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Prepared in cooperation with The Colville River Watershed Planning Team, for the 2000-2004 WRIA 59 Colville River Watershed Planning Project

Conceptual Model and Numerical Simulation of the Ground-Water-Flow System in the Unconsolidated Deposits of the Colville River Watershed, Stevens County, Washington

Scientific Investigations Report 2004–5237

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

Cover: Photograph of farmland southeast of Chewelah, Washington, looking northwest into the Colville River valley, Washington. (Photograph taken by Linda Kiefer, Watershed Coordinator, Stevens County, Chewelah, Washington, September 2004.)

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By D. Matthew Ely and Sue C. Kahle

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter
inch (in.)	25.4	millimeter
foot (ft)	.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
acre	.4047	hectare
acre	.004047	square kilometer
square foot (ft^2)	929.0	square centimeter
square foot (ft^2)	.09290	square meter
section (640 acres or 1 square mile)	259.0	square hectometer
square mile (mi^2)	259.0	hectare
square mile (mi^2)	2.590	square kilometer
	Volume	
gallon (gal)	3.785	liter
gallon (gal)	.003785	cubic meter
million gallons (Mgal)	3,785	cubic meter
cubic foot (ft^3)	.02832	cubic meter
acre-foot (acre-ft)	1,233	cubic meter
acre-foot (acre-ft)	.001233	cubic hectometer
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year
acre-foot per year (acre-ft/yr)	.001233	cubic hectometer per year
foot per day (ft/d)	.3048	meter per day
cubic foot per second (ft^3/s)	.02832	cubic meter per second
gallon per day (gal/d)	.003785	cubic meter per day
million gallons per day (Mgal/d)	.04381	cubic meter per second
inch per year (in/yr)	25.4	millimeter per year
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day

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

°F=(1.8×°C+32).

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

°C=(°F-32/1.8).

***Transmissivity**: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [($ft^3/d/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

DATUMS

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

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

Conceptual Model and Numerical Simulation of the Ground-Water-Flow System in the Unconsolidated Deposits of the Colville River Watershed, Stevens County, Washington

by D. Matthew Ely and Sue C. Kahle

Abstract

Increased use of ground- and surface-water supplies in watersheds of Washington State in recent years has created concern that insufficient instream flows remain for fish and other uses. Issuance of new ground-water rights in the Colville River Watershed was halted by the Washington Department of Ecology due to possible hydraulic continuity of the ground and surface waters. A ground-water-flow model was developed to aid in the understanding of the ground-water system and the regional effects of ground-water development alternatives on the water resources of the Colville River Watershed.

The Colville River Watershed is underlain by unconsolidated deposits of glacial and non-glacial origin. The surficial geologic units and the deposits at depth were differentiated into aquifers and confining units on the basis of areal extent and general water-bearing characteristics. Five principal hydrogeologic units are recognized in the study area and form the basis of the ground-water-flow model.

A steady-state ground-water-flow model of the Colville River Watershed was developed to simulate September 2001 conditions. The simulation period represented a period of below-average precipitation. The model was calibrated using nonlinear regression to minimize the weighted differences or residuals between simulated and measured hydraulic head and stream discharge.

Simulated inflow to the model area was 53,000 acre-feet per year (acre-ft/yr) from precipitation and secondary recharge, and 36,000 acre-ft/yr from stream and lake l eakage. Simulated outflow from the model was primarily through discharge to streams and lakes (71,000 acre-ft/yr), ground-water outflow (9,000 acre-ft/yr), and ground-water withdrawals (9,000 acre-ft/yr). Because the period of simulation, September 2001, was extremely dry, all components of the ground-water budget are presumably less than average flow conditions.

The calibrated model was used to simulate the possible effects of increased ground-water pumping. Although the steady-state model cannot be used to predict how long it would take for effects to occur, it does simulate the ultimate response to such changes relative to September 2001 (relatively dry) conditions. Steady-state simulations indicated that increased pumping would result in decreased discharge to streams and lakes and decreased ground-water outflow. The location of the simulated increased ground-water pumping determined the primary source of the water withdrawn. Simulated pumping wells in the northern end of the main Colville River valley diverted a large percentage of the pumpage from ground-water outflow. Simulated pumping wells in the southern end of the main Colville River valley diverted a large percentage of the pumpage from flow to rivers and streams.

The calibrated steady-state model also was used to simulate predevelopment conditions, during which no ground-water pumping, secondary recharge, or irrigation application occurred. Cumulative streamflow in the Colville River Watershed increased by 1.1 cubic feet per second, or about 36 percent of net ground-water pumping in 2001.

The model is intended to simulate the regional ground-water-flow system of the Colville River Watershed and can be used as a tool for water-resource managers to assess the ultimate regional effects of changes in stresses. The regional scale of the model, coupled with relatively sparse data, must be considered when applying the model in areas of poorly understood hydrology, or examining hydrologic conditions at a larger scale than what is appropriate.

Introduction

In recent years, increased withdrawal of ground- and surface-water supplies in several watersheds of Washington State has created concern that insufficient flows remain in streams for fish and other uses. In response, the Washington State legislature passed the Watershed Management Act of 1998 (HB 2514), which encourages and provides some funding for local watershed planning and delegates the planning to a local level. As part of this planning process, stakeholders within a Water Resources Inventory Area (WRIA) need to assess the status of water resources in the WRIA and determine whether water is available for allocation.

Surface water in the Colville River Watershed (WRIA 59, fig. 1) currently is available for further appropriation only from the mainstem of the Colville River and only from October 1 through July 15. All streams tributary to the Colville River are fully appropriated under existing water rights (Chung and Slattery, 1977). Issuance of new ground-water rights was halted in 1994 by the Washington Department of Ecology (DOE) owing to possible hydrologic connection of the ground- and surface-water systems. Although new wells for single and multi-family use are exempt, the ruling limits any major development of ground water in the Colville River Watershed.

The Colville River Watershed Planning Team (Planning Team) is working to develop a long-range watershed management plan to meet the needs of current and future water demands within the watershed, while also working to protect and improve its natural resources. The U.S. Geological Survey (USGS), in cooperation with the Planning Team, began Phase I of a two-part study in the summer of 2001 to investigate the ground-water system of the valley-fill deposits of the Colville River Watershed. Phase I was completed and the results published in Kahle and others (2003).

Following the completion of Phase I, the Planning Team requested that the USGS develop a steady-state, regional ground-water-flow model to improve understanding of the ground-water system and the regional effects of various ground-water use alternatives on the water resources of the Colville River Watershed. Development of the model, Phase II of the cooperative studies between the Planning Team and the USGS, was based on the hydrogeologic framework described in the Phase I report.

Purpose and Scope

This report documents a tool that can be used to simulate the ground-water-flow system in the Colville River Watershed. The report (1) describes the construction and calibration of the Colville River Watershed ground-water-flow model, (2) evaluates the applicability and accuracy of the model as a predictive tool for assessing low-flow conditions, and (3) discusses the limitations of the model. The broad objective of this study was to develop a better understanding of the ground-water-flow system of the Colville River Watershed to help manage the water resources. The specific objectives were to:

- Estimate the hydraulic properties of the major hydrogeologic units;
- Define and describe the regional ground-water-flow system in the unconsolidated deposits; and
- Estimate the effects of different ground-water use alternatives on the ground-water and surface-water systems.

The model was calibrated for September 2001 conditions, using 161 hydraulic-head measurements and 44 synoptic streamflow measurements. The streamflow measurements identified gaining and losing reaches over the unconsolidated valley deposits.

Description of Study Area

The Colville River Watershed occupies much of central Stevens County in northeastern Washington and covers about 1,000 mi^2 (fig. 1). It is a roughly north-south oriented watershed about 45 mi long and 23 mi wide, and extends from the town of Springdale and Loon Lake at the southern end of the watershed to near the town of Kettle Falls at the northwestern extent of the watershed. The Colville River begins at the confluence of Sheep and Deer Creeks at the south end of the watershed, flows generally north to the town of Chewelah and then continues north-northwest to the town of Colville. Beyond Colville, the river follows a more westerly course and empties into Franklin D. Roosevelt Lake (also know as Lake Roosevelt) 2 mi southwest of the town of Kettle Falls.

Physiographically, the watershed is composed of hilly and mountainous terrain of the Selkirk Mountains, which is bisected by the generally north-south river valley that is in most places less than 3 mi wide. Altitudes range from 1,290 ft at the mouth of the Colville River to near 7,000 ft in the upland areas. Colville River valley, which occupies the central part of the watershed, has an altitude of 1,920 ft near Springdale to 1,620 ft at Kettle Falls, about 43 mi downstream. The low drainage divide to the south, between the north-flowing Colville River and the south-flowing Chamokane Creek is underlain by recent alluvium, glacial outwash and till, and thick clay and silt deposited in large Pleistocene lakes. These unconsolidated deposits form a shallow drainage divide in an otherwise broad and continuous valley.

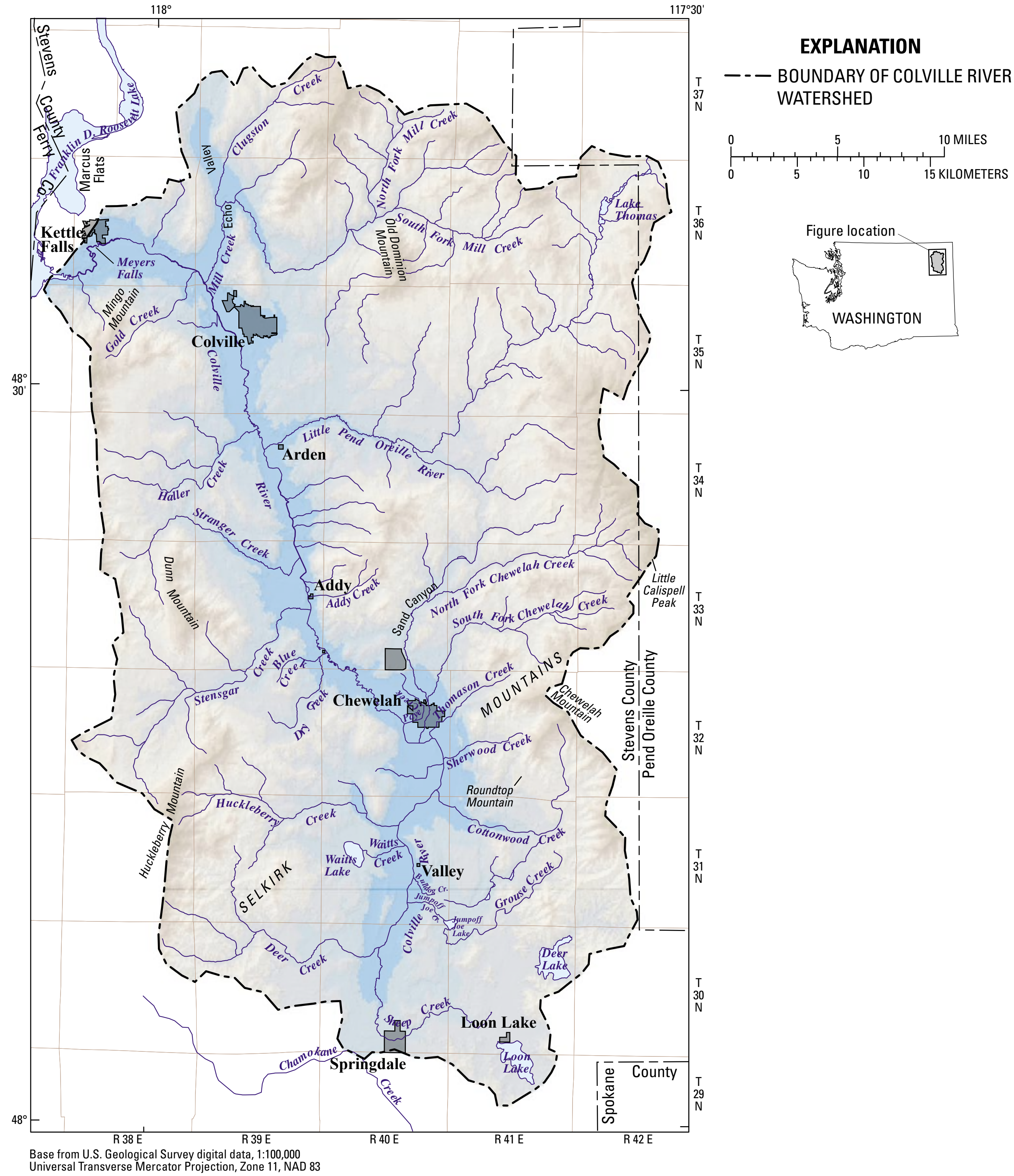


Figure 1. Location of Colville River Watershed, Stevens County, Washington.

Geologically, the watershed can be grouped into three types of formations; bedrock, glacial deposits, and valley alluvium. The bedrock, consisting of sedimentary, metamorphic, and igneous rocks, forms the hills and mountains of the watershed and underlies the lowland areas at generally unknown depths. Glacial deposits including silt, sand, gravel, clay, and till mantle much of the lowland areas and lower reaches of the hills and mountains. These sediments are the result of deposition during repeated ice advances of the Colville Lobe of the Cordilleran ice sheet during the Pleistocene Epoch. Sands and gravels deposited by glacial outwash streams are significant sources of ground water in the watershed. Recent valley alluvium is mostly limited to the Colville River valley, where it lies directly on the Pleistocene glacial deposits.

Most of the mountainous areas in the watershed are covered with pine, fir, and larch forests that are the basis for the large historical and present-day lumber industry in the area. Most agricultural activity occurs on the valley bottom and is mostly hay. The lowland areas support several towns and light commercial and industrial development, mostly in Colville and Chewelah. The estimated population for WRIA 59 is 22,430 residents based on the 2000 Census for Stevens County (Linda Kiefer, WRIA 59 Watershed Coordinator, Stevens County, written commun., March 2002). Population in the watershed has nearly doubled since the 1970s, thereby increasing the demand on present water supplies, both for drinking water and other uses. The Colville River and its tributaries are home to several species of fish, none of which are listed as endangered or threatened.

Acknowledgments

This study was completed with the assistance of many individuals and groups. The authors thank Linda Kiefer, Dick Price, and the members of the WRIA 59 Watershed Planning Team and the Stevens County Conservation District for contributing knowledge of current and historical conditions in the watershed. John Covert of the Washington State Department of Ecology's Water Resource Program provided helpful comments throughout the study. Fogle Pump and Supply provided additional drilling information that aided in the estimation of hydraulic properties.

Conceptual Model of the Ground-Water System

This section provides a generalized description and interpretation of the hydrogeologic framework of the ground-water system (the conceptual model) of the Colville River Watershed, including descriptions of the physical, lithologic, and hydrologic characteristics of the hydrogeologic units. An understanding of these characteristics is important in determining the occurrence and availability of ground water in the watershed. For a detailed description of the water resources of the Colville River Watershed, the reader is referred to Kahle and others (2003).

Geologic Setting

The geology of the Colville River Watershed is complex and comprises several types of bedrock (for example, shale, slate, dolomite, quartzite, granite, and basalt) overlain in many places with various types and thicknesses of unconsolidated sediment such as silt, sand, gravel, and clay. The sediments occur mostly as till, outwash, alluvium, and glacial-lake flood deposits. At least two periods of glaciation have influenced the topography and sedimentation of the region. Although sediments from the earliest glaciations can be identified in some deep wells, little surface evidence remains to reconstruct their depositional history. Only the most recent glacial history is recorded in exposed sediments in the study area.

During the climax of the most recent glaciation (about 15,000 years before present), most of northern Washington, including the Colville River valley, was covered by lobes of the Cordilleran ice sheet. The Okanogan Lobe, to the west of the Colville River valley, dammed the Columbia River and created a vast lake referred to as glacial Lake Columbia (Waitt and Thorson, 1983), which deposited thick, fine-grained sediments throughout much of the region.

As the Colville Lobe of the ice sheet advanced southward into the Colville River valley, large areas of outwash sands and gravels were deposited from glacial melt water, till was deposited beneath the ice, and fine-grained sediments were deposited as the lobe advanced into glacial Lake Columbia (Waitt and Thorson, 1983). The southern limit of the Colville Lobe is marked by a well-developed terminal moraine, the Springdale moraine, near the town of Springdale.

Although most of the surficial unconsolidated deposits in the study area are the result of glacial processes involving the Colville and Okanogan Lobes, the Purcell Trench Lobe in what is now northern Idaho also contributed directly to sedimentation in the southern part of the Colville River Watershed. Glacial Lake Missoula, dammed behind the Purcell Trench Lobe, was about 600 mi^3 in volume and reached a maximum depth of 2,200 ft (Waitt, 1980). Large catastrophic floods occurred periodically when the ice dam of the Purcell Trench Lobe failed, sending floodwaters west and southwest. The giant, present-day dunes north of Loon Lake record floodwaters exiting westward through the Sheep Creek spillway into the Colville River valley near Springdale (Carrara and others, 1995). Following the retreat of the Purcell Trench Lobe from the Colville River Watershed, the valley floor was slightly modified as streams reworked the surficial lake sediments to form a flood plain of variable width. The modern northward flow of the Colville River is the result of the outwash and moraine divide at Springdale.

The surficial geology of the Colville River Watershed consists of the following seven geologic units summarized in Kahle and others (2003).

- Alluvial deposits (Qal): Includes channel and overbank deposits in the modern Colville River and tributary flood plains and alluvial-fan deposits at the mouths of streams tributary to the Colville River. The unit consists mostly of stratified silt, sand, gravel, and minor amounts of clay deposited by flowing water. Thickness of the unit generally is from 1 to 30 ft.

- Glaciofluvial deposits (Qgf): Includes mostly stratified and well-sorted sand-and-gravel outwash deposited by glacial meltwater and other glaciofluvial deposits, including well-stratified and well-sorted sand-and-gravel kame moraines deposited by the retreating Colville Lobe and glacial-outburst flood deposits consisting of mostly stratified sand, gravel, and boulders. Although most of the Qgf is coarse-grained outwash, lenses of silt, clay, and till occur locally. The thickness of the unit generally is from 20 to 300 ft.

- Glacial till (Qti): Includes mostly unsorted and unstratified clay, silt, sand, and gravel deposited by the Colville Lobe. The unit underlies much of the high altitude area in the watershed and locally may contain till from previous glaciations. Near Springdale, the unit includes the terminal moraine of the Colville Lobe. Locally, the unit contains stratified sand and gravel. Thickness of the unit generally is from 10 to 100 ft.

- Glaciolacustrine deposits (Qla): Includes mostly clay and silt lake sediments deposited in ice-marginal lakes. The unit underlies large areas of the Colville River valley, but is overlain by Quaternary alluvial deposits (Qal) in many areas. The unit includes thin and discontinuous beds of sand and gravel. Overall thickness of the unit generally is 20 to 300 ft.

- Mass-wasting deposits (Qmw): Includes poorly sorted angular rock fragments deposited as talus at the base of steep slopes and heterogeneous mixtures of unconsolidated surficial material and rock fragments deposited by landslides. Thickness of the unit varies, but generally is less than 100 ft.

- Organic deposits (Qor): Includes peat, woody peat, muck, and organic-rich silt and clay that commonly occur in closed depressions. Thickness of the unit is from 1 to 30 ft.

- Bedrock (Tertiary to Middle Proterozoic) (Tybr): Includes sedimentary, metasedimentary, and intrusive and extrusive igneous rocks. Specific rock types include conglomerate, sandstone, siltstone, shale, quartzite, dolomite, argillite, granite, and basalt. The unit is exposed in much of the high-altitude areas of the watershed where it is not overlain by till (Qti). The depth to bedrock in the Colville River valley beneath the unconsolidated sediments is largely unknown and likely varies considerably.

Hydrogeologic Units

The surficial geologic units described previously and the deposits at depth were differentiated into aquifers and confining units on the basis of areal extent and general water-bearing characteristics (Kahle and others, 2003). An aquifer is saturated geologic material that is sufficiently permeable to yield water in significant quantities to a well or spring, whereas a confining unit has low permeability that restricts the movement of ground water and limits the usefulness of the unit as a source of water supply. Permeabilities generally are higher in well-sorted, coarse-grained deposits than fine-grained or poorly sorted deposits. In the Colville River Watershed, saturated glacial outwash or other coarse-grained deposits form the aquifers, whereas deposits such as till or glaciolacustrine sediments form the confining units. The aquifers and confining units identified herein are referred to as hydrogeologic units because the differentiation takes into account both the geologic and hydraulic characteristics of the units. Five principal hydrogeologic units are recognized in the study area:

- Upper outwash aquifer (UA);
- Till confining unit (TC);
- Colville Valley confining unit (VC);
- Lower aquifer (LA); and
- Bedrock (BR).

The lithologic and hydrologic characteristics of the hydrogeologic units are summarized in figure 2 and include the range of thickness for each unit based on data from field-located wells (Kahle and others, 2003). Although thin, discontinuous aquifer materials are present on the Colville River valley floor, they are not recognized in this study as a primary aquifer because of their limited extent and thickness. These deposits do, however, yield usable amounts of water, mostly to older, shallow dug wells on the valley floor. A simplified conceptual model of the hydrogeologic system of the Colville River Watershed is presented in figure 3.

Hydrogeologic unit	Unit label	Range of thickness [estimated average thickness], in feet	Lithologic and hydrologic characteristics
Upper outwash aquifer	UA	10-480 [100]	Unconfined aquifer consisting of sand, gravel, cobbles, and silt with minor clay or till interbeds. Unit occurs in most stream valleys and terraces tributary to the Colville River. Includes geologic units Qal, Qgf, and Qti.
Till confining unit	TC	4-250 [70]	Low-permeability unit consisting of compacted and poorly sorted clay, silt, sand, gravel, and cobbles with locally occurring sand and gravel lenses. Includes geologic unit Qti.
Colville Valley confining unit	VC	1-570 [150]	Low-permeability unit consisting mostly of glaciolacustrine silt and clay overlain in places by mostly fine-grained stream alluvium. Unit occurs throughout the length of the Colville River valley and part way up some of the tributary valleys. Discontinuous lenses of aquifer material within the unit contribute usable quantities of water to some wells. Includes geologic units Qal and Qla.
Lower aquifer	LA	2-289 [60]	Generally confined aquifer consisting mostly of sand and some gravel. Unit occurs in most of the Colville River valley beneath the Colville Valley confining unit. The unit is unconfined where it is not fully saturated or is exposed at land surface (near Kettle Falls). Thickness and extent of unit is not well known.
Bedrock	BR	—	Unit includes conglomerate, sandstone, siltstone, shale, quartzite, dolomite, argillite, granite, and basalt. Locally yields usable quantities of water where rocks are fractured. Yields generally are small. Includes geologic unit Tybr.

Figure 2. Lithologic and hydrologic characteristics of the hydrogeologic units in the Colville River Watershed, Stevens County, Washington.
(Modified from Kahle and others, 2003.)

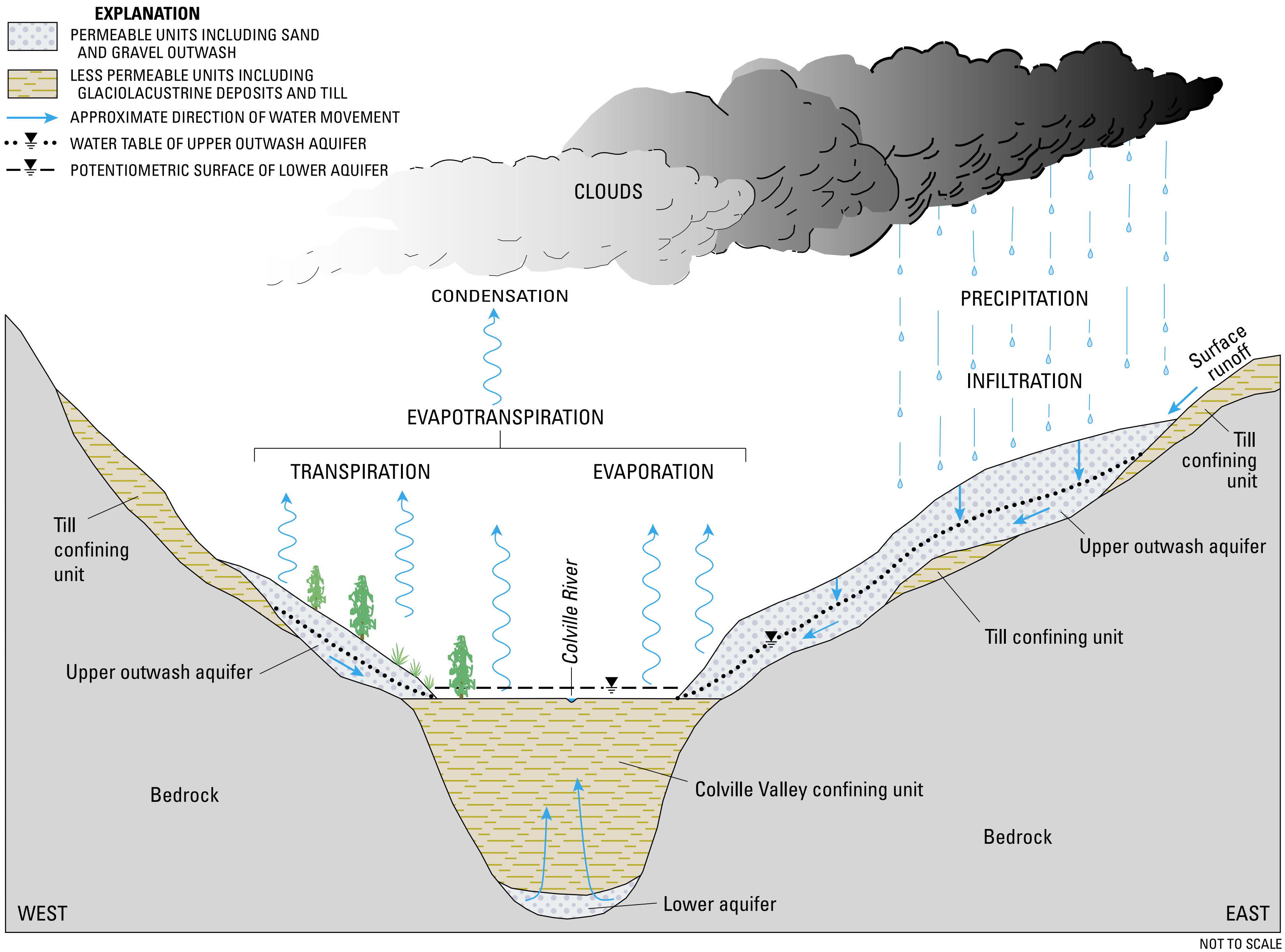


Figure 3. Simplified conceptual model of hydrogeologic system of the Colville River Watershed, Stevens County, Washington. (From Kahle and others, 2003.).

The Upper outwash aquifer (UA) is discontinuous but is a productive and widely used source of water supply. It comprises mostly glacial outwash sand and gravel (geologic unit Qgf) with lenses of clay and till occurring locally (geologic unit Qti) and some sandy alluvium along stream channels (geologic unit Qal).

The Upper outwash aquifer is present mostly in the stream valleys and terraces that are tributary to the Colville River. The average thickness of the unit is 100 ft, and the thickness at known well locations ranges from 10 to 480 ft. The unit is thickest in tributary valleys on the east side of the Colville River valley, greater than 300 ft thick in areas along the Little Pend Oreille River in Sand Canyon, along Cottonwood Creek, and between Deer and Loon Lakes.

The Till confining unit (TC) is a low-permeability unit consisting of compacted and poorly sorted clay, silt, sand, gravel, and cobbles with locally occurring sand-and-gravel lenses. The unit is present in much of the mountainous areas of the study area, where glacial till (geologic unit Qti) mantles bedrock. The estimated average thickness of the unit is 70 ft, and the thickness at known well locations ranges from 4 to 250 ft.

The Colville Valley confining unit (VC) is a thick, low-permeability unit consisting mostly of extensive glaciolacustrine silt and clay (geologic unit Qla) with locally occurring sand or gravel lenses overlain in places by fine-grained stream alluvium (geologic unit Qal). In some areas, glacial till was included with this unit where lake sediments are directly overlain by till. The confining unit is present throughout the length of Colville and Echo Valleys and in parts of some of the tributary valleys, including Mill Creek, Little Pend Oreille River, South Fork Chewelah Creek, Cottonwood Creek, and Jumpoff Joe Creek. The estimated average thickness of the Colville Valley confining unit is 150 ft, and the thickness at known well locations ranges from 1 to 570 ft. The greatest recorded thickness of the confining unit is more than 400 ft in areas near Addy and Kettle Falls.

The Lower aquifer (LA) consists of sand and gravel and likely is continuous along the length of the Colville River valley and Echo valley. It is present below the Colville Valley confining unit and above the bedrock. In most of the study area, the Lower aquifer is confined and many wells completed in this unit flow at land surface. The aquifer is unconfined where exposed at land surface along the Colville River downstream of Meyers Falls. The estimated average thickness of the unit is 60 ft. This may be an underestimate of thickness, however, because few wells fully penetrate the total thickness of the unit. On the basis of available drilling records and water levels, parts of the Lower aquifer extend to the mouth of the watershed and discharge into Lake Roosevelt, probably diverging around the bedrock high near Meyers Falls — to the north beneath Kettle Falls and to the south beneath the present drainage of the Colville River.

The Bedrock (BR) underlies all previously described hydrogeologic units at depths as great as 600 ft along the Colville River valley. In most of the watershed, however, bedrock is present at or near land surface, and is the only source of ground water for landowners who live in those areas. Bedrock typically has very low permeabilities, except where it is fractured. These fractures can produce small but usable quantities of water in wells.

Hydraulic Characteristics

Horizontal hydraulic conductivity was estimated for the hydrogeologic units on the basis of drawdowns from drillers' logs that were measured after pumping wells for periods that ranged from 1 to 100 hours. Only data from those wells that had a driller's log containing discharge rate, time of pumping, drawdown, static water level, well-construction data, and lithologic log were used to estimate horizontal hydraulic conductivity. Statistical summaries of estimated horizontal hydraulic conductivities were prepared by hydrogeologic unit (table 1). The median values of estimated hydraulic conductivities for the aquifers are similar to values reported by Freeze and Cherry (1979) for similar materials: Upper outwash aquifer, 84 ft/d; and Lower aquifer, 49 ft/d (table 1). The medians of estimated hydraulic conductivities for the Till confining unit (5.6 ft/d), for the Colville Valley confining unit (110 ft/d), and for the Bedrock (1.3 ft/d) are higher than is typical for most of the material in these units because specific-capacity tests for confining units usually are from zones where lenses of coarse material exist and, in the case of bedrock, where fractures exist. As a result, the data are biased toward the more productive zones in these units and are not representative of the entire unit. The minimum hydraulic conductivities for the hydrogeologic units indicate the presence of zones of low hydraulic conductivity in most units. The range of hydraulic conductivities is at least three orders of magnitude for most units, indicating a substantial amount of heterogeneity. The methods and assumptions used in making the estimates are included in detail in Kahle and others (2003).

Table 1. Summary of estimated horizontal hydraulic conductivities by hydrogeologic units in the Colville River Watershed, Stevens County, Washington.

Hydrogeologic unit	Number of wells	Horizontal hydraulic conductivity (feet per day)		
		Minimum	Median	Maximum
Upper outwash aquifer (UA)	24	1.9	84	2,400
Till confining unit (TC)	4	2.5	5.6	28
Colville Valley confining unit (VC)	8	14	110	930
Lower aquifer (LA)	17	1.1	49	15,000
Bedrock (BR)	3	.0011	1.3	4.4

Recharge

The Upper outwash aquifer is recharged by direct precipitation in the form of rain and snow, by seepage from lakes, and by losses from streams overlying the aquifer. Recharge to the Lower aquifer likely occurs in several areas. Water-level data indicate that recharge to the Lower aquifer occurs from the southern extent of the watershed to about 3 mi north of Springdale, where vertical head gradients generally are downward. Local recharge also may occur along the walls of the Colville River valley, where coarse talus or glacial or alluvial outwash fans overlie and possibly interfinger with the otherwise continuous Colville Valley confining unit.

Estimates of average annual ground-water recharge for six subbasins within the Colville River Watershed ranged from 1.6 in. in the Haller Creek watershed to 5.0 in. in the Mill Creek watershed (Kahle and others, 2003).

