–
19N/29E-29A01	470651119120401	47.1140	-119.2022	1,193	486	NP	NP	0	CRBG	–
19N/29E-30A01	470656119130601	47.1156	-119.2183	1,174	98	NP	NP	0	CRBG	–
19N/29E-30A02	470656119130501	47.1156	-119.2183	1,174	182	NP	NP	0	CRBG	–
19N/29E-31N01	470521119140401	47.0892	-119.2344	1,166	220	NP	0	19	CRBG	–
19N/29E-32G01	470552119115801	47.0976	-119.2006	1,195	628	NP	0	25	CRBG	–
19N/29E-33E01	470548119113401	47.0967	-119.1928	1,187	184	NP	0	24	CRBG	–
19N/29E-34C01	470603119095501	47.1008	-119.1653	1,261	100	0	NP	18	CRBG	–
19N/30E-07P02	470843119054701	47.1451	-119.0975	1,393	505	NP	NP	0	CRBG	–
19N/30E-08B02	470933119042701	47.1590	-119.0753	1,293	220	0	NP	55	CRBG	–
19N/30E-15L01	470814119020201	47.1376	-119.0375	1,447	1,180	NP	NP	0	CRBG	–
19N/30E-20D01	470747119050701	47.1296	-119.0864	1,430	1,010	NP	NP	0	CRBG	24
19N/30E-26A01	470656119000901	47.1154	-119.0036	1,383	470	NP	NP	0	CRBG	–
19N/30E-28C01	470655119031701	47.1151	-119.0558	1,375	580	NP	NP	0	CRBG	–
19N/30E-30B01	470652119055001	47.1149	-119.0975	1,364	960	NP	NP	0	CRBG	2.8
19N/30E-32N01	470515119042801	47.0882	-119.0858	1,288	351	NP	NP	0	CRBG	–
19N/30E-33R01 PE18	470515119025801	47.0874	-119.0486	1,184	104	0	NP	46	CRBG	–
19N/30E-36M02D1	470535118595402	47.0929	-118.9995	1,202	350	NP	NP	0	CRBG	–
20N/23E-04R01	471503119563201	47.2508	-119.9422	1,394	140	0	NP	20	CRBG	–
20N/23E-05M01	471505119585001	47.2512	-119.9817	992	90	0	NP	24	CRBG	480
20N/23E-06B01	471544119591601	47.2622	-119.9878	1,375	514	NP	NP	0	CRBG	–
20N/23E-07D02	471436120001501	47.2433	-120.0042	1,289	600	0	NP	74	CRBG	–
20N/23E-09N01	471404119573501	47.2344	-119.9597	1,485	99	0	13	24	CRBG	–
20N/23E-09Q01	471357119563801	47.2324	-119.9451	1,419	302	0	12	50	CRBG	–
20N/23E-10D01	471449119561501	47.2468	-119.9387	1,383	330	0	UK	UK	CRBG	–
20N/23E-11H02	471533119531701	47.2401	-119.8984	1,339	1,000	0	10	45	CRBG	–
20N/23E-12E01	471434119534701	47.2428	-119.8964	1,344	250	0	13	35	CRBG	–
20N/23E-15L01	471330119554901	47.225	-119.9303	1,354	138	0	19	45	CRBG	–
20N/23E-17H01	471345119575701	47.2292	-119.9658	1,526	495	0	10	39	CRBG	–
20N/23E-18D01	471349119595501	47.2303	-119.9986	927	296	0	NP	90	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
20N/23E-20C01	471305119581701	47.2181	-119.9714	1,535	431	0	20	98	CRBG	–
20N/23E-22M02	471246119561601	47.2126	-119.9389	1,353	413	0	7	54	CRBG	–
20N/23E-23A01	471307119535501	47.2185	-119.8998	1,294	63	0	24	50	CRBG	60
20N/23E-23M01	471240119544501	47.2110	-119.9137	1,314	450	0	20	59	CRBG	–
20N/23E-25E01	471149119534401	47.1968	-119.8967	1,304	480	0	25	48	CRBG	–
20N/23E-26G01	471158119542601	47.1994	-119.9072	1,304	91	0	11	28	CRBG	–
20N/23E-33A01	471121119562401	47.1892	-119.94	1,371	110	0	17	44	CRBG	–
