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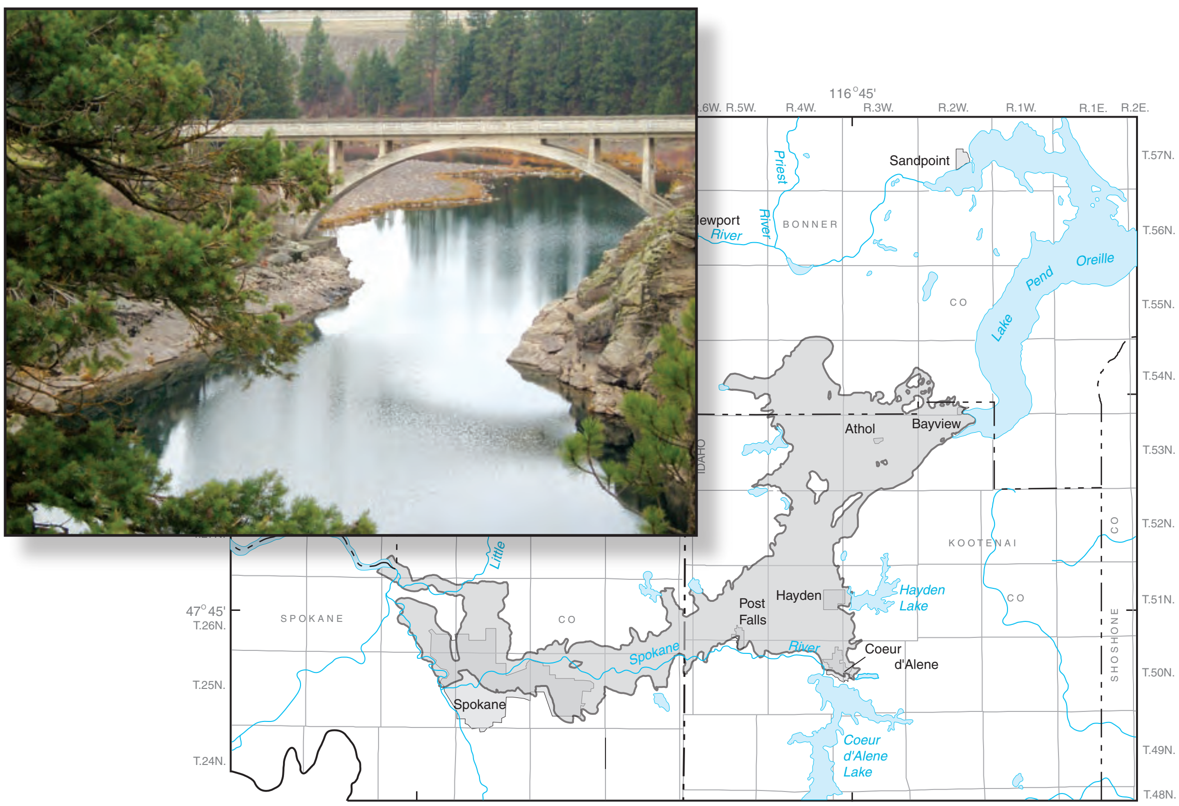
# Compilation of Geologic, Hydrologic, and Ground-Water Flow Modeling Information for the Spokane Valley—Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho




Scientific Investigations Report 2005–5227


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

**Cover:** Photograph of the Spokane River and the Washington Water Power bridge looking downstream (to the northwest) from the Post Falls Dam in Post Falls, Idaho. (Photograph taken by Sue Kahle, U.S. Geological Survey, November 9, 2005.)

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By Sue C. Kahle, Rodney R. Caldwell, and James R. Bartolino

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

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# Conversion Factors and Datums

## Conversion Factors

| Multiply | By | To obtain |
|---|---|---|
| acre-foot (acre-ft) | 1,233 | cubic meter |
| acre-foot (acre-ft) | 0.001233 | cubic hectometer |
| cubic foot per second ($ft^3/s$) | 0.02832 | cubic meter per second |
| foot (ft) | 0.3048 | meter |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot per mile (ft/mi) | 0.1894 | meter per kilometer |
| foot per second (ft/s) | 0.3048 | meter per second |
| foot per year (ft/yr) | 0.3048 | meter per year (m/yr) |
| foot squared per day ($ft^2/d$ | 0.09290 | meter squared per day |
| gallon (gal) | 3.785 | liter |
| gallon (gal) | 0.003785 | cubic meter |
| gallon per day (gal/d) | 0.003785 | cubic meter per day |
| gallon per minute (gal/min) | 0.06309 | liter per second |
| inch per year (in/yr) | 25.4 | millimeter per year |
| mile (mi) | 1.609 | kilometer |
| cubic mile ($mi^3$) | 4.168 | cubic kilometer |
| square mile ($mi^2$) | 2.590 | square kilometer |
| million gallons (Mgal) | 3,785 | cubic meter |
| million gallons per day (Mgal/d) | 0.04381 | cubic meter per second |

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

$$°F=(1.8×°C)+32.$$

## Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

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

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.

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# Compilation of Geologic, Hydrologic, and Ground-Water Flow Modeling Information for the Spokane Valley–Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho

By Sue C. Kahle, Rodney R. Caldwell, and James R. Bartolino

## Abstract

The U.S. Geological Survey, in cooperation with the Idaho Department of Water Resources and Washington Department of Ecology compiled and described geologic, hydrologic, and ground-water flow modeling information about the Spokane Valley–Rathdrum Prairie (SVRP) aquifer in northern Idaho and northeastern Washington. Descriptions of the hydrogeologic framework, water-budget components, ground- and surface-water interactions, computer flow models, and further data needs are provided. The SVRP aquifer, which covers about 370 square miles including the Rathdrum Prairie, Idaho and the Spokane valley and Hillyard Trough, Washington, was designated a Sole Source Aquifer by the U.S. Environmental Protection Agency in 1978. Continued growth, water management issues, and potential effects on water availability and water quality in the aquifer and in the Spokane and Little Spokane Rivers have illustrated the need to better understand and manage the region's water resources.

The SVRP aquifer is composed of sand, gravel, cobbles, and boulders primarily deposited by a series of catastrophic glacial outburst floods from ancient Glacial Lake Missoula. The material deposited in this high-energy environment is coarser-grained than is typical for most basin-fill deposits, resulting in an unusually productive aquifer with well yields as high as 40,000 gallons per minute. In most places, the aquifer is bounded laterally by bedrock composed of granite, metasedimentary rocks, or basalt. The lower boundary of the aquifer is largely unknown except along the margins or in shallower parts of the aquifer where wells have penetrated its entire thickness and reached bedrock or silt and clay deposits. Based on surface geophysics, the thickness of the aquifer is about 500 ft near the Washington–Idaho state line, but more than 600 feet within the Rathdrum Prairie and more than 700 feet in the Hillyard trough based on drilling records. Depth to water in the aquifer is greatest in the northern Rathdrum Prairie (about 500 feet) and least near the city of Spokane along the Spokane River (less than about 50 feet). Ground-water flow is south from near the southern end of Lake Pend Oreille and Hoodoo Valley, through the Rathdrum Prairie, then west toward Spokane. In Spokane, the aquifer splits and water moves north through the Hillyard Trough as well as west through the Trinity Trough. From the Trinity Trough water flows north along the western arm of the aquifer. The aquifer's discharge area is along the Little Spokane River and near Long Lake, Washington.

A compilation of estimates of water-budget components, including recharge (precipitation, irrigation, canal leakage, septic tank effluent, inflow from tributary basins, and flow from the Spokane River) and discharge (withdrawals from wells, flow to the Spokane and Little Spokane Rivers, evapotranspiration, and underflow to Long Lake) illustrates that these estimated values should be compared with caution due to several variables including the area and time period of interest as well as methods employed in making the estimates.

Numerous studies have documented the dynamic ground-water and surface-water interaction between the SVRP aquifer and the Spokane and Little Spokane Rivers. Gains and losses vary throughout the year, as well as the locations of gains and losses. September 2004 streamflow measurements indicated that the upper reach of the Spokane River between Post Falls and downstream at Flora Road lost 321 cubic feet per second. A gain of 736 cubic feet per second was measured between the Flora Road site and downstream at Green Street Bridge. A loss of 124 cubic feet per second was measured for the reach between the Green Street Bridge and the Spokane River at Spokane gaging station. The river gained about 87 cubic feet per second between the Spokane River at Spokane gaging station and the TJ Meenach Bridge. Overall, the Spokane River gained about 284 cubic feet per second between the Post Falls, Idaho, gaging station and the TJ Meenach Bridge. Estimated gains of 251 cubic feet per second were calculated for the reach between the Little Spokane River gaging stations at Dartford and near Dartford (a distance of about 6 river miles).

In the early 1980s, a two-dimensional computer flow model of the Washington side of the SVRP aquifer indicated that pumping at the current rate (1977) had little effect on water levels in the aquifer. During a 1-year simulation, pumping at twice the 1977 rate of 227 cubic feet per second resulted in calculated water-level declines of about 3 feet and Spokane River streamflow declines of about 150 cubic feet per second in the summer and about 50 cubic feet per second during the rest of the year. The increased pumping rate had a more significant effect on the discharge of the Spokane River than on the change in water levels in the aquifer. In the late 1990s, a three-dimensional flow model of the Washington side of the SVRP aquifer was constructed as part of a wellhead protection program and was designed to represent scenarios for September 1994 and April 1995. The calibrated model was used to estimate ground-water capture zones using particle tracking. Also in the late 1990s, the first ground-water flow model of the entire SVRP aquifer was constructed. The finite-difference, single-layer, steady-state model was designed as a tool for understanding the overall water balance. In 2004, a modeling report was completed for the Little Spokane River and Middle Spokane River watersheds, Spokane County, Washington. The model, representing water years 1994–99, was constructed for use in planning and managing watershed hydrologic resources.

Further data needs that would provide better understanding of the SVRP aquifer and provide a more comprehensive data set for the construction and calibration of a regional numerical flow model include:

- Quantification of ground-water inflow from surrounding bedrock boundaries and peripheral watersheds;
- Understanding of surface-water/ground-water interaction of lakes adjacent to the aquifer;
- Characterization of the cross sectional area and hydrostratigraphy of the aquifer at key locations;
- Updated ground-water withdrawals and estimates of consumptive use of water;
- Additional aquifer-head measurements near rivers in conjunction with stage and discharge measurements;
- Additional temporal and regional aquifer-wide head measurements;
- Understanding of possible ground-water discharge out of the SVRP basin beneath the Spokane and Little Spokane Rivers;
- Continued measurement of streamflow and (or) river stage at existing and (or) additional river locations; and
- Determination of water flow directions to or from the rivers using chemical tracers.

# Introduction

The Spokane Valley–Rathdrum Prairie (SVRP) aquifer is the sole source of drinking water for over 400,000 residents in Spokane County, Washington, and Bonner and Kootenai Counties, Idaho (fig. 1). The area includes the rapidly growing cities of Spokane, Spokane Valley, and Liberty Lake, Washington, and Coeur d'Alene and Post Falls, Idaho. Recent and projected urban, suburban, and industrial/commercial growth has raised concerns about potential future effects on water availability and water quality in the SVRP aquifer, and Spokane and Little Spokane Rivers. Water resource concerns include growing demands on ground water, low streamflow in reaches of the Spokane and Little Spokane Rivers, and water quality problems associated with changing land use activities. Water resource demands are increasing at a time when aquifer and river dynamics are not well understood. This understanding is essential in making proper management decisions concerning ground water and surface water appropriations in the SVRP area.

Management of the SVRP aquifer is complicated by the interstate, multi-jurisdictional nature of the aquifer. The States of Washington and Idaho have primary responsibility for water allocation and water quality. However, local governments increasingly are being called upon to consider water supply and quality implications in land use planning. Aquifer management also is complicated by the interconnection between ground water and surface water; ground water exchanges with surface channels may influence surface channel flow rates and surface-water quality.