Ground-Water Flow

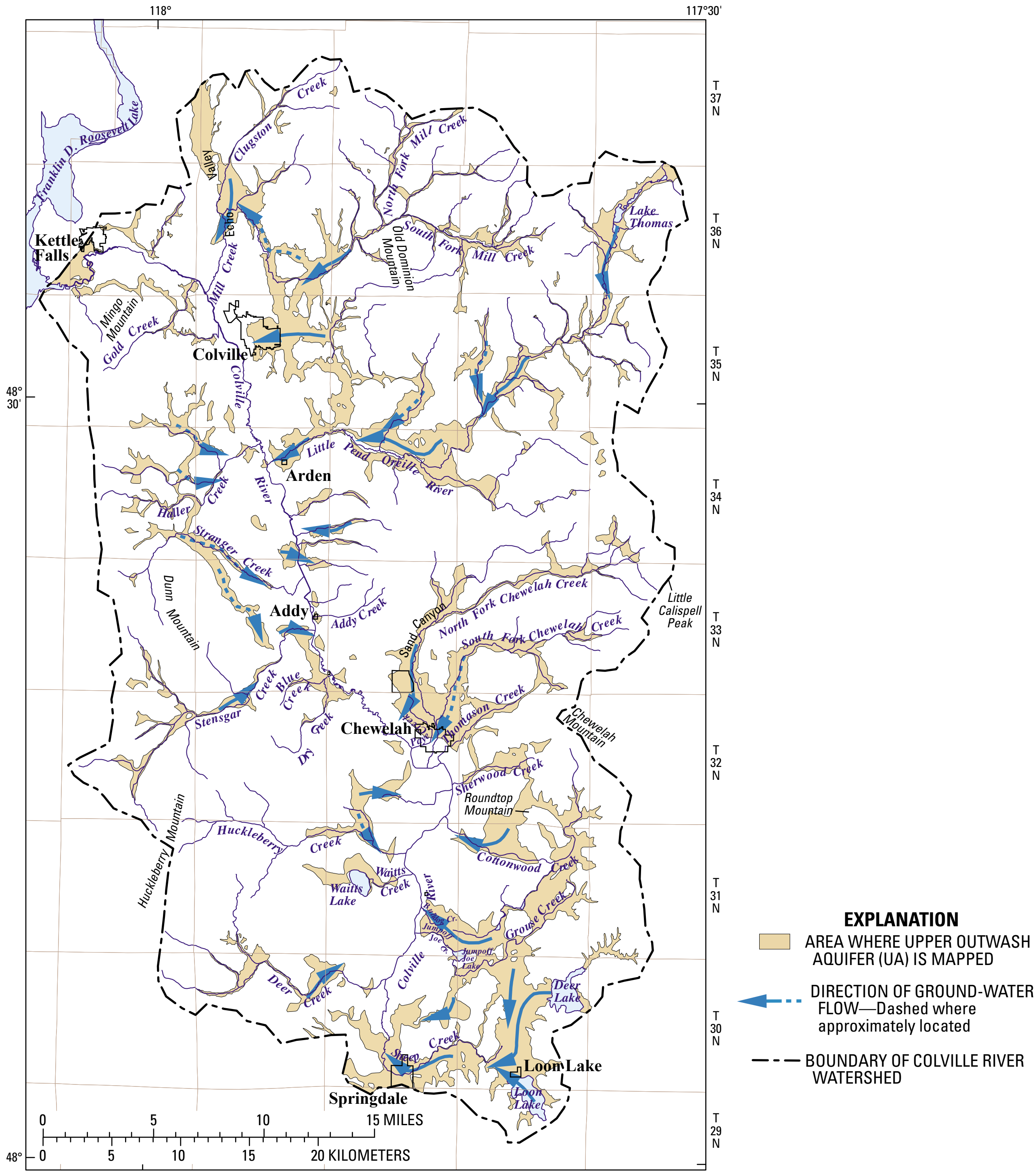
Lateral flow of water in the aquifers generally mimics the surface-water drainage pattern of the watershed. Ground water moves from the topographically high tributary-watershed areas toward the topographically lower Colville River valley floor (fig. 3).

On the basis of available water-level data, vertical flow of ground water in the watershed generally is downward in the high-altitude areas of the tributary basins, downward on the valley floor from near Springdale to near the mouth of Sheep Creek, then upward along much of the valley floor (indicated by flowing wells) to near Colville, where vertical gradients reverse to downward near the mouth of the watershed at Lake Roosevelt. Locally, gradients are upward along gaining reaches of streams, and also are indicated by flowing wells.

Over the entire watershed, water-level altitudes in the Upper outwash aquifer range from 3,149 ft near Lake Thomas to 1,569 ft near Colville. The general distribution of lateral ground-water gradients was 60 ft/mi between Loon Lake and Springdale, 100 ft/mi northeast of Jumpoff Joe Lake westward to Valley, 90 ft/mi in Sand Canyon, 70 ft/mi in the Little Pend Oreille River drainage, and 90 ft/mi in the terrace east of Colville. The smallest gradient in the Upper outwash aquifer, 20 ft/mi, was in the area between Deer and Loon Lakes. Most of the larger lakes in the watershed (including Deer, Loon, Jumpoff Joe, Waitts, and the Little Pend Oreille Lakes) are fairly well connected with the Upper outwash aquifer, and their levels likely rise and decline with the water table. Directions of ground-water flow in the Upper outwash aquifer are shown in figure 4.

At the outlet of the Colville River Watershed, near Kettle Falls, the directions of ground-water flow are less certain, but likely diverge around the bedrock high near Meyers Falls, with flow going both toward the southwest along the present Colville River drainage and to the northwest toward the Marcus Flats area of Lake Roosevelt. Along the valley floor, water-level altitudes within the Lower aquifer range from 1,895 ft near Springdale to 1,284 ft near Kettle Falls (fig. 5). Also on the valley floor, many wells within the unit flow at land surface from 3 mi north of Springdale to the confluence of Colville River valley and Echo Valley, indicating upward ground-water gradients in those areas. Horizontal gradients are 20 ft/mi from Springdale to Valley, 7 ft/mi from Valley to Chewelah, and 5 ft/mi from Chewelah to Colville. Between Colville and Kettle Falls, however, the gradients become much greater and range from 60 to 200 ft/mi.

The ground-water divide for the Lower aquifer is uncertain, but may be near the surface-water divide for the watershed near Springdale. Additional information is needed to determine the location of the ground-water divide, as well as the southern extent of the Lower aquifer.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

Figure 4. Areal extent and direction of ground-water flow in the Upper outwash aquifer in the Colville River Watershed, Stevens County, Washington.
(From Kahle and others, 2003.)

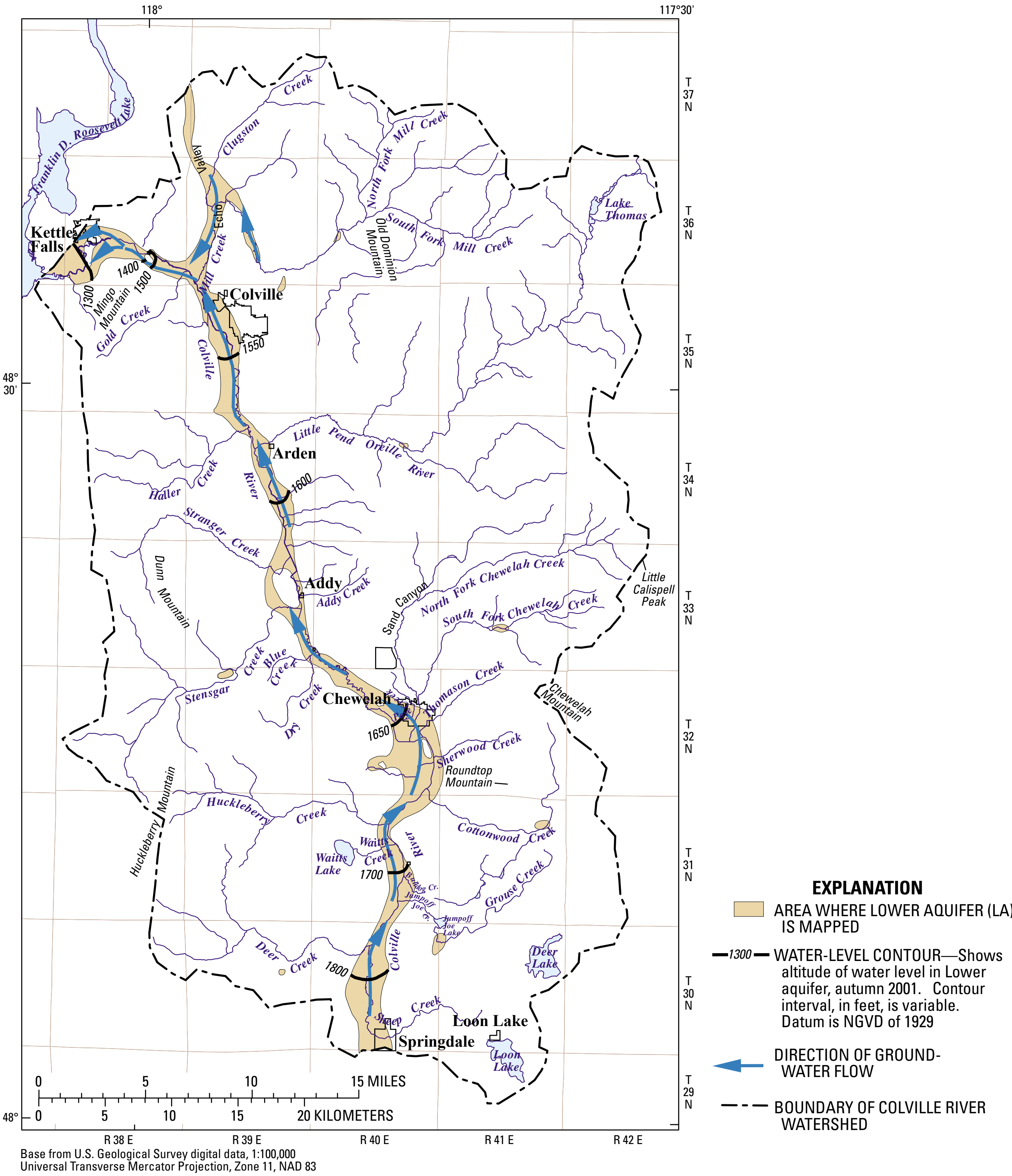


Figure 5. Areal extent, water-level altitudes, and direction of ground-water flow in the Lower aquifer in the Colville River Watershed, Stevens County, Washington.
(From Kahle and others, 2003.)

Ground-Water Discharge

Discharge from the Upper outwash aquifer takes place primarily as seepage to streams. Some interfingering of the coarse Upper outwash aquifer is likely present through the Colville Valley confining unit to the Lower aquifer, creating a direct conduit for discharge from the Upper outwash aquifer to the Colville River valley floor. Discharge also occurs as seepage along the upstream areas of lakes and through pumping from wells.

Downgradient of the Springdale area, many wells completed in the Lower aquifer flow at land surface and are points of discharge for the aquifer. The upward vertical head gradients referred to previously indicate that in some areas along the Colville River valley, ground water may move upward from the Lower aquifer, through the overlying Colville Valley confining unit, and eventually discharge to surface-water features such as the Colville River. Water pumped from wells is another form of discharge from the Lower aquifer.

Ground water discharges from the system by evapotranspiration where the water table is shallow. The total discharge by ground-water evapotranspiration is unknown, but is presumed to be insignificant compared to the other ouflows from the system.

Discharge at the lower end of the watershed near Kettle Falls is uncertain, but is likely through subsurface flow into Lake Roosevelt near the mouth of the Colville River. Ground water leaving the watershed at depth near Kettle Falls was estimated to be 25 ft^3/s, applying Darcy's equation with a hydraulic conductivity of 240 ft/d, a cross-sectional area through the Lower aquifer of 240,000 ft^2; and a gradient of 200 ft/mi. This estimate could be improved by redefining the cross-sectional area near the mouth of the watershed with geophysical surveys.

Numerical Simulation of the Ground-Water-Flow System

Development of a numerical model allows for a detailed analysis of the movement of water through the hydrogeologic units that constitute the ground-water-flow system. Ground-water flow in the unconsolidated deposits of the Colville River Watershed was simulated using the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model, MODFLOW-2000 (Harbaugh and others, 2000).

Model Description

The MODFLOW program uses data sets that describe the hydrogeologic units, recharge, discharge, and conceptual model of the ground-water-flow system, and calculates hydraulic heads at discrete points (nodes) and flow within the model domain. The program requires that the ground-water-flow system be subdivided, vertically and horizontally, into rectilinear blocks called cells. The hydraulic properties of the material in each cell are assumed to be homogeneous. The Colville River Watershed study area was subdivided by a horizontal grid of 112 columns and 180 rows; cells are a uniform 1,500 ft per side (fig. 6). Vertically, the study area was subdivided into six layers having varying thicknesses.

The large cell size and uniform grid spacing were chosen to reflect the regional scale of this study. The predominant flow direction in the study area is from south to north; therefore the grid is oriented similarly. The extents of active cells in each layer are outlined on figures 7*A-E*.

Five model layers were used to simulate the saturated unconsolidated sediments that overlie the bedrock and one layer of constant thickness was used to simulate the upper bedrock.

Hydrogeologic unit	Model layer
Upper outwash aquifer (UA)	1
Till confining unit (TC)	2
Colville Valley confining unit (VC)	3 and 4
Lower aquifer (LA)	5
Bedrock (BR)	6

All layers were simulated as confined due to numerical instabilities that would occur in the model where relatively thin unsaturated thicknesses could not be accurately simulated because of the coarse model grid. Adjustments were made to unit UA to account for large unsaturated thicknesses in some locations. The adjustments were accomplished by lowering the top of unit UA to correspond with the water table.

The Colville Valley confining unit is present throughout the length of the valley and therefore plays an important role in ground-water/surface-water interaction with the Colville River. MODFLOW represents the exchange of water between the stream and the ground-water system as a function of stream geometry and the difference between the head in the stream and the head at the center of an adjacent underlying model cell. To eliminate errors produced by this representation, the thick Colville Valley confining unit was subdivided into two model layers. Layer 3 is the upper 20 ft of unit VC and the remainder of the unit is layer 4.

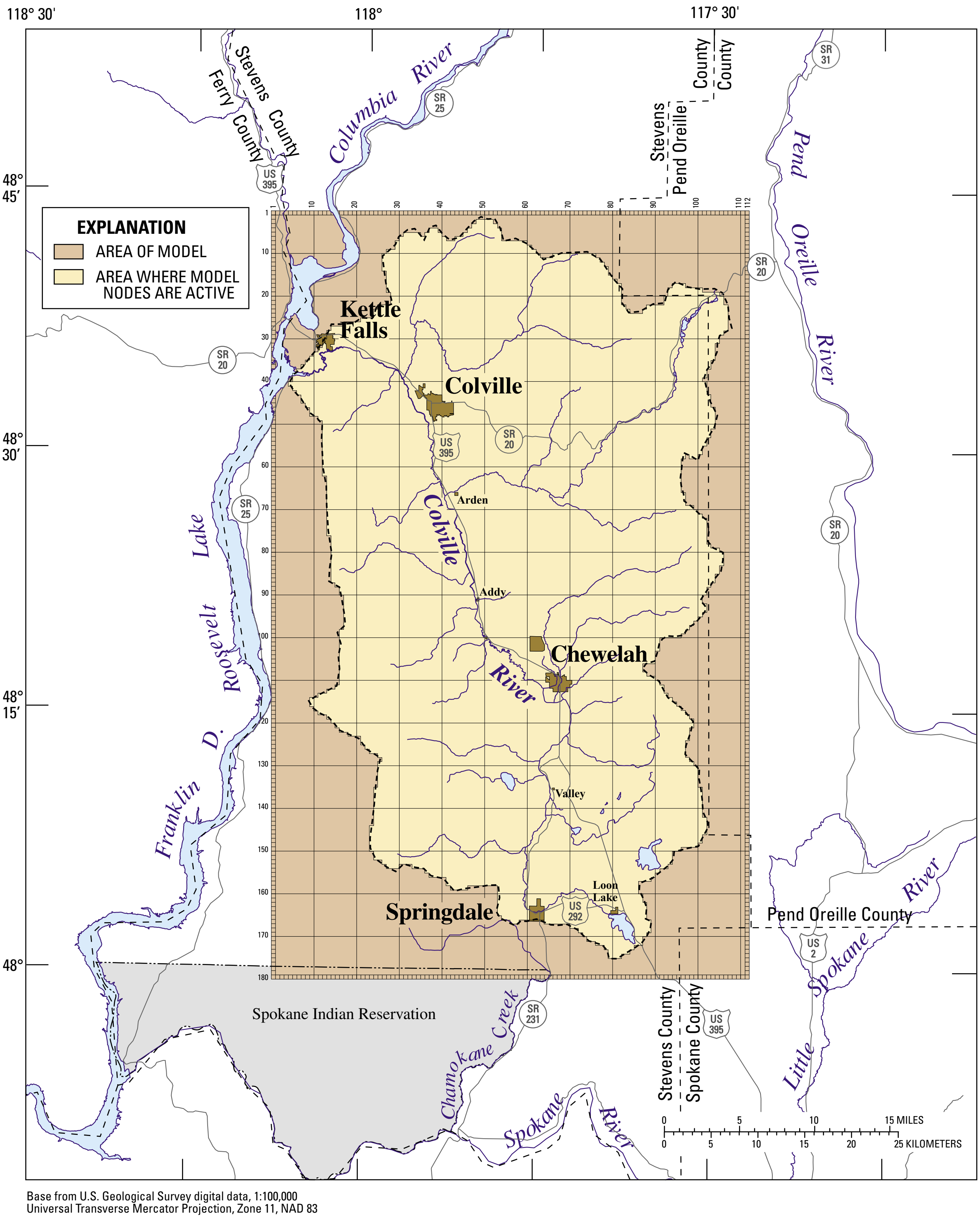
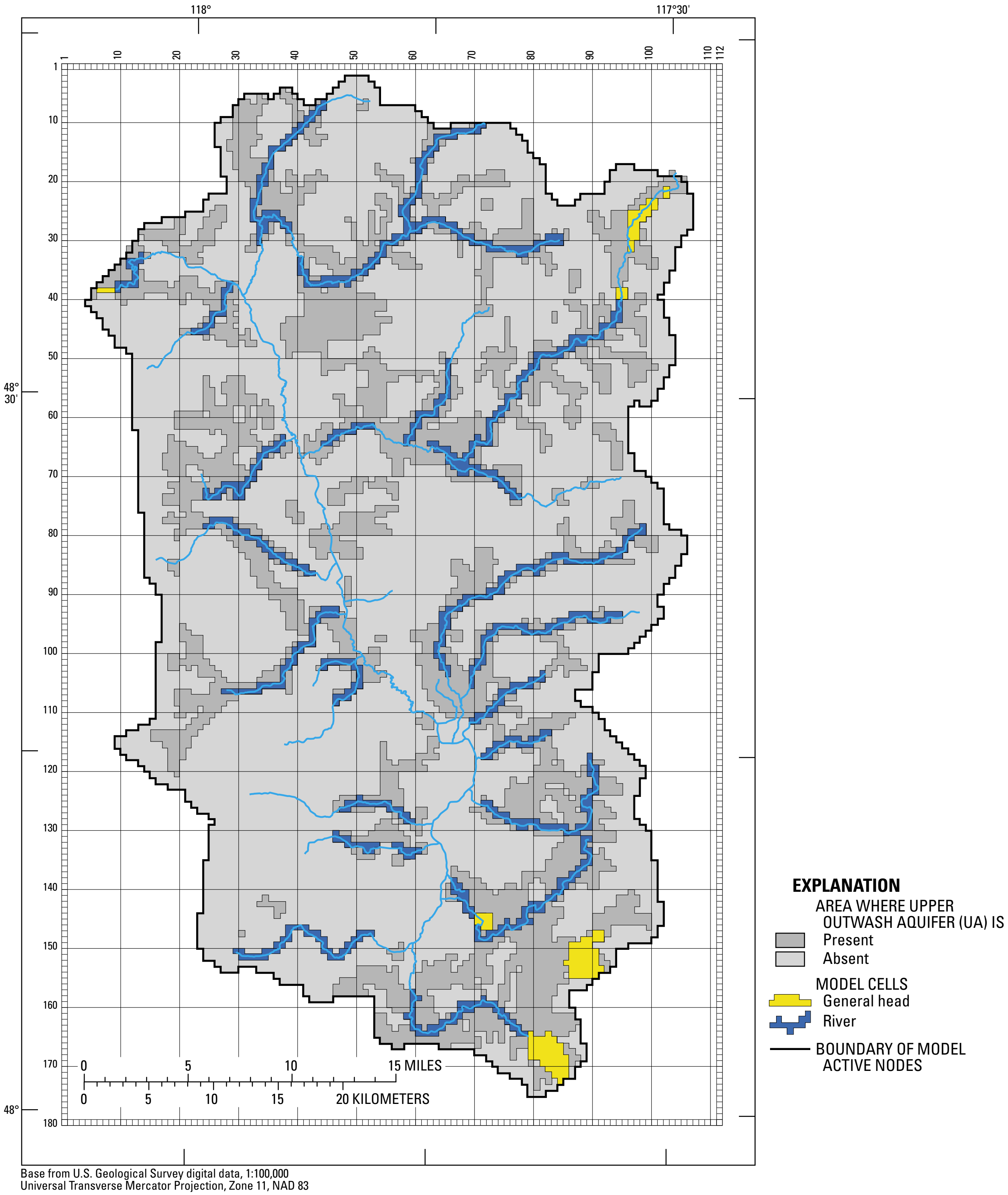
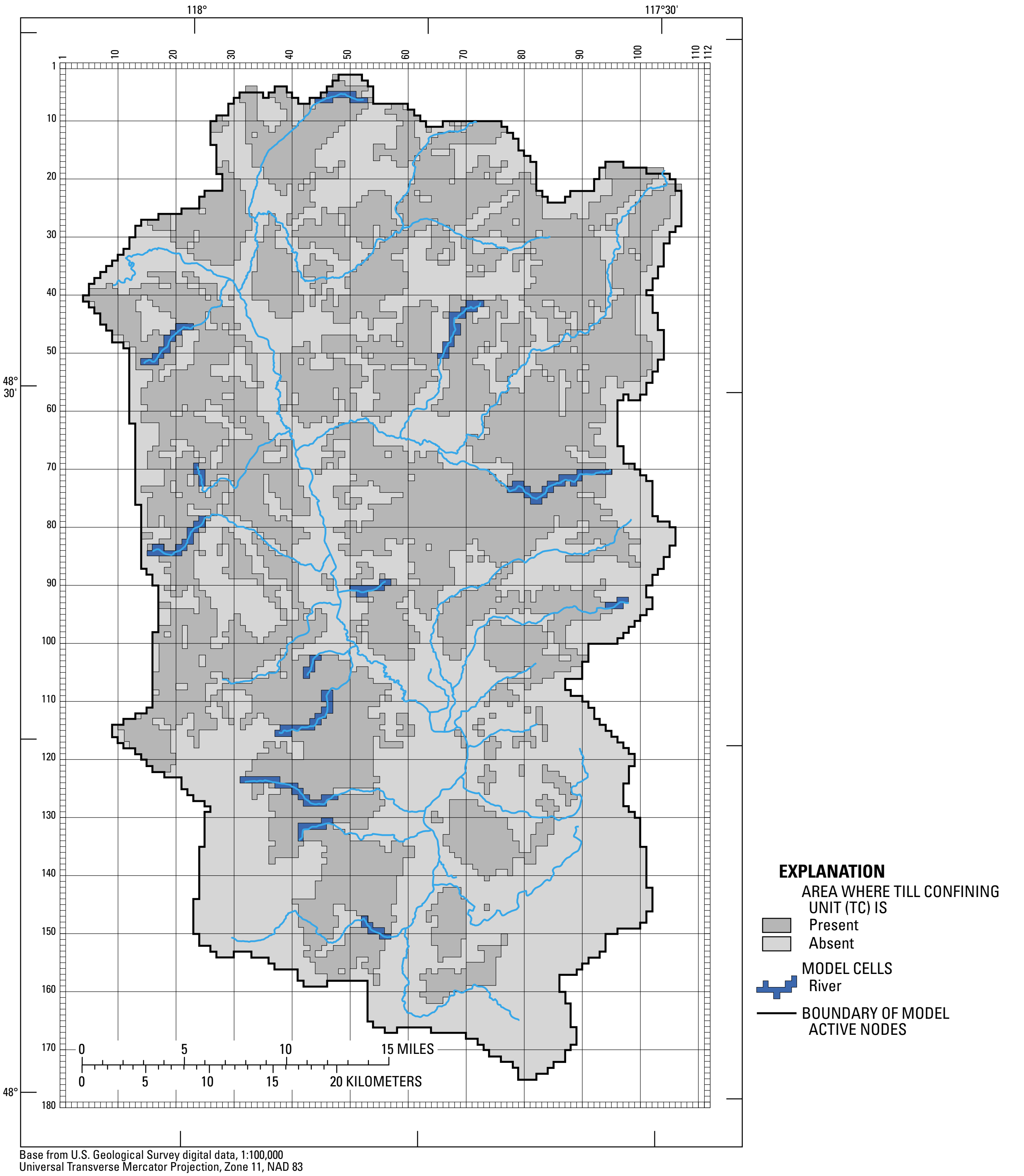


Figure 6. Location and extent of the ground-water-flow model for the Colville River Watershed, Stevens County, Washington.



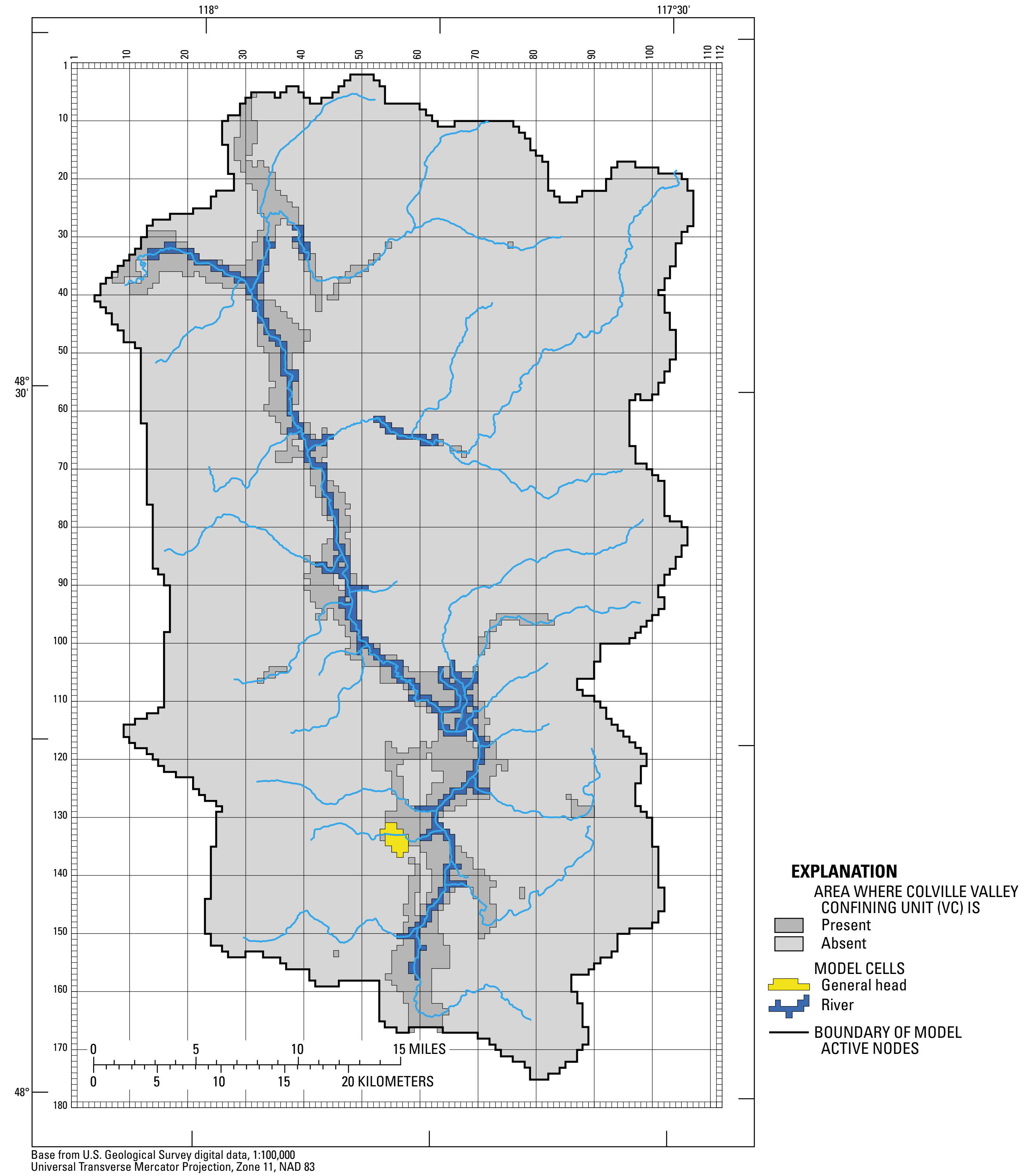
A. Model layer 1 – Upper outwash aquifer (UA)

Figure 7. Areal extents of model layers 1-3, and 5-6 and locations of river, drain, and general head cells, Colville River Watershed, Stevens County, Washington.



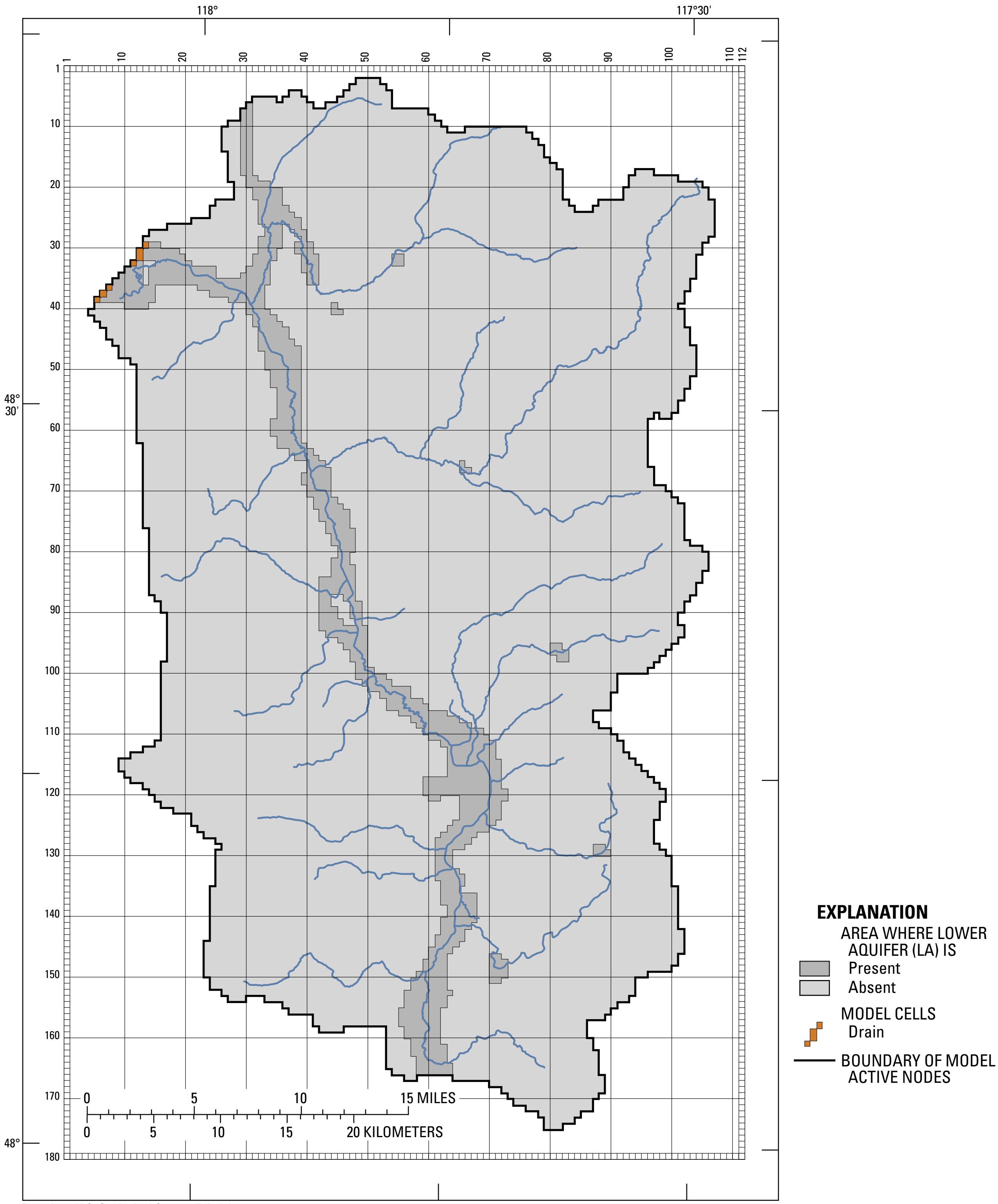
B. Model layer 2 – Till confining unit (TC)

Figure 7.—Continued.