20N/23E-34B01	471121119553801	47.1892	-119.9272	1,351	99	0	17	36	CRBG	–
20N/23E-35E01	471101119550101	47.1836	-119.9169	1,325	80	0	8	32	RING, CRBG	–
20N/24E-04K01	471513119490801	47.2536	-119.8189	1,339	240	0	NP	27	CRBG	–
20N/24E-06R01	471455119512001	47.2486	-119.8556	1,339	225	0	12	47	CRBG	–
20N/24E-07K01	471421119515601	47.2392	-119.8656	1,323	254	0	13	51	CRBG	68
20N/24E-07P01 PAS08	471413119511401	47.2360	-119.8648	1,317	406	0	18	56	CRBG	–
20N/24E-07Q01	471407119513301	47.2351	-119.8603	1,310	392	0	25	47	CRBG	94
20N/24E-08R01 MW-SW-QA1	471423119502001	47.2360	-119.8323	1,294	380	0	12	47	CRBG	770
20N/24E-09D02	471444119495201	47.2456	-119.8311	1,312	278	0	9	48	CRBG	–
20N/24E-12R01	471406119450701	47.235	-119.7519	1,249	160	0	45	63	CRBG	–
20N/24E-15D01	471400119482601	47.2332	-119.8084	1,269	237	0	UK	UK	CRBG	–
20N/24E-19M01	471231119523001	47.2086	-119.875	1,289	57	0	UK	UK	QDEP	–
20N/24E-23N01	471220119471901	47.2056	-119.7886	1,234	127	0	25	55	CRBG	700
20N/24E-25D01	471217119460301	47.2047	-119.7675	1,234	175	0	19	85	CRBG	–
20N/24E-28R02	471131119485101	47.1919	-119.8142	1,239	80	0	30	41	CRBG	–
20N/24E-29R03	471139119500101	47.1942	-119.8336	1,263	106	0	45	76	CRBG	–
20N/24E-31N01	471042119522801	47.1783	-119.8744	1,279	218	0	19	60	CRBG	–
20N/24E-32E01	471107119511101	47.1853	-119.8531	1,279	105	0	58	94	CRBG	–
20N/24E-33B03 PN33R	471120119485901	47.1889	-119.8163	1,246	21.5	0	UK	UK	QDEP	–
20N/25E-02M01	471515119393601	47.2542	-119.66	1,300	236	0	NP	18	CRBG	–
20N/25E-04M01	471519119415601	47.2551	-119.7031	1,303	674	0	NP	15	CRBG	–
20N/25E-05Q02	471500119424801	47.25	-119.7133	1,279	231	0	NP	35	CRBG	–
20N/25E-07A07	471449119433801	47.2468	-119.7284	1,263	150	0	NP	61	CRBG	–
20N/25E-08P01	471407119430601	47.2351	-119.7195	1,245	430	0	23	153	CRBG	–
20N/25E-10Q01	471417119400501	47.2381	-119.6681	1,215	130	0	37	62	CRBG	–
20N/25E-11R01	471407119383501	47.2353	-119.6431	1,220	120	0	68	76	CRBG	–
20N/25E-12Q01	471408119373101	47.2356	-119.6253	1,231	160	0	95	124	CRBG	–
20N/25E-15Q01	471316119401001	47.2210	-119.6706	1,222	190	0	UK	UK	CRBG	–
20N/25E-17Q01	471322119423201	47.2217	-119.7096	1,234	158	0	23	96	CRBG	10
20N/25E-19D01	471312119442601	47.2199	-119.7417	1,234	132	0	20	112	CRBG	–
20N/25E-20F03	471248119430001	47.2132	-119.7178	1,243	315	0	29	149	CRBG	–
20N/25E-21A02	471258119410801	47.2160	-119.6867	1,222	652	0	120	194	CRBG	–
20N/25E-23M01	471235119393401	47.2097	-119.6594	1,248	140	0	75	UK	RING	–
20N/25E-24R01	471227119370801	47.2075	-119.6189	1,266	337	0	147	329	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
20N/25E-27J01	471155119394101	47.1986	-119.6614	1,212	290	0	56	282	CRBG	–
20N/25E-27Q01	471130119401801	47.1917	-119.6717	1,201	240	0	42	196	CRBG	–