The SVRP aquifer primarily consists of thick layers of coarse-grained sediments—gravels, cobbles, and boulders—deposited during a series of outburst floods resulting from repeated collapse of the ice dam that impounded ancient Glacial Lake Missoula (Bretz, 1930). Sources of recharge to the aquifer include infiltration from precipitation, return flow from water applied at land surface, leakage from the Spokane and Little Spokane Rivers and adjacent lakes, and surface- and ground-water inflow from tributary basins. The aquifer discharges into the Spokane and Little Spokane Rivers and through withdrawals from wells. The aquifer was designated a "Sole Source Aquifer" by the U.S. Environmental Protection Agency (USEPA) in 1978 (under the provisions of the Federal Safe Drinking Water Act of 1974) in response to local concerns about aquifer vulnerability to water quality degradation. The USEPA defines such an aquifer as one that supplies at least 50 percent of the drinking water consumed in the area overlying the aquifer (U.S. Environmental Protection Agency, 2000). Communities depending on a sole-source aquifer generally do not have a viable alternative drinking-water source.

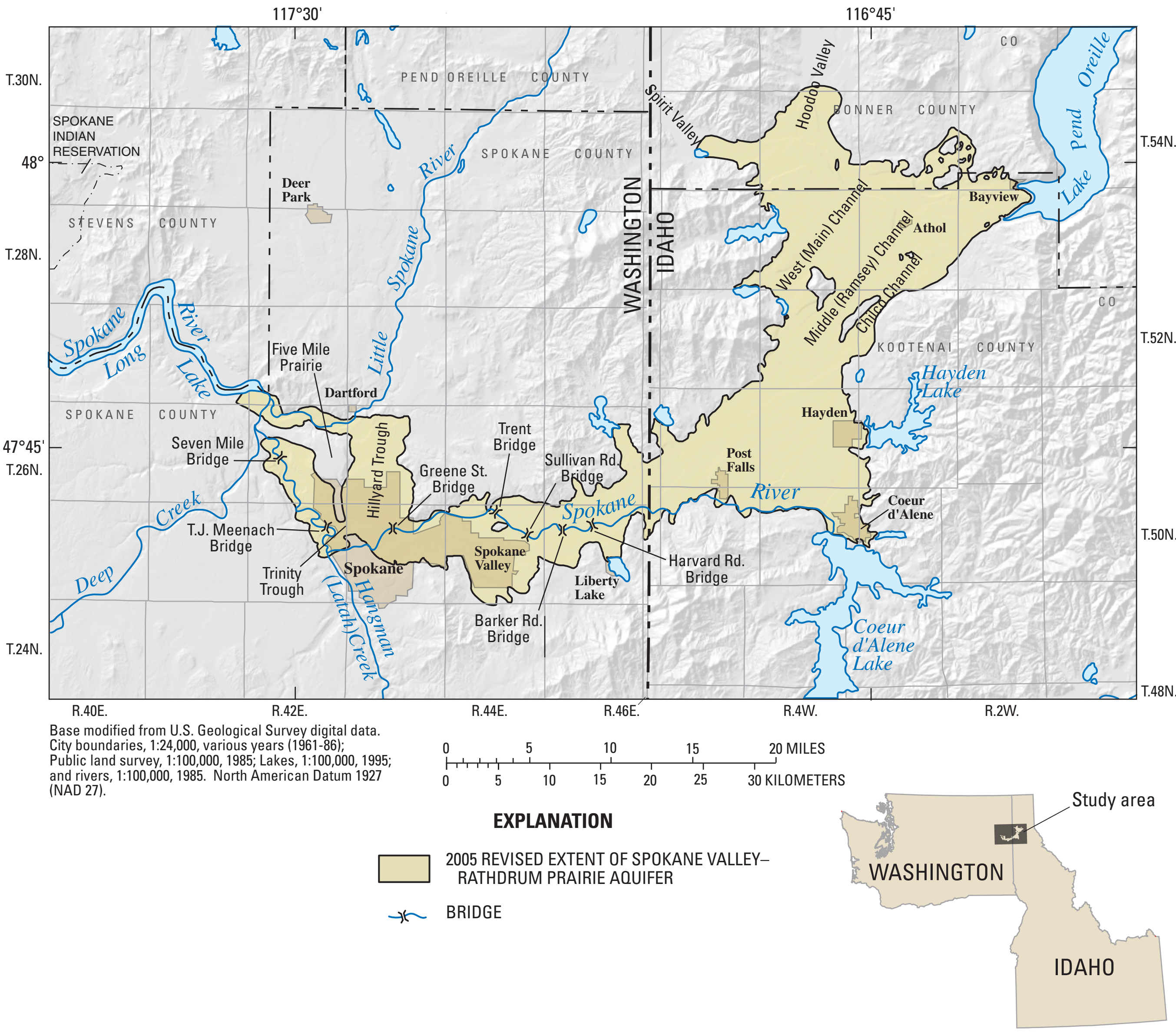


**Figure 1.** Location of the Spokane Valley–Rathdrum Prairie aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho.

Water management issues in this rapidly growing bi-state area have increasingly become regional in nature. Several groups, therefore, have initiated a comprehensive, regional study of the SVRP aquifer to serve as a scientific basis for addressing regional water concerns. In 2004, the Washington Department of Ecology (WDOE), the Idaho Department of Water Resources (IDWR), and the U.S. Geological Survey (USGS) in consultation with local stakeholders developed a comprehensive work plan for a study to gain a better understanding of ground water and surface water resources in the SVRP study area. The initial study objective is the development of a comprehensive data set to provide an improved scientific basis for water management of the SVRP aquifer. A concurrent phase of the study will include the construction of numerical ground- and surface-water flow models to support the conjunctive management of ground and surface water in the SVRP area. The results of this study are intended to provide tools to evaluate alternative water resource management scenarios.

This document, summarizing the current (2004) understanding of the hydrogeologic framework, existing ground-water flow models, water-budget components, ground-water/surface-water interactions, and data needs, is one of several reports that will be produced during this study. The first report produced during this study summarized the long-term trends in discharge of the Spokane River (Hortness and Covert, 2005). The next report described a water-level map of the aquifer for September, 2004 (Campbell, 2005). Future reports are planned that will document the updated conceptual model of the aquifer and the numerical flow models that are the final products of this investigation.

## Purpose and Scope

This report provides a summary of geologic, hydrologic, and ground-water flow modeling information available as of June 2005 for the SVRP aquifer. As such, this information is directly relevant to the construction of the flow model being developed for the SVRP aquifer. Based on available data, the needs of the models, and the data gaps identified, it may be determined that additional hydrologic and (or) hydrogeologic data would be helpful in reducing uncertainties associated with the numerous data requirements of the models. The purpose of this report is to present the current knowledge base regarding the physical nature of the SVRP aquifer that in turn, can be used by the States of Washington and Idaho in order to evaluate the adequacy of available data for the construction of the models and to guide additional data collection.

This report describes previous investigations including the current understanding of the hydrogeologic framework, surface geophysics, water budget components, ground-water/surface-water interactions, and ground-water flow modeling in the SVRP aquifer study area. The scope of the report includes the regional and local geologic history, the surficial and subsurface geology, the physical characteristics of the aquifer and adjacent units, ground-water flow directions, summaries of surface- and ground-water withdrawals in the study area, estimates of ground-water recharge, and a description of the ground-water/surface interaction between the Spokane River and the SVRP aquifer. Additional data needs that would allow for a more refined understanding of the area's water resources also are provided.

## Description of Study Area

The SVRP aquifer underlies about 370 $mi^2$ of a relatively flat, alluvium-covered valley surrounded by bedrock highlands (pl. 1). The aquifer extends south from Lake Pend Oreille to Coeur d'Alene Lake and westward across the Washington–Idaho state line to near Nine Mile Falls northwest of the City of Spokane. Land surface altitudes of the valley range from about 1,500 to nearly 2,600 ft above the National Geodetic Vertical Datum of 1929 (NGVD 29). Several lakes are located along the margins of the aquifer, the largest of which are Coeur d'Alene Lake and Lake Pend Oreille in Idaho (pl. 1). The valley generally is void of surface drainage other than the Spokane and Little Spokane Rivers (pl. 1).

Ground water is the primary source for public supply, domestic, irrigation, and industrial water use in the area (Hutson and others, 2004). In 2000, estimates of ground-water use in Spokane, Kootenai, and Bonner Counties were more than 188 Mgal/d (Hutson and others, 2004). Although these estimates include entire counties, which extend beyond the area of the SVRP aquifer, the majority of the ground water used in those counties is derived from the SVRP aquifer. In Spokane County alone, estimates of ground-water use in 2000 were about 110 Mgal/d for public supply, 12 Mgal/d for domestic use, 9 Mgal/d for irrigation, and 8 Mgal/d for industrial use, accessed September 2004 at http://water.usgs.gov/watuse/data/2000/index.html. Peak summer daily ground-water withdrawals from the SVRP aquifer are estimated to be about 450 Mgal/d (MacInnis and others, 2000).

Primary land-use types overlying the SVRP aquifer include agriculture and urban (Nakagaki, Hitt, and McNamara, U.S. Geological Survey, written commun., 2001) (fig. 2). Agricultural land is predominantly used for hay production, wheat, grass seed, barley, oats, and for pasture. Urban areas supplied by the aquifer include the Spokane metropolitan area in Washington and Coeur d'Alene and Post Falls in Idaho. Residential and commercial development is rapidly increasing in the area as evidenced between the 1990 and 2000 censuses, with a 16 percent population increase in Spokane County, Washington and nearly 56 percent increase in Kootenai County, Idaho (U.S. Census Bureau, 2002). The upland areas surrounding the aquifer area primarily are covered with coniferous forests and residential housing.