C. Model layer 3 – Colville Valley confining unit (VC)

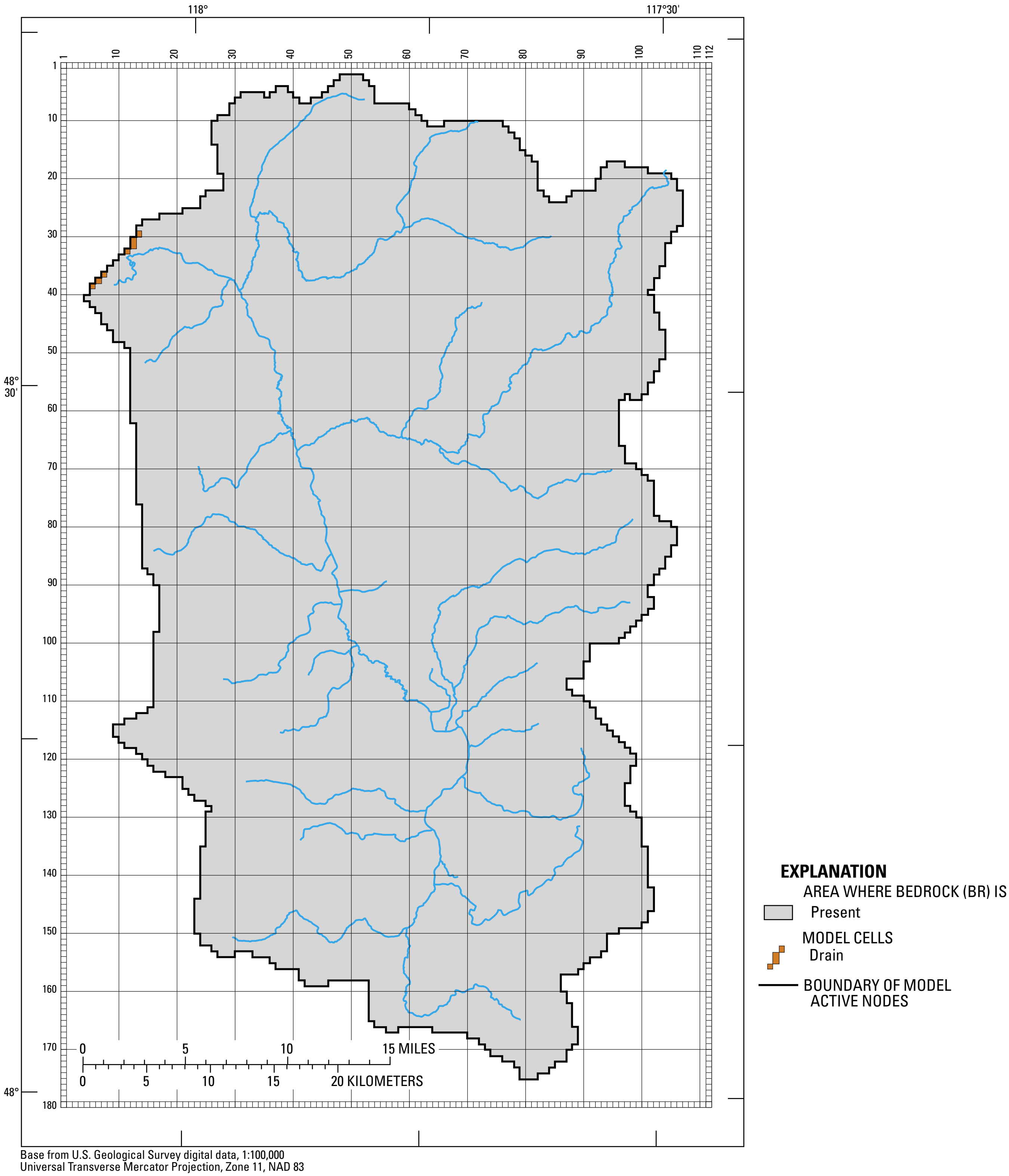
Figure 7.—Continued.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

D. Model layer 5 – Lower aquifer (LA)

Figure 7.—Continued.



E. Model layer 6 – Bedrock (BR)

Figure 7.—Continued.

Bedrock has low permeability except for where it is fractured, but the fractures are at too small a scale to be represented in a regional model, and little is known about the hydraulic properties of the bedrock at depth. Owing to these uncertainties and necessary simplifications, layer 6 was assigned a constant thickness of 200 ft.

The MODFLOW-2000 user interface requires that all layers be present in all active nodes in the model. A method similar to one described in Drost and others (1999) was used to ensure proper model operation. A 0.1-foot thickness was assigned where a unit was not present and the hydraulic properties were altered to represent a large vertical hydraulic conductivity (1,000 ft/d) and a small horizontal hydraulic conductivity (0.00001 ft/d). This results in the simulated flow passing vertically through the "missing" layer as if it were not present, while introducing insignificant inaccuracies in lateral flow.

Hydrogeologic Framework

The 3-dimensional digital hydrogeologic framework developed for the ground-water-flow model is based on the primary data used by Kahle and others (2003): Digital Elevation Model (DEM), geologic maps, cross sections, and lithologic well logs. These data types were manipulated with stratigraphic analysis software and a Geographic Information System (GIS).

The electronic data were assembled into one 3-dimensional, spatially distributed hydrogeologic representation using GIS for incorporation into the ground-water-flow model. Existing data included (1) surficial geology maps, (2) map extents of the four unconsolidated hydrogeologic units, (3) well-log point values for tops and thicknesses of units UA, VC, and LA, (4) well-log point values for the top of bedrock, (5) thickness contours for units UA and VC, and (6) 26 hydrogeologic cross sections.

Elevations of each hydrogeologic unit were determined relative to the surface elevation grid (30-meter DEM). A systematic approach was developed using GIS to determine the presence of a unit and, if present, the thickness of that unit. This method was performed at 100-meter resolution and then scaled up to match the model grid. Thickness contours for units UA and VC were converted to values for each cell and subtracted from land surface, if present at the surface, or the bottom of the overlying unit. TC thickness was estimated to range from 10 to 100 ft; little comprehensive thickness data exist. For the ground-water model, an average thickness of 75 ft was assigned where unit TC was present. Thickness data generally are unavailable for unit LA because few wells penetrate the full thickness of the unit. A constant thickness of 200 ft was assigned where LA was present at the surface. In most locations, LA was present beneath unit VC and was assigned a thickness of 75 ft. Bedrock is present at all locations.

The six-layer, 3-dimensional grid was then compared to the 26 hydrogeologic cross sections and adjusted where appropriate. An effort was made to honor the geologist's interpretation so the model construction was as representative as possible. Large data gaps and the regional scale of the ground-water model created some discrepancies, but the method described above created a reproducible hydrogeologic representation that was used to create the model framework.

Boundary Conditions

Boundary conditions in a ground-water-flow model define the locations and manner in which water enters and exits the active model domain. The general conceptual model for the Colville River Watershed is that water enters the system as precipitation and exits the system as streamflow and ground-water discharge near the mouth of the watershed. Three types of boundaries were used in the Colville River Watershed model: no-flow (outer model boundary), head-dependent flux (rivers, drains, and general head) (figs. 7*A*-*E*), and specified-flux (recharge). The boundaries of the model coincide as much as possible with natural topographic, geologic, and hydrologic boundaries.

Topographic Boundaries

Major topographic divides primarily define the lateral model boundaries. These natural features act as no-flow boundaries as they are considered coincident with ground-water divides. The topographic divides are either exposed bedrock or bedrock covered by a shallow layer of unconsolidated sediments. The entire outer model boundary is simulated as a no-flow boundary, with the exception of the mouth of the system near Kettle Falls. Water exits the system at this location through both surface-water and ground-water flow. A small section of the southern boundary, near the town of Springdale, probably forms a very shallow ground-water divide. This section is the southern extent of the VC and LA units as mapped within the Colville River Watershed. A stress on the system, such as increased ground-water pumping near the boundary, could induce flow across the boundary.

Hydrologic-Process Boundaries

River Conductances and Stages

Ground-water/surface-water exchange is an important process in the ground-water-flow system and the model. The movement of water between the two systems is controlled by the differences in ground-water hydraulic head and river stage (altitude). The Colville River and 20 tributaries were simulated using the MODFLOW River (RIV) package (figs. 7*A*-*C*). Stream stages, which were specified in the model, were determined from USGS 1:24,000 scale topographic maps at stream confluences, streamflow-measurement locations, reaches with steep gradients, and various locations along the streams. Stages were linearly interpolated between input points. Contour intervals on the topographic maps were predominantly 40-foot with a few at 20-foot contour intervals. Stream stages estimated from the maps had an accuracy of plus-or-minus one-half the contour interval. Some inaccuracy was introduced by averaging stream stages and ground-water altitudes within model cells. This uncertainty was not deemed a problem along the gentle relief of the Colville River valley floor but introduced greater uncertainty in the steep headwaters.

The simulated quantity of water moving between the ground-water and surface-water systems is equal to the product of streambed conductance and the head difference between the stream and underlying hydrogeologic units. Streambed conductance was determined empirically during model calibration. Initial values of streambed conductance were based on measured stream width during September 2001, stream length (determined using GIS), and assumed stream depth of 2 ft and streambed thickness of 1 ft for all stream reaches. Initial streambed hydraulic conductivity was assumed to equal the vertical hydraulic conductivity of the hydrogeologic unit in which the stream was in direct connection. Streambed conductances were initially grouped into five parameter values (table 2), as a function of vertical hydraulic conductivity, stream width, and streambed thickness. The values in table 2 reflect all of the terms for streambed counductance except for stream reach length. The model internally mulitplies the value in table 2 (ft/d) by the stream reach length (ft), resulting in the streambed conductance (ft^2/d).

Table 2. Initial parameter values used in the model simulation, Colville River Watershed, Stevens County, Washington.

[Values for streambed conductance are shown in feet per day and must be multiplied by stream reach length (feet). ft/d, foot per day; in/yr, inch per year]

Hydrogeologic unit	Parameter label	Value
Horizontal hydraulic conductivity (ft/d)		
Upper outwash aquifer (UA)	HK_UA	50
Till confining unit (TC)	HK_TC	1
Colville Valley confining unit (VC)	HK_VC	1
Lower aquifer (LA)	HK_LA	50
Bedrock (BR)	HK_BR	.1
Vertical anisotropy		
Upper outwash aquifer (UA)	VANI_UA	10
Till confining unit (TC)	VANI_TC	1,000
Colville Valley confining unit (VC)	VANI_VC	1,000
Lower aquifer (LA)	VANI_LA	10
Bedrock (BR)	VANI_BR	100
Streambed conductance for tributary reaches (ft^2/d)		
Colville River	RIV_CLV	0.034
High—over unit UA	RIV_UA1	50
Low—over unit UA	RIV_UA2	5
Over unit TC	RIV_TC	.002
Over unit VC	RIV_VC	.007
Area of recharge (in/yr)		
Valley floor	RCH_VAL	0.5
Low	RCH_LOW	.5
Medium	RCH_MED	3
High	RCH_HI	6

Drain Conductances and Stages

The MODFLOW Drain (DRN) package was used to simulate subsurface discharge from the Lower aquifer and Bedrock units below Kettle Falls into Franklin D. Roosevelt Lake. The simulated quantity of water exiting the system at a drain cell is equal to the product of a user-specified drain conductance and the difference between the simulated hydraulic head in the drain cell and the specified altitude of the drain (lake stage). The drain conductance is a function of the surrounding hydrogeologic material and the cell geometry.

The Colville River Watershed model simulates ground water exiting the system at only one location, through the Lower aquifer and Bedrock units below Kettle Falls (figs. *7D-E*). All drain altitudes were assigned the stage of Franklin D. Roosevelt Lake in September 2001. The conductances for the drains in the model were computed in the same general way as were the stream conductances, but the assumptions followed those made by Morgan and Jones (1999): the area of the ground-water flow spans the entire width and length of the cell, Hydraulic conductivity was the same as that of the hydrogeologic unit of the cell, and the length of the flowpath was the distance from the cell center to the cell face (750 ft).

Lake Conductances and Stages

The MODFLOW general head boundary (GHB) package was used to simulate subsurface discharge from the lakes to the underlying aquifers (figs. *7A* and *7C*). An external source (lake stage) provides flow into and out of a cell in proportion to the difference between the head in the cell and the specified head of the external source. The specified lake stages were determined from USGS 1:24,000-scale topographic maps with the exception of Loon Lake, where lake stage data were available. The lake-bottom conductance is a function of the surrounding hydrogeologic material and the lake area.

Ground-Water Pumping Rates

Ground-water pumping rates were specified in the model by two different methods representing public-supply and exempt (domestic) wells. Pumping rates for public-supply wells for September 2001 were derived from reported and estimated water-use data. Forty-five public-supply wells withdrawing a total of 6.0 Mgal/d, or 18.4 acre-ft/d) were assigned to the appropriate location and hydrogeologic unit (table 3; fig. 8).

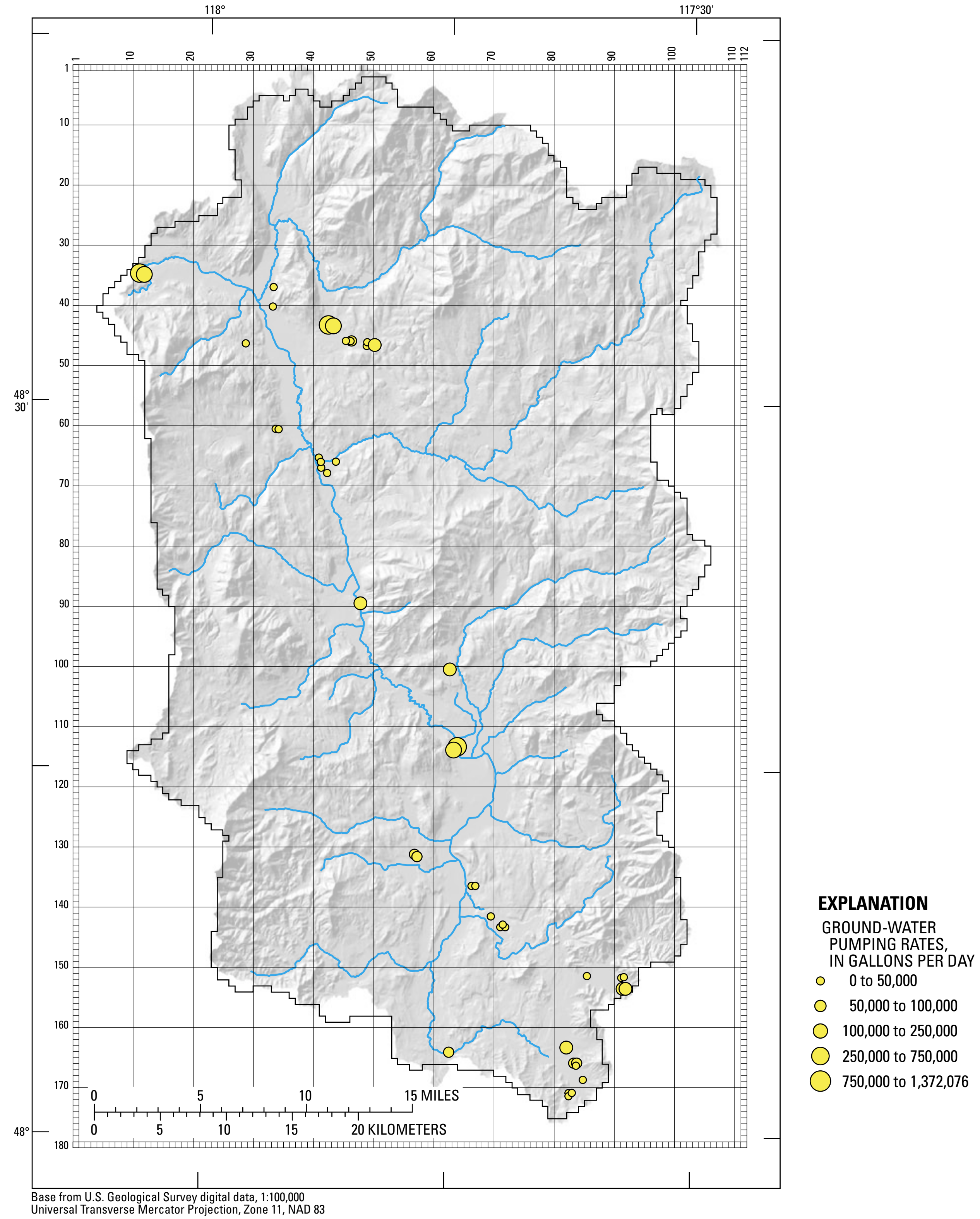


Figure 8. Location of ground-water pumping rates of public-supply wells, Colville River Watershed, Stevens County, Washington, September 2001.

Table 3. Pumping rates from public-supply wells used in model simulation, Colville River Watershed, Stevens County, Washington.

Well or system name	Pumping rate (gallons per day)
Upper outwash aquifer (UA)	
Arden Hills Water System	12,474
Chewelah Golf Course, City of	121,567
Colville, City of	
S01	56,900
S03	0
S02	17,733
S04	522,167
S06	103,267
S07	941,433
Country Villa Mobile Park	594
Crossroads Café	480
Dominion View Water Association	10,692
Elm Tree Water and Sewer Association	8,316
Granite Point Park	594
Kettle Falls (well 4)	457,292
Pine Grove Menonite Church	87
Pinelow Park	4,376
Springdale, City of	85,536
Stevens County	
PUD—Deer Lake, S03	135,269
PUD—Loon Lake SW, S01	23,964
PUD—Loon Lake SW, S02	34,090
PUD—Jump off Joe Lake	38,642
PUD—Jump off Joe Lake	3,973
PUD—Loon Lake shop, S01	221,313
PUD—Valley, S01	20,340
PUD—Valley, S02	0
PUD—Sunset Bay, S03	34,122
PUD—Sunset Bay New, S04	77,114
Colville Valley confining unit (TC)	
Stevens County	
PUD—Waitts Lake, S01	52,237
PUD—Waitts Lake, S02	60,400
Stimson (domestic use)	4,800
Lower aquifer (LA)	
Chewelah, City of	
S03	299,500
S04	763,933
Kettle Falls (wells 2, 3, and 5)	1,371,875
NW Alloys (well field)	175,667
Panorama Mobile Home Park	297
Stevens County PUD (Jump off Joe Lake)	3,973
Bedrock (BR)	
Corbett Creek Water System	23,760
Panorama Mobile Home Park	297
Stevens County	
PUD—Deer Lake, S03	135,269
PUD—Loon Lake SW, S01	23,964
PUD—Sunset Bay New, S04	77,114
Timothy Park Subdivision (3 wells)	2,376
Town of Addy Stevens County	
PUD—S02	22,161
PUD—S03	40,579
Williams Lake Road Subdivision	8,316

Less information is available for exempt wells. The DOE maintains a database of exempt wells located only by township, range, section, and quarter section, resulting in more than one well at most model cells (fig. 9). No information existed as to which hydrogeologic units the wells were open. The DOE database contained 3,600 wells at 569 locations. (All wells in the DOE database are not active and some wells that are not in the database existed before the DOE began keeping records.) Pumping rates were calculated by dividing the total estimated ground-water pumpage from exempt wells (1.7 Mgal/d) (Kahle and others, 2003) by the total number of exempt wells. Simulated annual pumpage was 472 gal/d per exempt well. The pumping rate was then multiplied by the number of wells assigned to each pumping cell. The well was assigned to a model layer on the basis of a simple assumption. If the Upper aquifer existed at the well location, the well was assigned to model layer 1. If no UA existed and LA did exist, the well was assigned to model layer 5. If neither UA nor LA existed at the location, the well was assigned to model layer 6 (Bedrock). Because the well location was approximate, this assumption probably resulted in the assignment of too few wells to model layer 1 and too many wells to model layer 6.

Simulated pumpage from exempt wells accounted for only 6.5 percent of total ground-water use. The approximations involved in estimating the exempt wells were considered sufficient because of the relatively small percentage of the total ground-water budget they represent.

Recharge

The Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983) was used to compute initial ground-water recharge estimates. Kahle and others (2003) provided long-term average annual ground-water recharge estimates for the entire watershed, but the ground-water-flow model requires spatially distributed recharge for the simulation period.

In PRMS, a watershed is conceptualized as an interconnected series of reservoirs whose collective output produces the total hydrologic response. These reservoirs include interception storage in the vegetation canopy, storage in the soil zone, subsurface storage between the surface of a watershed and the water table, and ground-water storage. The system inputs included daily precipitation and daily maximum and minimum air temperature. Streamflow at a watershed outlet is the sum of surface, subsurface, and ground-water flows.

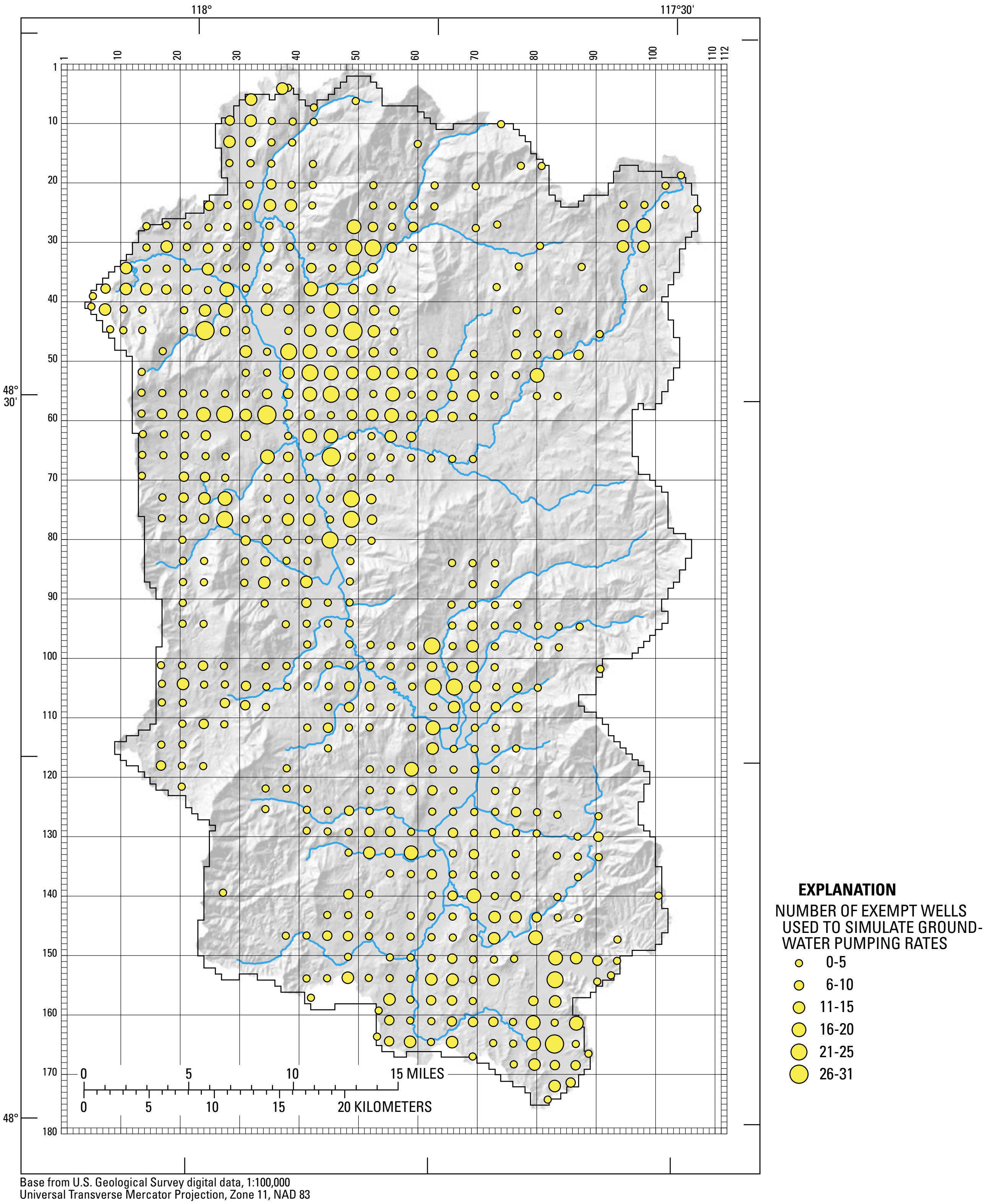


Figure 9. Locations and numbers of exempt wells (private) used to simulate ground-water pumping rates, Colville River Watershed, Stevens County, Washington, September 2001.

Surface runoff is related to a dynamic source area that expands and contracts to precipitation characteristics, and to the capability of the soil mantle to store and transmit water (Troendle, 1985). As conditions become wetter, the proportion of precipitation diverted to surface runoff increases, while the portion that infiltrates to the soil zone and subsurface reservoirs decreases. Daily infiltration is computed as the net precipitation minus surface runoff. Precipitation retained on the land surface is modeled as surface-retention storage. Once the maximum retention storage is satisfied, excess water becomes surface runoff. When free of snow, the retention storage is depleted by evaporation.

Precipitation that falls through the vegetation canopy infiltrates the soil zone. The soil zone is conceptualized as a two-layer system. Moisture in the upper soil (or recharge) zone and in the lower soil zone is depleted through root uptake and seepage to lower zones. Evaporation also depletes the upper soil zone of moisture. The depths of the soil zones are defined on the basis of water-storage characteristics and the average rooting depth of the dominant vegetation.

Potential evapotranspiration (PET) losses were computed as a function of solar radiation and the number of cloudless days (Jensen and Haise, 1963). When soil moisture is available, evapotranspiration equals PET. When soil moisture is limiting, actual evapotranspiration (AET) is computed from PET-to-AET relations for soil types as a function of the ratio of current available water in the soil profile to the maximum available water holding capacity of the soil profile (Zahner, 1967).

Water can move to a ground-water reservoir from both the soil zone and the subsurface reservoir. Soil water in excess of field capacity moves to the ground-water reservoir and is limited by a maximum daily recharge rate. When average moisture exceeds this daily rate, excess soil water moves to the subsurface reservoir. Excess moisture in the subsurface reservoir either percolates to a ground-water reservoir or flows to a discharge point above the water table. Seepage to the ground-water reservoir is computed first from the soil zone and then as a function of a recharge rate coefficient and the volume of water in the subsurface reservoir. The ground-water reservoir is the source of all baseflow and water entering this reservoir is considered recharge.

Most snow, and thus spring runoff from snowmelt, originates at high altitudes. Annual snowpack is depleted by mid-July. The simulation period, September 2001, was the low-flow period of a low precipitation year. Mean annual streamflow for the Colville River at Kettle Falls for 1923-2001 is 309 ft^3/s, and September mean streamflow is 97.5 ft^3/s. The September 2001 monthly mean streamflow was only 50.9 ft^3/s. The simulation period does not represent either a mean annual value or a mean September value.

An evaluation of mean annual precipitation at Chewelah, and September mean flow of the Colville River (fig. 10) shows contribution from precipitation to recharge occurs on an annual basis. During late summer and autumn, ground-water discharge contributes a substantial portion of baseflow. Water year 2001 (October 2000 – September 2001) was an extremely low precipitation year and baseflow for that time period also was extremely low. This relation demonstrates that most precipitation recharged to the ground-water system is discharged to the surface-water system within an annual cycle.

Simulated (model) recharge from precipitation was determined from the initial mean annual recharge estimates from PRMS. Estimated recharge from PRMS reflects the net effect of precipitation, surface runoff, evapotranspiration, and water released from storage and can be considered an “effective” recharge rate (Halford, 1999). The simulated recharge was then lumped into four recharge zones – valley floor, low, medium, and high (table 2; fig. 11). Precipitation generally is lowest at the low altitudes along the main valley floor. Additionally, the valley floor has the low-permeability valley confining unit at the surface. Recharge along the valley floor was initially assigned a value of 0.5 in/yr. Most snowpack resides in the high altitudes on exposed bedrock, a unit with very low infiltration rates. To represent the depleted snowpack and minimal recharge through the bedrock, all recharge simulated where bedrock was exposed at the surface was uniformly reduced to 0.5 in/yr, the rate for the low recharge zone. This procedure “removed” much of the snow from the simulation in order to represent baseflow conditions. The recharge rate for the medium recharge zone was specified at 3 in/yr and the recharge rate for the high recharge zone was specified at 6 in/yr.

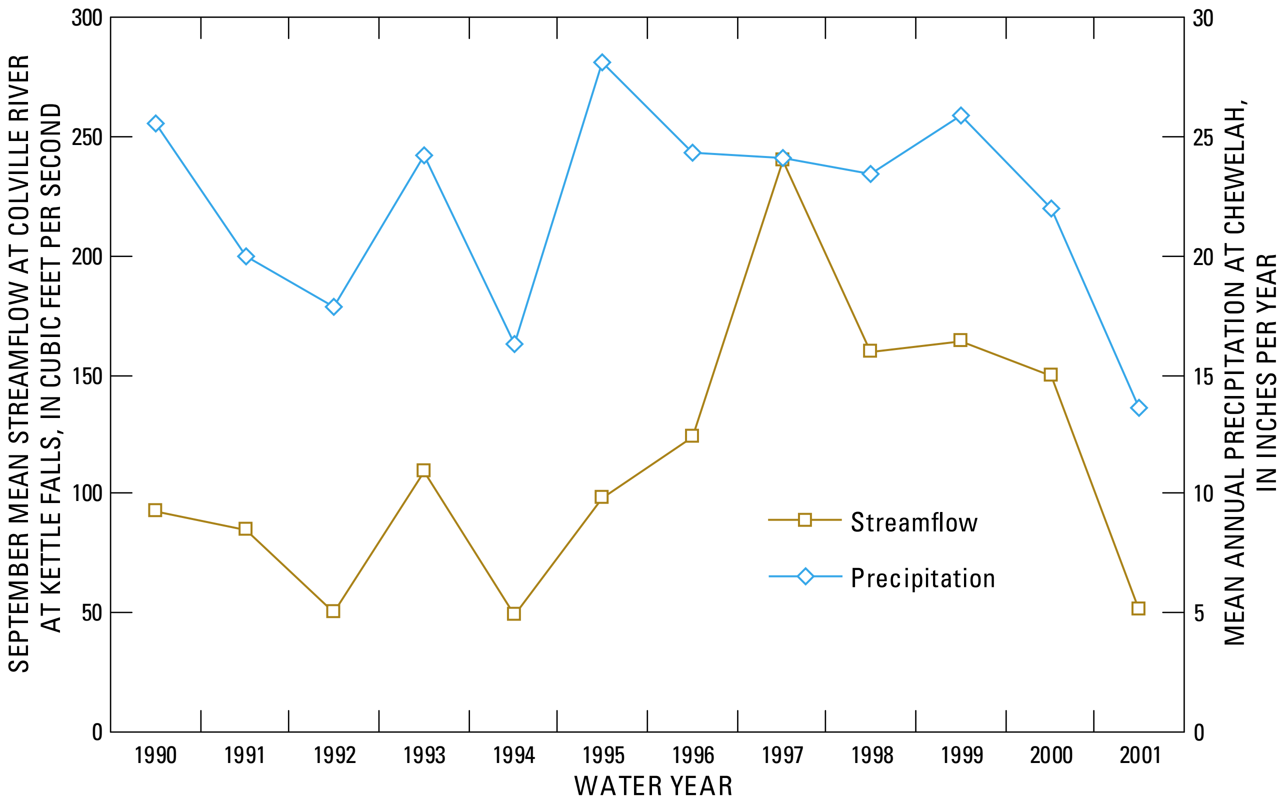


Figure 10. Mean annual precipitation for National Weather Service climate station 451395, Chewelah, Washington, and September mean streamflow for U.S. Geological Survey streamflow-gaging station 12409000, Colville River at Kettle Falls, Colville River Watershed, Stevens County, Washington, water years 1990-2001.

Secondary recharge was simulated by hypothetical injection wells. In most instances, secondary recharge was applied to the row and column in the model grid from which water was withdrawn (pumped) but assigned to the uppermost model layer to reflect the shallow nature of septic systems relative to ground-water pumping. If the location of the public sewage disposal facility was known, that location was assigned as a secondary recharge point. A uniform rate of 50 percent of ground-water pumping was applied for secondary recharge.

Recharge from irrigation was assumed equivalent to deep percolation. Seventy-five model cells representing areas of irrigation were assigned a uniform recharge rate of 4.3 in/yr, which is 12 percent of a 36 in/yr application rate (Drost and others, 1997), totaling 2.5 Mgal/d. The presumed application rate is an average water requirement for alfalfa (Molenaar and others, 1952; James and others, 1982; Cline and Collins, 1992; Ely, 2003). The location of irrigated agricultural areas was determined from the USGS National Land Cover Data map.

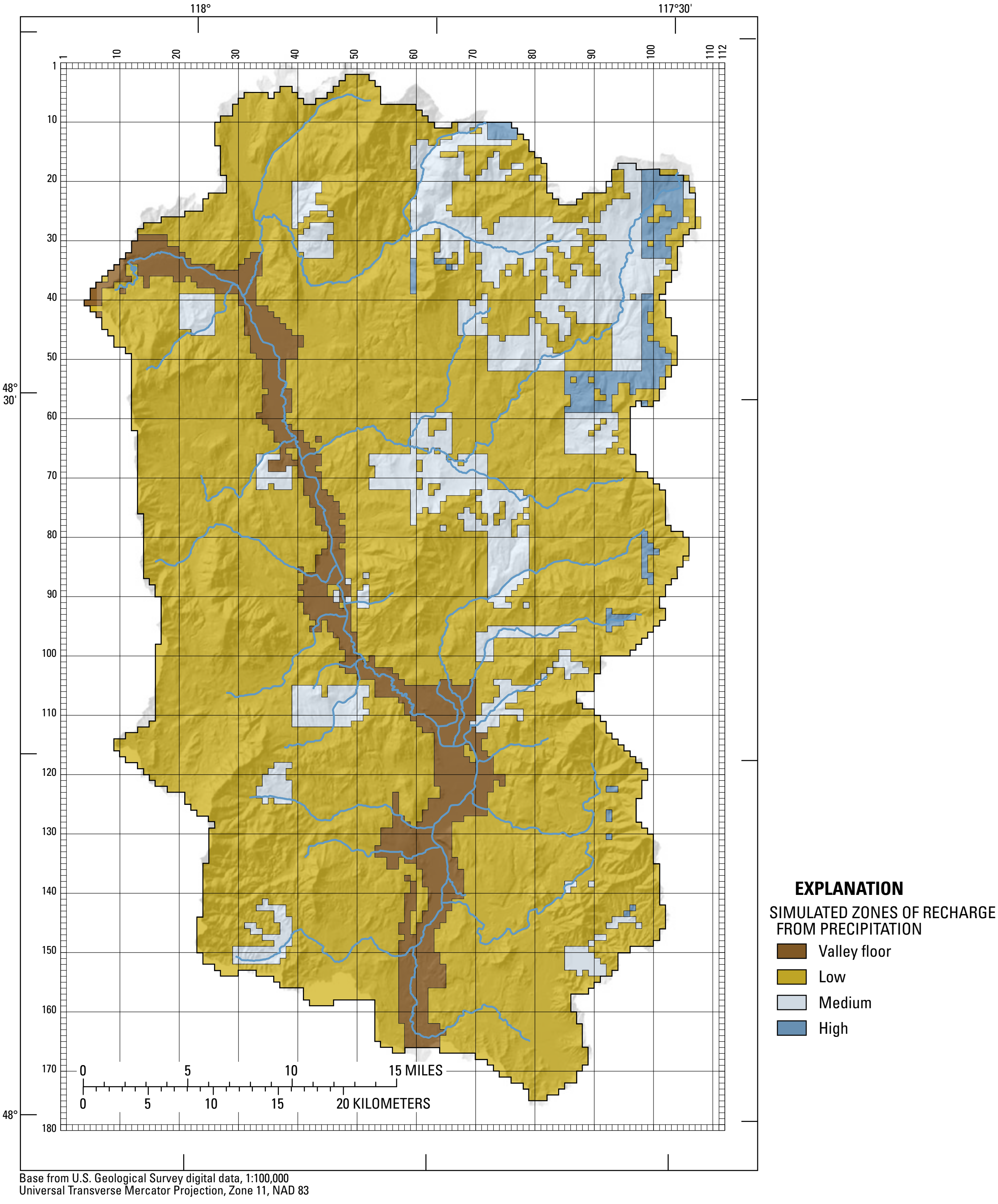


Figure 11. Distribution of initial simulated zones of recharge from precipitation, Colville River Watsrshed, Stevens County, Washington.