20N/25E-32F01	471104119425101	47.1843	-119.7153	1,236	354	0	36	154	CRBG	–
20N/25E-33P01	471049119413901	47.1803	-119.6942	1,211	276	0	140	190	CRBG	–
20N/25E-36B01	471128119373801	47.1910	-119.6284	1,214	250	0	73	UK	RING	–
20N/26E-01M01	471521119303001	47.2558	-119.5083	1,275	260	0	NP	64	CRBG	–
20N/26E-03E01	471540119330901	47.2611	-119.5525	1,293	240	NP	NP	0	CRBG	–
20N/26E-04R01	471510119332101	47.2528	-119.5558	1,290	160	0	NP	28	CRBG	–
20N/26E-06R01	471506119354701	47.2517	-119.5964	1,246	95	0	UK	UK	QDEP	–
20N/26E-07M01	471432119364801	47.2422	-119.6133	1,209	120	0	41	51	CRBG	–
20N/26E-09H01	471438119331501	47.2439	-119.5542	1,293	420	0	54	79	CRBG	–
20N/26E-11H01	471446119304601	47.2461	-119.5128	1,270	240	0	NP	73	CRBG	–
20N/26E-13Q02	471324119295301	47.2233	-119.4981	1,264	220	0	132	UK	RING	–
20N/26E-16E01	471347119342801	47.2297	-119.5744	1,234	220	0	83	UK	RING	–
20N/26E-18G01	471350119360901	47.2306	-119.6025	1,242	320	0	118	302	CRBG	–
20N/26E-21A01	471314119331201	47.2204	-119.5545	1,240	489	0	95	256	CRBG	–
20N/26E-24K01	471245119295601	47.2125	-119.4989	1,263	380	0	155	290	CRBG	–
20N/26E-25P01	471144119300101	47.1954	-119.5014	1,253	479	0	140	321	CRBG	20
20N/26E-30Q01	471132119362801	47.1922	-119.6078	1,229	310	0	92	UK	RING	–
20N/26E-32N01	471039119355401	47.1774	-119.5995	1,204	172	0	90	UK	RING	–
20N/26E-34J01	471054119320101	47.1817	-119.5336	1,255	230	0	148	UK	RING	–
20N/27E-04N01	471508119264701	47.2522	-119.4464	1,155	220	0	NP	116	CRBG	–
20N/27E-09A01	471459119254301	47.2497	-119.4286	1,160	220	0	NP	121	CRBG	–
20N/27E-09P01	471419119263101	47.2386	-119.4419	1,170	220	0	NP	138	CRBG	–
20N/27E-11N01	471408119241901	47.2356	-119.4053	1,224	220	0	NP	173	CRBG	–
20N/27E-13H01	471346119220301	47.2294	-119.3675	1,224	320	0	NP	170	CRBG	–
20N/27E-13L01	471329119223001	47.2247	-119.375	1,236	195	0	165	UK	RING	–
20N/27E-15E01	471345119253401	47.2292	-119.4261	1,131	200	0	NP	103	CRBG	–
20N/27E-15Q01	471319119244401	47.2219	-119.4122	1,159	214	0	NP	135	CRBG	–
20N/27E-18E01	471355119291501	47.2318	-119.4886	1,264	425	0	142	176	CRBG	–
20N/27E-19E01	471304119291701	47.2178	-119.4881	1,259	220	0	167	UK	RING	–
20N/27E-22D01	471305119252701	47.2181	-119.4242	1,147	200	0	NP	131	CRBG	–
20N/27E-23F01	471248119235401	47.2133	-119.3983	1,165	360	0	86	154	CRBG	–
20N/27E-25F01	471155119223501	47.1986	-119.3764	1,123	280	0	78	174	CRBG	–
20N/27E-26J01	471150119230601	47.1972	-119.385	1,122	240	0	82	198	CRBG	–
20N/27E-27F01	471200119250001	47.2	-119.4167	1,129	200	0	104	178	RING, CRBG	–
20N/27E-30C01	471219119284801	47.2053	-119.48	1,164	230	0	89	230	QDEP, RING	–
20N/27E-31M01	471103119291901	47.1842	-119.4886	1,265	230	0	160	UK	RING	–