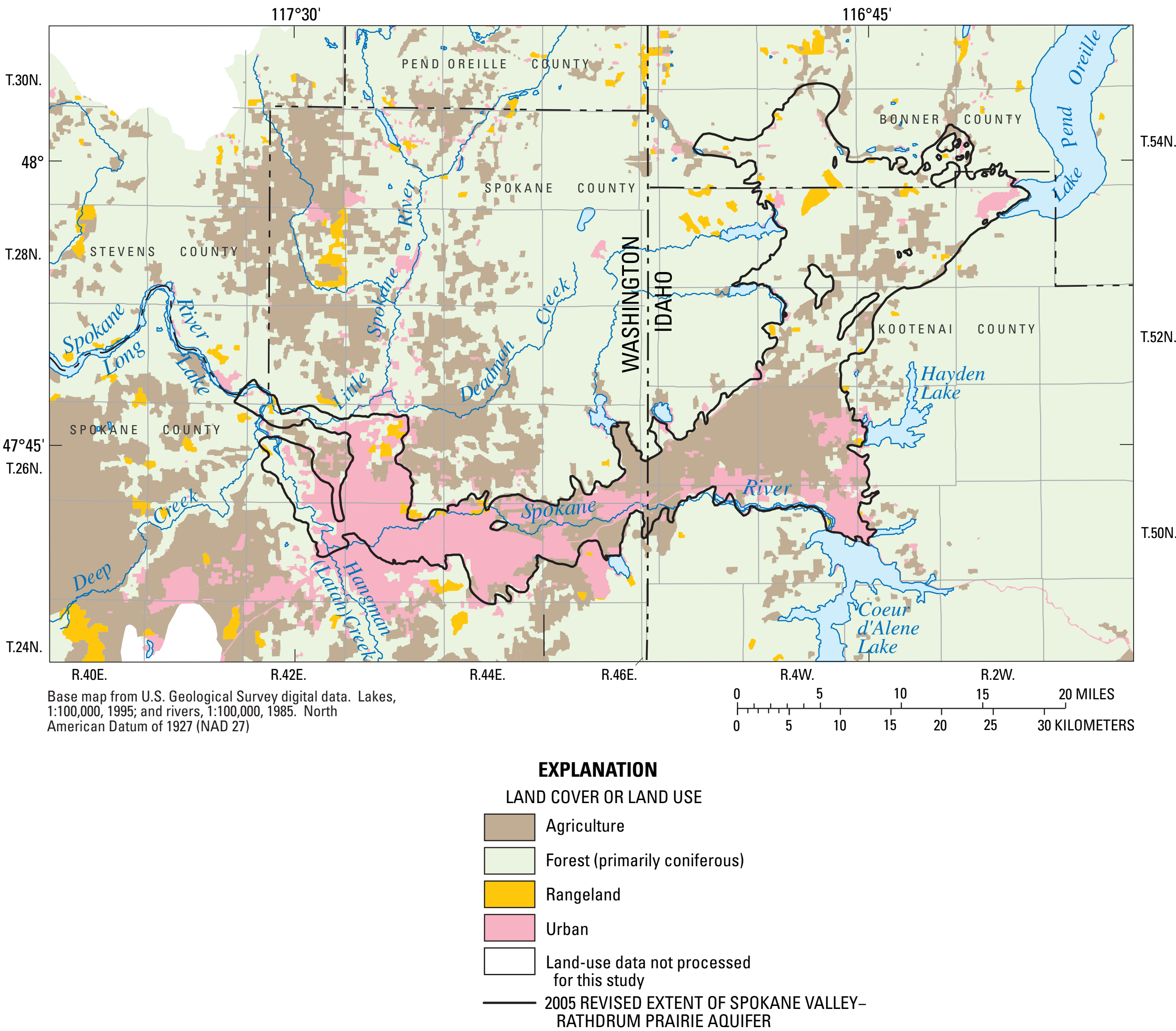


**Figure 2.** Generalized land cover or land use in the Spokane Valley–Rathdrum Prairie area, Washington and Idaho.

Climate in the study area varies from subhumid to semiarid with warm, dry summers and cool, moist winters (Molenaar, 1988). Mean annual (1971-2000) precipitation at weather stations in the area were 16.7 in/yr at the Spokane Airport, Washington, 25.9 in/yr near Bayview, Idaho, and 28.1 in/yr at Coeur d'Alene Airport, Idaho (Western Regional Climate Center, 2005). Most precipitation falls as snow from November through March (Molenaar, 1988). The distribution of average annual precipitation for 1961-90 in the study area is shown in figure 3.

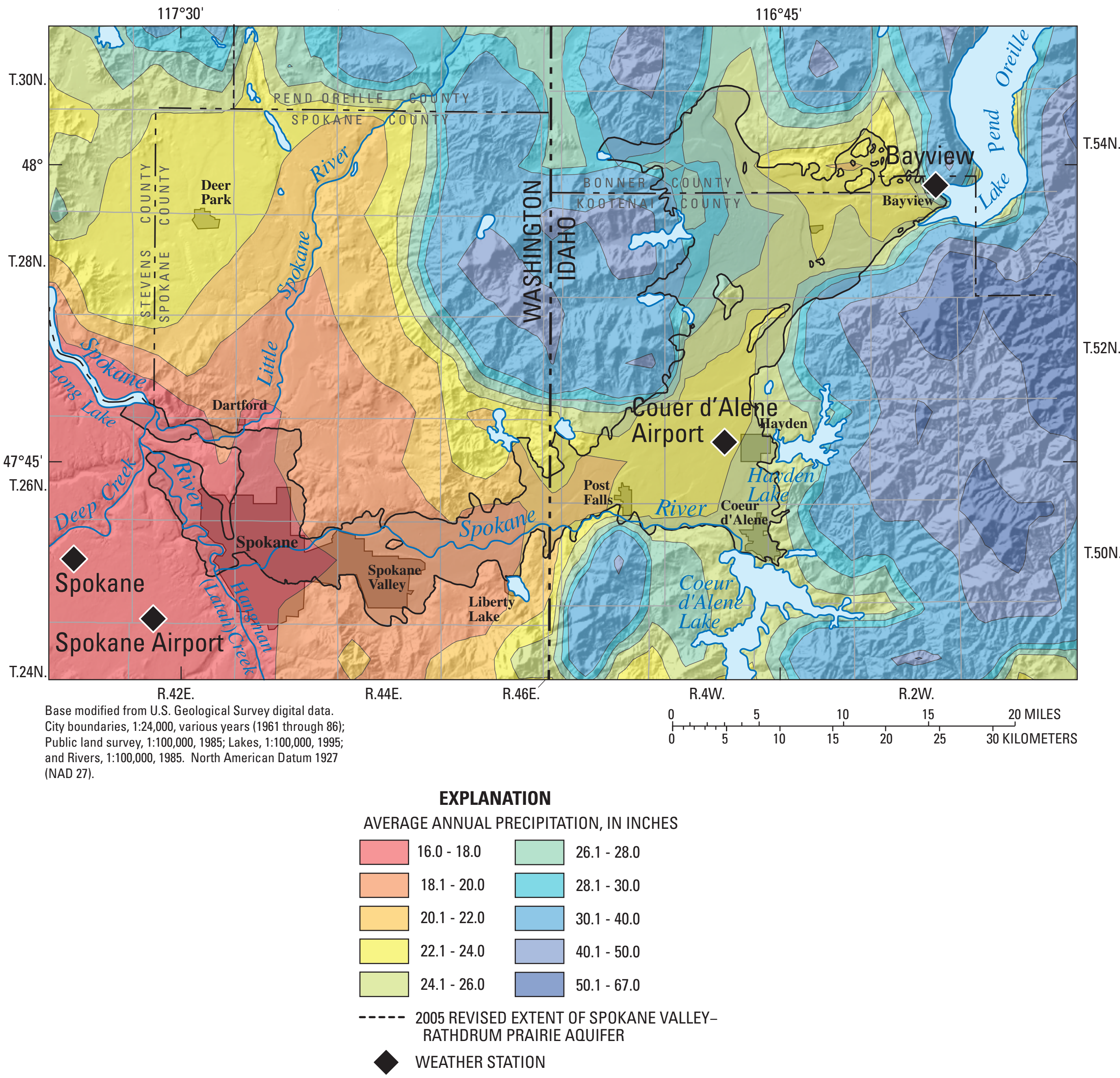


**Figure 3.** Average annual precipitation based on 30 years of record, 1961–90, in the Spokane Valley–Rathdrum Prairie area, Washington and Idaho.
(Data obtained from Oregon State University, 2005.)

## Acknowledgments

This report was completed with the assistance of many individuals and groups. The authors thank the members of the Spokane Valley–Rathdrum Prairie Aquifer Technical Advisory Committee who provided technical insights, historical and recent data, and guidance on data collection needs. Private landowners; water purveyors; city, county, and State agencies; consulting firms; and local colleges and universities provided access to private property, data, special collections, and (or) field assistance that was invaluable in completing this report. The staff of the Post Falls, Idaho, and Spokane, Washington, USGS field offices provided ongoing support for field data collection as well as coordination and planning required by the project.

# Previous Investigations

Numerous reports document investigations regarding the physical framework and hydrologic characteristics of the SVRP aquifer, some regional in nature and some site-specific. Each investigation has contributed to an improved understanding of the aquifer within the limitations of the scope of the particular investigation or investigative techniques available at the time the study was conducted.

The earliest aquifer-wide studies were done in the early 1930s by Fosdick (1931) and Newcomb (1933). These investigators described basic geologic, physiographic, and hydrologic features of the aquifer and its recharge and discharge areas. In the 1940's, Piper and Huff (1943), Huff (1943), and Piper and La Rocque (1944) studied the aquifer in more detail and provided water-level data from a series of wells, made estimates of hydraulic gradient, and made estimates of recharge and discharge from various sources.

Interest in the aquifer grew considerably in the 1950s. Nace and Fader (1950) tabulated all available USGS data on wells tapping the aquifer. In support of developing water resources for irrigation needs on the Rathdrum Prairie, the Bureau of Reclamation summarized the sources and volumes of water, seepage losses, storm flows, and recharge in several unpublished documents (Lenz, 1950, Anderson, 1951, Meneely, 1951). Fader (1951) compiled water-level data from wells on the Rathdrum Prairie and near Lakes Pend Oreille, Hayden, and Coeur d'Alene. Weigle and Mundorff (1952) compiled well records and water-level and water-quality data for wells in the Washington part of the aquifer. Newcomb and others (1953) provided the first thickness information for the aquifer with the results of his seismic refraction profiles done near the Washington–Idaho state line and in the Hillyard Trough.

Sources and amounts of recharge to the aquifer were studied by Thomas (1963), Frink (1964) and Walker (1964). In 1968, Pluhowski and Thomas developed a ground-water budget for the aquifer. Cline (1969) studied the western end of the aquifer in Washington and the Little Spokane River basin to the north.

Hammond (1974) described the hydrogeologic framework and ground-water movement in the northern Rathdrum Prairie area between Lake Pend Oreille and the town of Rathdrum. In 1976, a 13-volume report on water resources of the metropolitan Spokane region was compiled by the U.S. Army Corps of Engineers and Kennedy-Tudor Engineers (1976) that focused on waste-water management considerations. Drost and Seitz (1978b) produced a report that was used in the "sole source" petition to USEPA. Based on data available at the time, they described the hydrologic characteristics, patterns of water use and disposal, water quality in the aquifer, and alternative water sources.

Bolke and Vaccaro (1981) summarized a ground-water flow model for the Washington part of the aquifer. Hydrologic data used in model construction is summarized in Bolke and Vaccaro (1979). Jehn (1988) summarized existing hydrologic and land-use data for the Rathdrum Prairie aquifer and identified major potential contaminant sources. Molenaar (1988) described the geologic history and the water-bearing and water-quality characteristics of the Spokane aquifer in a report designed to appeal to the lay reader.

Painter (1991a) described ground water contamination and monitoring activities on the Rathdrum Prairie and identified areas outside USEPA's designated Sole Source Aquifer that are in direct hydraulic connection with the aquifer. Painter (1991b) provided an estimate of recharge from all sources to the Rathdrum Prairie aquifer. In the late 1990s, hydrogeologic investigations were conducted and associated ground-water flow models were constructed for the Washington part of the aquifer as part of the city of Spokane and the Spokane Aquifer Joint Board's Wellhead Protection Programs (CH2M HILL, 1998, 2000a).

Golder Associates, Inc. (2003, 2004) described data collection and modeling efforts during the Little and Middle Spokane Watershed Assessment Program that included parts of Spokane, Pend Oreille, and Stevens Counties, including a small northwestern part of the SVRP aquifer. MacInnis and others (2000, 2004) produced the 2000 version and the 2004 update of the popular Spokane Valley–Rathdrum Prairie Aquifer Atlas that describes the aquifer's formation, use, history, and physical characteristics.

Caldwell and Bowers (2003) studied the surface-water/ground-water interactions of the aquifer and the Spokane River between Post Falls, Idaho, and Spokane, Washington. Stevens (2004) described the hydrogeology and water chemistry of the Rathdrum Prairie near Twin Lakes. Baldwin and Owsley (2005) described the hydrogeology of the Middle (Ramsey) Channel adjacent to Round Mountain on the Rathdrum Prairie.

# Geologic Information

The SVRP study area has undergone a complex series of geologic events that have resulted in the surface and subsurface geologic framework that exists today. A basic understanding of these geologic events and the general order in which they occurred is helpful in understanding the occurrence of ground water in the study area. A simplified geologic time scale (table 1) is provided to aid the reader in understanding the sequence of geologic events and the magnitude of geologic time over which they occurred.

Descriptions of the region's geologic history are available at various levels of detail in numerous documents listed in the "Selected References" section of this report. The summary that follows is based in part on descriptions contained in Conners (1976), McKiness (1988a), Molenaar (1988), Adema (1999), Breckenridge and Othberg (2001), Kiver and Stradling (2001), and Lewis and others (2002).

In this report, a simplified geologic history is described for three major time periods. The pre-Tertiary geology includes mostly Precambrian sedimentary rocks that have been metamorphosed and disrupted in places by igneous intrusions. The Tertiary geology includes the Columbia River basalts and interbedded lacustrine deposits of the Latah Formation. The Quaternary geology includes mostly glacial and interglacial deposits of varying grain size that overly the older rocks.