Model Flow Parameters

Initial Horizontal Hydraulic Conductivity

Horizontal hydraulic conductivities used for the hydrogeologic units in the model were those determined from specific-capacity data (Kahle and others, 2003). The scarcity and lack of trends in the existing data precluded an initial zonation of hydraulic conductivity. Because there is no evidence that hydraulic conductivity varies with direction, horizontal isotropy was assumed, and each model layer was assigned one horizontal hydraulic conductivity (table 2). An initial value of 50 ft/d was used for hydrogeologic units UA and LA. The confining units were assumed to have horizontal hydraulic conductivities of 1 ft/d. Bedrock hydraulic conductivity was uniformly specified at 0.1 ft/d.

Initial Vertical Hydraulic Conductivity

Vertical hydraulic conductivities were initially derived as ratios of the vertical to the horizontal values (table 2). The ratios for aquifers were assumed to be 1:10, and for confining units, were initially assumed to be 1:1,000. Bedrock ratios were assumed to be 1:100.

Model Calibration

The steady-state Colville River Watershed ground-water-flow model was calibrated to September 2001 conditions. September 2001 does not represent average conditions, as it was an extremely dry period. Therefore, all results and alternatives derived from the model simulations are a conservative representation of the system. The below-average precipitation during water year 2001 would cause a decline in water levels, but whether that decline was fully observed by September 2001, when water levels were measured, is unknown. Differences between water levels measured in late summer 2001 and spring 2002 are small relative to the overall, long-term range in water levels and the large hydraulic gradients present in the tributary basins, and would be within the range of model error. The primary reason for choosing the September 2001 conditions for calibration is the existence of basin-wide synoptic water-level and streamflow measurements for this period. Streamflow measurements provide the best calibration targets and most effectively constrain the calibration process. Long-term water-level data are scarce but nothing in the record suggests that the regional ground-water-flow system in the Colville River Watershed is not in long-term equilibrium with the natural climatic cycle.

The calibration procedure used in this study largely followed that used and described by Gannett and Lite (2004) for their study in the Upper Deschutes River Watershed, Oregon. The theory behind the method of nonlinear regression and automated calibration follow the techniques described by Cooley and Naff (1990). Hill (1998) presents the methods and guidelines for effective model calibration.

Calibration Data

The hydraulic-head data used for calibration consisted primarily of water-level measurements in 161 wells between August and November 2001. An attempt was made to acquire a uniform areal distribution of water-level measurements in wells completed in the unconsolidated deposits of the study area, including the main Colville River valley floor and side valleys. This was not possible in all areas, however, mostly due to lack of development in much of the watershed and to a much lesser extent, lack of access to wells (Kahle and others, 2003). Depth to water (water level) was measured in most wells using a calibrated electric tape or graduated steel tape, both with accuracy to 0.01 ft. Well locations were plotted on USGS 1:24,000-scale topographic maps. Altitude of the land surface at each site was interpolated from the topographic maps, with an accuracy of ±20 ft (one-half the contour interval). A Global Positioning System (GPS) receiver with a horizontal accuracy of one-half a second (about 50 ft) was used to determine latitude and longitude at each well. Water-level measurements in wells completed in bedrock were not used in the calibration. Information from the bedrock wells was used, however, to help understand the connection between the unconsolidated deposits and the bedrock unit.

Synoptic streamflow measurements were made along the Colville River and its tributaries to quantify the ground-water discharge to, or recharge from, the surface-water system at baseflow conditions, and to identify gaining and losing reaches of the stream over the unconsolidated valley deposits. To identify gaining and losing stream reaches, a low-flow seepage run (a set of streamflow measurements representing approximately steady-flow conditions) was conducted in early September 2001 with a few follow-up measurements in early October 2001. The September time frame was chosen because streamflows in the watershed are usually near their annual minimums at this time, and fluctuation owing to precipitation also is minimal, allowing for meaningful comparison of measurements. Calibration of this model benefited greatly from the availability of these streamflow measurements. A total of 78 streamflow measurements plus 3 observations of no flow were made during the study (table 4; Kahle and others 2003). Some of these measurements were made at active or discontinued streamflow-gaging stations, but most were made at sites that had not been previously measured (fig. 12).

Table 4. Miscellaneous discharge measurements made in the Colville River Watershed, Stevens County, Washington, 2001 and 2002.

[ft^3/s, cubic foot per second; ^oC, degrees Celsius; –, no data]

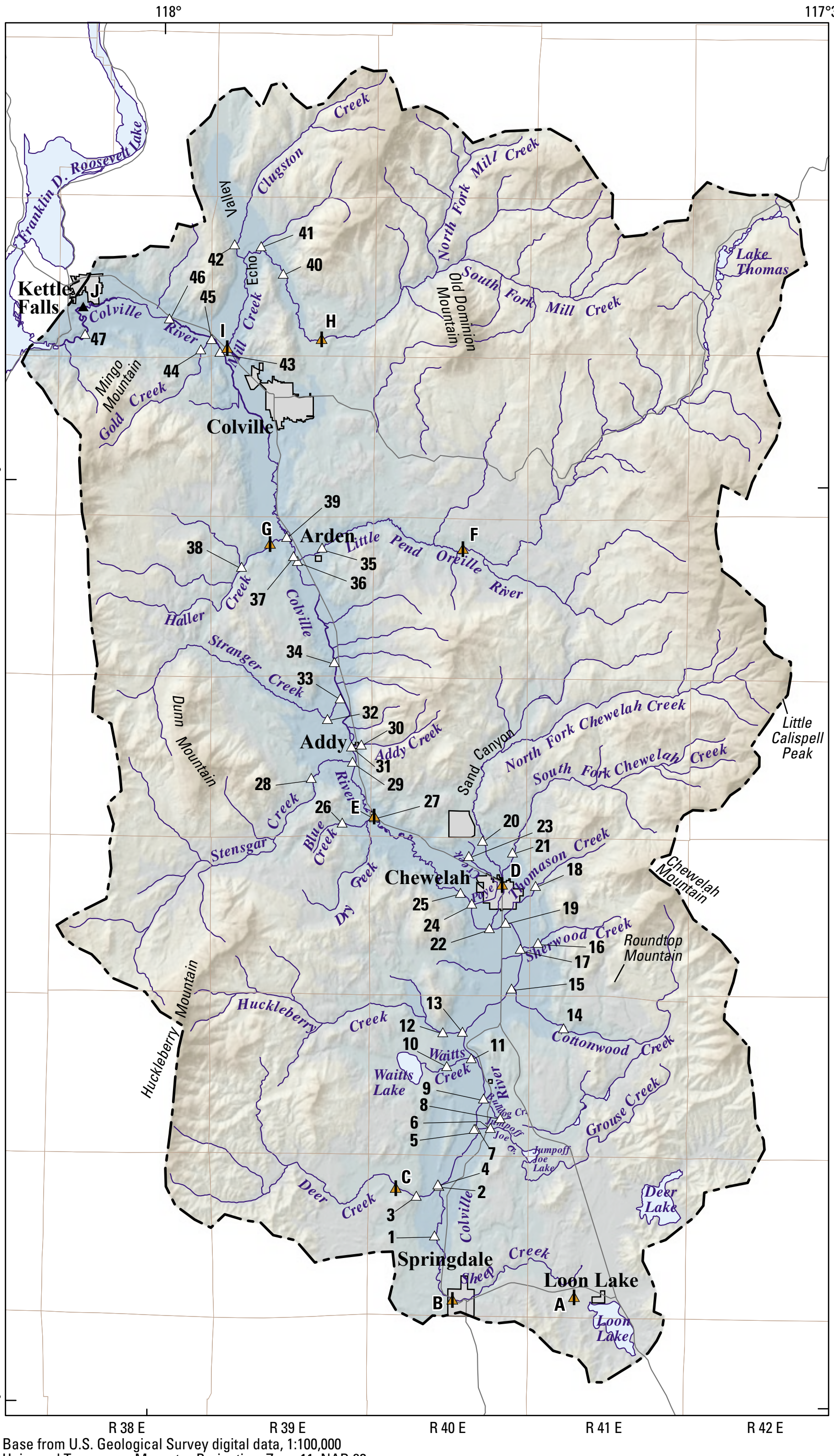
Map No. (see fig. 12)	Site name	Date	Discharge (ft^3/s)	Water temperature (^oC)
B	Sheep Creek at Springdale (station 12407500)	09-04-01	5.55	–
		04-16-02	10.9	6.5
1	Sheep Creek at Forest Center Road, near Springdale	09-04-01	8.02	16.5
		04-16-02	11.9	9
2	Sheep Creek at mouth, near Springdale	09-11-01	6.91	14.5
3	Deer Creek near Springdale	09-05-01	4.66	11
		04-23-02	63.5	5.5
4	Deer Creek at mouth, near Springdale	09-11-01	4.13	13
5	Colville River at Betteridge Road, near Valley	09-05-01	12.9	15
		04-17-02	163	5.5
6	Jumpoff Joe Creek near Valley	09-05-01	2.77	15.5
		04-11-02	7.97	9.5
		04-16-02	9.92	10
7	Jumpoff Joe Creek at mouth, near Valley	09-11-01	2.75	18.5
8	Bulldog Creek near Valley	09-11-01	2.84	10
		04-11-02	4	9
		08-16-02	4.62	11
9	Bulldog Creek at mouth, at Valley	10-02-01	[1] 7.32	–
		08-16-02	[1] 7.97	13.5
10	Waitts Creek near Valley	10-02-01	.11	–
11	Waitts Creek at mouth, near Valley	10-02-01	.18	–
12	Huckleberry Creek near Valley	09-05-01	.52	13.5
		04-18-02	106	5
13	Huckleberry Creek at mouth, near Valley	09-11-01	.07	18
14	Cottonwood Creek near Chewelah	09-05-01	2.38	17.5
		04-12-02	46.4	7.5
15	Cottonwood Creek at mouth, near Chewelah	09-11-01	2.71	18
16	Sherwood Creek near Chewelah	09-05-01	.52	13.5
		04-15-02	12	4.5
17	Sherwood Creek at mouth, near Chewelah	09-13-01	.42	13
18	Thomason Creek near Chewelah	09-07-01	.89	10.5
		04-15-02	1.73	4.5
19	Thomason Creek at mouth, near Chewelah	09-13-01	.76	12.5
20	North Fork Chewelah Creek near Chewelah	09-07-01	3.73	10
		04-18-02	103	5.5
21	South Fork Chewelah Creek near Chewelah	09-07-01	3.65	10
		04-19-02	36.6	3.5
22	Chewelah Creek at mouth, at Chewelah	09-13-01	7.14	–
23	Paye Creek near Chewelah	09-07-01	3.39	11
		04-15-02	4.37	5.5
24	Paye Creek at mouth, at Chewelah	09-13-01	3	–
25	Colville River at Schmidlekofer Road, at Chewelah	09-11-01	31.6	14
		04-17-02	757	9
26	Blue Creek near Blue Creek	09-06-01	.09	10
		04-15-02	2.88	7

Table 4. Miscellaneous discharge measurements made in the Colville River Watershed, Stevens County, Washington, 2001 and 2002.—Continued

[ft^3/s, cubic foot per second; ^oC, degrees Celsius]

Map No. (see fig. 12)	Site name	Date	Discharge (ft^3/s)	Water temperature (^oC)
27	Blue Creek at mouth, at Blue Creek	09-13-01	0.04	–
E	Colville River at Blue Creek (station 12408000)	09-05-01	31.3	17
		04-17-02	707	9
28	Stensgar Creek near Addy	09-06-01	.32	14
		04-15-02	90.2	5.5
29	Stensgar Creek at mouth, at Addy	09-13-01	.04	–
30	Addy Creek at Addy	09-06-01	.1	12
		04-16-02	11.8	4
31	Addy Creek at mouth, at Addy	09-13-01	.01	–
32	Stranger Creek near Addy	09-06-01	.24	14
		04-16-02	62.1	5
33	Stranger Creek at mouth, near Addy	09-13-01	.04	–
34	Colville River at 12 Mile Road, near Addy	09-06-01	30.9	15
		04-15-02	753	8.5
35	Little Pend Oreille River at Arden	09-05-01	13.6	15
		04-24-02	290	4
36	Little Pend Oreille River at mouth, at Arden	09-13-01	9.63	–
37	Colville River at Arden	09-05-01	40.6	16
		04-17-02	1,040	7.5
38	Haller Creek below Cole Creek, near Arden	09-06-01	.96	8
		04-12-02	22.3	5
39	Haller Creek at mouth, near Arden	09-13-01	no flow	–
H	Mill Creek near Colville (station 12408500)	09-04-01	4.73	13
		04-24-02	171	3
40	Mill Creek at Douglas Falls, near Colville	09-04-01	3.77	12
		04-24-02	197	5.5
41	Gillette Creek near mouth, near Colville	08-27-01	no flow	–
42	Clugston Creek near mouth, near Colville	09-07-01	.38	14
		04-19-02	3.95	4
43	Mill Creek at mouth, near Colville	09-13-01	6.41	19
44	Gold Creek near Colville	09-07-01	.003	14
		04-16-02	22.2	5
45	Gold Creek at mouth, near Colville	08-27-01	no flow	–
46	Colville River at Greenwood Loop Road, near Kettle Falls	09-04-01	[2] 46.7	18
		04-15-02	1,630	6.5
J	Colville River at Kettle Falls (station 12409000)	09-04-01	46	–
		04-15-02	[2] 1,560	–
		08-16-02	[3] 61	21
47	Colville River near mouth, near Kettle Falls	08-16-02	59.4	23

[1] Includes 0.67 ft^3/s discharge from Lane Mountain Silica Plant.
[2] Daily mean discharge.
[3] Instantaneous discharge at time discharge was measured at Colville River near mouth, near Kettle Falls on August 16, 2002.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

EXPLANATION

— — — BOUNDARY OF COLVILLE RIVER WATERSHED

USGS STREAMFLOW-GAGING STATION—
Letter designation corresponds to station name

▲ **Continuous-record station**
J Colville River at Kettle Falls (12409000)

Discontinued station
A Sheep Creek at Loon Lake (12407000)
B Sheep Creek at Springdale (12407500)
C Deer Creek near Valley (12407520)
D Chewelah Creek at Chewelah (12407700)
E Colville River at Blue Creek (12408000)
F Little Pend Oreille River near Colville (12408300)
G Haller Creek near Arden (12408420)
H Mill Creek near Colville (12408500)
I Mill Creek at mouth, near Colville (12408700)

△ DISCHARGE-MEASUREMENT SITE —
Number designation corresponds to site name

1 Sheep Creek at Forest Center Road, near Springdale
2 Sheep Creek at mouth, near Springdale
3 Deer Creek near Springdale
4 Deer Creek at mouth, near Springdale
5 Colville River at Betteridge Road, near Valley
6 Jumpoff Joe Creek near Valley
7 Jumpoff Joe Creek at mouth, near Valley
8 Bulldog Creek near Valley
9 Bulldog Creek at mouth, at Valley
10 Waitts Creek near Valley
11 Waitts Creek at mouth, near Valley
12 Huckleberry Creek near Valley
13 Huckleberry Creek at mouth, near Valley
14 Cottonwood Creek near Chewelah
15 Cottonwood Creek at mouth, near Chewelah
16 Sherwood Creek near Chewelah
17 Sherwood Creek at mouth, near Chewelah
18 Thomason Creek near Chewelah
19 Thomason Creek at mouth, near Chewelah
20 North Fork Chewelah Creek near Chewelah
21 South Fork Chewelah Creek near Chewelah
22 Chewelah Creek at mouth, at Chewelah
23 Paye Creek near Chewelah
24 Paye Creek at mouth, at Chewelah
25 Colville River at Schmidlekofer Road, at Chewelah
26 Blue Creek near Blue Creek
27 Blue Creek at mouth, at Blue Creek
28 Stensgar Creek near Addy
29 Stensgar Creek at mouth, at Addy
30 Addy Creek at Addy
31 Addy Creek at mouth, at Addy
32 Stranger Creek near Addy
33 Stranger Creek at mouth, near Addy
34 Colville River at 12 Mile Road, near Addy
35 Little Pend Oreille River at Arden
36 Little Pend Oreille River at mouth, at Arden
37 Colville River at Arden
38 Haller Creek below Cole Creek, near Arden
39 Haller Creek at mouth, near Arden
40 Mill Creek at Douglas Falls, near Colville
41 Gillette Creek near mouth, near Colville
42 Clugston Creek near mouth, near Colville
43 Mill Creek at mouth, near Colville
44 Gold Creek near Colville
45 Gold Creek at mouth, near Colville
46 Colville River at Greenwood Loop Road, near Kettle Falls
47 Colville River near mouth, near Kettle Falls

0 5 10 MILES
0 5 10 15 KILOMETERS

Figure 12. Locations of U.S. Geological Survey continuous-record streamflow-gaging stations, and other sites at which measurements of discharge were made during 2001-02 in the Colville River Watershed, Stevens County, Washington
(From Kahle and others, 2003.)

Steady-State Calibration Procedure

The steady-state calibration procedure was done using MODFLOW-2000's Observation, Sensitivity, Parameter Estimation (OSP) process (Hill and others, 2000). The OSP process uses a nonlinear least-squares regression to find the set of parameter values that will minimize the weighted sum-of-squared-errors objective function (Hill, 1998):

$$S(\underline{b}) = \sum_{i=1}^{ND} w_i \left[y_i - y_i'(\underline{b}) \right]^2 , \quad (1)$$

where

$\underline{b}$ is a vector containing values for each of the parameters being estimated,

ND is the number of observations,

y_i is the ith observation being matched by regression,

y_i' is the simulated value corresponding to the ith observation, and

w_i is the weight assigned to the ith observation.

The differences between the measured and simulated values are residuals. Residuals are weighted to allow a meaningful comparison of measurements with different units (weighted residuals are dimensionless) and to reduce the influence of measurements with large errors or uncertainty. The observation weight is defined as the inverse of the variance of the measurement error.

The observation weights were assigned using the methods suggested by Hill (1998). Hydraulic-head measurement errors were limited by the accuracy of the topographic map used to determine land-surface altitude. As previously noted, the depth to water measured by a calibrated electric tape or graduated steel tape was accurate to 0.01 ft. That measurement, however, was then subtracted from a land-surface altitude with an accuracy of ±20 ft. A standard deviation of measurement error was estimated for each measurement by assuming that the 95-percent confidence interval for the actual head was equal to the hydraulic-head measurement ± 0.5 the contour interval of the topographic map used to determine the well altitude.

Discharge measurements used to calibrate the Colville River Watershed model also were weighted by estimating the standard deviation of the measurement error. The USGS rates the accuracy of its streamflow records based on the quality of the measurements. Accuracy levels of "good" indicate that 95 percent of the measurements are within 10 percent of the actual values and "fair" indicates that 95 percent of the measurements are within 15 percent of actual values. On the basis of field notes supplied by the hydrologic technicians that completed the measurements, all measurements were "good." Where a single discharge measurement was used as a flow observation in the model, the confidence interval was ±10 percent. Where the observation was the gain or loss between two discharge measurements, the combined error of both measurements defined the confidence interval.

Model Parameters

Hill (1998) discusses the importance of parsimony in model construction. Building a complex model with more parameters than the data support may reduce the residuals but does not ensure a more accurate, reliable model. Following the principle of parsimony, only selected hydraulic parameters and stresses were estimated during calibration. The drain conductances near Kettle Falls, lake conductances, and ground-water pumping rates were not adjusted during calibration. No data exist to estimate ground-water flow out of the system or recharge from lakebed seepage. Ground-water pumping rates were supplied by the Planning Team and were considered reliable. The parameters adjusted during calibration included horizontal hydraulic conductivities, recharge zones, and river conductances. Throughout the calibration process, no adjustments were made that conflicted with the general understanding of the geology and hydrology.

Parameter Sensitivity

The ability to estimate a parameter value using nonlinear regression is a function of the sensitivity of simulated values to changes in the parameter value. Parameter sensitivity reflects the amount of information about a parameter provided by the observation data. Generally speaking, if a parameter has a high sensitivity, observation data exist to effectively estimate the value. If the parameter has low sensitivity, changing the parameter value will have little effect on the sum of squared errors.

The diagnostic statistics generated by MODFLOW-2000 were the dimensionless scaled sensitivities and the composite scaled sensitivities (Hill, 1998). Dimensionless scaled sensitivities indicate the sensitivity of the simulated equivalent of each observation (here, hydraulic heads and streamflow) to the parameter. The dimensionless scaled sensitivity, ss_{ij}, is calculated as (Hill, 1998):

$$ss_{ij} = \left(\frac{\partial y'_i}{\partial b_j} \right) b_j \omega_{ii}^{1/2} , \qquad (2)$$

where

- i identifies one of the observations,
- j identifies one of the parameters,
- y'_i is the simulated value associated with the ith observation,
- b_j is the jth estimated parameter,
- $\frac{\partial y'_i}{\partial b_j}$ is the sensitivity of the simulated value associated with the ith observation with respect to the jth parameter, and is evaluated at the final parameter values; and
- ω_{ii} is the weight for the ith observation.

Composite scaled sensitivities (CSS) summarize all the sensitivities for one parameter. CSS are calculated for each parameter using the scaled sensitivities for all observations (here, hydraulic heads and streamflow). Because they are dimensionless, CSS can be used to compare the amount of information provided by different types of parameters. Model simulation results will be more sensitive to parameters with large CSS. The CSS for the jth parameter, css_j, is calculated as (Hill, 1998):

$$css_j = \left[\frac{\sum_{i=1}^{ND} \left(ss_{ij} \right)^2 \Big|_{\underline{b}}}{ND} \right]^{\frac{1}{2}} \qquad (3)$$

where

- ND is the number of observations being used in the regression,
- $\underline{b}$ is a vector which contains the parameter values at which the sensitivities are evaluated;

The CSS of all parameters at their initial values divided by the maximum CSS (normalized) are shown in figure 13. Large initial CSS for the hydraulic conductivity of unit UA indicated sufficient information existed to support some zonation of the parameter. Initial hydraulic head and streamflow residuals supported the addition of another zone of hydraulic conductivity. A zone of lower hydraulic conductivity was added to unit UA in the upper reaches of Clugston, Chewelah, and Thomason Creeks.

Final Parameter Values

The final parameter values are shown in table 5 and the normalized CSS for all parameters are shown in figure 14. Simulated zones of hydraulic conductivity for model layer 1, Upper outwash aquifer, is shown in figure 15. Hydraulic conductivity for most of unit UA, which represents mostly glacial outwash sand and gravel, was estimated to be 50 ft/d. Simulated hydraulic conductivity for unit TC, which represents compacted and poorly sorted clay, silt, sand, gravel, and cobbles, was estimated to be 0.25 ft/d. Simulated hydraulic conductivity for unit VC, which represents a thick, low-permeability unit consisting mostly of extensive glaciolacustrine silt and clay, was estimated to be 0.25 ft/d. Simulated hydraulic conductivity for unit LA, which represents mostly sand and some gravel, was estimated to be 250 ft/d. This final parameter value for unit LA is higher than the mean value reported in Kahle and others (2003) but falls within the reported range. A difference in depositional mechanisms for units UA and LA could explain the large difference in simulated horizontal hydraulic conductivity. Unit LA perhaps represents a period of major streamflow through the valley and out to the south (prior to the emplacement of the end moraine). Unit UA may have originated from more localized outwash flows. Hydraulic conductivity for bedrock was specified at 0.1 ft/d.

Vertical anisotropy, the ratio of vertical to horizontal hydraulic conductivity, was assigned a value of 1:10 for units UA and LA and 1:1,000 for unit TC. The regression was insensitive to these parameters so no estimation was performed. The vertical anisotropy for unit VC was assigned a value of 1:100. The vertical anisotropy for the bedrock unit was assigned a value of 1:100.

Final recharge rates generally were adjusted downward to match both hydraulic heads and streamflow. Recharge along the Colville River valley floor was estimated to be 0.25 in/yr. Large initial CSS for the “Low” recharge zone supported its subdivision into three recharge zones based on precipitation, elevation, and soil type. Recharge on bedrock (RCH_LOW1) remained 0.5 in/yr. Zone of low recharge 2 (RCH_LOW2) also was 0.5 in/yr. Zone of low recharge 3 (RCH_LOW3) was estimated to be 1 in/yr. The zone of medium recharge (RCH_MED) was adjusted to 2 in/yr. The zone of high recharge (RCH_HI) remained 6 in/yr. Final recharge zones and rates are shown in figure 16 and table 5.

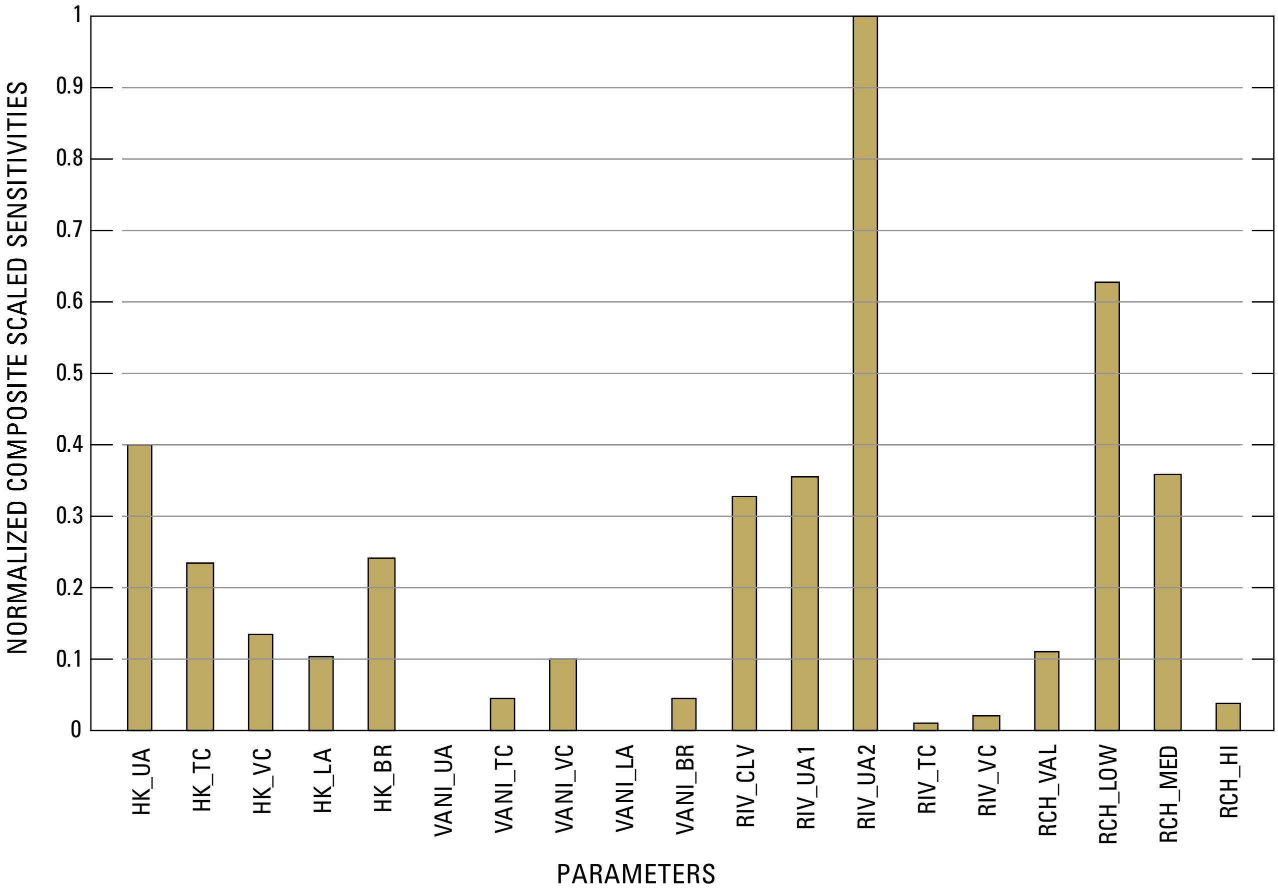


Figure 13. Initial normalized composite scaled sensitivities of model parameters.

Streambed conductances were based on measured stream depth, stream width, and streambed thickness, which was estimated to be 1 ft. Streambed hydraulic conductivity was initially assigned the value of the vertical hydraulic conductivity of the surrounding hydrogeologic unit. During the calibration phase, however, the streams were grouped by the predominant hydrogeologic unit in which they flowed and were adjusted to achieve a good fit between simulated and measured gains and losses. Streambed conductance values of tributary reaches that flowed over unit TC and VC were assigned a value of 0.002 and 0.007 ft/d, respectively, and multiplied by the stream reach length. The greatest streambed conductance was assigned to Sheep Creek (100 ft/d × stream reach length) to reflect the coarse material present along the stream. Streambed conductance values for the Colville River and tributaries that flowed over unit UA were estimated during calibration.

No information exists to constrain drain and lake conductances, and no data exist for ground-water flow out of the model domain. Therefore, the conductances were based on the geometry of the boundary condition and the hydraulic conductivity of the surrounding hydrogeologic unit. No adjustments were made to these parameters.

Steady-State Calibration Model Fit

The measure of model fit can be represented with many statistical and graphical methods, as described by Hill (1998). One measure of model fit is based on the difference between simulated and measured heads and flows, or residuals. The overall magnitude of the residuals is considered, but the distribution of those residuals, both statistically and spatially, can be equally important. The magnitude of residuals can initially point to gross errors in the model, the data (measured quantity), or how the measured quantity is simulated (Hill, 1998). As the model is refined and gross errors are corrected, more complex statistics are examined. Several statistical and graphical analyses of residuals are presented in this section. A complete discussion of the statistical measures discussed in this section is found in Hill (1998).

Table 5. Estimated values and the 95-percent linear confidence intervals for the estimated parameters of the final calibrated model, Colville River Watershed, Stevens County, Washington.

[The confidence intervals are not symmetric about the estimated value for the log-transformed parameters. Values for streambed conductance are shown in feet per day and must be multiplied by stream reach length (feet). ft/d, foot per day; in/yr, inch per year]

Hydrogeologic unit	Parameter label	Estimated value	95-percent linear confidence upper/ lower intervals on the estimate
Horizontal hydraulic conductivity (ft/d)			
Upper outwash aquifer (high)	HK_UA1	50	80.9 / 30.9
Upper outwash aquifer (low)	HK_UA2	10	35 / 2.9
Till confining unit	HK_TC	.25	2.03 / 0.03
Colville Valley confining unit	HK_VC	.25	94.5 / 0.0007
Lower aquifer	HK_LA	250	431 / 145
Bedrock	HK_BR	.1	0.26 / 0.04
Streambed conductance for tributary reaches (ft/d)			
Colville River	RIV_CLV	0.1	0.16 / 0.06
High—over unit UA	RIV_UA1	2	6.0 / 0.7
Low—over unit UA	RIV_UA2	1	1.7 / 0.6
Area of recharge (in/yr)			
Valley floor	RCH_VAL	0.25	5.9 / 0.01
Bedrock	RCH_LOW1	.5	1.3 / 0.2
Low–1	RCH_LOW2	.5	1.0 / 0.2
Low–2	RCH_LOW3	1	1.8 / 0.5
Medium	RCH_MED	2	3.4 / 1.2
High	RCH_HI	6	50.8 / 0.7

Statistical Measures of Model Fit and Parameter Uncertainty

A commonly used indicator of the overall magnitude of the weighted residual is the calculated error variance. The calculated error variance is the weighted sum of squared errors from equation 1 divided by the number of observations, minus the number of parameters. The square root of the calculated error variance is called the standard error of regression. Smaller values of both terms indicate a closer fit to the measured values. The expected value for both terms is 1.0 if the model fit is completely consistent with the data accuracy, but the calculated error variance is almost always greater than 1.0. The calculated error variance and standard error of regression for the calibrated model in this study are 150.6 and 12.3, respectively.

The calculated error variance and standard error of regression are dimensionless and therefore not intuitively informative about goodness of fit. The fitted standard deviation is the product of the standard error of regression and the statistic used to determine weights. The weights for hydraulic heads in the model are based on the error introduced by determining well altitudes from the topographic maps. For the hydraulic heads alone, the standard error of regression is 8.8. In this study, all hydraulic heads were assigned the standard deviation of measurement error of 10.2 ft. Multiplying this value by the standard error of regression results in a fitted standard deviation for heads of 89.8 ft. The fitted standard deviation represents the overall fit of the hydraulic heads.