20N/27E-35G02	471112119232701	47.1867	-119.3908	1,084	210	0	77	155	CRBG	–
20N/28E-02D01	471539119163501	47.2608	-119.2764	1,254	178	0	NP	94	CRBG	–
20N/28E-03P01	471506119172401	47.2517	-119.29	1,144	266	0	NP	19	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
20N/28E-06P01	471507119211101	47.2519	-119.3531	1,234	305	0	140	180	CRBG	–
20N/28E-08R01D1	471415119191301	47.2375	-119.3203	1,165	450	0	NP	95	CRBG	180
20N/28E-10M01	471423119174401	47.2397	-119.2956	1,118	205	0	NP	26	CRBG	–
20N/28E-11R01	471402119154001	47.2347	-119.2549	1,256	110	0	NP	30	CRBG	–
20N/28E-14K01	471329119154701	47.2247	-119.2631	1,211	204	0	NP	44	CRBG	–
20N/28E-15N01	471312119174001	47.2201	-119.2956	1,153	113	0	74	93	QDEP, RING, CRBG	–
20N/28E-16D01	471401119185601	47.2336	-119.3156	1,159	222	0	NP	72	CRBG	–
20N/28E-20D01	471311119201701	47.2196	-119.3392	1,222	805	0	UK	239	CRBG	–
20N/28E-24B01	471256119144401	47.2156	-119.2456	1,273	360	0	NP	97	CRBG	–
20N/28E-25A01	471215119141801	47.2042	-119.2383	1,263	128	0	NP	124	CRBG	–
20N/28E-26P02	471136119160901	47.1933	-119.2692	1,116	460	0	NP	17	CRBG	–
20N/28E-27E01	471158119175501	47.1997	-119.2981	1,157	134	0	NP	105	QDEP, CRBG	–
20N/28E-32C01 MW-SU-136	471112119195101	47.1896	-119.3317	1,195	725	0	124	200	CRBG	22
20N/28E-32H01	471050119191501	47.1796	-119.3267	1,192	712	0	91	178	CRBG	–
20N/28E-32H02	471109119191601	47.1860	-119.3211	1,178	475	0	NP	131	CRBG	–
20N/28E-33E01 MW-SU-137	471102119191401	47.1832	-119.3186	1,173	791	0	85	142	CRBG	–
20N/28E-34A01	471117119164201	47.1881	-119.2783	1,119	260	0	NP	57	CRBG	–
20N/28E-35G01	471102119160101	47.1839	-119.2669	1,083	224	NP	NP	0	CRBG	–
20N/28E-36B01	471122119142001	47.1893	-119.2400	1,244	142	0	NP	131	CRBG	–
20N/28E-36D01	471110119150501	47.1861	-119.2514	1,102	550	NP	NP	0	CRBG	3.6
20N/29E-05D01	471548119124601	47.2633	-119.2128	1,385	325	NP	NP	0	CRBG	–
20N/29E-06P01	471455119133701	47.2486	-119.2269	1,322	120	NP	NP	0	CRBG	–
20N/29E-07H02	471427119124701	47.2407	-119.2139	1,308	1,220	0	NP	20	CRBG	–
20N/29E-08D02	471439119123501	47.2442	-119.2097	1,316	220	0	NP	12	CRBG	–
20N/29E-09P01	471406119110201	47.235	-119.1839	1,312	225	0	NP	40	CRBG	16
20N/29E-17D01	471355119123901	47.2319	-119.2108	1,294	145	0	NP	21	CRBG	–
20N/29E-18J02	471330119125501	47.225	-119.2153	1,281	129	0	NP	15	CRBG	–
20N/29E-18N02	471310119140201	47.2194	-119.2339	1,281	160	0	46	89	CRBG	–
20N/29E-20D02	471305119124101	47.2181	-119.2114	1,284	155	0	NP	23	CRBG	–
20N/29E-21L01	471227119105901	47.2075	-119.1831	1,321	142	0	NP	16	CRBG	–
20N/29E-22C01	471301119093501	47.2168	-119.1608	1,329	865	0	NP	70	CRBG	–
20N/29E-25C01	471205119125001	47.2011	-119.1175	1,442	1,355	NP	NP	0	CRBG	–
20N/29E-27J01	471139119091401	47.1940	-119.1550	1,212	388	0	NP	42	CRBG	–