## Pre-Tertiary Geology

The oldest rocks in the region surrounding and underlying the SVRP aquifer study area are metamorphosed, fine-grained sediments that were originally deposited in a large, shallow north-south trending marine basin during the Precambrian Era. These rocks are in outcrop today as low-grade metasedimentary rocks including argillite, siltite, and quartzite, which grade locally into more highly metamorphosed schists and gneisses.

Following deposition and metamorphism, as much as 20,000 ft of the Precambrian rocks were eroded before the Paleozoic Era began (Conners, 1976). During the Cambrian, additional sedimentation occurred in shallow seas that resulted in shale, limestone, and sandstone being deposited over the Precambrian rocks. However, from the end of Cambrian time to the present, the region mostly has been emergent and much of the post-Cambrian sediments have been eroded from the area leaving few surface exposures. Emplacement of various igneous intrusive bodies, along with associated metamorphism and deformation, occurred over a long time between the Jurassic and Tertiary. During the Cretaceous, faulting and emplacement of large granitic bodies resulted in the formation of the north-south trending Purcell Trench, a geomorphically low feature, that extends from north of the Canadian Border south to the Rathdrum Prairie (pl. 2). Approximate fault locations in the study area, from Zientek and others (2005), are shown on plate 2. Movement on faults mapped within the SVRP aquifer extent (pl. 2) ended by Miocene time when drainages in the area were invaded by Columbia River basalt (Lewis and others, 2002).

In pre-Tertiary time, the region's surface-water drainage was from a vast area to the north and east of the SVRP study area. Streams flowed southward from the Purcell Trench and Clark Fork Valley into presumably a large river that flowed through the Rathdrum Prairie and then westward through the Spokane Valley to the ancient Columbia River. The pre-Tertiary landscape was characterized by ridge crests and valley bottoms with considerable relief, probably 4,000 ft or more in places (Molenaar, 1988).

## Tertiary Geology

During the Miocene, basalt flows of the Columbia River Group spread northeastward from the Columbia Plateau, filling the deep canyons of the pre-Tertiary landscape. Drainage systems that previously transported sediment out of the area, now deposited their sediment at the margins of the basalt flows. Early Miocene basalt flows dammed drainages, including the ancient Rathdrum–Spokane River, creating lakes in which sand, silt, and clay of the Latah Formation were deposited. The Latah sediments consist predominantly of lacustrine silt and clay, with some fluvially deposited sand and gravel units (McKiness, 1988a). The older basalt flows likely did not extend to the eastern and northern Rathdrum Prairie and a relatively thick section of sediment accumulated in those areas. Late Miocene basalt flows eventually overrode the entire Rathdrum Prairie region, creating alternating layers of basalt and Latah Formation interbeds, as recorded in drillers' logs for wells in the northeastern Rathdrum Prairie (Hammond, 1974).

During a period of slow downcutting from the Late Miocene to the Early Pleistocene, as much as 590 ft of Latah sediments were removed from the region (Anderson, 1927). Streams in the developing drainages eroded much of the exposed Latah beds and some of the younger basalt near the margins of the basin. Accurate estimates of thickness and extent of the remaining Latah sediments are difficult to determine due to the cover of Pleistocene drift and a scarcity of boreholes that penetrate below the water table. Anderson (1940) discovered a 980 ft thick bed of Latah Formation below an exposed basalt flow when drilling a well west of Hayden Lake.

Late Tertiary landscape likely was characterized by the ancient Spokane–Rathdrum River following a course similar to today's Spokane River except in north Spokane where the river's course probably followed the Hillyard Trough on the east side of the basalt plateau of Fivemile Prairie (Newcomb and others, 1953). The river then flowed west along the present reach of the Little Spokane River valley toward the present main valley near Long Lake. Tertiary sediments associated with this ancient river may occur at depth along its historic course, now buried by Pleistocene drift.

**Table 1.** Geologic timescale with simplified geologic units of the study area.

[Modified from http://geology.er.usgs.gov/paleo/geotime.shtml and http://www.geosociety.org/science/timescale/timescl.htm, accessed February 8, 2005. **Abbreviations:** –, indicates a gap in the geologic record resulting from erosion and (or) nondeposition]

| | | | | |
|---|---|---|---|---|
| Phanerozoic Eon (544 million years ago to present) | Cenozoic Era (65 million years ago to present) | Quaternary Period (1.8 million years ago to present) | Holocene Epoch (8,000 years ago to present) | Recent non-glacial sediment |
| | | | Pleistocene Epoch (1.8 million to 8,000 years ago) | Glacial deposits and catastrophic flood deposits |
| | | Tertiary Period (65 to 1.8 million years ago) | Pliocene Epoch (5.3 to 1.8 million years ago) | – |
| | | | Miocene Epoch (23.8 to 5.3 million years ago) | Basalt and older sediments |
| | | | Oligocene Epoch (33.7 to 23.8 million years ago) | – |
| | | | Eocene Epoch (55.5 to 33.7 million years ago) | Intrusive igneous rocks |
| | | | Paleocene Epoch (65 to 55.5 million years ago) | |
| | Mesozoic Era (248 to 65 million years ago) | Cretaceous Period (145 to 65 million years ago) | | |
| | | Jurassic Period (213 to 145 million years ago) | | – |
| | | Triassic Period (248 to 213 million years ago) | | |
| | Paleozoic Era (544 to 248 million years ago) | Permian Period (286 to 248 million years ago) | | |
| | | Carboniferous Period (360 to 286 million years ago) | | |
| | | Devonian Period (410 to 360 million years ago) | | |
| | | Silurian Period (440 to 410 million years ago) | | |
| | | Ordovician Period (505 to 440 million years ago) | | |
| | | Cambrian Period (544 to 505 million years ago) | | Sedimentary rocks |
| Precambrian Time (4,500 to 544 million years ago) | Proterozoic (2,500 to 544 million years ago) | | | Metamorphic rocks |
| | Archean (3,800 to 2,500 million years ago) | | | – |
| | Hadean (4,500 to 3,800 million years ago) | | | |

## Quaternary Geology

During the Pleistocene Epoch as the Earth's climate experienced warming and cooling periods, the study area repeatedly was subjected to erosional and depositional processes associated with glacial and interglacial periods. Although as many as six major glaciations affected the region, only the most recent can be described with any level of certainty. Sediments from earlier periods are encountered locally in some wells, but little surface evidence remains to reconstruct their depositional history.

During the climax of the most recent Pleistocene glaciation (about 15,000 years before present), much of northern Washington, Idaho, and westernmost Montana, was covered by lobes of the Cordilleran ice sheet (fig. 4). The large ice sheet formed in the mountains of British Columbia and flowed south, filling valleys and overriding low mountain ranges in the northern parts of Washington, Idaho, and Montana. The Pend Oreille River and Purcell Trench lobes contributed vast quantities of sediment into the study area via melt-water streams from the glacial lobes. The Okanogan and Columbia River lobes influenced the SVRP study area by occasionally blocking westward drainage of the ancestral Columbia and Spokane Rivers and creating large ice-age lakes. Glacial Lake Columbia (fig. 4) was created when the Okanogan Lobe blocked the ancestral Columbia River (Waitt and Thorson, 1983).

The Purcell Trench lobe in northern Idaho blocked the drainage of the ancestral Clark Fork River in northwestern Montana and created Glacial Lake Missoula (fig. 4). Glacial Lake Missoula had a maximum surface elevation of about 4,200 ft, a maximum depth of about 2,000 ft, and a maximum surface area of about 3,000 $mi^2$. Catastrophic failure of the Clark Fork ice dam released as much as 500 $mi^3$ of water at a rate 10 times the combined flow of all the present-day rivers on earth. The torrent of flood water crossed the states of Montana, Idaho, Washington, and Oregon before reaching the Pacific Ocean. The continuous southward flow at the ice front repeatedly blocked the Clark Fork River and refilled Lake Missoula. This cycle was repeated as many as 100 times (Atwater, 1986) until the end of the last glaciation. The largest of the Missoula floods, many of which probably occurred relatively early in the lake-filling and flooding cycle, overwhelmed local drainages and topped the 2,400-ft divide west of Spokane and spilled southward towards Cheney and beyond, creating the Channeled Scablands (fig. 4). Smaller floods that made their way through the Rathdrum Prairie and Spokane River Valley likely discharged through lower elevation drainages including the present day Little Spokane River, Long Lake, and Hangman (Latah) Creek (pl. 1).

The southern end of Lake Pend Oreille at Farragut State Park marks the location of the outbreak of these floods (pl. 1). Most of the flood waters flowed south through the Rathdrum Prairie area and then westward toward the Spokane area. Flood deposits are mostly composed of gravels of glaciofluvial origin derived from glacial outwash of the Purcell Trench Lobe and reworked by flood events. Near-surface deposits include coarser gravels located centrally in the valley, with finer sands and gravels along the margins. Flood bars of these deposits are along the valley margins and dam the outlets of Spirit, Twin, Hayden, Coeur d'Alene, Liberty, and Newman Lakes.

Glacial Lake Columbia was another large lake impounded by an ice dam, created by the Okanogan Lobe, and was the largest glacial lake in the path of the Missoula floods (fig. 4). This lake was long-lived (2,000-3,000 years) and its surface altitudes typically were 1,640 ft but reached 2,350 ft during maximum blockage by the Okanogan Lobe and increased as high as 2,460 ft during floods from Glacial Lake Missoula (Atwater, 1986). Glacial Lake Columbia's higher level likely occurred early in glacial time, whereas, the lower and more typical lake level was later (Richmond and others, 1965; Waitt and Thorson, 1983; and Atwater, 1986). At the lower level (1,640 ft), Glacial Lake Columbia extended eastward to the Spokane area, where clayey lake sediment is intercalated with Missoula flood sediment (Waitt and Thorson, 1983). At the higher level of Glacial Lake Columbia (2,350 ft), the Rathdrum Prairie would have been flooded to within a few miles of the Purcell Trench Lobe that dammed Glacial Lake Missoula.

Sedimentation associated with Glacial Lake Columbia resulted in thick, fine-grained sediments throughout much of the region. Clay and silt deposits in the study area, presumed to be Glacial Lake Columbia sediments, have been recorded in drilling records for deep boreholes in the Hillyard Trough and north Spokane areas, and in the Hangman (Latah) Creek Valley. At least 16 beds of Glacial Lake Missoula flood deposits have been identified within Glacial Lake Columbia deposits in the Hangman (Latah) Creek Valley, just south of Spokane (Waitt and Thorson, 1983). These fine-grained deposits generally occur at depth beneath late glacial deposits of the Missoula floods and likely occur elsewhere in the study area. Alternating beds of lake and flood deposits may occur at considerable depth (400-600 ft) throughout parts of the study area.

Although Glacial Lake Columbia apparently inundated most of the SVRP study area at least periodically, the last of the Missoula floods may have come through an area devoid of a glacial lake. From the Spokane River Valley to its confluence with the Columbia River 65 mi downstream, a complex of flood bars are present that develop only when standing water is very shallow or absent (Kiver and Stradling, 2001). The present surface morphology of the Rathdrum Prairie and Spokane River Valley developed during the last outburst floods between 13,000 and 11,000 years ago (Waitt, 1985). These late glacial deposits comprise much of the upper part of the SVRP aquifer.