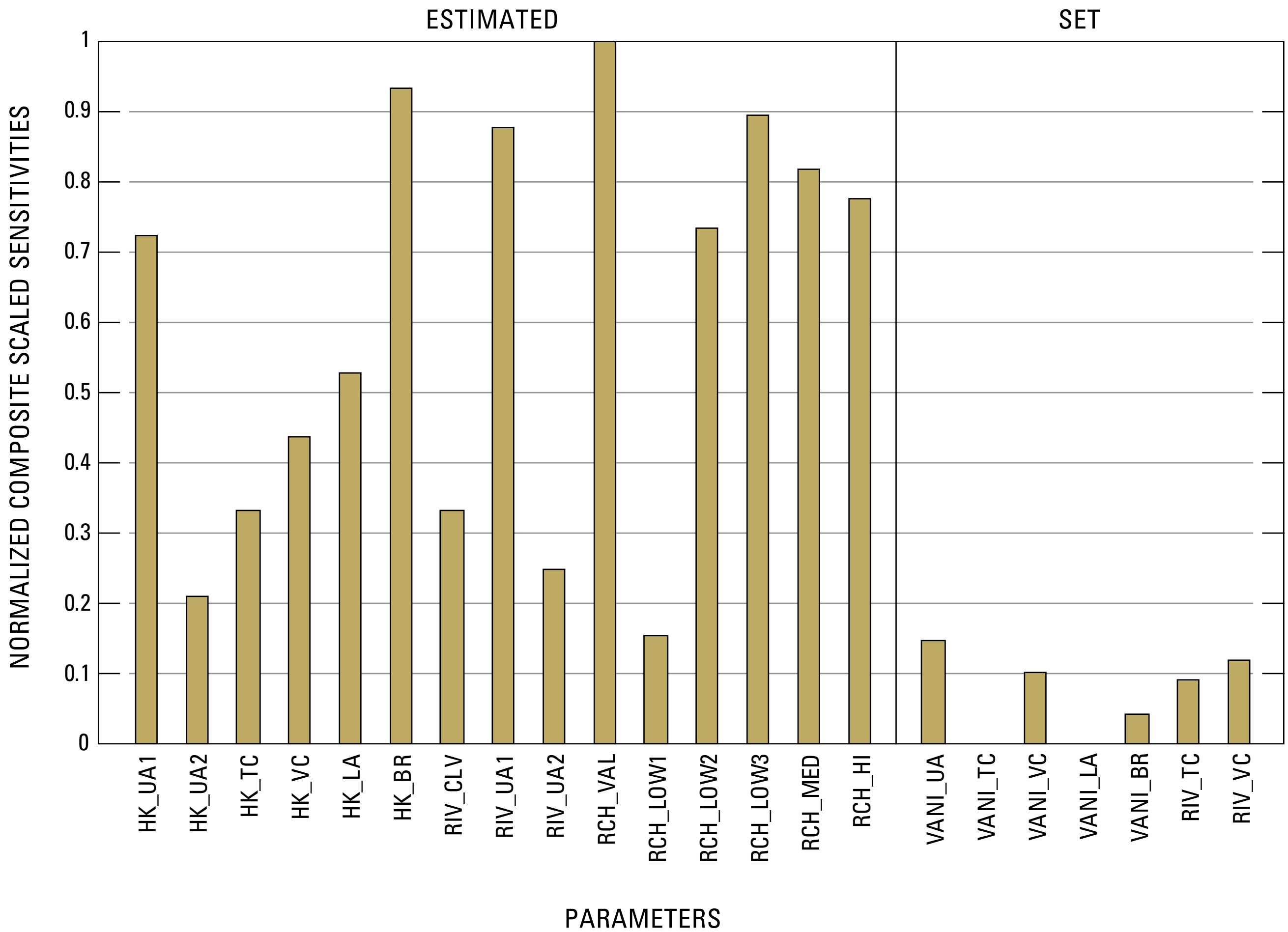


Figure 14. Final normalized composite scaled sensitivities of model parameters.

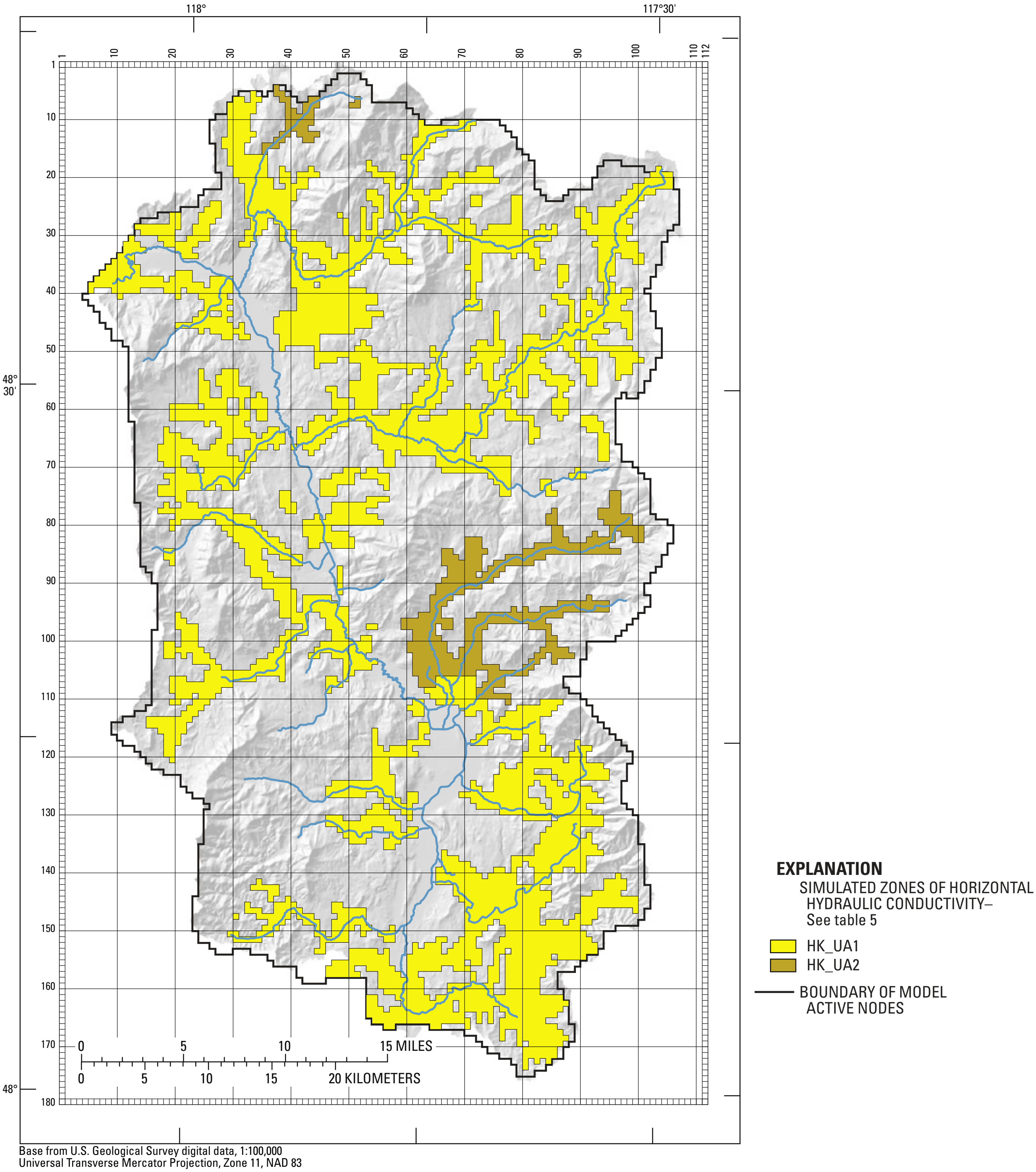


Figure 15. Simulated zones of horizontal hydraulic conductivity for model layer 1, Upper outwash aquifer, Colville River Watershed, Stevens County, Washington.

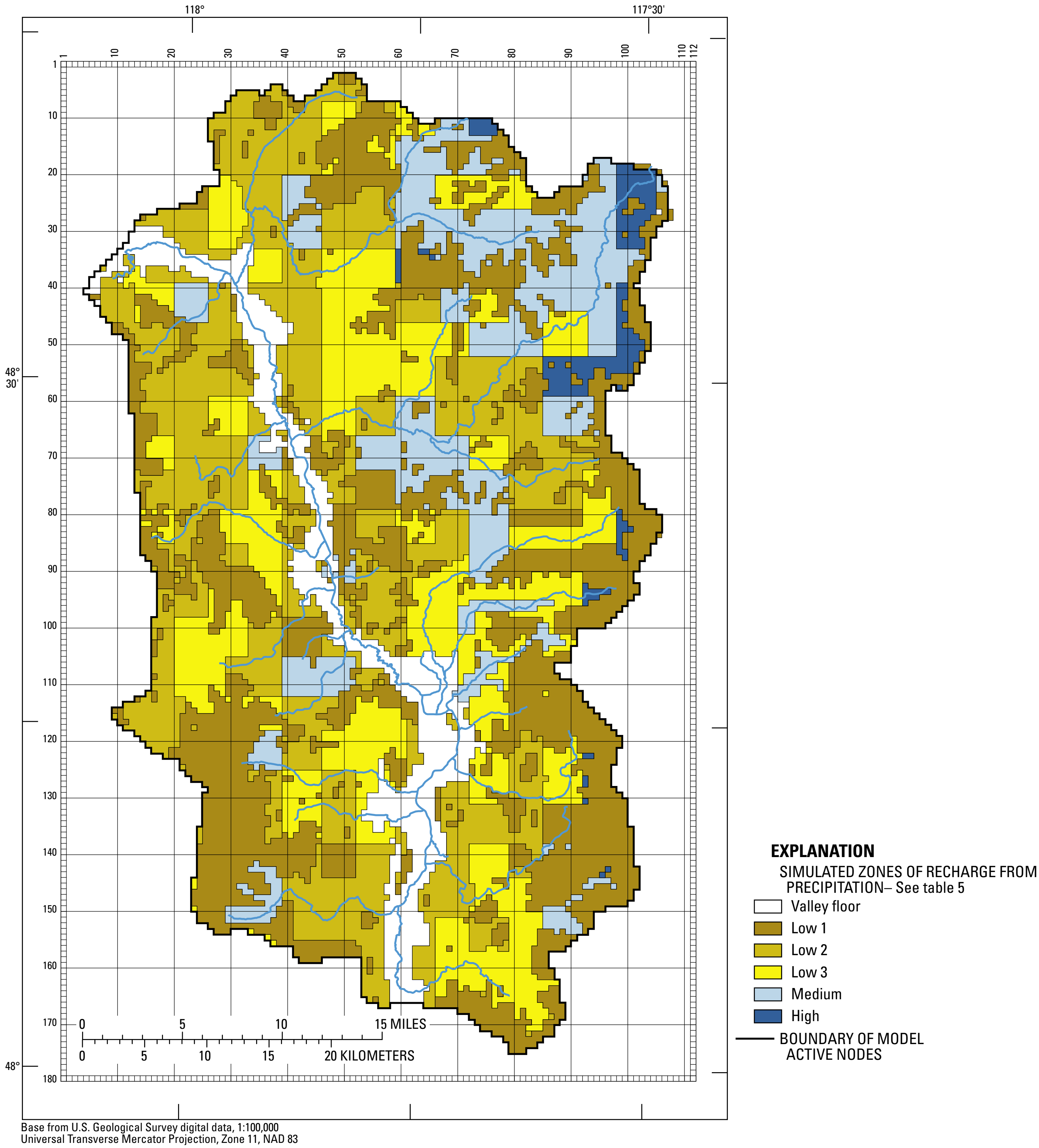


Figure 16. Distribution of final simulated zones of recharge from precipitation, Colville River Watershed, Stevens County, Washington.

Weighted residuals should be independent, random, and normally distributed. A graphical analysis of the weighted residuals should display an evenly scattered distribution about 0.0. No trends should be apparent, such as consistently larger residuals in a specific hydrogeologic unit or area of the model. Weighted residuals plotted in figure 17 generally meet these conditions for hydraulic heads. The average weighted residual ideally equals zero, and the calibrated model produces an absolute value of the average hydraulic head weighted residual of 0.1. A large bias exists, however, for the streamflow weighted residuals. Of the 44 streamflow measurements, 31 were less than 1.0 ft^3/s. The model generally did not reproduce the losing reaches. Most discharge measurements were made along the valley floor, where simulated hydraulic heads generally exceeded measured hydraulic heads. The movement of water between the ground-water and surface-water systems is controlled by the differences in hydraulic head and river altitude. The hydraulic head bias along the valley floor would, therefore, result in a similar bias in simulated discharge. The absolute value of the average weighted residual for all observations was 0.3.

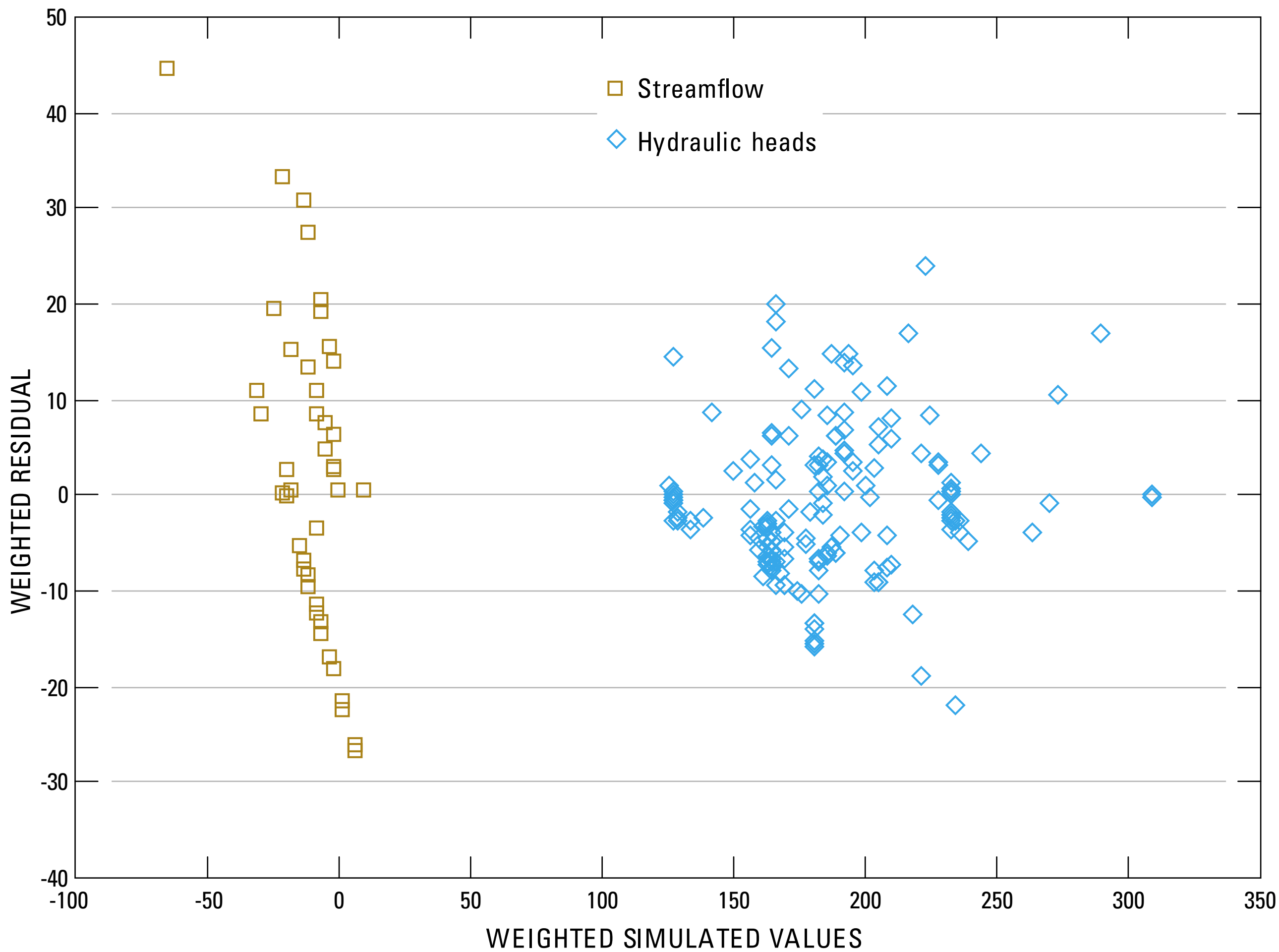


Figure 17. Weighted residuals as a function of weighted simulated residuals in the ground-water-flow model of the Colville River Watershed, Stevens County, Washington.

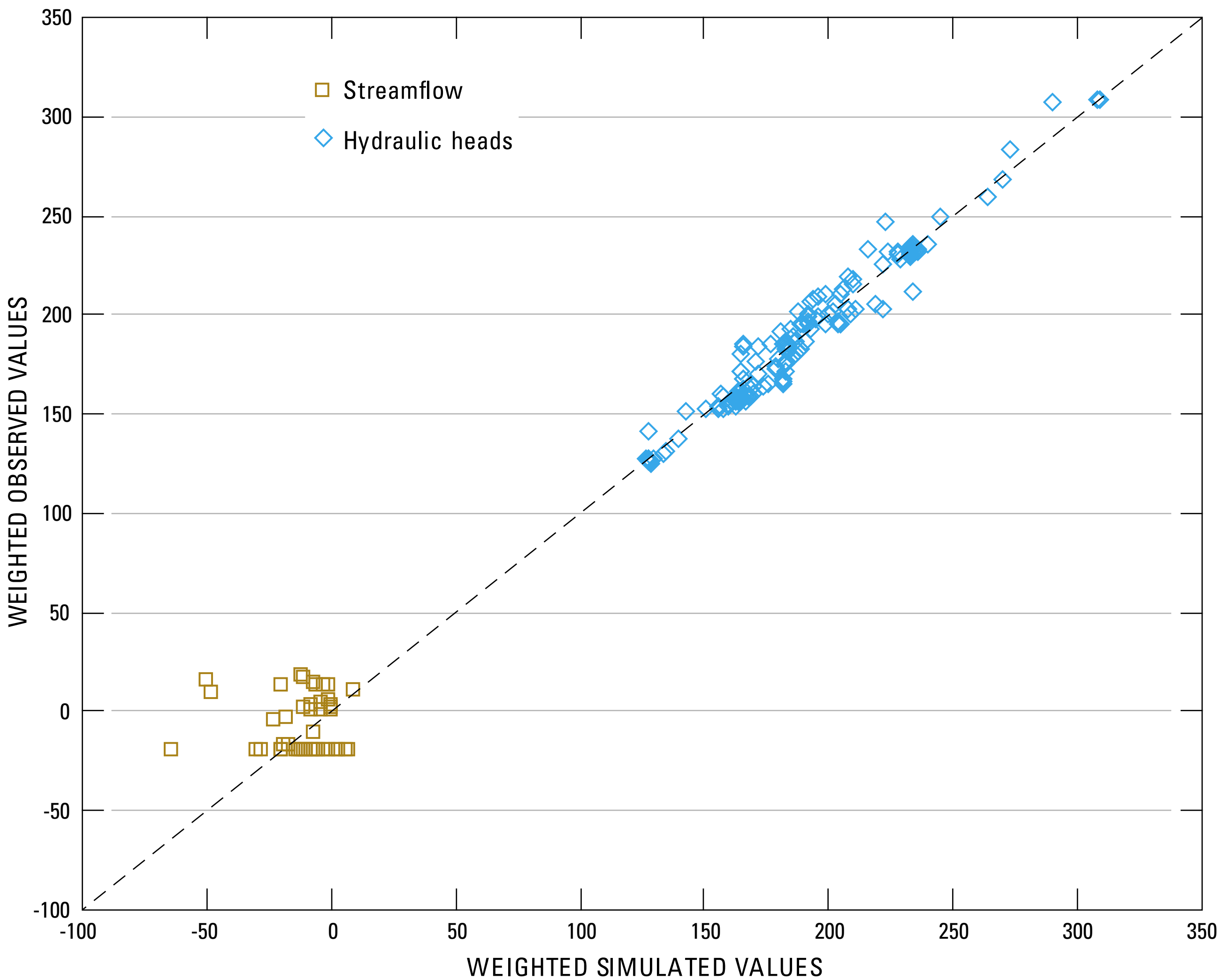


Figure 18. Weighted observations as a function of weighted simulated values in the ground-water-flow model of the Colville River Watershed, Stevens County, Washington.

A useful graphical analysis is a simple plot of weighted observations as a function of weighted simulated values. The residuals should plot close to a line with a slope equal to 1.0 and an intercept of zero. The weighted observations versus weighted simulated values shown in figure 18 generally fall along a straight line with a slope of 1.0 but an intercept of 4.4. The significant deviation from the zero intercept is caused by the streamflow residuals.

Another statistic for testing the normality of the residual distribution is the correlation coefficient between the weighted residuals from smallest to largest and the order statistics from a normal probability distribution function, denoted as R^2_N (Hill, 1998). The ideal value of R^2_N is 1.0, and values significantly less than that indicate the weighted residuals are not likely independent and normally distributed. The critical value for 200 measurements as listed in Appendix D of Hill (1998) is 0.987. The calibrated model has 205 observations and an R^2_N of 0.879, indicating the weighted residuals cannot be considered independent and normally distributed. The critical value for the 161 hydraulic-head measurements is 0.983 and the R^2_N for hydraulic heads is 0.968, indicating a more independent and closer to normal distribution without the discharge measurements.

Information regarding parameter uncertainty is provided by the 95-percent linear confidence intervals shown in figure 19 and table 5. Confidence intervals represent the uncertainty in the simulated values that is a propagation of the uncertainty in the estimated parameter values (Poeter and Hill, 1998). A relatively small range indicates there was sufficient information to accurately estimate the parameter value. The logarithmic scale of figure 19 makes it difficult to see the actual size of the confidence interval. To correct this difficulty, figure 20 shows the upper and lower confidence intervals computed as a percentage of the final value. Linear confidence intervals were assumed to adequately approximate the actual nonlinear confidence intervals (Cooley, 1997; Hill, 1998).

The upper and lower 95-percent confidence intervals should be reasonable values. The confidence intervals for hydraulic conductivity (except unit VC) and river conductance parameters spanned a reasonable range, indicating sufficient information exists to estimate the parameter value.

If two parameters are highly correlated, they cannot be uniquely estimated. Parameter correlations range from -1.0 to +1.0, and for any set of parameters, an absolute value greater than 0.95 indicate a potential problem. All correlation coefficients were within acceptable range except the hydraulic conductivity and vertical anisotropy for unit VC.

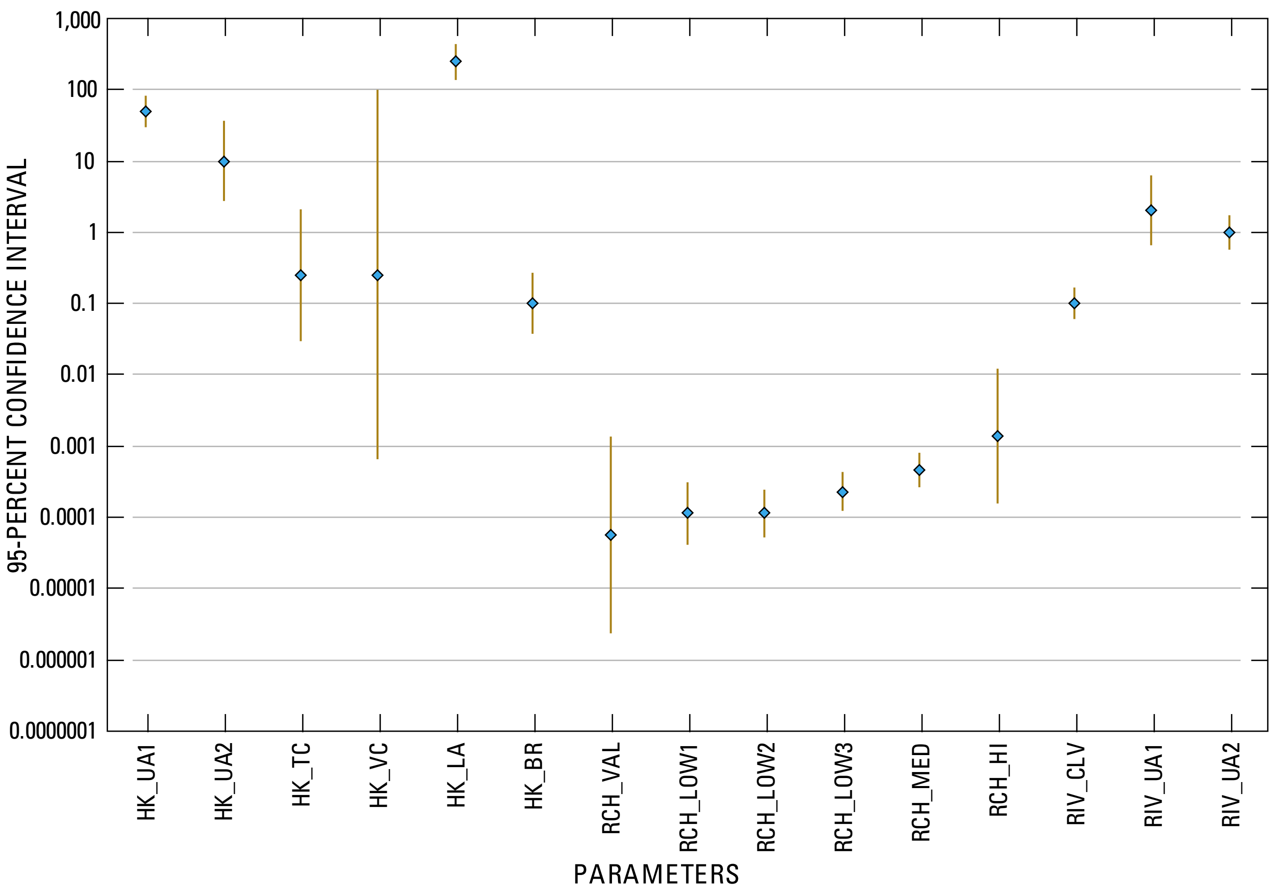


Figure 19. Final parameter values and 95-percent confidence intervals for the parameter values for the ground-water-flow model of the Colville River Watershed, Stevens County, Washington.

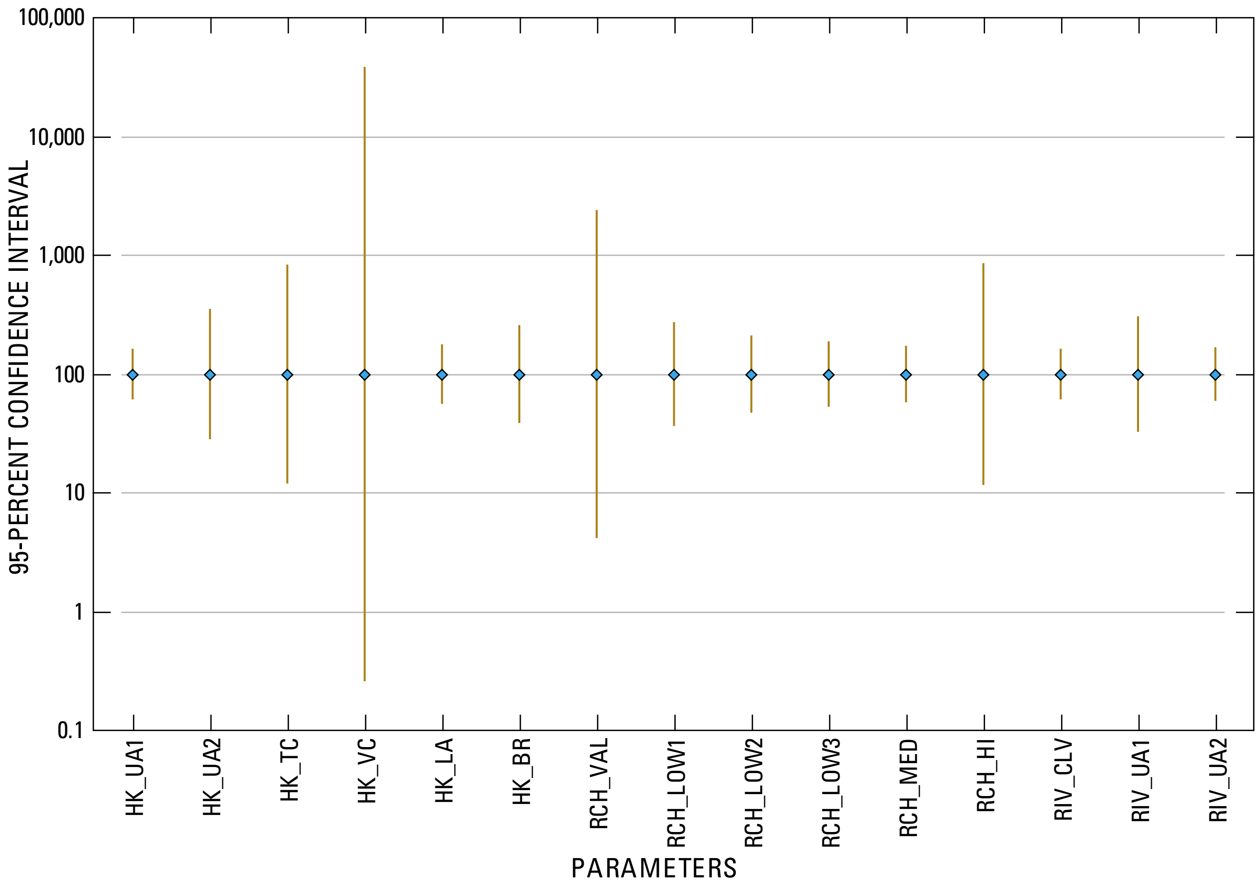


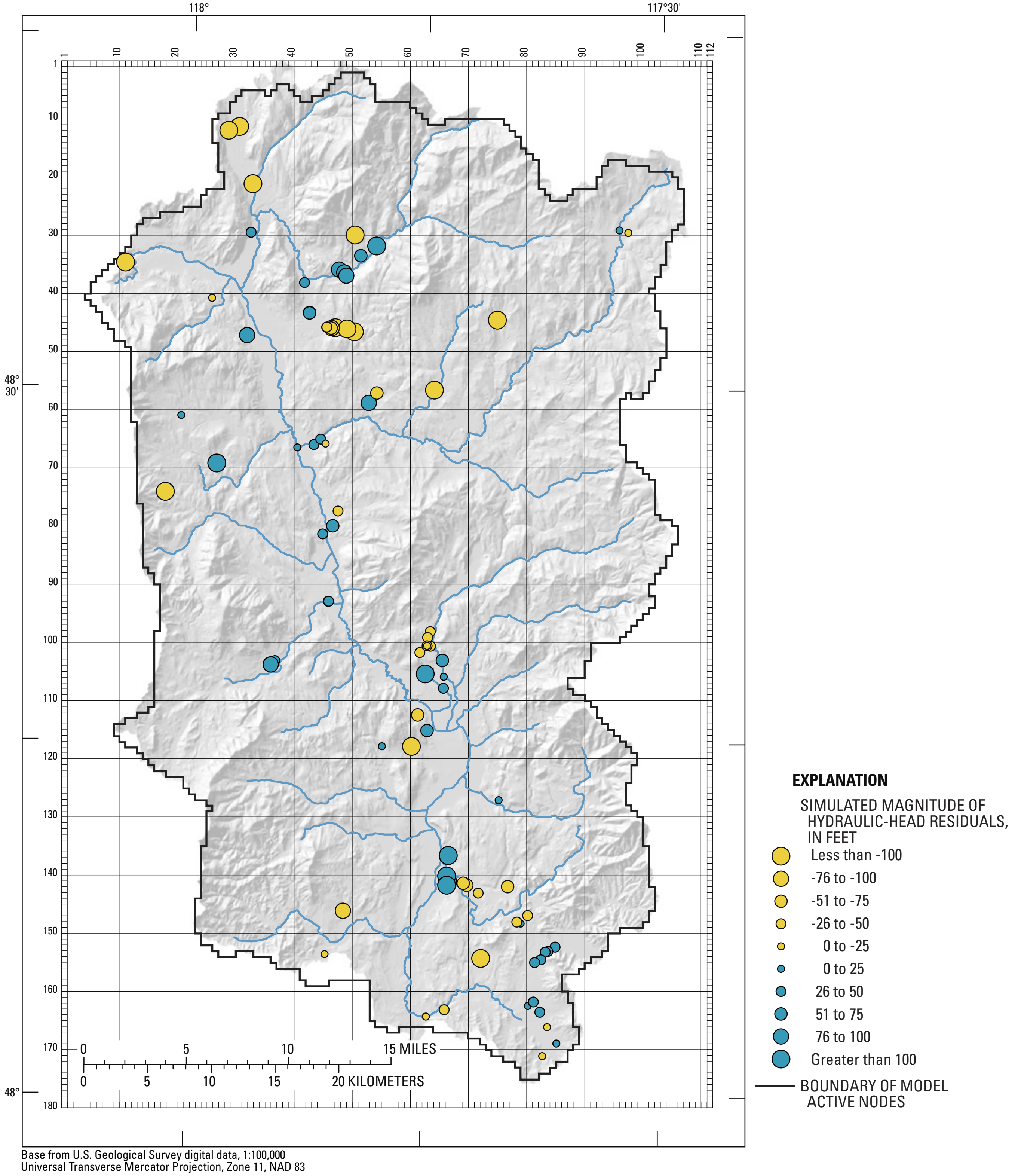
Figure 20. 95-percent confidence intervals as a percentage of the final parameter values for the ground-water-flow model of the Colville River Watershed, Stevens County, Washington.