20N/29E-28B01	471212119104201	47.2032	-119.1795	1,312	290	NP	NP	0	CRBG	–
20N/29E-29M01	471138119123701	47.1939	-119.2103	1,264	74	NP	NP	0	CRBG	–
20N/29E-30M01	471144119134801	47.1956	-119.23	1,263	522	0	NP	74	CRBG	–
20N/29E-31F01	471102119133901	47.1838	-119.2286	1,240	335	0	NP	38	CRBG	–
20N/29E-32B01	471112119120401	47.1867	-119.2011	1,277	420	0	NP	32	CRBG	–
20N/29E-33J01	471048119101301	47.1799	-119.1714	1,336	658	0	NP	22	CRBG	2.7
20N/29E-34J02	471049119091101	47.1803	-119.1531	1,256	200	NP	NP	0	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
21N/23E-26H01	471709119543101	47.2857	-119.8976	1,669	310	NP	NP	0	CRBG	–
21N/23E-35D01	471630119550701	47.275	-119.9186	1,548	220	NP	NP	0	CRBG	–
21N/23E-36N01	471548119534101	47.2633	-119.8947	1,409	200	NP	NP	0	CRBG	–
21N/24E-26D01	471732119472001	47.2926	-119.7900	1,873	850	NP	NP	0	CRBG	–
21N/24E-26F01	471718119464701	47.2882	-119.7809	1,752	410	NP	NP	0	CRBG	–
21N/24E-31G01	471621119515201	47.2725	-119.8644	1,511	295	NP	NP	0	CRBG	–
21N/24E-32K01	471613119502301	47.2703	-119.8397	1,518	310	0	NP	15	CRBG	–
21N/24E-33M01	471603119494301	47.2675	-119.8286	1,471	318	NP	NP	0	CRBG	–
21N/24E-35M01	471612119472301	47.27	-119.7897	1,510	238	NP	NP	0	CRBG	–
21N/25E-30P01	471645119443001	47.2792	-119.7417	1,633	462	NP	NP	0	CRBG	–
21N/25E-32D03	471635119433401	47.2764	-119.7261	1,580	378	NP	NP	0	CRBG	–
21N/25E-33H01	471629119410101	47.2743	-119.6870	1,512	396	0	NP	40	CRBG	–
21N/25E-35J01	471620119383501	47.2722	-119.6431	1,437	418	NP	NP	0	CRBG	–
21N/25E-35P01	471559119390801	47.2662	-119.6534	1,390	312	0	NP	35	CRBG	–
21N/26E-02A01	472109119305101	47.3525	-119.5142	1,253	295	0	10	257	CRBG	–
21N/26E-02D01	472109119315501	47.3525	-119.5319	1,276	236	0	30	180	RING, CRBG	–
21N/26E-03Q01	472034119322201	47.3428	-119.5394	1,264	200	0	22	142	RING, CRBG	–
21N/26E-06A01	472105119300001	47.3526	-119.5981	2106	280	NP	NP	0	CRBG	–
21N/26E-08N01	471934119352601	47.3262	-119.5928	1,585	450	NP	NP	0	CRBG	–
21N/26E-10F01	472009119325701	47.3358	-119.5492	1,267	200	NP	0	161	RING, CRBG	–
21N/26E-10L02	471955119324701	47.3318	-119.5475	1,264	122	NP	0	UK	CRBG	–
21N/26E-12F01	472009119300101	47.3357	-119.5014	1,259	183	0	UK	UK	QDEP	–
21N/26E-14L01	471901119312901	47.3163	-119.5264	1,285	1,020	0	80	210	CRBG	–
21N/26E-15D01	471928119330401	47.3243	-119.5523	1,283	365	NP	0	170	CRBG	–
21N/26E-15H01	471920119320501	47.3185	-119.5370	1,325	1,850	0	NP	95	CRBG	6.9
21N/26E-16A01	471920119332601	47.3221	-119.5584	1,296	1,360	NP	0	70	CRBG	–
21N/26E-21Q01	471757119334501	47.2992	-119.5625	1,246	170	0	54	88	CRBG	–
21N/26E-22N02	471749119330101	47.2969	-119.5503	1,309	220	0	77	UK	RING	–
21N/26E-25M01	471713119303001	47.2869	-119.5083	1,273	158	0	NP	35	CRBG	–