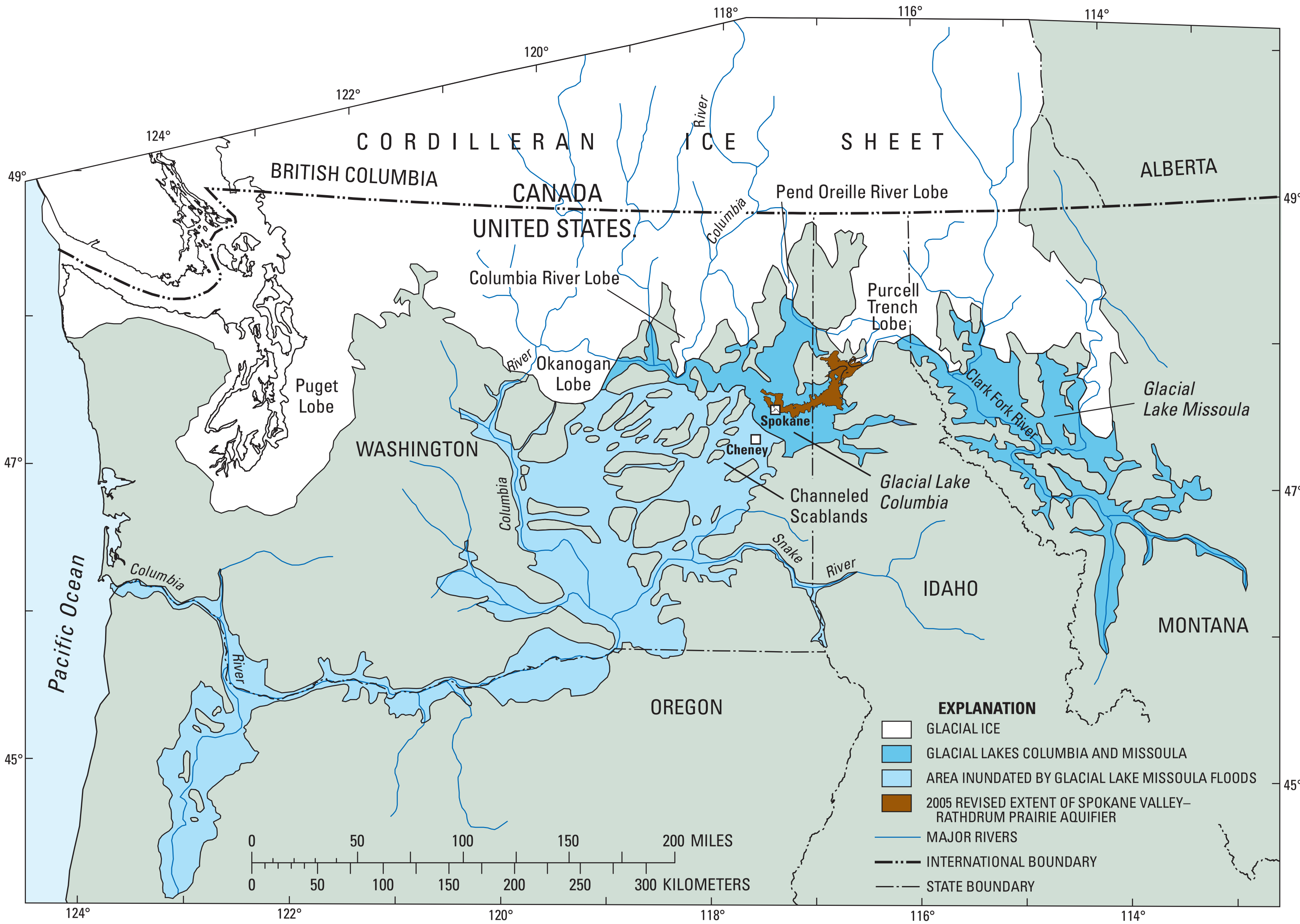


**Figure 4.** Extent of glacial ice and glacial lakes in northern Washington, Idaho, and parts of Montana. ((Modified from Allen and Burns, 1986, and Atwater, 1986).

## Geologic Units

Recent surficial geologic mapping is available for most of the SVRP area and was compiled for this study (pl. 2, table 2) based on original mapping by Derkey (1997), Breckenridge and Othberg (1998a, b; 1999a, b; 2000, 2004), Derkey and others (1998, 1999, 2003, 2004a-d), Lewis and others (2002), and Hamilton and others (2004). Surficial geologic mapping is needed but not currently available in southern Bonner County near the southern outlet of Spirit and Hoodoo Valleys. Detailed surficial geologic mapping in the southern areas shown on the Blanchard, Careywood, Cocolalla, and Edgemere 7.5 minute quadrangles would greatly improve the understanding of shallow sediment along the upstream extent of the SVRP aquifer.

The surficial geology of the SVRP study area consists of 11 geologic units described below and are shown on the surficial geologic map (pl. 2).

*Undifferentiated glacial and alluvial deposits* (Qu): Pleistocene glacial or glaciofluvial deposits and Holocene alluvium in the northern part of the study area where recent deposits have not been differentiated in Bonner County, Idaho.

*Recent non-glacial sediment* (Qs): mostly Holocene sediment including alluvium in stream channels, lacustrine deposits associated with study area lakes, mass-wasting deposits most commonly detected along the base of basalt bluffs in Spokane County, peat associated with poorly drained and organic rich areas, and wind-blown deposits on the surface of prairies and the basalt plateaus.

**Table 2.** List of surficial geologic mapping available in the Spokane Valley–Rathdrum Prairie area, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho.

[**State:** ID, Idaho; WA, Washington. **Section orientation:** ESE, east, southeast; NE, northeast; N-S, north-south; NW, northwest; NW-SE, northwest-southeast; SE, southeast; SSW-NNE, south, southwest-north, northeast; SW, southwest; SW-NE, southwest-northeast; WE, west-east; WNW, west, northwest. **Abbreviations:** USGS, U.S. Geological Survey]

| USGS quadrangle name(s) | Scale | State | Name of section(s) published with map in study area | Section orientation | Notes | Reference |
|---|---|---|---|---|---|---|
| Coeur d'Alene | 1:24,000 | ID | | | Southeast Rathdrum Prairie | Breckenridge and Othberg, 1999b |
| | 1:100,000 | ID | A-A´ | WNW-ESE | Quaternary sediments undifferentiated on section A-A´ | Lewis and others, 2002 |
| Fernan Lake | 1:24,000 | ID | | | Eastern edge of Rathdrum Prairie | Breckenridge and Othberg, 2004 |
| Hayden | 1:24,000 | ID | | | Central Rathdrum Prairie | Breckenridge and Othberg, 1999a |
| Hayden Lake | 1:24,000 | ID | Unnamed schematic section, not to scale | W-E | Eastern edge of Rathdrum Prairie | Breckenridge and Othberg, 2000 |
| Post Falls and Liberty Lake (ID portion) | 1:24,000 | ID | Unnamed schematic section, not to scale | N-S | Southwest Rathdrum Prairie, Post Falls | Breckenridge and Othberg, 1998a |
| Rathdrum and Newman Lake (ID portion) | 1:24,000 | ID | Unnamed schematic section, not to scale | N-S | Southwest Rathdrum Prairie, Newman Lake | Breckenridge and Othberg, 1998b |
| Airway Heights | 1:24,000 | WA | | | Western edge of aquifer | Derkey and others, 2004a |
| Dartford | 1:24,000 | WA | B-B´ | SSW-NNE | Downstream extent of aquifer | Derkey and others, 1998 |
| Greenacres | 1:24,000 | WA | A-A´<br>B-B´ | N-S<br>N-S | Spokane valley | Derkey and others, 2004b |
| Mead | 1:24,000 | WA | D-D´<br>I-I´ | NW-SE<br>W-E | Downstream extent of aquifer | Derkey, 1997 |
| Newman Lake and Liberty Lake (WA portions) | 1:24,000 | WA | A-A´<br>B-B´<br>C-C´ | W-E<br>N-S<br>N-S | Outlet of Newman Lake Spokane valley | Derkey and others, 2004d |
| Nine Mile Falls | 1:24,000 | WA | | | Downstream extent of aquifer | Derkey and others, 2003 |
| Spokane NE and Spokane SE | 1:24,000 | WA | A-A´ | N-S | Spokane valley | Derkey and others, 1999 |
| Spokane NW | 1:24,000 | WA | A-A´<br>B-B´ | SW-NE<br>SSW-NNE | Central Spokane | Derkey and others, 2004c |
| Spokane SW | 1:24,000 | WA | A-A´ | SW-NE | Hangman (Latah) Creek | Hamilton and others, 2004 |

*Glacial outwash and till* (Qot): includes late Pleistocene glacial outwash and minor till near the southern end of Lake Pend Oreille, Idaho, that postdates the older Missoula flood deposits. The outwash consists of very coarse boulder gravels with sand deposited by meltwater streams from either overflow of the Lake Pend Oreille basin during Cordilleran deglaciation of the Purcell Trench, or from noncatastrophic drainage of Glacial Lake Missoula. At the southern end of Lake Pend Oreille, the unit consists of bouldery clay till and boulder outwash deposits that form a modified end moraine.

*Glacial lake deposits* (Qgl): includes glaciolacustrine deposits of Glacial Lake Columbia. The unit is composed of silt and fine sand, with clay interbeds, scattered boulders, and some sand and gravel lenses. In the study area, this unit is mapped along Deadman and Hangman (Latah) Creeks, Washington. In areas, especially along Hangman (Latah) Creek, the unit is interbedded with glacial-flood deposits.

*Catastrophic flood deposits, gravel* (Qfg): includes flood deposits from catastrophic draining of Glacial Lake Missoula that are a mixture of boulders, cobbles, pebbles, and sand with lenses of sand and silt. These deposits occur from near the outlet of Lake Pend Oreille through the Rathdrum Prairie and the Spokane River Valley.

*Catastrophic flood deposits, sand* (Qfs): includes flood deposits from catastrophic draining of Glacial Lake Missoula that are predominantly sand with sparse pebbles, cobbles, and boulders. Exposures of the unit mapped in Washington are believed to be sediment that was deposited when outburst floods flowed into a high stand of Glacial Lake Columbia. These deposits are most widespread in the Hillyard Trough and areas west of Five Mile Prairie, Washington. Smaller exposures are mapped along the SVRP aquifer boundaries near the Washington–Idaho state line where the unit consists of sand and silt with some gravel that was mostly deposited in waning floodwaters.

*Older sediments* (Ts): includes the Latah Formation, which is composed of lacustrine and fluvial deposits of siltstone, claystone, and minor sandstone. The unit generally is gray or tan except in more weathered areas where it is brownish yellow or orange. The unit is interbedded in places with the Columbia River basalt.

*Basalt* (Tb): includes the Columbia River basalts, which are fine-grained dark gray, greenish gray, or black basalt. Surface exposures of the unit are common in upland areas surrounding the SVRP aquifer in Washington. In Idaho, the largest exposures are near Coeur d'Alene and Hayden Lakes.

*Intrusive igneous rocks* (TKg): includes Cretaceous to Eocene granite and orthogneiss. Surface exposures occur throughout much of the study area in the upland areas.

*Sedimentary rocks* (€s): composed of Cambrian limestone, shale, and quartzite with a very limited exposure in the study area near the southern end of Lake Pend Oreille.

*Metamorphic rocks* (p€m): consists of Precambrian metasedimentary rocks including argillite, siltite, and quartzite. Surface exposures of the unit occur throughout the highland areas of the eastern two-thirds of the study area.

## Bedrock

Bedrock, which includes the Precambrian to Tertiary metamorphic and intrusive igneous rocks and Tertiary basalt and their interbeds, underlies and laterally bounds the SVRP aquifer. These rocks are generally low permeability units, and as such, generally produce small amounts of water and are not considered major aquifers within the SVRP study area. The crystalline structure of the metamorphic and intrusive igneous rocks generally inhibits their ability to store and transmit water. However, weathered or fractured zones within these rocks can transmit usable amounts of ground water. Similarly, the basalts and their interbeds, can produce significant discharges for domestic use, but are discontinuous and not considered important aquifers within the study area.

Except along the SVRP aquifer margins where some wells penetrate unconsolidated deposits and reach bedrock, the buried bedrock surface configuration is unknown. No known wells penetrate the entire thickness of these deposits in the area between Lake Pend Oreille and Spirit Lake, and to the south in the central Rathdrum Prairie, or in the Hillyard Trough. Few wells penetrate the entire thickness of deposits in the Spokane Valley.