Comparison of Simulated and Measured Hydraulic Heads

A more traditional and intuitive assessment of model calibration can be achieved by visually comparing the magnitude and spatial distribution of unweighted residuals. Figures 21*A-C* show the simulated hydraulic-head residuals for units UA, VC, and LA. For simulated hydraulic heads to be acceptable, the distribution of heads and the patterns of flow in units UA, VC, and LA had to match the general water-level distributions and flow patterns measured in the field. Also, root-mean-square (RMS) error of the difference between simulated and measured hydraulic heads in the 161 observation wells, divided by the total difference in water levels in the ground-water system (Anderson and Woessner, 1992, p. 241), had to be less than 10 percent to be acceptable.

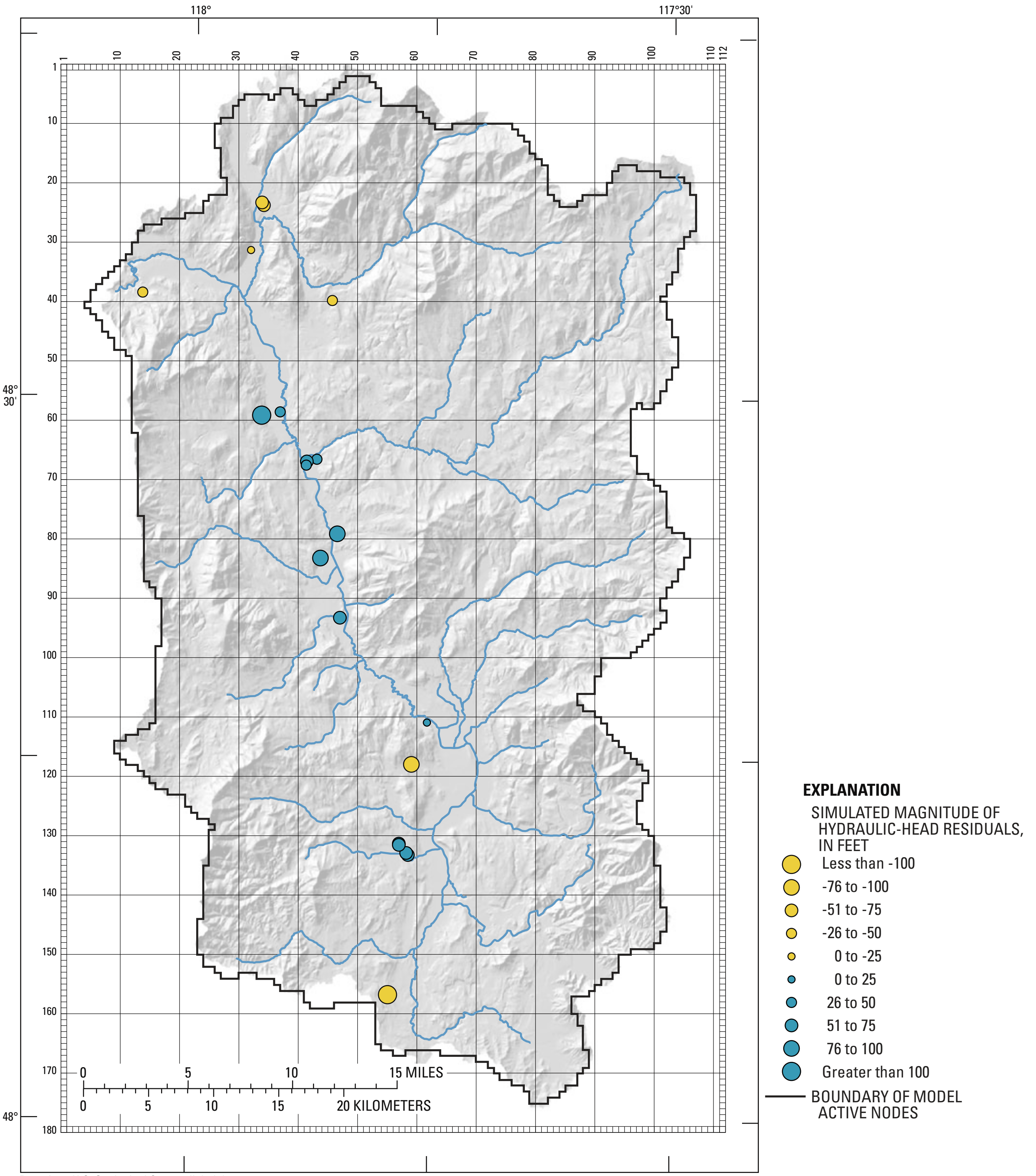
The calibrated model produces an RMS error divided by the total difference in water levels (RMSTD) of 4 percent. RMSTD for units UA, VC, and LA, are 3, 3, and 2 percent, respectively. Sixty-one percent of the 161 simulated hydraulic heads exceeded measured heads and the spatial distribution of the hydraulic head residuals show definite patterns of bias. In unit UA, 54 percent of simulated heads exceeded measured heads and these exceedances occurred throughout the model. A more prevalent bias is associated with units VC and LA. Most simulated hydraulic heads along the main Colville River valley floor exceeded the measured hydraulic heads with the exception of heads in unit LA near Kettle Falls. The nonrandom distribution of residuals in hydraulic heads for units VC and LA is a weakness in the final model.

Although a bias exists toward simulated hydraulic heads exceeding measured hydraulic heads, general ground-water-flow patterns indicated by the simulation results match those measured in the field. Kahle and others (2003) measured water levels that indicated downward ground-water flow on the valley floor from near Springdale to near the mouth of Sheep Creek, then upward along much of the valley floor until near Colville, where vertical gradients reverse to downward near the mouth of the watershed at Lake Roosevelt. These general flow patterns are produced by the calibrated model (fig. 22).



A. Model layer 1 – Upper outwash aquifer (UA)

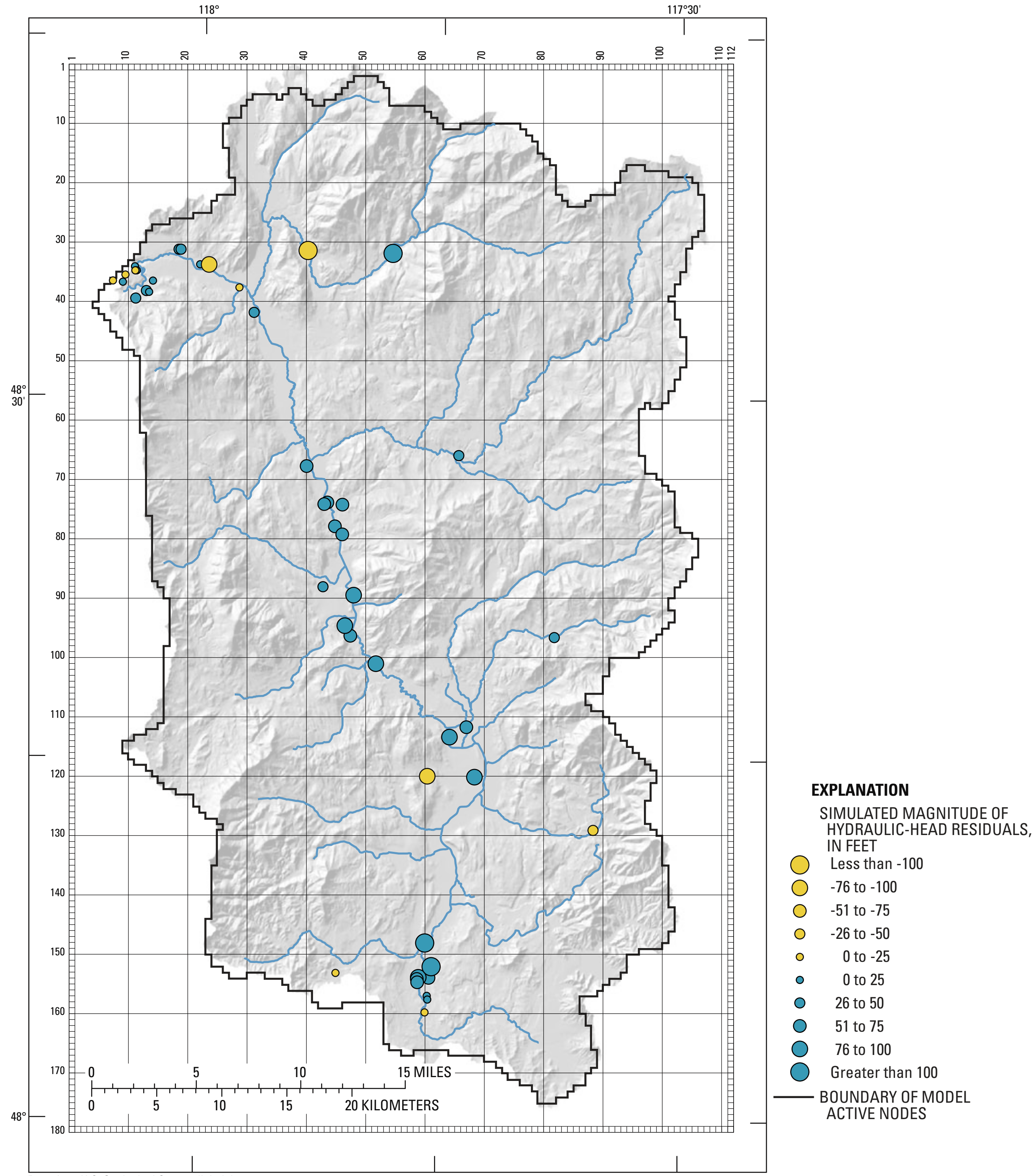
Figure 21. Locations and simulated magnitudes of hydraulic-head residuals for model layers 1, 3, and 5, Colville River Watershed, Stevens County, Washington.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

B. Model layer 3 – Colville Valley confining unit (VC)

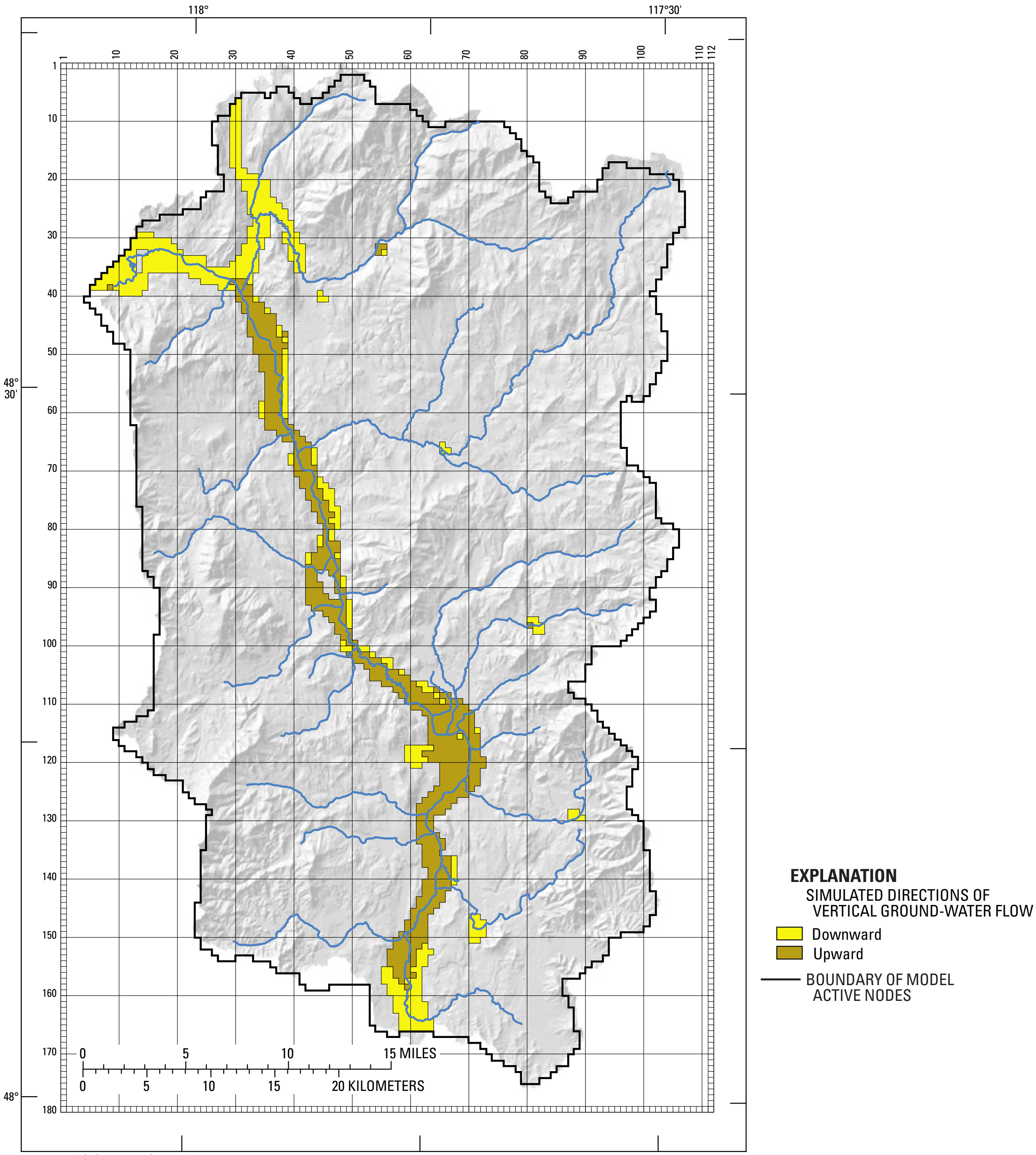
Figure 21.—Continued



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

C. Model layer 5 – Lower aquifer (LA)

Figure 21.—Continued



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

Figure 22. Simulated directions of vertical ground-water flow, Colville River, Watershed, Stevens County, Washington.

Comparison of Simulated and Measured Discharges

The steady-state model calibration benefited greatly from a complete set of seepage measurements (discharge) conducted in September 2001 (fig. 12). These measurements quantified the ground-water discharge to (gaining reach), or recharge from (losing reach) streams. The model was calibrated to 44 discharge measurements. Simulated and measured discharges are shown in table 6 and figure 23. Simulated gains and losses reasonably match the measured discharges but spatial bias does exist. Six of the seven simulated discharge values for the Colville River exceeded measured discharge, including a large discrepancy for the Colville River at Schmidlekofer Road. The measured value for this river reach was a net loss of 5.6 ft^3/s (Kahle and others, 2003). The model was unable to reasonably simulate any loss for this reach, instead simulating a net gain of 3.4 ft^3/s. Kahle and others (2003) noted that low-flow conditions in the Colville River in 1960 and 1961 were significantly different for this reach than for other reaches along the river. The discharge of the Colville River at Schmidlekofer Road increased by amounts ranging from about 8 to 13 ft^3/s during 1960 and 1961. The large difference in discharge was not measured in other reaches along the Colville River. The 1960 and 1961 discharge measurements also indicate that flow conditions can change quickly along the Colville River. Because of this knowledge, the large difference for this reach was considered acceptable. Most tributaries lost flow as the creeks entered the Colville River valley. The model generally simulated slight gains but the absolute values of the residuals were small.

Table 6. Simulated and measured discharge and residuals from the calibrated model, Colville River Watershed, Stevens County, Washington.

[Postitive values indicate gains. Negative values indicate losses. **Abbreviations**: ft^3/s, cubic foot per second]

Map No. (figure 12)	Stream	Discharge		
		Simulated (ft^3/s)	Measured (ft^3/s)	Residual (ft^3/s)
1	Sheep Creek at Forest Center Road, near Springdale	8.7	8.0	0.7
2	Sheep Creek at mouth, near Springdale	0.1	-1.1	1.2
3	Deer Creek near Springdale	1.9	4.7	-2.8
4	Deer Creek at mouth, near Springdale	0.1	-0.5	0.6
5	Colville River at Betteridge Road, near Valley	0.9	1.9	-1.0
6	Jump Off Joe Creek near Valley	-0.4	2.8	-3.2
7	Jump Off Joe Creek at mouth, near Valley	0.0	-0.0	0.0
8	Bulldog Creek near Valley	2.2	2.8	-0.6
9	Bulldog Creek at mouth, near Valley	5.2	4.5	0.7
10	Waitts Creek near Valley	0.2	0.1	0.1
11	Waitts Creek at mouth, near Valley	0.1	0.1	0.0
12	Huckleberry Creek near Valley	0.5	0.5	0.0
13	Huckleberry Creek at mouth, near Valley	0.0	-0.4	0.4
14	Cottonwood Creek near Chewelah	0.8	2.4	-1.6
15	Cottonwood Creek at mouth, near Chewelah	2.2	0.3	1.9
16	Sherwood Creek near Chewelah	0.2	0.5	-0.3
17	Sherwood Creek at mouth, near Chewelah	0.1	-0.1	0.2
18	Thomason Creek near Chewelah	-0.3	0.9	-1.2
19	Thomason Creek at mouth, near Chewelah	0.4	-0.1	0.5
20	North Fork Chewelah Creek, near Chewelah	2.7	3.7	-1.0
21	South Fork Chewelah Creek, near Chewelah	0.9	3.7	-2.8
22	Chewelah Creek at mouth, near Chewelah	2.0	-0.2	2.2
23	Paye Creek near Chewelah	0.3	3.4	-3.1
24	Paye Creek at mouth, at Chewelah	1.9	-0.4	2.3
25	Colville River at Schmidlekofer, at Chewelah	3.4	-5.7	9.1
26	Blue Creek near Blue Creek	0.0	0.1	-0.1
27	Blue Creek at mouth, at Blue Creek	0.3	-0.1	0.4
E	Colville River at Blue Creek (station 12408000)	1.0	-0.3	1.3
28	Stensgar Creek near Addy	1.0	0.3	0.7

Table 6. Measured and simulated streamflow gains and losses and residuals from the calibrated model, Colville River Watershed, Stevens County, Washington.—Continued

[Postitive values indicate streamflow gains. Negative values indicate streamflow losses. **Abbreviations**: ft^3/s, cubic foot per second]

Map No. (figure 12)	Stream	Discharge		
		Simulated (ft^3/s)	Measured (ft^3/s)	Residual (ft^3/s)
29	Stensgar Creek at mouth, at Addy	0.5	-0.3	0.8
31	Addy Creek at mouth, at Addy	0.0	-0.1	0.1
32	Stranger Creek near Addy	1.3	0.2	1.1
33	Stranger Creek at mouth, near Addy	0.0	-0.2	0.2
34	Colville River at 12 Mile Road, near Addy	1.4	-0.5	1.9
35	Little Pend Oreille River at Arden	13.3	13.6	-0.3
36	Little Pend Oreille River at mouth, at Arden	0.3	-4.0	4.3
37	Colville River at Arden	0.8	-0.1	0.9
38	Haller Creek below Cole Creek, near Arden	0.5	1.0	-0.5
39	Haller Creek at mouth, near Arden	0.5	-1.0	1.5
40	Mill Creek at Douglas Falls, near Colville	5.3	3.8	1.5
42	Clugston Creek near mouth, near Colville	-0.3	0.4	-0.7
43	Mill Creek at mouth, near Colville	-0.1	-2.3	2.2
46	Colville River at Greenwood Loop Road, near Kettle Falls	0.8	-0.3	1.1
J	Colville River at Kettle Falls (station 12409000)	-0.7	-0.7	0.0

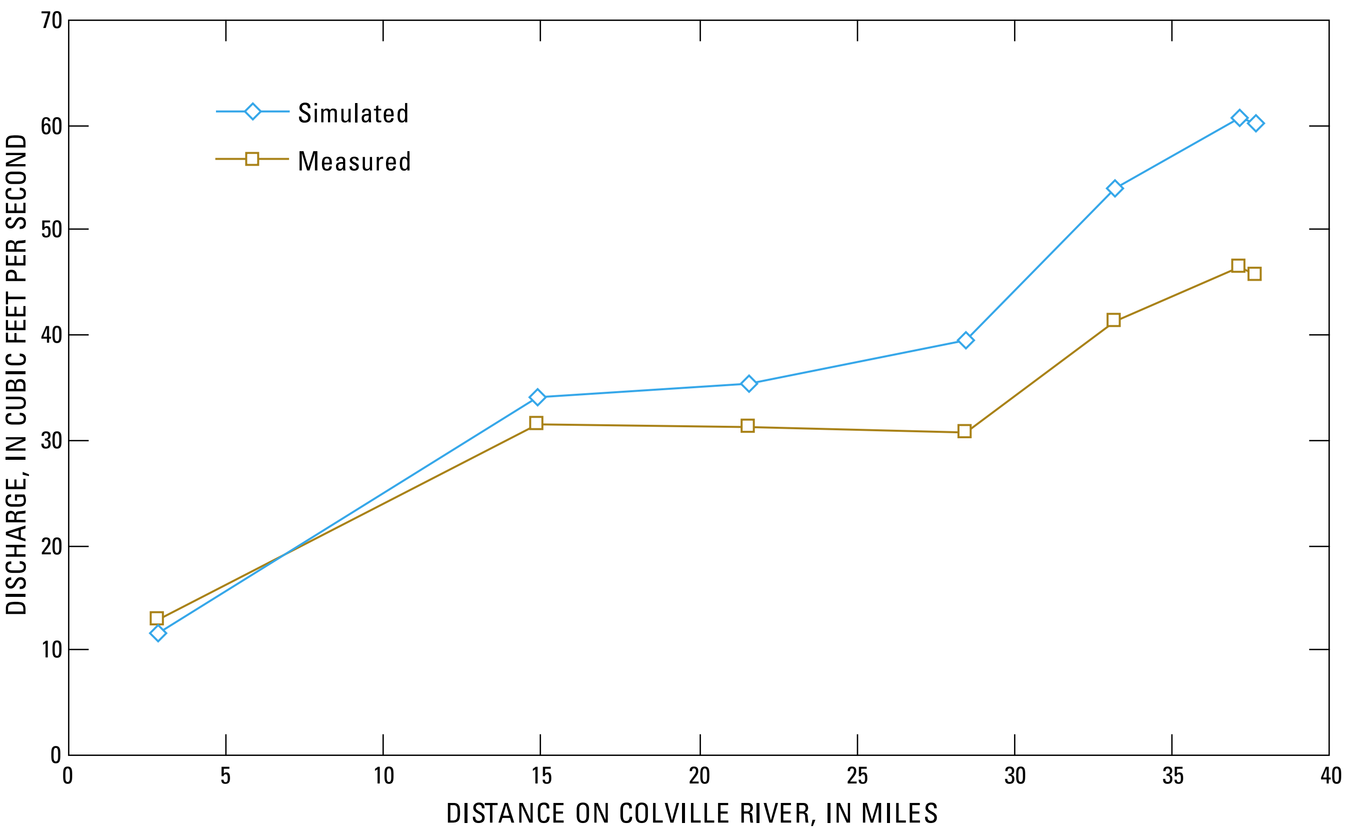


Figure 23. Simulated and measured discharge of the Colville River, Stevens County, Washington.

Discharge measurements of the tributary upper reaches of the Colville River Watershed created some statistical difficulties with the nonlinear calibration. The accuracy of the measurements was considered excellent and therefore a high weight was assigned to them. The actual discharge values, however, were very small. Fourteen of the 19 measured discharges were less than 2 ft^3/s. Large weighted residuals for the discharges in some minor tributaries were considered acceptable.

The upstream tributary discharge measurements were made where the stream enters the Colville River valley floor, and the discharge measured at these locations is presumed to include the total ground-water discharge to the stream for the entire subbasin. No information exists to quantify where the recharge occurs along the stream or the volume of ground water that flows beneath the stream. Small residuals for these locations indicate only that the total streamflow is correct. There is no way to know if all the hydrologic processes of the subbasin are being simulated correctly. Simulations of the subbasins therefore have a large degree of uncertainty and users are cautioned against extending predictions past the appropriate level for the regional model.

Model Limitations

A ground-water-flow model represents a complex, natural system with a set of mathematical equations that describe the 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 are as follows:

1. Data on types and thicknesses of hydrogeologic units, water levels, and hydraulic properties were taken from Kahle and others (2003) and represent only approximations of actual values. Most of the data were concentrated along the Colville River valley and in a few other populated areas, so that for most of the study area, little information is available to constrain the model. The hydraulic property data generally come from specific capacity tests, which typically measure drawdown at one time and at one pumping rate. Broad ranges of hydraulic property parameter values are possible. No short- or long-term data exist that provide information about how the system responds to changing, transient stresses such as increased ground-water pumping rates. With no long-term data, it is unknown if the simulated steady-state response is truly representative.

   Another possible deficiency is a lack of understanding of the geology at the mouth of the watershed. The complex geology near Kettle Falls could possibly control ground-water flow for a large part of the watershed. Much additional data would be required to understand the influence of alternative conceptual geologic conditions on the hydrologic conditions near Kettle Falls. Finally, there is a paucity of the data needed to explain the connection between the unconsolidated sediments and the bedrock. The conceptual model on which the numerical model is based presumes negligible or insignificant flow between the unconsolidated sediments and the bedrock and no flow from outside the Colville River Watershed. It is doubtful that the bedrock supplies a large source of water but an underestimation would result in model error.

2. A numerical model cannot represent completely, or "capture" all the physical processes of a watershed. 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 into a model undoubtedly affect the results of the simulation. The assumption that the system was in steady state during September 2001, and the associated implications, clearly is important. The simulation period does not represent average conditions but rather the 25th percentile of low-flow periods (fig. 24). The system is considered to be in dynamic equilibrium, but flows in the Colville River at Kettle Falls in September 2001 ranged from 32 to 73 ft^3/s. Between mid-August and November, flow increased by 73 ft^3/s.

   If the *regional, steady-state* ground-water-flow model is used appropriately for the stated specific purposes, the effects of the simplifications 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.

3. Errors in parameter estimates occur when improper values are chosen during the calibration process. Various combinations of parameter values can result in low residual error, yet improperly represent the actual system. An acceptable degree of agreement between simulated and measured values does not guarantee that the estimated model parameter values reasonably represent the actual parameter values. The use of nonlinear regression and associated statistics, such as composite scaled sensitivities and correlation coefficients, removes some of the effects of non-uniqueness, but certainly does not eliminate the problem entirely.

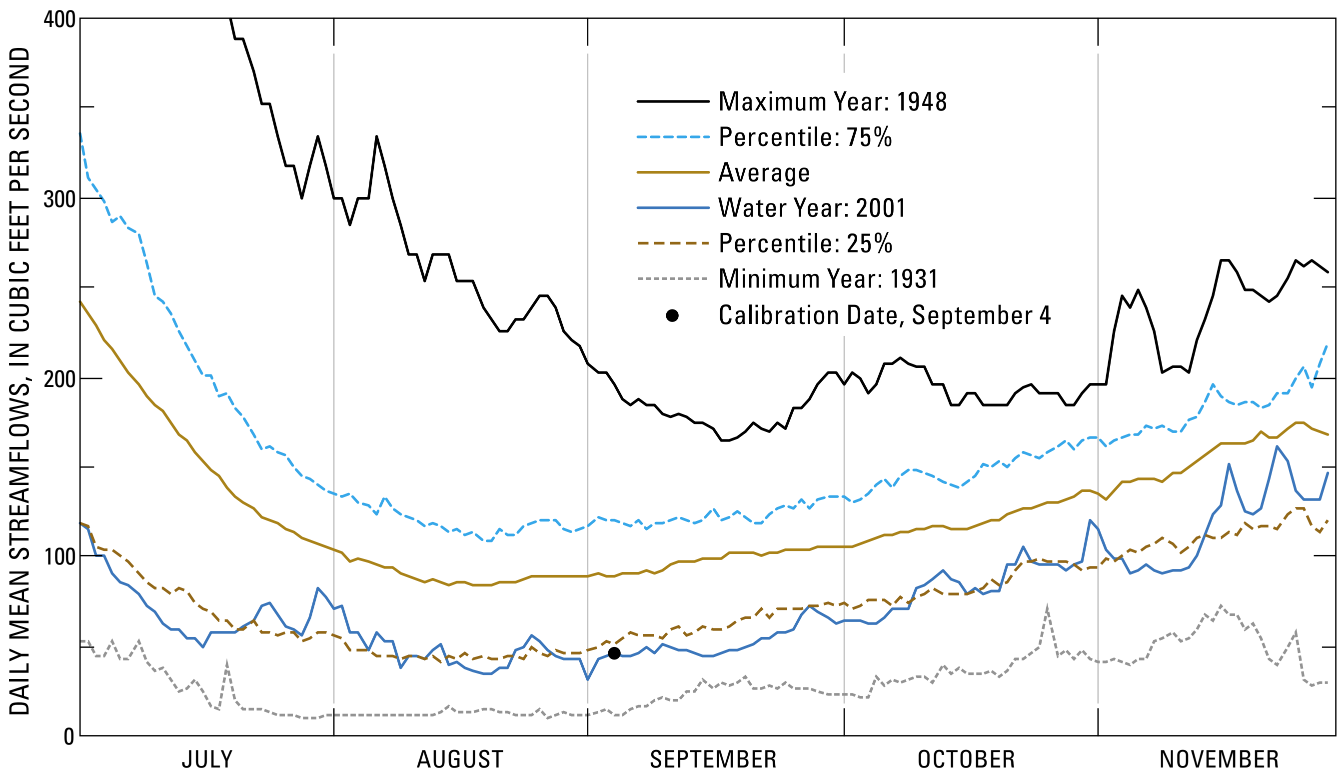


Figure 24. Statistical summary of mean daily discharges at the Colville River at Kettle Falls, Washington (station 12409000) during July – November for 1923-2001 and for 2001.

Model Applications

The calibrated model can be used to derive components of the ground-water budget or estimate the response of the regional system to new stresses such as alternative ground-water management strategies. Water-resource managers can use that information to make informed decisions to plan for future ground-water development. The uncertainty associated with inaccuracies in the ground-water-flow model is carried forward to the model applications.

Model-Derived Ground-Water Budget

A ground-water budget for September 2001 in the model area is expressed by the following equation:

$$GW_{in} + R = GW_{out} + D + \Delta S, \qquad (4)$$

where

GW_{in} is ground-water inflow to the model area,
GW_{out} is ground-water outflow from the model area,
R is recharge,
D is discharge, and
ΔS is change in ground-water storage.

Recharge to the ground-water system occurs primarily as precipitation and seepage from streams and lakes. Secondary recharge occurs as seepage from septic systems and deep percolation of irrigation water. Discharge from the system occurs as seepage to streams and lakes, as evaporation of ground water from soils and transpiration from plants, as ground-water outflow, and as pumping from wells. A more detailed representation of the ground-water budget of the Colville River Watershed model is provided by the equation:

$$GW_{in} + R_{ppt} + R_{sw} + R_{sec} = GW_{out} + D_{sw} + D_{et} + D_{ppg} + \Delta S, \qquad (5)$$

where

R_{ppt} is recharge from precipitation,
R_{sw} is recharge from streams and lakes,
R_{sec} is secondary recharge,
D_{sw} is discharge to streams and lakes,
D_{et} is ground-water discharge by evapotranspiration,
D_{ppg} is pumping from wells.

All water-budget components can be quantified on the basis of the calibrated model except discharge by evapotranspiration and change in ground-water storage. Evapotranspiration from the ground-water system is unknown but was largely accounted for in the determination of recharge and assumed to be relatively insignificant (D_{et} = 0). The Colville River Watershed model is a steady-state representation of the system, that is, inflow to the system is assumed to be equal to outflow from the system, resulting in no change in the volume of water stored within the system (ΔS = 0). The conceptual model for the Colville River Watershed assumes no ground-water inflow from outside the watershed.

Substituting the calibrated-model values and above assumptions into equation 6 yields the following (all terms are as defined above and all values are in thousands of acre-feet per year):

IN	Rate (acre-ft/yr) × 1000	OUT	Rate (acre-ft/yr) × 1000
GW_{IN}	0	GW_{OUT}	9
R_{PPT}	47	D_{SW}	71
R_{SW}	36	D_{ET}	0
R_{SEC}	6	D_{PPG}	9
Totals................	89		89

The calibrated ground-water model budget can be used to make general conclusions about the flow system. Total flow through the ground-water system was about 89,000 acre-ft/yr. Precipitation was the primary source of ground-water recharge in the Colville River Watershed; secondary recharge was 12 percent of the total recharge. Total ground-water withdrawals for September 2001 were about 10 percent of the total flow. Ground-water outflow from the model area was 9,000 acre-ft/yr, or 10 percent of the total ground-water flow. Kahle and others (2003) reported an estimated annual ground-water discharge of 16,100 acre-ft. Considering that Kahle and others (2003) estimated a long-term annual average, the simulated ground-water discharge for September 2001 was considered reasonable. Net streamflow (gains minus losses) for all river cells was 49 ft^3/s. The September 2001 monthly mean streamflow for the Colville River at Kettle Fall (station 12409000) was 50.9 ft^3/s. The period of simulation, September 2001, was extremely dry so all components of the ground-water budget are presumably below average.

Simulation of Increased Ground-Water Pumping

In 1994, the DOE halted the issuance of new ground-water rights in the Colville River Watershed owing to possible hydraulic connection of the ground- and surface waters. However, the 2001 estimate of the actual water use of ground water in the Colville River Watershed was only 25 percent of the existing water right permits, certificates, and claims (Kahle and others, 2003). The challenge of the Planning Team is to supply additional water resources while limiting any adverse effects on surface water and maintaining sufficient instream flows for all users.