21N/26E-26P01	471701119312301	47.2836	-119.5231	1,275	254	0	22	69	CRBG	–
21N/26E-28K02	471713119333801	47.2868	-119.5617	1,232	244	0	UK	60	CRBG	–
21N/26E-29M02	471714119354701	47.2871	-119.5975	1,521	448	0	NP	71	CRBG	–
21N/26E-30F01	471722119363701	47.2893	-119.6114	1,697	592	0	NP	39	CRBG	–
21N/26E-31D01	471638119370701	47.2772	-119.6186	1,426	360	0	NP	50	CRBG	–
21N/26E-33E01	471634119342001	47.2760	-119.5734	1,269	360	NP	NP	0	CRBG	–
21N/26E-33G01	471629119335401	47.2747	-119.565	1,216	320	0	62	91	CRBG	–
21N/26E-34C01	471651119325201	47.2808	-119.5478	1,286	200	0	74	194	RING, CRBG	–
21N/26E-35A01	471644119304701	47.2789	-119.5131	1,273	120	0	NP	23	CRBG	–
21N/26E-35L01	471616119312701	47.2711	-119.5242	1,314	265	0	NP	58	CRBG	–
21N/27E-02G01	472056119232501	47.3489	-119.3903	1,244	244	0	NP	74	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
21N/27E-04A01	472112119254001	47.3532	-119.4289	1,242	208	0	NP	170	CRBG	–
21N/27E-04G01	472101119261001	47.3503	-119.4361	1,230	285	0	NP	136	CRBG	–
21N/27E-09B01	472016119261001	47.3378	-119.4361	1,230	277	0	162	242	CRBG	–
21N/27E-09P01	471936119263201	47.3267	-119.4422	1,109	350	NP	NP	0	CRBG	–
21N/27E-13M01	471901119225201	47.3169	-119.3811	1,200	285	0	NP	26	CRBG	–
21N/27E-13Q01	471847119221801	47.3131	-119.3717	1,213	95	0	NP	51	CRBG	–
21N/27E-21N01	471801119263801	47.3003	-119.4439	1,102	140	0	NP	47	CRBG	–
21N/27E-24Q01	471748119222101	47.2967	-119.3725	1,201	242	0	NP	48	CRBG	–
21N/27E-25D01	471742119224401	47.295	-119.3789	1,179	200	0	NP	30	CRBG	–
21N/27E-25H01	471721119214601	47.2892	-119.3628	1,205	115	0	NP	62	CRBG	–
21N/27E-27P01	471703119251101	47.2842	-119.4197	1,267	260	0	152	188	CRBG	–
21N/27E-28D01	471741119263801	47.2947	-119.4439	1,073	80	0	NP	25	CRBG	–
21N/27E-29M01	471710119280501	47.2861	-119.4681	1,188	240	0	NP	17	CRBG	–
21N/27E-32R01	471616119270301	47.2711	-119.4508	1,085	122	0	NP	47	CRBG	–
21N/27E-33D01	471655119264901	47.2819	-119.4469	1,073	162	0	NP	36	CRBG	–
21N/27E-33Q01	471615119261301	47.2708	-119.4369	1,175	305	0	NP	125	CRBG	–
21N/28E-02E01	472052119163101	47.3476	-119.2764	1,324	107	NP	NP	0	CRBG	–
21N/28E-03F01	472048119173001	47.3465	-119.2928	1,340	535	0	UK	65	CRBG	–
21N/28E-05H01	472055119192001	47.3486	-119.3222	1,282	280	0	NP	50	CRBG	–
21N/28E-08P02	471928119195301	47.3244	-119.3314	1,308	160	0	NP	81	CRBG	–
21N/28E-11P01	471924119161201	47.3233	-119.27	1,318	77	0	NP	20	CRBG	–
21N/28E-13N02	471830119151901	47.3083	-119.2553	1,268	323	0	NP	18	CRBG	–
21N/28E-14D01	471913119163101	47.3201	-119.2764	1,314	85	0	NP	15	CRBG	–
21N/28E-15C01	471922119171801	47.3228	-119.2883	1,320	100	0	NP	15	CRBG	–
21N/28E-19F02	471725119214501	47.3046	-119.3525	1,164	115	0	NP	62	CRBG	–