### Surface Geophysics

Numerous geophysical investigations have been conducted to determine the configuration of the base of the SVRP aquifer using several surface geophysical methods to investigate the subsurface characteristics of deposits and bedrock, including seismic refraction (Newcomb and others, 1953, Tanaka, 1975, Dion and Sumioka, 1991, HartCrowser, 2003), seismic reflection (SeisPulse Development Corporation and others, 1993; Gerstel and Palmer, 1994; Palmer and

Gerstel, 1994; Palmer and others, 1995a, b; CH2M HILL, 1998, 2000a; and S. Palmer, Washington Department of Natural Resources, written commun., 2005), and gravity (Purves, 1969; Hammond, 1974; and Adema, 1999).

Although most of these studies were intended to better define the bedrock configuration at depth, it should be noted that this bedrock surface is not necessarily the base of the aquifer as is sometimes reported or assumed. In places, the bottom of the aquifer is marked by the contact of coarse aquifer sediment with much finer-grained clay and silt beneath it. The extent of fine-grained deposits beneath the aquifer generally is unknown except in wells along some parts of the aquifer margin where drillers' logs report fine-grained sediment beneath the aquifer.

Additional caution should be used when comparing the estimated depths to bedrock presented in these geophysical studies because "bedrock" is defined differently by different investigators, presumably based on the goals of the investigation and limitations of the methods employed. This is an important distinction to keep in mind when comparing these investigation results where the phrase "depth to bedrock" has been used with the following meanings: (1) depth to the crystalline bedrock including pre-Tertiary metamorphic and intrusive igneous rocks; (2) depth to sedimentary deposits of the Latah Formation and Columbia River basalts; or (3) depth to Columbia River basalts and crystalline bedrock excluding the Latah Formation.

A brief summary of surface geophysical studies completed as of 2004 is provided in this report. No attempt has been made to evaluate methods used or investigation results or to compare appropriateness of one surface geophysical method over another. Approximate locations of surface geophysical transects from investigations that report estimated depths to bedrock along profiles in the SVRP study area are shown on plate 2.

### Seismic Refraction

Newcomb and others (1953) completed two seismic refraction profiles near Spokane in 1951 in an effort to locate the base of the glacial-outwash aquifer, determine the type of materials underlying the aquifer, and locate the crystalline bedrock of the ancestral valley. One section trended north-south across the Spokane Valley east of the Washington–Idaho state line; the other trended east-west across the Hillyard Trough in northeast Spokane (pl. 2). Five units were identified in their refraction: 1) soil and subsoil of the glacial outwash; 2) unsaturated glacial outwash; 3) saturated glacial outwash; 4) Latah Formation with intercalated igneous rocks; and 5) granitic rock. In the state-line area, Newcomb and others (1953) interpreted the central and deepest part of the v-shaped ancestral valley floor to be granitic rock about 1,280 ft below present-day land surface, with 340 ft of primarily glacial and glaciofluvial deposits overlying 940 ft of Latah Formation with intercalated basalt. Along the transect that crosses the Hillyard Trough, Newcomb and others (1953) mapped a slightly undulating granitic bedrock surface with the deepest part being about 860 ft below present-day land surface, with 310 ft of glacial and glaciofluvial deposits overlying 550 ft of Latah Formation.

Tanaka (1975) reports similar results as Newcomb and others (1953) for the state-line and Hillyard Trough areas, as well as two additional seismic refraction profiles used to determine depth to crystalline and metamorphic bedrock. A northeast-southwest profile from the base of Five Mile Prairie across the Spokane River indicates that bedrock is over 880 ft below land surface near the river in sec.28, T.26 N., R.42 E. A second northeast-southwest profile, in the Little Spokane River Valley, shows that bedrock is less than 300 ft below land surface beneath the river in sec.3, T.26 N., R.42 E. Details of this work were unavailable in the abstract that describes the results (Tanaka, 1975).

Dion and Sumioka (1991) describe the results of seismic refraction profiles conducted north of Pasadena Park in Spokane as part of an investigation to document extent and source of organic solvents in ground water. Although site-specific in nature and outside the SVRP aquifer boundary, this study illustrates how this and other tributary valleys contain ground water that is hydraulically connected to the SVRP aquifer. Cross sections shown in the report indicate a depth to bedrock of 30 to more than 130 ft, based on geophysical transects and drilling records.

In 1994, S.D. Schwarz and Associates (*in* HartCrowser, 2003, Appendix O) conducted a seismic refraction survey at the Kaiser Trentwood Facility south of Trentwood in the Spokane Valley. The purpose of the survey was to define the depth and configuration of the ground water surface and underlying bedrock at selected locations beneath the facility. In the investigation, bedrock was defined as pre-Tertiary metamorphic complex (HartCrowser, 2003). Although the presence of Columbia River basalt and the Latah Formation was not reported during installation of wells at the site, it was reported that these units may be present at depth and probably would occur as discontinuous erosional remnants over bedrock and below the base of the glacial and flood deposits. Three 1,500 ft seismic refraction lines at the site yielded an approximate depth to bedrock ranging from 200 to 350 ft below ground surface (HartCrowser, 2003).

### Seismic Reflection

In the early- to mid-1990s, the Washington Department of Natural Resources, SeisPulse Development Corporation, and Spokane County tested and conducted shallow seismic reflection studies using a new impulsive seismic source (SeisPulse Development Corp., and others, 1993; Palmer and Gerstel, 1994; Gerstel and Palmer, 1994; and Palmer and others, 1995a). This work was done primarily to define the bedrock reflection beneath the SVRP aquifer in the Spokane Valley (SeisPulse Development Corp., and others, 1993).

When comparing a shallow seismic reflection profile conducted near the Washington–Idaho state line (Palmer and Gerstel, 1994) with Newcomb and others (1953) transect near the same location, it appears that in the more recent investigation bedrock may be defined as including the Latah Formation, whereas, Newcomb and others (1953) differentiated the Latah Formation and associated Columbia River basalt as a separate unit from the underlying crystalline "granitic" bedrock. The seismic reflection data for the state-line area transect of Palmer and Gerstal (1994) show that bedrock is 450 to 550 ft below land surface. Newcomb and others (1953) reported that depths to the Latah Formation ranged from 350 to 500 ft below ground surface in the same area. A north-south profile shot west of Otis Orchards (Palmer and others, 1995a), resulted in a calculated depth to bedrock greater than 500 ft in the center of the main valley.

As part of the city of Spokane's Wellhead Protection Program, SeisPulse Development Corporation did seismic reflection profiling along 10 transects in September 1994 (CH2M HILL, 1998, Appendix G). This work was done to examine bedrock characteristics in the area between Spokane Falls and Five Mile Prairie and to refine the apparent aquifer thickness along the eastern edge of the city. Reported depths to bedrock ranged from about 250 to 340 ft along the north-south transect through the Trinity Trough and from about 260 to 520 ft along the north-south transect near Parkwater. The composition of the bedrock was not noted in CH2M HILL, 1998.

Shallow seismic reflection profiling also was done for the Spokane Aquifer Joint Board Wellhead Protection Program in 1996 to define aquifer thickness and bedrock topography in the Spokane Valley area between Pines Road Knoll and the community of Greenacres (CH2M HILL, 2000a, Appendix F). In this investigation, "bedrock" was defined as both Columbia River basalt and older granitic gneiss (CH2M HILL, 2000a, Appendix F). The seismic reflection data indicate the presence of a strong reflector thought to represent the top of bedrock in contact with glaciofluvial and alluvial valley fill deposits. It is not known, however, whether the valley fill materials at depth have a similar water-bearing capacity to the upper part of the aquifer (CH2M HILL, 2000a). The 5-mi long north-south transects across the Spokane Valley, indicated a valley-like bedrock profile, with its deepest point, about 600 ft from land surface to bedrock, near present-day Spokane River (CH2M HILL, 2000a).

In Idaho, the Washington Department of Natural Resources and SeisPulse Development Corporation conducted seismic reflection profiling between the southern ends of Twin Lakes and Round Mountain in the early-1990s (S. Palmer, Washington Department of Natural Resources, written commun., 2005). At the east end of the transect, water wells completed in granitic bedrock provided good control on the depth to bedrock, which ranged from 220 to 260 ft. A velocity survey was done in a nearby well to convert the seismic reflection travel time to depth, and the reflection data indicated a 240 ft depth to bedrock (S. Palmer, Washington Department of Natural Resources, written commun., 2005). The resulting basin profile is deeper on its west side, with a maximum depth of 550-600 ft beneath Highway 41 (S. Palmer, Washington Department of Natural Resources, written commun., 2005). The seismic reflection profile indicates bedrock becomes shallow west of Highway 41 to the end of the profile, which is about 1,000 ft east of the southern end of Twin Lakes.

### Gravity

Purves (1969) conducted a gravity survey throughout the Spokane Valley and adjoining western part of the Rathdrum Prairie. Purves used the supposition that, in a relatively simple geologic system, the Bouguer gravity field generally mimics the underlying bedrock configuration. This buried bedrock configuration was determined through density contrasts between the bedrock and the overlying unconsolidated material. Although estimates of actual depth to bedrock were not feasible at the time, Purves work has proved useful in indicating the shape of the buried bedrock surface. A significant finding of Purves' (1969) was the existence of a probable west-northwest trending subsurface drainage divide within the Rathdrum Prairie basin about 2 mi west of the Washington–Idaho state line. East of this divide, in the Rathdrum Prairie, Purves reported that the subsurface configuration appeared to be dominantly influenced by glacial erosion, with the u-shaped trough filled almost exclusively with glacial and flood deposits and minimal basalt. His survey was inconclusive as to the existence of Latah Formation in the Rathdrum Prairie section and he reported that, "To surmise the presence or absence of the Latah Formation strains the capabilities of gravity interpretation" (Purves, 1969). West of the divide, in the Spokane Valley section of the aquifer, Purves reported that the basement configuration appeared to be a fluvially dissected erosional valley with erosional terraces composed of either a complex basement or basalt.

Hammond (1974) published gravity survey results of a study done in 1969 in northern Rathdrum Prairie to help refine previous estimates of underflow moving toward the Rathdrum Prairie from the Athol area and to quantify water being recharged to the aquifer by Lake Pend Oreille. A detailed gravity survey was done to define the configuration of the pre-Tertiary bedrock surface and to calculate the thickness of the unconsolidated material from the southern end of Lake Pend Oreille south to the West (Main), Middle (Ramsey), and Chilco Channels. Few details regarding the methods used and transect locations are included in the report, but resultant contours of the buried pre-Tertiary bedrock surface indicate that the greatest depth to bedrock is in the West (Main) Channel and is more than 1,400 ft below the present-day land surface (Hammond, 1974). Because the work reported by Hammond (1974) provides only a pre-Tertiary bedrock surface (metamorphic and intrusive igneous rocks), the presence or absence of the Latah Formation and Columbia River basalt remains unknown.

Building on previous seismic and gravity geophysical investigations, Adema (1999), modeled 5 geologic cross-sections of the Rathdrum Valley profile by using 630 gravity measurements, 146 of which were newly collected to complement existing data. For modeling purposes, Adema grouped materials of similar densities: metamorphic and intrusive igneous rocks, and the Miocene basalts were all grouped and referred to as bedrock; Latah Formation, flood deposits, and intermingled sands and clays were modeled and referred to as sediment. The modeled data show a generally smooth valley floor, with an incised channel in the western part of the Rathdrum Prairie. Adema's interpretation suggests an approximate sediment thickness of more than 1,150 ft between Post Falls and Rathdrum. Although Adema's work provides a valuable update on the bedrock depth and morphology of the Rathdrum Prairie, estimating the actual thickness of the SVRP aquifer was beyond the limits of the gravity study. As stated in Adema's report, no attempt was made to identify specific hydrologic boundaries within the sediments, as such divisions would be overwhelmingly subjective due to the low density contrasts involved (Adema, 1999).

### Microgravity

During the Spokane Aquifer Joint Board Wellhead Protection Program, a microgravity gradiometry survey was done in the northwestern end of the Hillyard Trough to determine the sediment thickness and the basement topography where lithologic conditions were reported to limit the application of seismic reflection methodologies (CH2M HILL, 2000a, Appendix G). Microgravity surveys provide increased resolution of near-surface structures over standard gravity methods. The north Hillyard Trough area warranted additional study due to limited evidence of a deep, confined aquifer separated from the upper SVRP aquifer by low-permeability glacial lake deposits (CH2M HILL, 2000a). Results of the 2-mi long southwest-northeast trending transect indicate a depth to bedrock at about 490 to 590 ft in this area (CH2M HILL, 2000a).