Ground water that discharges naturally is not necessarily available for further water development. Theis (1940) and Bredehoeft and others (1982) state any new discharge (withdrawal) superimposed on a previously stable system must be balanced by an increase in recharge, a decrease in the original discharge, a loss of aquifer storage, or by a combination of these factors. Theis (1940) reported on the hydrologic principles that govern the response of the ground-water system to increased pumping. At first, water is removed from storage as the water level declines but eventually, if the stress continues, the increased ground-water pumping will begin to reduce the natural discharge of ground water. Reduction in ground-water discharge is manifested by reduced inflow to streams and springs, reduced ground-water outflow, less evapotranspiration, and reductions in other discharge mechanisms. Increased ground-water pumping also can induce recharge from surface-water bodies such as streams and lakes. These effects can be reduced only by an increase in recharge. There is no evidence to suggest that recharge from precipitation will increase, but rather the effects of continued population growth (such as an increase in area of impervious surface) may even result in decreased precipitation recharge. (Secondary recharge would mitigate the adverse effects somewhat but at a probable reduction in water quality.) Additional ground-water pumping, therefore, would most likely result in a loss of storage (decline in ground-water levels), and a reduction in natural discharge.

The steady-state model was used to simulate the effects of several ground-water pumping alternatives. No change was made in secondary recharge from the calibrated model. Actual long-term consumptive use of water in the Colville River Watershed is small. Water used within the watershed generally is returned to the system (minus ground-water evaporation). Assuming some of the additional ground water withdrawn would become secondary recharge (through septic systems, sewage disposal, and irrigation), this method represents a conservative approach.

The uncertainty associated with inaccuracies in the model is carried forward to the ground-water pumping alternatives and new uncertainties are introduced. Drawdown in a specific model cell is an average over the entire cell. Actual drawdown in a pumped well would be much greater. The increased pumping rate assigned to a well may even exceed the actual maximum production rate of the well. For the purposes of the simulation, the pumping rate in any model cell, represented as being from a single well or a group of wells, has little effect on the results.

Some additional error may exist in the simulated drawdowns because unit UA is simulated as confined. Because the model represents unit UA as confined, the transmissivity (hydraulic conductivity times saturated thickness) remains constant instead of gradually decreasing as drawdowns increase. Actual drawdown in unit UA would then be greater than that simulated.

Effects of Increased Ground-Water Pumping at Chewelah, Loon Lake, Springdale, Addy, Kettle Falls, and Colville

Current ground-water pumping rates throughout the Colville River Watershed is less than the maximum existing water rights. The ground-water model can be used to simulate different water- management alternatives and provide information about the potential effects of simulating those alternatives. Additional ground-water pumping was simulated at seven locations by increasing pumping rates at current public-supply well locations. At five locations, the increased rate of pumping was based on 2025 projections supplied by the Planning Team. For two locations, Springdale and Addy, the rate of ground-water pumping was increased over the projected rate to provide a meaningful stress to the system. Due to the steady-state nature of the model, simulated effects are an "ultimate" response and do not indicate the time required to reach this result. In addition, all simulated alternative management strategies (different pumping rates and locations) are imposed on September 2001 conditions. Because of the below-normal precipitation for this period, the model would produce very conservative results. Patterns in system response would likely be similar during a period of average or above average precipitation, but drawdowns and associated decreases in streamflow would be smaller.

Kahle and others (2003) reported that 93 percent of the precipitation not lost to evapotranspiration ultimately discharges to the rivers and streams of the Colville River Watershed. The simulations indicate that any increase in the amount of pumping would come from increased river and lake leakage and decreased ground-water flow exiting the system (table 7). The rivers and streams were divided into two groups: Colville River valley floor and tributaries. A few of the areas of simulated increased ground-water pumping are near the confluence of the Colville River and a tributary, and it is difficult to assess what percentage of the withdrawal would come from each source.

Table 7. Location of simulated ground-water pumping rates and major sources of water for the ground-water pumping alternatives, Colville River Watershed, Stevens County, Washington.

[Mgal/d, million gallons per day]

Location of increased simulated ground-water pumping	Rate of simulated increased ground-water pumping (Mgal/d)	Source of simulated ground-water pumping, as a percentage of total			
		From Colville Valley floor	From tributaries	From ground-water outflow	From ground-water flow to lakes
Chewelah (South)	0.53	85	15	0	0
Chewelah (North)	.31	37	63	0	0
Loon Lake	.14	0	0	0	100
Springdale	.34	17	83	0	0
Addy	.53	75	22	3	0
Kettle Falls	.55	18	1	81	0
Colville	.29	7	89	4	0

Morgan and Jones (1999) reported that the capture of ground water that would otherwise discharge naturally, expressed as a percentage of the pumping rate, is nearly constant, and therefore the percentage of decrease in streamflow is directly proportional to the pumping rate of the well. This linear response is owing, in part, to the simulated constant transmissivity of the hydrogeologic units. Similar conclusions were found in the ground-water pumping alternatives presented in this report, so only one pumping rate increase for each alternative and location is presented here.

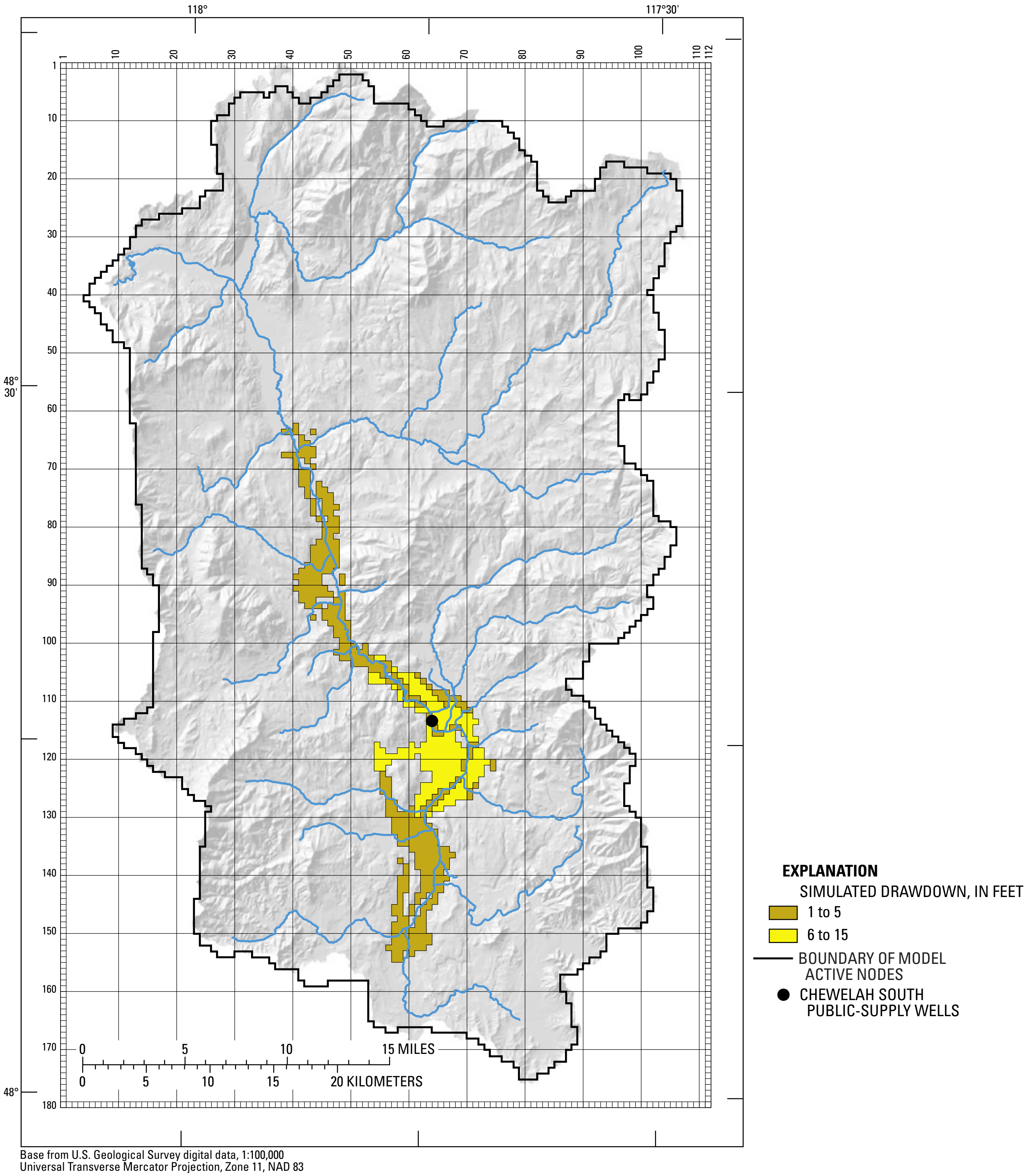
All ground-water pumping alternatives were simulated as withdrawals from unit LA, where that unit was present. For Chewelah North, Loon Lake, and Colville, unit UA was the only aquifer present. Varying the depth of the pumping well was not investigated because of the simple vertical discretization. Morgan and Jones (1999) found that pumping from successively deeper model layers will spread the capture zone over a wider downstream area. Simulating ground-water pumping immediately adjacent to a river cell would strongly localize the effects on the nearby stream.

Surface-water features on the Colville River valley floor would be most affected by increased pumping at the Chewelah South public-supply wells. Surface water on the valley floor would supply about 85 percent of the ground-water pumpage and Chewelah Creek and a few other tributaries would supply about 15 percent. Simulated increased pumping at the Chewelah North wells is relatively small compared to the larger pumping rates to the south, and Chewelah Creek would be the source of most of the ground water withdrawn (63 percent).

Another way to examine the effects of increased ground-water pumping is the drawdown produced by the additional pumping. The spatial extent and magnitude of simulated drawdowns in response to increased pumping from unit LA at the City of Chewelah South public-supply wells is shown in figures 25*A-B*. Maximum simulated drawdowns of 15 and 14 ft occur in units VC and LA, respectively. The affected area extends from the confluence of Sheep and Deer Creek and the Colville River to Arden. The simulated drawdown for most of that area is 1 ft. The spatial extent and magnitude of drawdowns for the increased pumping from unit UA at the City of Chewelah North public-supply wells is shown in figure 26. Unit UA is relatively thin and discontinuous, and the simulated drawdowns reflect this fact. The spatial extent of drawdown is less than the Chewelah South alternative but the magnitude of drawdown is more. Water levels in the area surrounding the pumping well are lowered by as much as 37 ft.

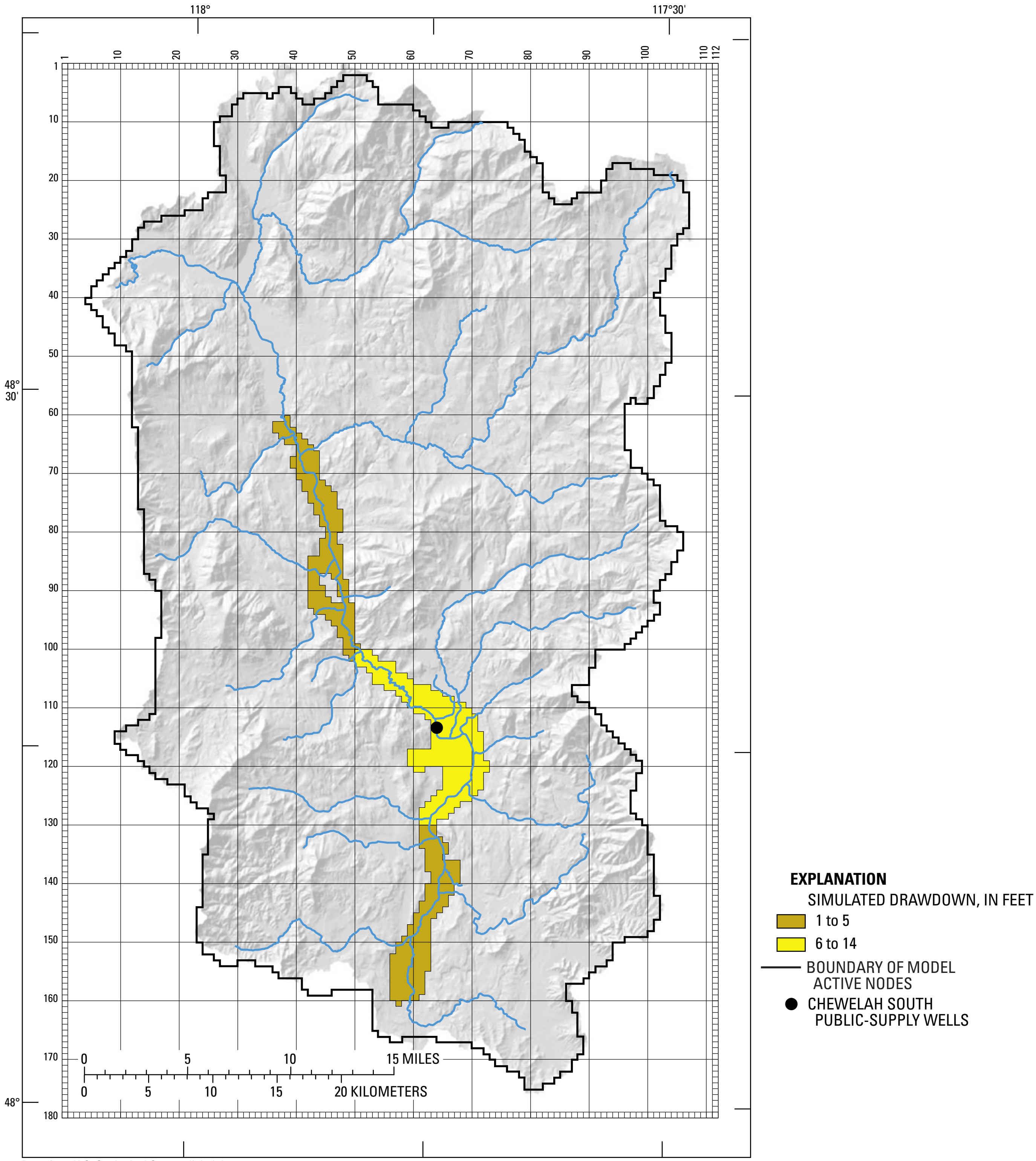
Eighty-three percent of the increased pumping at Springdale would come from upper Sheep Creek and 17 percent from the valley floor (which includes a part of Sheep Creek). This area of the watershed most likely has a very shallow ground-water divide and any new stress to the steady-state environment may result in a shift of that divide and capture water from the watershed to the south. The Addy public-supply well would draw water from the Colville River valley floor (75 percent) and Colville River tributaries (22 percent). Increased pumping from public-supply wells near Loon Lake would have little effect on the flow of Sheep Creek. About 100 percent of the increased ground-water pumping would come from increased lake leakage to the ground-water system. The simulation of increased pumping at Kettle Falls indicates that ground water would come primarily from decreased ground-water discharge from the Lower aquifer and Bedrock. Some inaccuracies for the simulations near Loon Lake and Kettle Falls exist due to their proximity to model boundaries. In both locations, a lake is represented by a general head boundary. In the steady-state model, lake elevations remain constant and supply an infinite source of water. Lake leakage is controlled by a conductance term. The constant lake elevation maintains water levels in the area surrounding the lake, thereby minimizing simulated drawdowns. In reality, the increased leakage from the lake that would result from the increased pumping would cause a decline in lake levels.

The City of Colville public-supply wells are completed in the relatively thin and discontinuous Upper aquifer (unit UA). Simulated drawdown in unit UA is shown in figure 27 for the 20 percent increase in pumping. Drawdowns in model cells adjacent to the pumping location range from 15 to 36 ft and decrease with distance from the pumping. The simulated drawdown in the outlying, disconnected cells is likely an artifact of the simplified model construction and probably would not be observed in the field. Mill Creek is the major source of water for the increased pumping (table 7).



A. Unit LA at the City of Chewelah South public-supply wells (unit VC)

Figure 25. Spatial extent and magnitude of simulated drawdown in response to increased ground-water pumping, Colville River Watershed, Stevens County, Washington.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

B. Unit LA at the City of Chewelah South public-supply wells (unit LA)

Figure 25.—Continued

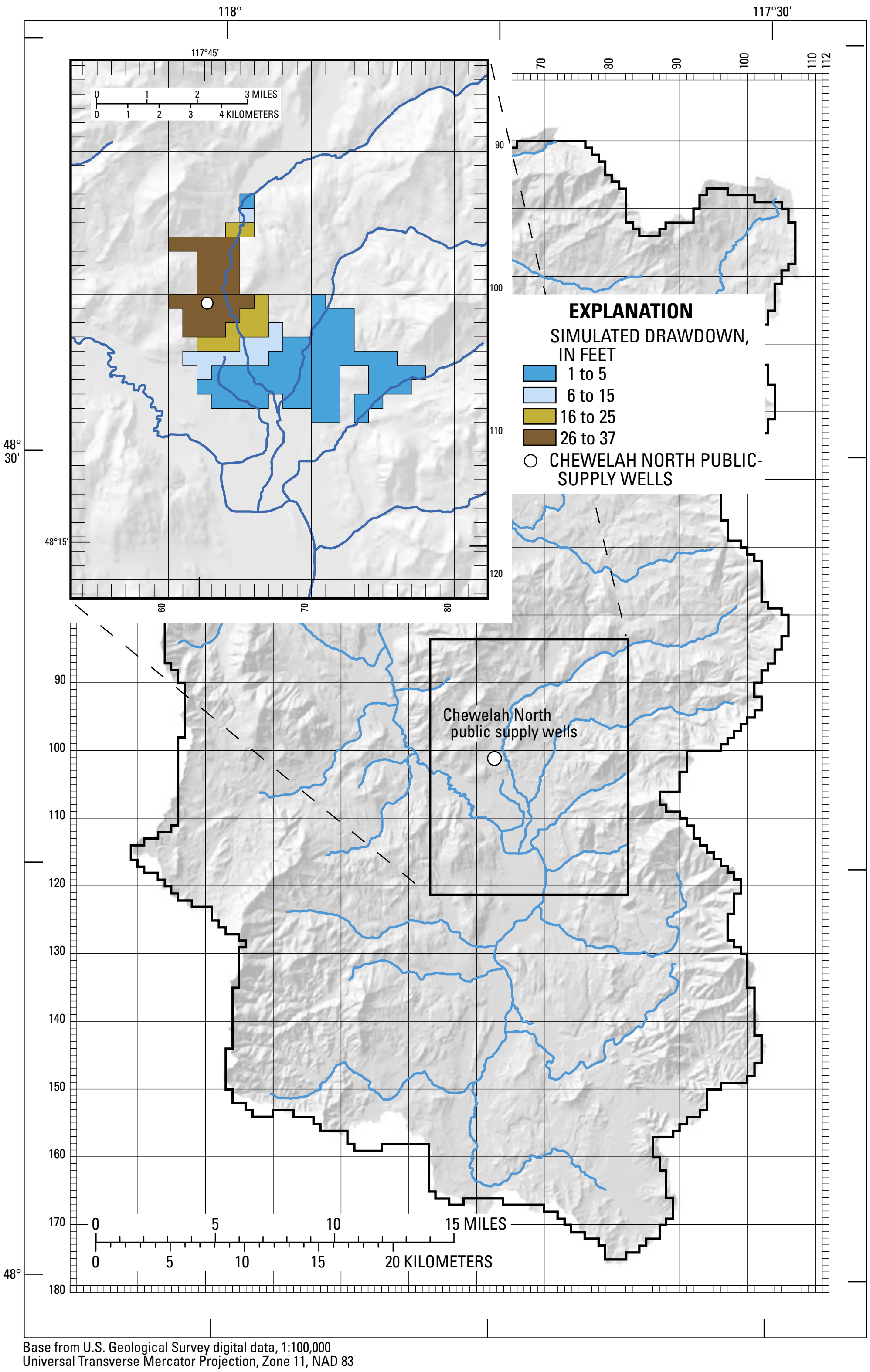
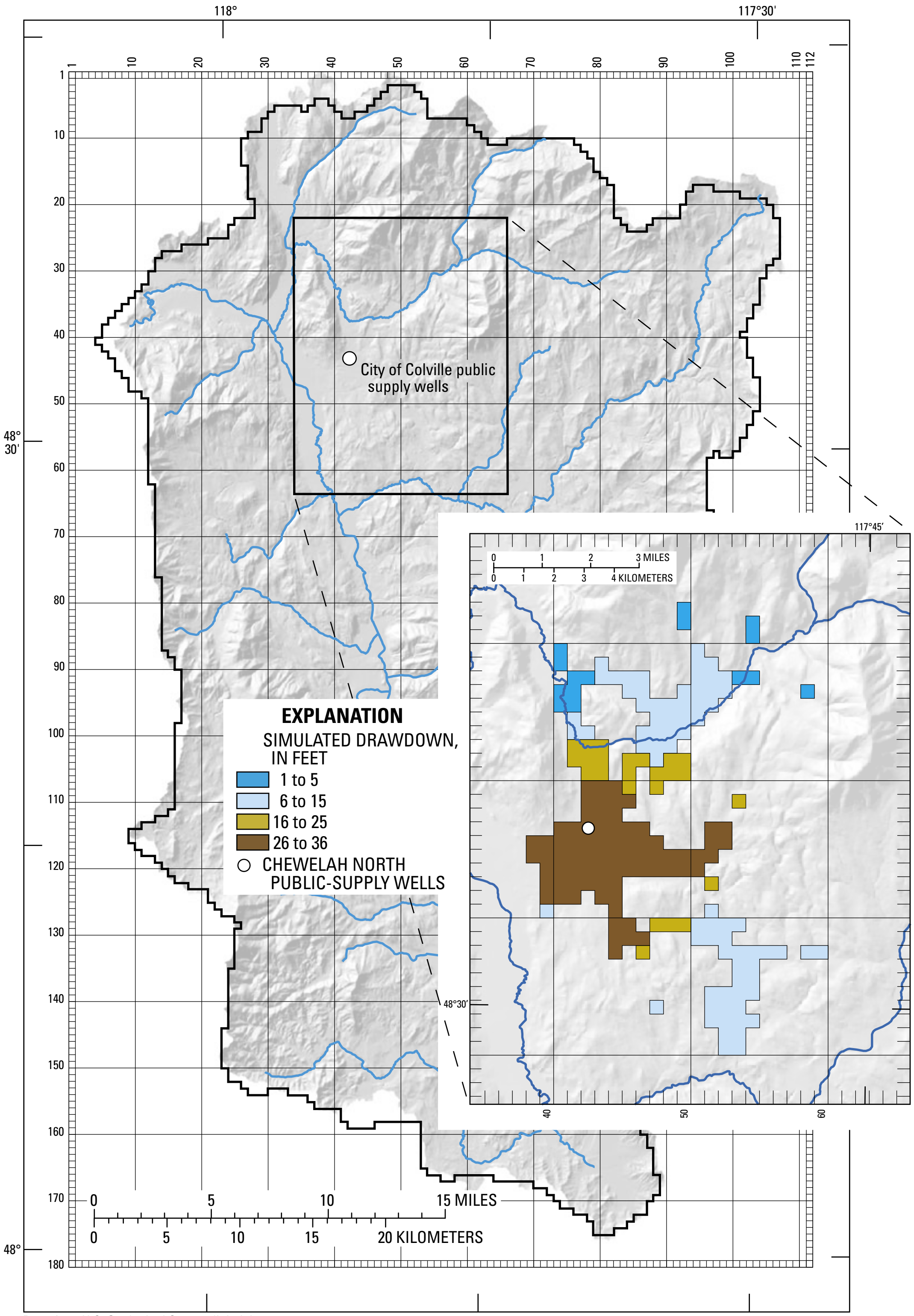


Figure 26. Spatial extent and magnitude of simulated drawdown in response to increased ground-water pumping from unit UA at the City of Chewelah North public-supply wells (unit UA), Colville River Watershed, Stevens County, Washington.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

Figure 27. Spatial extent and magnitude of simulated drawdown in the Upper outwash aquifer in response to a 20-percent increase in current ground-water pumping at the City of Colville public-supply wells, Colville River Watershed, Stevens County, Washington.

Effects of Ground-Water Pumping from the Lower Aquifer Along the Colville River Valley

It has been suggested that the Lower aquifer (unit LA) along the main valley floor is the best potential source for further ground-water development. (Unit LA is a continuous, relatively thick unit separated from the Colville River by the thick Colville Valley confining unit.) To examine this possibility, three alternatives were simulated to examine the effects of location and pumping rate on the ground- and surface-water resources.

- Alternative 1 — simulated a pumping well near the City of Colville withdrawing water at 1.44 Mgal/d (4.4 acre-ft/d).
- Alternative 2 — simulated a pumping well near Chewelah withdrawing water at 1.44 Mgal/d (4.4 acre-ft/d).
- Alternative 3 — simulated four wells along the main Colville River valley, each pumping at a rate of 0.36 Mgal/d (1.1 acre-ft/d) for a total withdrawal of 1.44 Mgal/d (4.4 acre-ft/d).

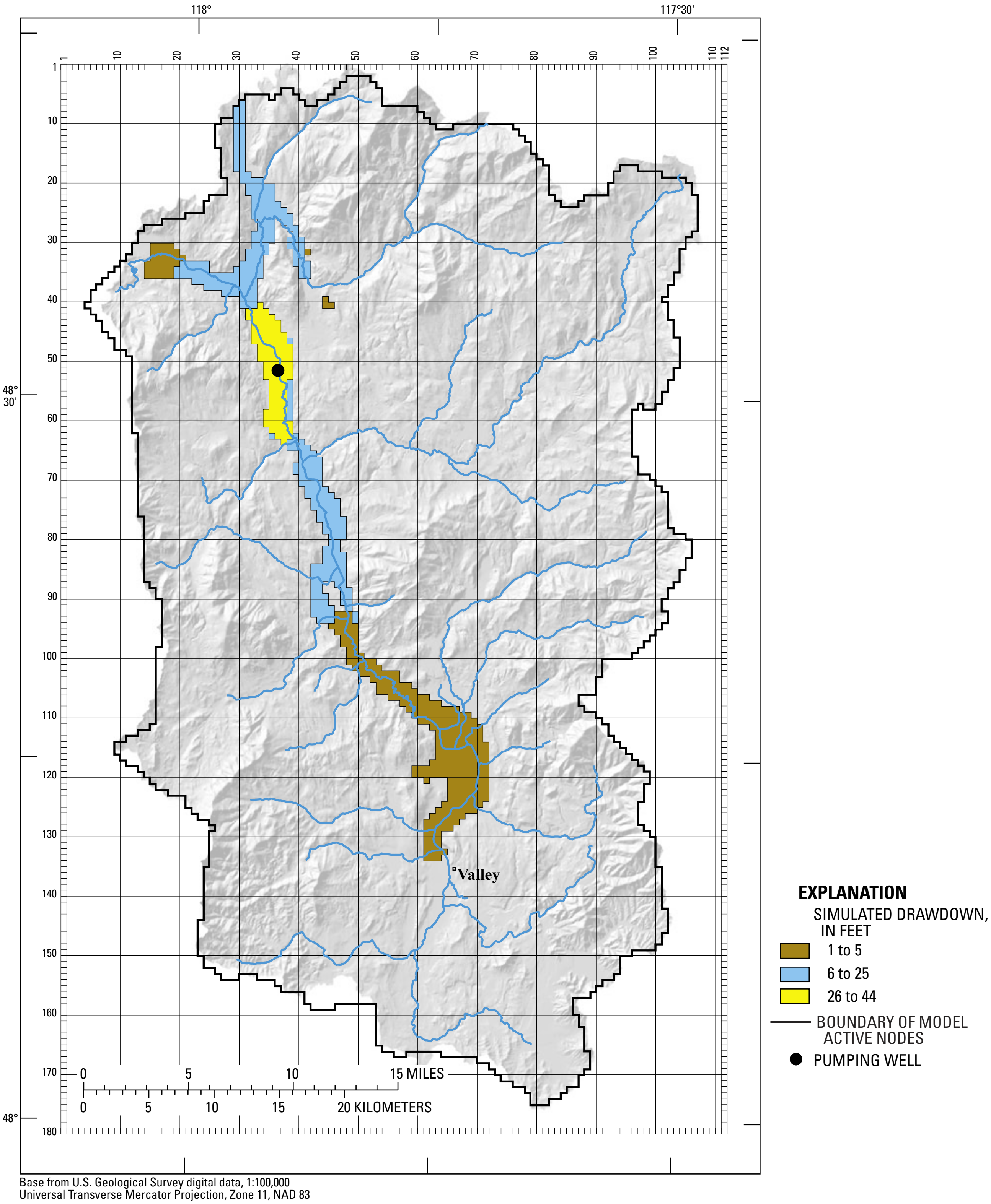
Alternative 1 results in simulated water-level declines in unit LA reaching a maximum of 44 ft near the well and extending from the northern boundary of the watershed to the town of Valley (fig. 28*A*). This simulated drawdown exceeds the few measured drawdown values. The ultimate response simulated by a steady-state model calibrated to a drier than average low-period undoubtedly exceeds the actual response of the system to the simulated stress under average conditions. The major sources of ground water for the withdrawal are distributed among the Colville River valley floor (44 percent), tributaries (32 percent), and ground-water outflow (24 percent) (table 8). Simulated drawdowns for alternative 2 are generally less than those for alternative 1, with maximum drawdowns reaching 38 ft (fig. 28*B*). The difference in drawdowns between the alternatives is owing, in part, to the wide valley floor near Chewelah. The sources of water for this alternative also are quite different. Eighty-two percent of the ground-water withdrawal is from the Colville River valley floor and 18 percent from Chewelah Creek. The greater distance of the wells from the ground-water outflow (drains) near Kettle Falls is the significant reason for the differences.

In alternative 3, water is withdrawn at the same rate as in alternatives 1 and 2 but the pumping is spread along the Colville River valley floor. Drawdowns were much less in this alternative, with a maximum water-level decline of 13 ft (fig. 29). The area affected by pumping, however, spanned the length of the unit. The sources of water for alternative 3 reflect the pumping well distribution. As the wells are spread out, so too are the major sources of pumped water. The Colville River valley floor, its tributaries, and ground-water outflow contribute 46, 29, and 25 percent, respectively.

Table 8. Locations of simulated ground-water pumping rates along the Colville River valley floor, and major sources of water for the ground-water pumping alternatives, Colville River Watershed, Stevens County, Washington.

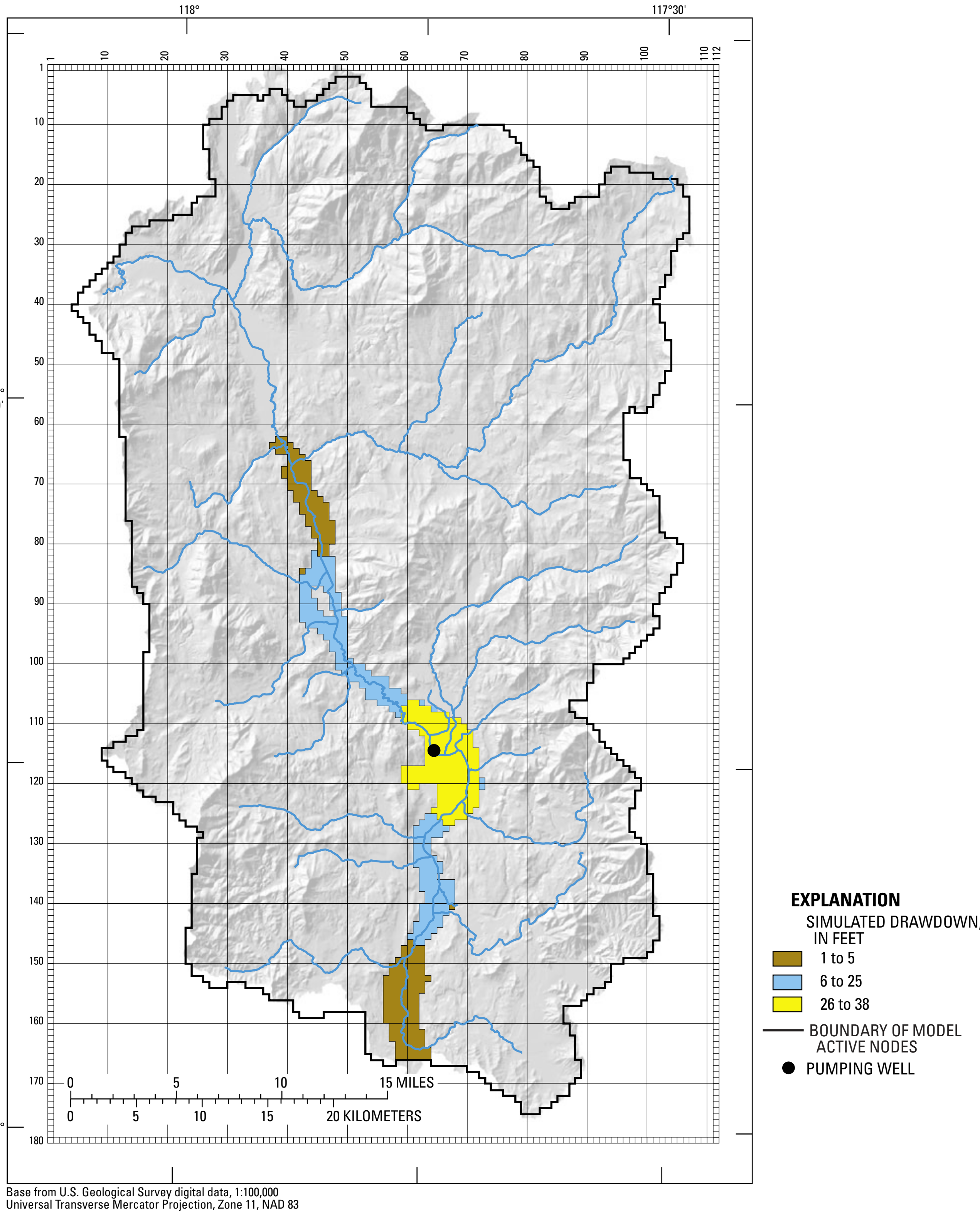
[Mgal/d, million gallons per day]

Alternative	Location of increased simulated ground-water pumping		Rate of simulated increased ground-water pumping (Mgal/d)	Source of simulated ground-water pumping, as a percentage of total			
	Row	Column		From Colville Valley floor	From tributaries	From ground-water outflow	From ground-water flow to lakes
1	52	37	1.44	44	32	24	0
2	115	65	1.44	82	18	0	0
3	35	23	.36	46	29	25	0
	52	37	.36				
	115	65	.36				
	147	62	.36				



A. Lower aquifer near Colville

Figure 28. Spatial extent and magnitude of simulated drawdowns in the Lower aquifer in response to an additional 1.44 million gallons per day ground-water pumping near Colville and Chewelah, Stevens County, Washington.