21N/28E-21R01	471740119175501	47.2944	-119.2986	1,253	214	0	NP	15	CRBG	–
21N/28E-22A01	471828119163801	47.3078	-119.2772	1,299	108	0	NP	106	QDEP, CRBG	–
21N/28E-23D01	471827119162301	47.3074	-119.2742	1,298	150	0	NP	83	QDEP, CRBG	–
21N/28E-24A01	471826119140801	47.3072	-119.2356	1,260	100	0	NP	28	CRBG	–
21N/28E-26A01	471729119152601	47.2914	-119.2572	1,257	96	NP	NP	0	CRBG	–
21N/28E-26R01	471655119152901	47.2818	-119.2592	1,264	134	0	UK	UK	CRBG	–
21N/28E-27P01	471649119173101	47.2803	-119.2919	1,252	86	0	NP	28	CRBG	–
21N/28E-35E01	471630119163001	47.275	-119.275	1,265	242	0	NP	45	CRBG	–
21N/28E-36R01	471606119142901	47.2646	-119.2350	1,280	138	0	NP	77	CRBG	–
22N/26E-01K01	472558119295201	47.4328	-119.4978	1,150	160	0	NP	68	CRBG	–
22N/26E-12B08	472530119300001	47.4249	-119.5011	1,108	120	0	NP	31	CRBG	–
22N/26E-13A01	472435119292701	47.4097	-119.4908	1,115	172	0	NP	24	CRBG	–
22N/26E-14N01	472353119314301	47.3981	-119.5286	1,467	500	NP	NP	0	CRBG	–
22N/26E-23P01	472303119313901	47.3842	-119.5275	1,359	110	NP	NP	0	CRBG	–
22N/26E-23R01	472304119305101	47.3844	-119.5142	1,325	220	0	87	116	CRBG	–
22N/26E-24B01	472340119295901	47.3944	-119.4997	1,087	110	0	NP	52	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
22N/26E-24F02	472328119301101	47.3911	-119.5031	1,141	901	0	UK	UK	CRBG	170
22N/26E-25A02	472258119293801	47.3828	-119.4939	1,143	180	0	NP	54	CRBG	–
22N/26E-25M04	472230119304101	47.375	-119.5114	1,246	595	0	NP	190	CRBG	–
22N/26E-27J01	472233119320401	47.3758	-119.5344	1,393	200	NP	NP	0	CRBG	–
22N/26E-28A02	472256119332701	47.3821	-119.5586	1,609	130	NP	NP	0	CRBG	–
22N/26E-36B01	422155119300501	47.3654	-119.4975	1,217	451	0	NP	140	CRBG	–
22N/27E-02B01	472623119232801	47.4397	-119.3911	1,390	385	0	NP	38	CRBG	–
22N/27E-04M01	472600119263501	47.4333	-119.4431	1,528	235	NP	NP	0	CRBG	–
22N/27E-11R01	472448119230501	47.4132	-119.3859	1,292	315	0	NP	149	CRBG	–
22N/27E-13L01	472408119222601	47.4022	-119.3739	1,307	300	0	NP	134	CRBG	–
22N/27E-14L01	472413119234501	47.4036	-119.3958	1,309	277	0	NP	140	CRBG	–
22N/27E-17D01	472438119275201	47.4106	-119.4644	1,394	340	NP	NP	0	CRBG	–
22N/27E-18P02	472402119284901	47.4006	-119.4803	1,270	205	NP	NP	0	CRBG	–
22N/27E-19H01	472340119281101	47.3944	-119.4697	1,225	207	NP	NP	0	CRBG	–
22N/27E-19N01 PAS10	472318119290301	47.3882	-119.4853	1,104	466	0	NP	54	CRBG	–
22N/27E-20M01	472315119274601	47.3874	-119.4639	1,192	160	0	NP	10	CRBG	–
22N/27E-21C01	472341119262301	47.3947	-119.4397	1,254	170	0	NP	42	CRBG	–
22N/27E-22H01	472330119242501	47.3915	-119.4103	1,205	345	0	NP	30	CRBG	–
22N/27E-23N01	472302119241201	47.3839	-119.4033	1,216	158	0	NP	UK	QDEP	–
22N/27E-24M01	472314119225801	47.3872	-119.3828	1,205	220	0	NP	39	CRBG	–