# Hydrologic Information

## Spokane Valley–Rathdrum Prairie Aquifer

The SVRP aquifer is composed of the previously described unconsolidated coarse-grained sand, gravel, cobbles, and boulders primarily deposited by a series of catastrophic glacial outburst floods. The material deposited in this high-energy depositional environment is coarser-grained than is typical for most basin-fill deposits, resulting in one of the most productive aquifers in the world. Water volume in the entire SVRP aquifer is estimated to be about 10 trillion gallons with an average of about 250 to 650 Mgal of water flowing through the aquifer daily at the Idaho–Washington border (MacInnis and others, 2000).

The aquifer generally has a greater percentage of finer material near the margins of the valley and becomes more coarse and bouldery near the center of the valley. Near Athol and between Athol and Rathdrum, several bodies of perched water have been reported in the flood deposits where downward water percolation is slowed by clay lenses or low-permeability till (Anderson, 1951). In the Spokane Valley, the aquifer is reported to contain no significant layers of low-permeability materials. In the Hillyard Trough, however, a clay layer appears to separate the aquifer into upper and lower units (pl. 2, section *A-A'*) (CH2M HILL, 2000). This clay layer is presumed to be glacial lake deposits from glacial Lake Columbia. In north Spokane County, the glaciolacustrine deposits are difficult to distinguish from the Latah sediments, especially in well logs (Boese, 1996).

In the Spokane area, CH2M HILL (1998) reports that the SVRP aquifer in the west part of the Spokane area consists of two relatively independent systems mostly separated by a buried basalt ridge that extends about 2 mi south of Five Mile Prairie. The main body of the aquifer is east of the ridge and in the Hillyard Trough and part of Spokane Valley. An area referred to as Trinity Trough is a breach across this basalt ridge and probably connects the east and west parts of the aquifer in that vicinity. The small portion of the aquifer between Spokane Falls and Nine Mile Dam has been referred to as to the western arm of the aquifer (J. Covert, Washington Department of Ecology, written commun., 2005) and the downriver segment (CH2M HILL, 1998).

In the downriver segment of the SVRP aquifer, at the former city of Spokane North Landfill site, monitoring well drillers' logs indicate that SVRP aquifer flood deposits are underlain by glacial lake deposits (silt and clay) except in lower elevation areas near the Spokane River where the aquifer is underlain by basalt (CH2M HILL, 1988).

### Areal Extent

The areal extent of the SVRP aquifer designations differ somewhat between investigators and over time. Many recent aquifer-related documents, including the SVRP Atlas (MacInnis and others, 2000, 2004), used a modified version of the original Spokane Valley–Rathdrum Prairie Sole Source Aquifer boundary designated by the USEPA in 1978 (fig. 5). Earlier studies tended to use a somewhat larger aquifer boundary as shown in Drost and Seitz (1978b, fig. 5). A slightly larger extent, that includes more of the surficial deposits adjacent to and in hydraulic connection with the Sole Source Aquifer, is shown in Berenbrock and others (1995, fig. 5).

For modeling purposes, it may be important to use a more inclusive aquifer boundary to better represent contributions from adjacent surficial deposits that are in hydraulic connection with the Sole Source Aquifer. An example of this is in the Chilco channel area where ground water flows into the Rathdrum Prairie portion of the Sole Source SVRP aquifer from an area in hydraulic connection with the aquifer but outside the official aquifer boundary (Painter, 1991a, 1991b, Graham and Buchanan, 1994). Similarly, Baldwin and Owsley (2005) have documented about 200 ft of saturated alluvium within the Middle (Ramsey) Channel that has similar water levels to the surrounding Sole Source Aquifer. They also suggested that this area be incorporated into the official aquifer extent in order for this area to be treated with the same levels of aquifer protection as the rest of the aquifer.

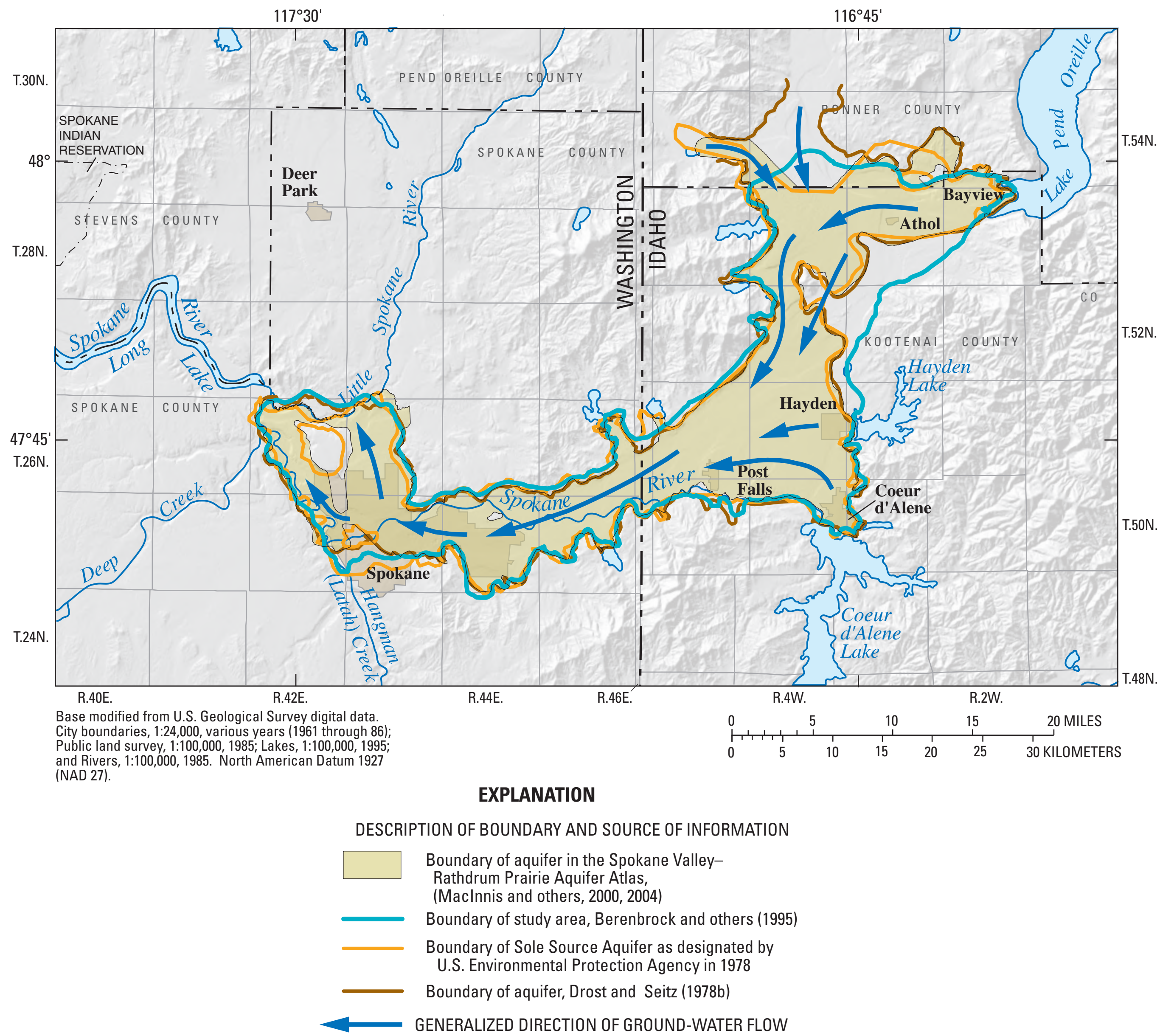


**Figure 5.** Boundary of the Sole Source Spokane Valley–Rathdrum Prairie aquifer, other study area extents, and generalized directions of ground-water flow, Washington and Idaho.

A revised extent map was drawn for this investigation that includes unconsolidated coarse-grained deposits based on the most recent surficial geologic mapping (pl. 2), including the Middle (Ramsey) and Chilco Channels. The revised map reflects adjustments that were made by moving the boundaries of the aquifer within Hoodoo and Spirit Valleys and near Careywood, Idaho, to ground-water divides that were mapped during previous investigations (Walker, 1964; Parliman and others, 1980).

The revised extent map also includes revisions to the aquifer boundary along the western arm of the aquifer near Riverside State Park in Washington (pl. 2). Recent analysis of ground-water level data, Nine Mile Reservoir elevation data, bedrock outcrops, and historical streamflow data have resulted in redrawing the western arm of the aquifer boundary ending near Nine Mile Falls rather than being continuous through that area as shown in previous aquifer boundaries. A bedrock ridge extending northwest from Five Mile Prairie to Nine Mile

Dam forms the northern boundary of the western arm of the aquifer (J. Covert, Washington Department of Ecology, written commun., June 2005). The aquifer ends about one mile south of Nine Mile Dam and the water moving through this arm of the aquifer re-emerges into the Spokane River (Nine Mile Reservoir) before the dam. Summer streamflow data from the 1950s show that the Spokane River gained as much as 400 $ft^3/s$ between Hangman (Latah) Creek and Nine Mile Dam from the aquifer (J. Covert, Washington Department of Ecology, written commun., June 2005). Following completion of Nine Mile Dam, summer reservoir levels have been maintained at a constant level by changing the volume of water discharged through the dam. The water-table in the western arm of the aquifer is controlled by the elevation of Nine Mile Reservoir and ground water levels in the area between Seven Mile bridge and the dam follow the trend exhibited by Nine Mile Reservoir (J. Covert, Washington Department of Ecology, written commun., June 2005).

## Aquifer Thickness

SVRP aquifer thickness generally is unknown except along its margins where wells have been drilled through its entire thickness. Since many wells in the SVRP aquifer are extremely productive, few wells in the aquifer extend more than 100 ft into the saturated zone. Well depths in the USGS National Water Information System (NWIS) database range from less than 10 to about 700 ft with a median of 162 ft. The greatest known thickness was recorded in Hillyard Trough where a 780-ft well did not penetrate the full thickness of the glacial and flood deposits (Cline, 1969). Coarse aquifer deposits in the Hillyard Trough area are separated by a layer of clay, silt, and sand at about 360 to 490 ft below land surface. The aquifer thickness is about 500 to 550 ft near the Idaho–Washington State line east of Spokane, Washington (Gerstel and Palmer, 1994) and overall, aquifer deposits are about 150-ft to more than 600-ft deep (MacInnis and others, 2000). Generalized hydrogeologic cross sections (simplified from CH2M HILL 1998, 2000a, and Baldwin and Owsley, 2005) for the Hillyard Trough (*A–A'*), Spokane Valley (*B–B'*), state line area (*C–C'*), and West (Main), Middle (Ramsey), and Chilco Channel areas (*D–D'*) are shown on plate 2.

To date (2004), the only aquifer-wide digital representation of the aquifer extent and bottom was prepared by Buchanan (2000), as input for a ground-water flow model of the SVRP aquifer system. His map of estimated bottom elevations of the aquifer's bedrock base was based in part on seismic reflection profiling done in the 1990s (Buchanan, 2000). Although Buchanan's work provides an aquifer-wide gross estimate of aquifer bottom, refinements are needed to better determine depth to bedrock, as well as determine the depth to the aquifer base where the aquifer is underlain by fine-grained unconsolidated material rather than consolidated bedrock.