B. Lower aquifer near Chewelah

Figure 28.—Continued

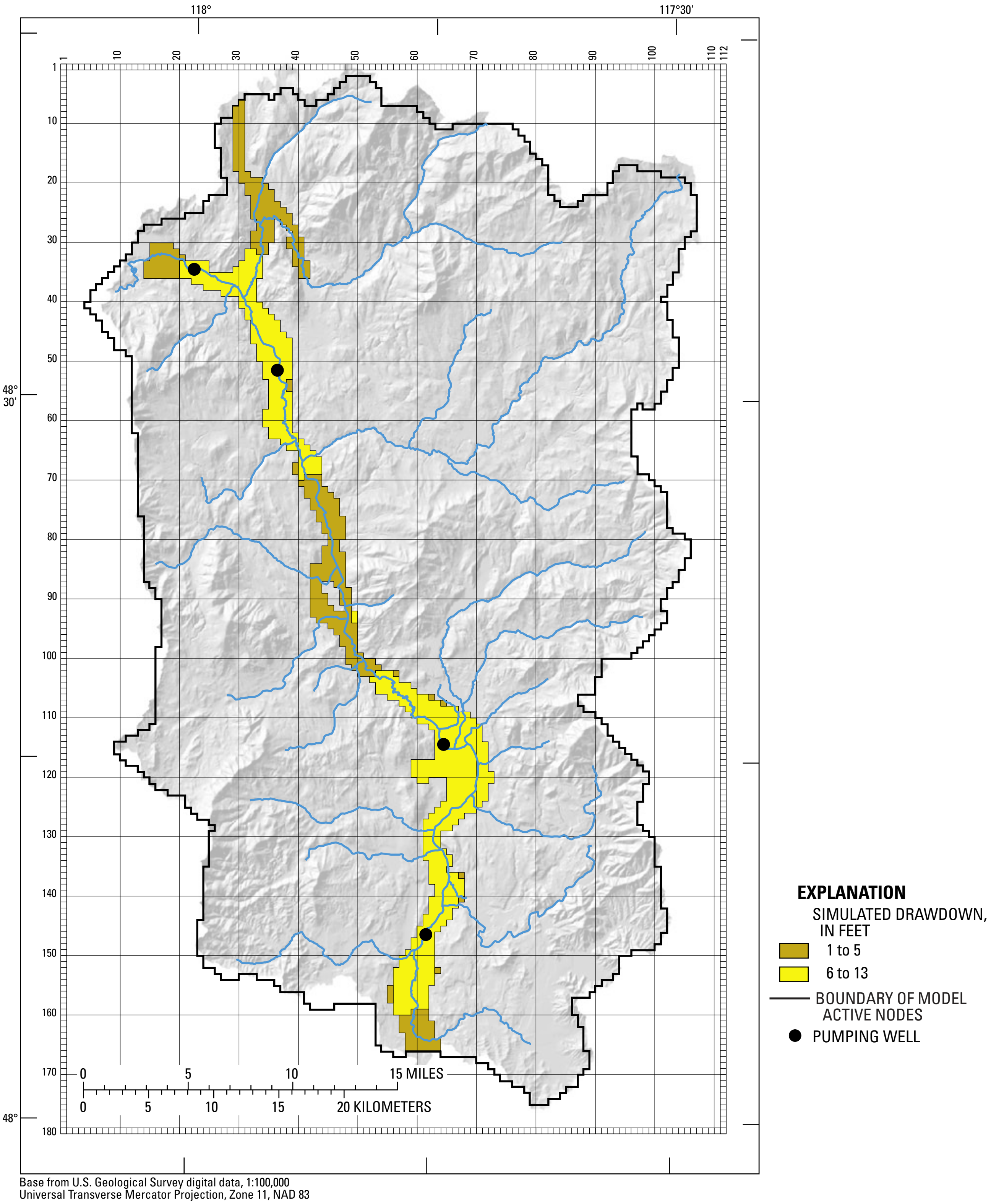


Figure 29. Spatial extent and magnitude of simulated drawdown in the Lower aquifer in response to four separate ground-water pumping rates of 0.36 million gallons per day.

The effects of secondary recharge were examined by simulating an injection well in the same row and column as the ground-water pumping alternatives but located in the surficial unit. (A rate of 50 percent of the ground-water pumping rate was used for the injection well). Drawdowns in unit LA decreased in all three alternatives, from 44, 38, and 13 ft to 39, 34, and 12 ft, respectively. The source of the ground-water withdrawal presented in table 8 would not change, but the decrease in measured discharge would be less, as the injected water recharged the Colville River.

Simulation of Predevelopment Ground-Water and Surface-Water Conditions

Human activity and water appropriation predates any formal system of water measurements and, as a result, predevelopment streamflow conditions are unknown. The calibrated steady-state model was used to simulate flow conditions as if no ground-water pumping, secondary recharge, or irrigation application were occurring (predevelopment conditions). Simulated changes in ground-water levels in units UA, VC, and LA are shown in figures 30*A*-30*C*. The changes represent the deviation of current conditions from predevelopment conditions. Areas of positive ground-water level change represent areas where secondary recharge such as irrigation application and sewage disposal are applied. In these areas, ground-water levels would rise due to the application of the artificial recharge during the dry month of September. Predevelopment streamflow in the Colville River Watershed increased by 1.1 ft^3/s (from present-day flows), or about 37 percent of net ground-water withdrawal (ground-water withdrawal minus secondary recharge). The simulated predevelopment conditions also resulted in increased ground-water outflow and lake recharge.

Simulation of Ground-Water Flow to Loon Lake, Chewelah, and Colville

Projected growth and development in three areas — Loon Lake, Chewelah, and Colville — were addressed, in part, by examining ground-water flow to local public-supply wells. These ground-water flow pathlines were estimated using the water-level contours from the areas of discharge to the areas of recharge (contributing area). The uncertainty associated with inaccuracies in the ground-water-flow model is carried forward to the contributing area.

Contributing Area for Ground-Water Pumping near Chewelah

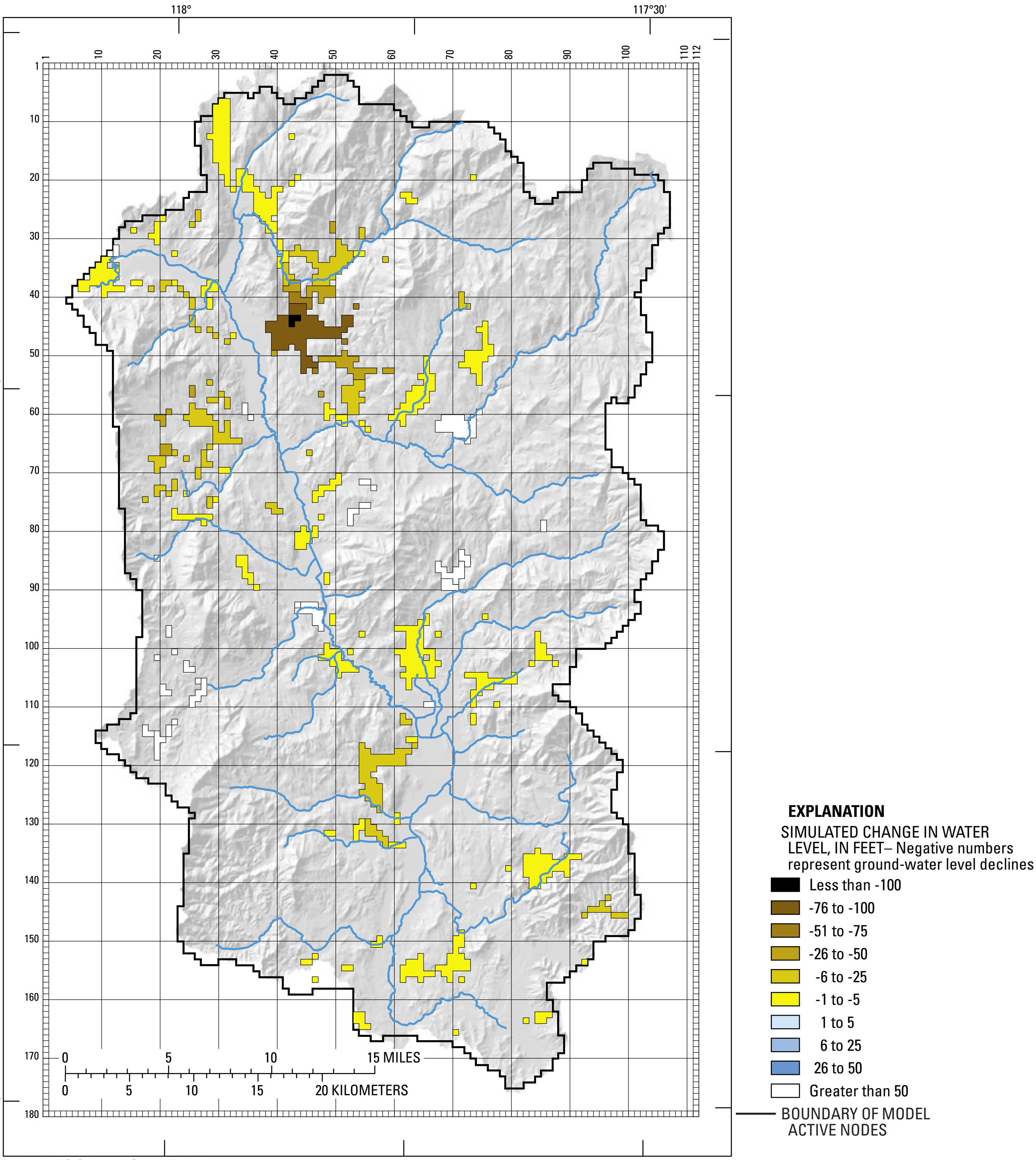
Results of the simulations estimate the contributing area for ground-water pumping near the City of Chewelah. The pumpage in this area originated as precipitation recharge and secondary recharge up gradient along the Colville River valley (from Springdale to Chewelah). A small portion of the ground-water entered the system in the area near Springdale moved deeply into the system and upward through the bedrock. The simulated pumping wells also withdrew ground water from a few downgradient (to the north) model cells.

Contributing Area for Ground-Water Pumping near Loon Lake

The ground-water-flow model simulated six public-supply wells in the Loon Lake area with a total pumping rate of 0.39 Mgal/d (1.2 acre-ft/d) from unit UA. The water withdrawn by these wells came mostly from Loon Lake. As previously discussed, Loon Lake is represented by constant head boundary cells that (in the simulation) can supply an infinite source of water. Ground water flowing to the north side of Loon Lake came from precipitation recharge to the north and leakage from Deer Lake. The simulated contributing area was limited by the proximity of Loon Lake to the southeastern no-flow boundary. Model cells in this area are recharged locally.

Contributing Area for Colville Public-Supply Wells

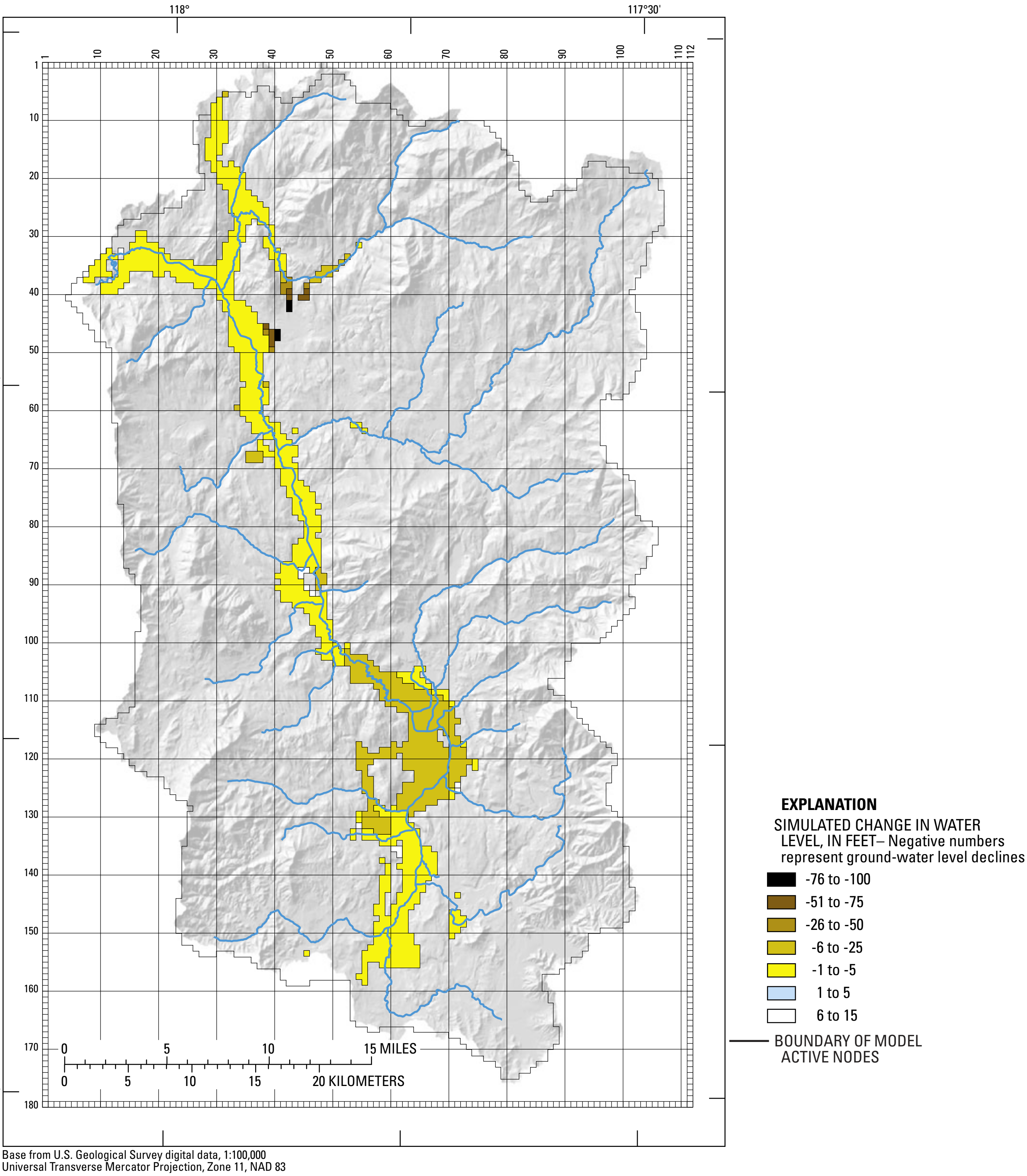
The model represented the City of Colville public-supply wells with two pumping wells in unit UA withdrawing a total of 1.5 Mgal/d (4.5 acre-ft/d). River leakage from Mill Creek was a major source of the water withdrawn by the simulated wells. The water withdrawn by these wells also came from precipitation recharge, secondary recharge, and irrigation near the pumping centers.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

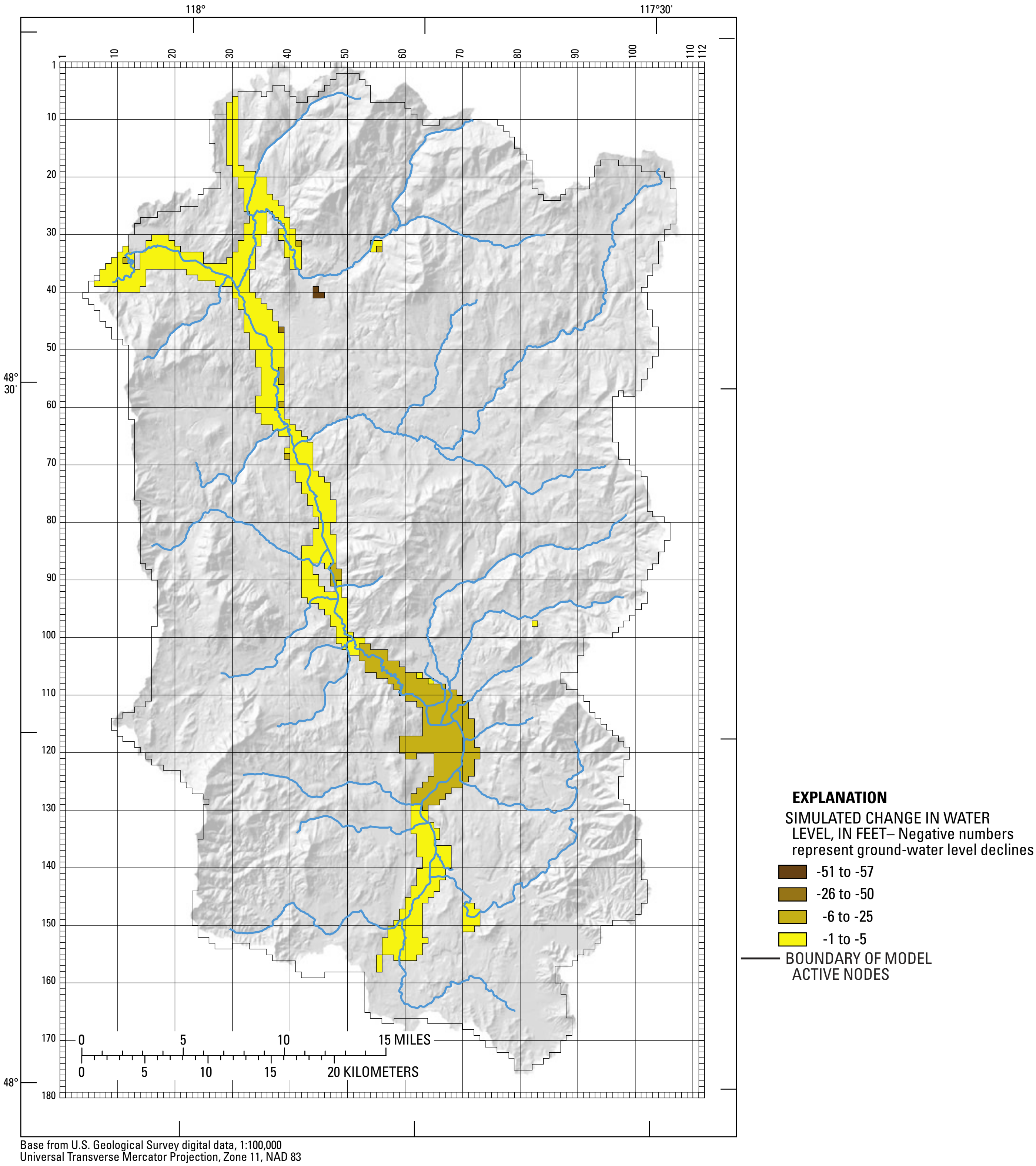
A. Upper outwash aquifer (UA)

Figure 30. Simulated water-level change of current conditions from predevelopment conditions in the Upper outwash aquifer, Colville Valley confining unit, and the Lower aquifer, Colville River Watershed, Stevens County, Washington.



B. Colville Valley confining unit (VC)

Figure 30.—Continued



C. Lower aquifer (LA)

Figure 30.—Continued

Summary

In recent years, increased use of ground- and surface-water supplies in watersheds of Washington State has created concern that insufficient instream flows remain for fish and other uses. Presently, surface water is available for further appropriation only from the mainstem of the Colville River from October 1 through July 15, all streams tributary to the Colville are considered to be fully appropriated by the Washington Department of Ecology under existing water rights, and issuance of new ground-water rights has been halted by the Washington Department of Ecology. The U.S. Geological Survey (USGS), in cooperation with the Colville River Watershed Planning Team, began a two part study in the summer of 2001 to investigate the ground-water system of the valley-fill deposits of the Colville River Watershed. Following the successful completion of the first phase, the USGS continued studies with the Colville River Watershed Planning Team to construct a steady-state, regional ground-water-flow model to develop a better understanding of the ground-water system and the potential regional effects of various ground-water use alternatives on the water resources of the Colville River Watershed.

The Colville River Watershed is underlain by unconsolidated deposits of glacial and non-glacial origin. Geologically, the basin can be grouped into three types of formations: bedrock, glacial deposits, and valley alluvium. The surficial geologic units and the deposits at depth were differentiated into aquifers and confining units on the basis of areal extent and general water-bearing characteristics. Five principal hydrogeologic units are recognized in the study area and form the basis of the ground-water-flow model: Upper outwash aquifer (UA), Till confining unit (TC), Colville Valley confining unit (VC), Lower aquifer (LA), and Bedrock (BR).

Ground-water flow in the unconsolidated sediments underlying the Colville River Watershed is simulated using the USGS modular three-dimensional finite-difference ground-water-flow model (MODFLOW). Five model layers were used to simulate the saturated unconsolidated sediments that overlie the bedrock and one layer of constant thickness was used to simulate the upper part of the bedrock. The boundary of the watershed was simulated as a no-flow boundary except in the area near the outlet where ground-water outflow is approximated. All major streams and lakes are included in the model as head-dependent flux boundaries. Ground-water recharge from precipitation was estimated using the USGS-developed Precipitation-Runoff Modeling System. Secondary recharge from septic systems, sewage disposal, and irrigation application was estimated from reported usage rates and from land-cover and land-use maps. Ground-water pumping from public-supply and domestic wells are included in the simulations. Initial hydraulic properties were estimated from specific capacity tests reported in the first phase of the Colville River Watershed study.

The steady-state Colville River Watershed ground-water-flow model was calibrated to September 2001 conditions using parameter estimation programs and methods that involve automated calibration procedures. Nonlinear regression analyses were applied to minimize the weighted differences, or residuals, between simulated and measured hydraulic head and streamflow measurements. Hydraulic-head measurements for calibration consisted of water-level measurements from 161 wells. To identify gaining and losing stream reaches, a low-flow seepage run (a set of streamflow measurements representing approximately steady-flow conditions) was conducted during September 2001. A total of 44 streamflow measurements were used in the calibration process.

Horizontal hydraulic conductivity values in the calibrated model ranged from 10 to 250 feet per day (ft/d) in the aquifer layers. Vertical hydraulic conductivity values of the confining units were estimated to be 0.0025 ft/d.

Simulated inflow to the model area was 53,000 acre-feet per year (acre-ft/yr) from precipitation and secondary recharge, and 36,000 acre-ft/yr from stream and lake leakage. Simulated outflow from the model was primarily through discharge to streams and lakes (71,000 acre-ft/yr), ground-water outflow (9,000 acre-ft/yr), and ground-water withdrawals (9,000 acre-ft/yr). The period of simulation, September 2001, was extremely dry so all components of the ground-water budget are presumably less than average flow conditions.

The challenge of the Colville River Watershed Planning Team is to supply additional water resources while limiting adverse effects on surface water and maintaining sufficient instream flows for all users. The numerical model was used to simulate the possible effects of increasing ground-water pumping. The model indicated that the increased pumping would come from reduced discharge to streams and lakes and reduced ground-water outflow. Because of the steady-state nature of the model, however, simulated effects are an “ultimate” response and do not indicate the time required to reach this result. The ultimate response simulated by the steady-state model constructed here – on the basis of conditions during a drier-than-average period undoubtedly exceeds the actual response of the system to the simulated stress under average conditions.

The location of the simulated increase in ground-water pumping determined the primary source of the water withdrawn. Pumping wells in the northern end of the main Colville River valley derived a large proportion of the water from reduced ground-water outflow. Pumping wells located in the southern end of the main Colville River valley, however derived a large proportion of the water from reduced flow to rivers and streams. Alternatives simulating ground-water pumping in the relatively thin, discontinuous Upper aquifer resulted in the largest drawdowns.

The calibrated steady-state model was used to simulate ground-water-flow conditions as if no ground-water pumping, secondary recharge, or irrigation application occurred. In this simulation, the cumulative streamflow in the Colville River Watershed increased by 1.1 ft^3/s, or about 37 percent of the present-day net ground-water withdrawal.

The model is intended to simulate the regional ground-water-flow system of the Colville River Watershed and can be used as a tool for water-resource managers to assess the regional effects of changes in stresses to the steady-state system. The regional scale of the model, coupled with relatively sparse data, spatially and temporally, must be considered when applying the model in less well understood areas or examining hydrologic conditions at a smaller scale than what is appropriate.

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Appendix A. Simplified Monthly Water Budget for the Colville River Watershed

A simplified monthly water budget for a typical year is a useful tool to understand the relation between ground-water and surface-water flow. It also is a necessary tool for water-resource management decisions. The simplified water budget presented in this section differs from the ground-water budget discussed in a previous section. The simplified water budget expresses the distribution of precipitation. The ground-water budget expresses the distribution of recharge, or that volume of precipitation that enters the ground-water system.

The two largest components of the simplified water budget are precipitation and evapotranspiration (Kahle and others, 2003). To estimate monthly values for these two terms, measured precipitation, air temperature, and stream discharge time-series data were used to make Precipitation-Runoff Modeling System (PRMS) simulations of the Colville River Watershed. The period of climate record used in model simulations was water years 1990-99. Precipitation for this period was above average, so annual totals of precipitation and streamflow are greater than the numbers presented in Kahle and others (2003).

Rainfall and temperature data are typically point measurements, whereas the model requires input distributed throughout the study area. Precipitation and temperature algorithms used a distance-weighted average approach, in which monthly mean precipitation ratios between climate stations and Modeling Response Units (MRU) were calculated from the Parameter-estimation Regressions on Independent Slopes Model (PRISM) estimates (Daly and others 1994; 1997). MRUs are similar to irregularly shaped model cells that are delineated in a manner that reflects spatially distributed attributes such as slope, aspect, elevation, soils, and vegetation, and which respond similarly to hydrologic inputs such as precipitation. Each MRU is a smaller polygon area of a subbasin in which these physical characteristics are assumed to be homogeneous.

Daily precipitation totals used in the PRMS model simulations were measured at precipitation gages located throughout the Colville River Watershed and surrounding watersheds. Precipitation gages operated by the U.S. National Weather Service (NWS) provided data from a total of 5 gages (fig. A1). The rain module used by PRMS requires mean monthly estimates of precipitation for each MRU to compute ratios between rain gage locations and the MRU. For this purpose, the PRISM model estimates (Daly and others, 1994; 1997) were used.

Measured, daily, minimum-, and maximum-air temperature data were collected by the NWS at five locations (fig. A1). To account for differences in elevation between the stations and the watershed, PRMS adjusts the temperature data on the basis of a calculated lapse rate for every 1,000-foot increase in elevation.

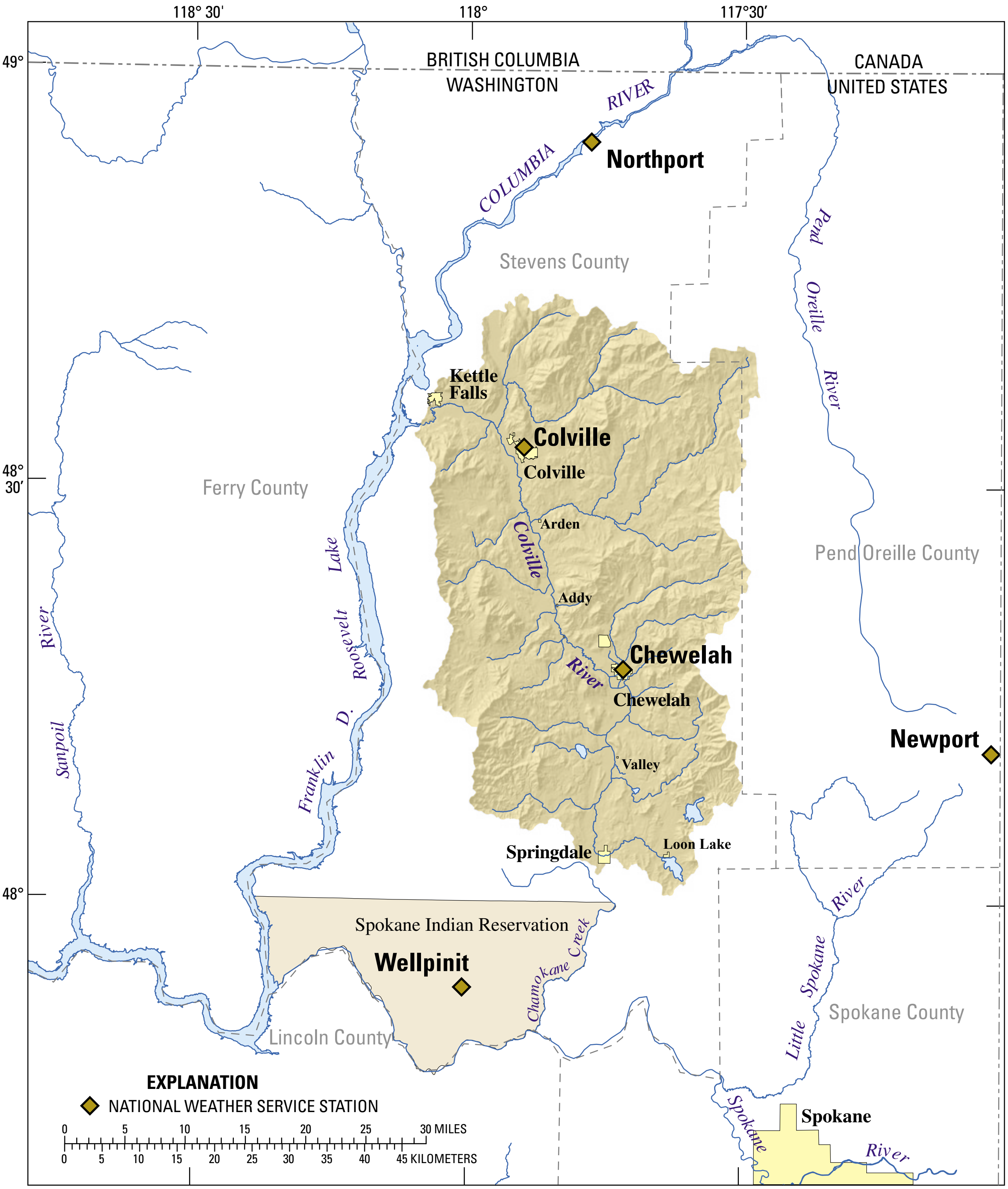
In addition to elevation, slope, and aspect, ancillary information concerning soils, land use and land cover, and vegetation was assigned to each MRU. Digital soil data were obtained from a modified version of the State Soil Geographic Database (STATSGO) general soil maps (U.S. Department of Agriculture, 1994). Parameters from the contiguous U.S. Forest Type Groups map and U.S. Forest Density map provided vegetation information (Zhu and Evans, 1992; Powell and others, 1998). Digital land cover data were obtained from the USGS, the University of Nebraska-Lincoln, and the European Commission’s Joint Research Centre global land cover characteristics database (Loveland and others, 1991; U.S. Geological Survey, 1992).

Ground-water discharge near Kettle Falls was simulated in PRMS as a ground-water sink. The daily accretion to the sink is a function of a seepage constant and the ground-water reservoir storage. The PRMS model was calibrated to the annual ground-water discharge presented in Kahle and others (2003). Mean monthly streamflow values for the Colville River at Kettle Falls (station 12409000) are available for the period of simulation. Net ground-water pumping were estimated to be the reported ground-water pumping (Kahle and others, 2003) minus secondary recharge (50 percent of ground-water pumping).

It is assumed that, in the long term, inflow to the watershed equals outflow and there is little change in the amount of water stored within the watershed. (This assumption is not true at the seasonal or monthly time scale, but for purposes of the simplified water budget, change in storage will equal zero.) The following equation illustrates the relation:

Precipitation = Evapotranspiration + Streamflow at outlet + Net ground-water pumping + Ground-water outflow

The monthly water budget is shown in table A1. The budget is for a period of higher precipitation than the long-term average, so precipitation and streamflow are slightly higher than those values reported in Kahle and others (2003). Evapotranspiration is 21.8 in., as compared to 22.5 in reported in Kahle and others (2003). Estimated ground-water outflow was 0.3 in. in both annual water budgets.



Base from U.S. Geological Survey digital data, 1:100,000
Universal Transverse Mercator Projection, Zone 11, NAD 83

Figure A1. Location of climate data-collection network for the Colville River Watershed, Stevens County, Washington.

Table A1. Estimated monthly water budget for the Colville River Watershed, Stevens County, Washington.

Month	Precipi-tation	Evapotrans-piration	Streamflow	Net ground-water withdrawal (withdrawal minus secondary recharge)	Ground-water outflow
January	3.2	0.1	3.2	0.04	0.02
February	2.4	.3	4.7	.04	.02
March	2.3	1.1	8.7	.05	.02
April	2.1	2.5	12.1	.05	.03
May	3.2	6.9	10.2	.08	.03
June	2.9	4.7	7.2	.14	.03
July	1.7	3.5	3.2	.26	.03
August	.8	1.3	1.7	.26	.02
September	1.0	.7	1.6	.09	.02
October	2.0	.4	1.6	.05	.02
November	3.1	.2	2.0	.04	.02
December	3.4	.1	2.5	.03	.02
Annual	28.10	21.80	4.90	1.13	.28

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