22N/27E-26H01 PN103	472246119225901	47.3792	-119.3843	1,196	98	0	NP	UK	QDEP	–
22N/27E-27B01	472251119244501	47.3808	-119.4125	1,251	320	0	NP	166	CRBG	–
22N/27E-28R01	472211119254801	47.3697	-119.43	1,259	177	0	NP	95	CRBG	–
22N/27E-29A01	472250119270701	47.3806	-119.4519	1,225	160	0	26	104	RING, CRBG	–
22N/27E-29E01	472244119280201	47.3789	-119.4672	1,180	222	0	15	45	CRBG	–
22N/27E-30P01	472212119284801	47.3699	-119.4811	1,156	304	0	UK	UK	CRBG	–
22N/27E-31M01	472131119291901	47.3586	-119.4886	1,209	190	0	97	139	CRBG	–
22N/27E-33N02	472126119264801	47.3572	-119.4467	1,224	380	0	NP	33	CRBG	–
22N/27E-33Q01	472119119260801	47.3553	-119.4356	1,235	175	0	UK	UK	QDEP	–
22N/27E-35K01	472140119232301	47.3611	-119.3897	1,215	163	0	NP	14	CRBG	–
22N/28E-03K01	472540119170001	47.4276	-119.2845	1,284	170	0	NP	UK	QDEP	–
22N/28E-03R04	472537119164001	47.4269	-119.2778	1,264	240	0	NP	130	CRBG	–
22N/28E-07M01	472503119213301	47.4174	-119.3603	1,284	357	0	NP	135	CRBG	–
22N/28E-10A01	472521119165601	47.4225	-119.2822	1,271	260	NP	NP	0	CRBG	–
22N/28E-11N02	472446119162901	47.4128	-119.2747	1,483	530	NP	NP	0	CRBG	–
22N/28E-27C01	472241119172501	47.3779	-119.2914	1,405	675	NP	NP	0	CRBG	–
22N/28E-28B01	472247119181901	47.3796	-119.3064	1,384	508	NP	NP	0	CRBG	–
22N/28E-28Q01	472208119182001	47.3688	-119.3067	1,357	552	0	NP	62	CRBG	24
22N/28E-29C01	472249119193101	47.3803	-119.3253	1,322	497	NP	NP	0	CRBG	–
22N/28E-30L01	472228119211001	47.3744	-119.3528	1,340	406	0	NP	16	CRBG	–
22N/28E-31B01	472201119210301	47.3669	-119.3508	1,326	260	0	NP	45	CRBG	–

Table 5. Selected physical and hydrologic data for the project wells in the Quincy Basin study area, Washington. —Continued

Well No.	USGS site identification No.	Latitude	Longitude	LSA (feet)	Well depth (feet)	Depth to top of hydrogeologic unit (feet)			Hydrogeologic unit of open interval	K (ft/d)
						QDEP	RING	CRBG		
22N/28E-34H02	472131119164601	47.3585	-119.2806	1,344	284	0	NP	60	CRBG	–
22N/29E-05F01	472558119121401	47.4326	-119.2050	1,267	270	0	NP	95	CRBG	–
22N/29E-06E01	472552119135201	47.4310	-119.2322	1,287	240	0	NP	60	CRBG	–
23N/27E-14Q01	472913119231801	47.4865	-119.3898	1,277	400	0	NP	25	CRBG	6.7
23N/27E-23F02	472848119235301	47.48	-119.3981	1,295	200	0	NP	UK	QDEP	–
23N/27E-32R01	472641119270701	47.4446	-119.4531	1,458	570	NP	NP	0	CRBG	–
23N/28E-27E01	472746119174101	47.4632	-119.2942	1,699	660	NP	NP	0	CRBG	–
23N/28E-32N01	472630119201201	47.4415	-119.3378	1,395	291	0	NP	17	CRBG	–
23N/28E-36E01	472650119151401	47.4471	-119.2550	1,339	187	0	NP	42	CRBG	–
23N/29E-34B01D1	472701119092202	47.4501	-119.1572	1,682	1,600	NP	NP	0	CRBG	–

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