In Washington, Poelstra and others (2005) have developed a preliminary, and as yet unreleased, three-dimensional digital geologic model for the Washington part of the SVRP aquifer system based on surface geology maps, geologic and geophysical cross sections, and well logs. Originally developed to evaluate the ground-motion amplification effect of soft soils in the upper 100 ft of the soil-rock column (Palmer and others, 2004), this three-dimensional model was expanded to include the full thickness of these "soft soils" as represented by unconsolidated deposits overlying bedrock. The preliminary model is composed of three separate unconsolidated units based on the dominant grain texture including gravel, sand, and silt-clay (S. Palmer, Washington Department of Natural Resources, written commun, February 2005). The gravel unit corresponds to SVRP's major water productive section, as exhibited in the eastern part of the Spokane Valley. The sand unit consists of significantly thick slackwater flood deposits, typified by the thick accumulation exposed at the surface in the Hillyard Trough. The silt-clay unit corresponds to subsurface occurrences of Glacial Lake Columbia sediments present only in the subsurface in the Hillyard Trough and in the Little Spokane River drainage (S. Palmer, Washington Department of Natural Resources, written commun, February 2005).

## Hydraulic Properties

A number of investigators have estimated hydraulic properties of the SVRP aquifer, including specific yield, hydraulic conductivity, and transmissivity. Hydraulic conductivity values for most of the central SVRP aquifer generally are large. Currently (2004), the USGS has information available in the NWIS database for about 1,200 wells inventoried as part of previous studies of the SVRP aquifer and surrounding basin-fill aquifers (table 3).

Wells in the aquifer generally yield large volumes of water with relatively little drawdown. Wells in the saturated coarse-grained deposits can yield several thousand gallons per minute (Bolke and Vaccaro, 1979; Stone and others, 1996), with several wells near Spokane reportedly yielding over

**Table 3.** Summary statistics for 1,190 wells completed in the Spokane Valley–Rathdrum Prairie aquifer and surrounding basin-fill aquifers.

[**Summary statistics:** From U.S. Geological Survey National Water Information System database. **Abbreviation**: <, less than]

| | Altitude (feet above sea level) | Well depth (feet) | Water level (feet below land surface) | Yield (gallons per minute) |
|---|---|---|---|---|
| Minimum | 1,540 | 7 | 2 | <2 |
| Maximum | 2,587 | 600 | 573 | 25,000 |
| Median | 2,053 | 162 | 106 | 500 |

5,000 gal/min. Reported yields for wells in the SVRP aquifer in the USGS database range from less than 2 to 25,000 gal/min with a median of 500 gal/min (table 3).

Although much of the SVRP aquifer is considered highly permeable, hydraulic characteristics are locally variable and include less-permeable, fine-grained sedimentary material. Several previous studies including Drost and Seitz (1978b), Bolke and Vaccaro (1981), and CH2M HILL (1998) have calculated aquifer characteristics based on aquifer tests and ground-water model simulations. Although hydraulic properties of the aquifer were variable, most results indicated that hydraulic conductivity (a measure of the ability of the aquifer material to transmit water) and transmissivity (the rate at which water is transmitted through a unit width of the aquifer under a unit hydraulic gradient, equal to the hydraulic conductivity multiplied by the aquifer thickness) values were on the upper end of values measured in the natural environment. Drost and Seitz (1978b) reported transmissivity values that ranged from less than 130,000 $ft^2$/d in the western part of the aquifer to more than 13 million $ft^2$/d near the Washington–Idaho state line. Estimated ground-water velocities exceeded 60 ft/d near the state line to about 47 ft/d in the Hillyard Trough (fig. 1). Bolke and Vaccaro (1981) estimated hydraulic conductivity values of between about 2,600 to 6,000 ft/d for most of the aquifer on the Washington side, with a value of about 860 ft/d in the less permeable Hillyard Trough area. CH2M HILL (1998) reported hydraulic conductivity values ranging from about 100 to 6,200 ft/d, with most values greater than 1,000 ft/d.

Vertical anisotropy is the ratio of horizontal hydraulic conductivity to vertical hydraulic conductivity. Bolke and Vaccaro (1981) stated the available data suggested no vertical stratification of the aquifer lithology, and therefore, no vertical anisotropy. Golder Associates, Inc. (2004) used an initial vertical anisotropy of 3:1. CH2M HILL (1998) assumed a vertical anisotropy of 10:1 that produced conservative (large) estimates of well capture zones.

## Ground-Water Occurrence and Movement

Depth to ground water in the SVRP aquifer ranges from near land surface to more than 500 ft below land surface (Bolke and Vaccaro, 1979; Berenbrock and others, 1995; Briar and others, 1996; Stone and others, 1996; MacInnis and others, 2000). The greatest depth to ground water occurs in the northern Rathdrum Prairie in Idaho and the shallowest depth (less than 50 ft in places) is near Spokane along the Spokane River. Water levels measured in wells and recorded in the USGS database (2004) range from 2- to 573-ft deep with a median depth of 106 ft (table 3). Seasonal water-level fluctuations in the aquifer generally are less than 15 ft in most areas (Drost and Seitz, 1978b).

The water table in the SVRP aquifer generally reflects the land-surface topography and slopes from Hoodoo Valley and Lake Pend Oreille, Idaho, to Nine Mile Falls, Washington. Ground water generally flows in a southward direction from the area near the southern end of Lake Pend Oreille with a water-level altitude of about 2,150 ft, towards the city of Coeur d'Alene, and then westward towards the city of Spokane with an altitude of about 1,500 ft near the Little Spokane River (Drost and Seitz, 1978b; Molenaar, 1988; and MacInnis and others, 2000). The water table in the northeastern-most part of the aquifer slopes about 20 ft/mi, while the major part, from north of Round Mountain, Idaho, to the southern end of the Hillyard Trough, Washington, slopes gently from 2 to 10 ft/mi (Drost and Seitz, 1978b). Steeper slopes, sometimes more than 60 ft/mi, are in the Hillyard and Trinity Trough areas and along the Spokane River west of Five Mile Prairie. Generalized ground-water flow directions based on water-level elevations measured in the aquifer are shown in figure 5.

SVRP aquifer upstream margins include the southern parts of the Hoodoo and Spirit Valleys and Careywood in southern Bonner County, Idaho, in addition to the outlet at the southern end of Lake Pend Oreille (pl. 2). In the Cocolalla Valley, a ground-water divide is reported near Careywood along U.S. Highway 95 (Parliman and others, 1980). Ground water north of the divide flows northeast toward the Pend Oreille River; ground water south of the divide flows southwest toward Athol and the main body of the SVRP aquifer. In the Hoodoo Valley, historical water-level elevations indicated that a water-table divide was between Edgemere and Harlem (Walker, 1964). Ground water north of the divide moved northward toward the Pend Oreille River; ground water south of the divide moved southward toward Athol. In Spirit Valley, the ground-water divide was near Blanchard Lake (Parliman and others, 1980). West of the divide, ground water flows northwestward toward the Pend Oreille River; east of the divide, ground water flows southeastward into the main body of the SVRP aquifer.

Hammond (1974) reported that ground-water flow can be variable between Lake Pend Oreille and Athol. When the lake level declines below the adjacent water table an apparent ground-water mound (divide) is formed near Farragut State Park (Hammond, 1974). At such times, ground water can flow toward the lake from a distance of at least one-third of a mile and possibly farther (Hammond, 1974).

Most ground water from the SVRP aquifer discharges either to the Spokane and Little Spokane Rivers or is withdrawn by wells (Drost and Seitz, 1978b; Molenaar, 1988). An unknown amount of ground water may leave the system from the lower part of the aquifer in the Hillyard Trough and Little Spokane River area near Long Lake. Recharge occurs by infiltration of precipitation, snowmelt, irrigation water, subsurface inflow from adjoining highlands and tributary valleys, and leakage from adjacent and overlying surface-water sources (Molenaar, 1988). Several investigations reported that the Spokane River varies from losing to gaining along its course as it flows over the SVRP aquifer (Gearhart and Buchanan, 2000; Marti and Garrigues, 2001; and Caldwell and Bowers, 2003).

## Ground-Water Levels

In 2004, an observation network was established by the USGS to measure water levels within the SVRP aquifer and adjacent hydrogeologic units. A monthly network of 47 wells was established in June 2004 to manually measure depth to water in wells throughout the aquifer. In July 2004, an eight-well network was established where depth to water is recorded hourly. As of 2005, both monthly and recorder networks are ongoing. During one week in September 2004, the depth to water was measured in 268 wells to develop a water-table map of the SVRP aquifer. Wells were visited by personnel from IDWR, WADOE, and USGS. The well locations in the observation networks and wells measured in September 2004 are shown on plate 1. The September 2004 water-table map and the supporting data are reported in Campbell (2005).

In addition to water-level data collected by USGS, water-level data are available from other sources for hundreds of wells throughout the SVRP aquifer. These data are available from several local and State government agencies, colleges and universities, water purveyors, and environmental consulting firms. Wells with multiple water-level measurements and measurement frequencies ranging from every 15 minutes (continuous recorders) to every few months are available for more than 100 wells. City and county government agencies have collected water levels as part of several programs including landfill monitoring, ground-water/ surface-water interaction studies, and wellhead protection. Water-level data from statewide monitoring well networks and local investigations are available from State agencies like IDWR and WADOE. Universities and colleges have collected water-level data as part of graduate thesis studies, class projects, and projects conducted by faculty members. Several water purveyors have been proactive in monitoring water levels in public water-supply and monitoring wells: some purveyors have collected over twenty years of data. Environmental consulting firms have collected water-level data from parts of the SVRP aquifer for several studies

## Lake Levels

Lake stage data collection has been continuous at Coeur d'Alene, Hayden, and Pend Oreille Lakes, Idaho, and Long Lake, Washington, since the early 1900s (table 4, fig. 6). Historical data are available for Twin Lakes, Idaho, and Newman and Liberty Lakes, Washington, from the 1950s to the late 1960s or 1980s (table 4, fig. 6). As part of this study, gaging stations were re-established at Liberty and Newman Lakes, Washington, in August 2004, and at Twin Lakes, Idaho, in October, 2004. Also, in October 2004, gaging stations were established at Spirit and Hauser Lakes, Idaho, where no gaging stations were located previously. Currently (2005), USGS is making monthly lake stage measurements at Spirit, Twin, Hayden, and Hauser Lakes, Idaho, and Newman and Liberty Lakes, Washington. Hourly measurements are recorded at long-term measurement sites at Lakes Coeur d'Alene (USGS) and Pend Oreille (U.S. Army Corps of Engineers), Idaho and Long Lake (Avista Corporation), Washington. Liberty Lake Sewer and Water District began monitoring lake stage of Liberty Lake, Washington, January 1, 2004 (Liberty Lake Sewer and Water District, accessed June 1, 2005, http://207.88.115.227/libertylakemonitoring/liberty_lake.htm).

**Table 4.** Summary of historical or project-related lake stage data collection sites for lakes along the margins of the Spokane Valley–Rathdrum Prairie aquifer, Washington and Idaho.

[Locations of stations are shown on figure 6. **Period of record:** At the time of publication of this report, the period of record is expected to continue beyond 2005 at each of these sites. **Abbreviations**: ID, Idaho; WA, Washington; USGS, U.S. Geological Survey]

| Gaging station name | USGS gaging station No. | Period of record | Measurements (2005) | |
|---|---|---|---|---|
| | | | Frequency | Method |
| Lake Pend Oreille near Hope, ID | 12392500 | 1914–2005 | Hourly | Recorder |
| Spirit Lake at Spirit Lake, ID | 4757351165224 | 2004–05 | Monthly | Temporary gage |
| Twin Lakes near Rathdrum, ID | 12419200 | 1958–68, 2004–05 | Monthly | Staff gage |
| Hayden Lake at Hayden Lake, ID | 12417000 | 1920–2005 | Monthly | Staff gage |
| Coeur d'Alene Lake at Coeur d'Alene, ID | 12415500 | 1903–2005 | Hourly | Recorder |
| Hauser Lake at Hauser, ID | 4746121170104 | 2004–05 | Monthly | Temporary gage |
| Newman Lake near Newman Lake, WA | 12419800 | 1958–80, 2004–05 | Monthly | Staff gage |
| Liberty Lake at Liberty Lake, WA | 12420000 | 1950–89, 2004–05 | Monthly | Staff gage |
| Long Lake at Long Lake, WA | 12432500 | 1913–2005 | Hourly | Recorder |

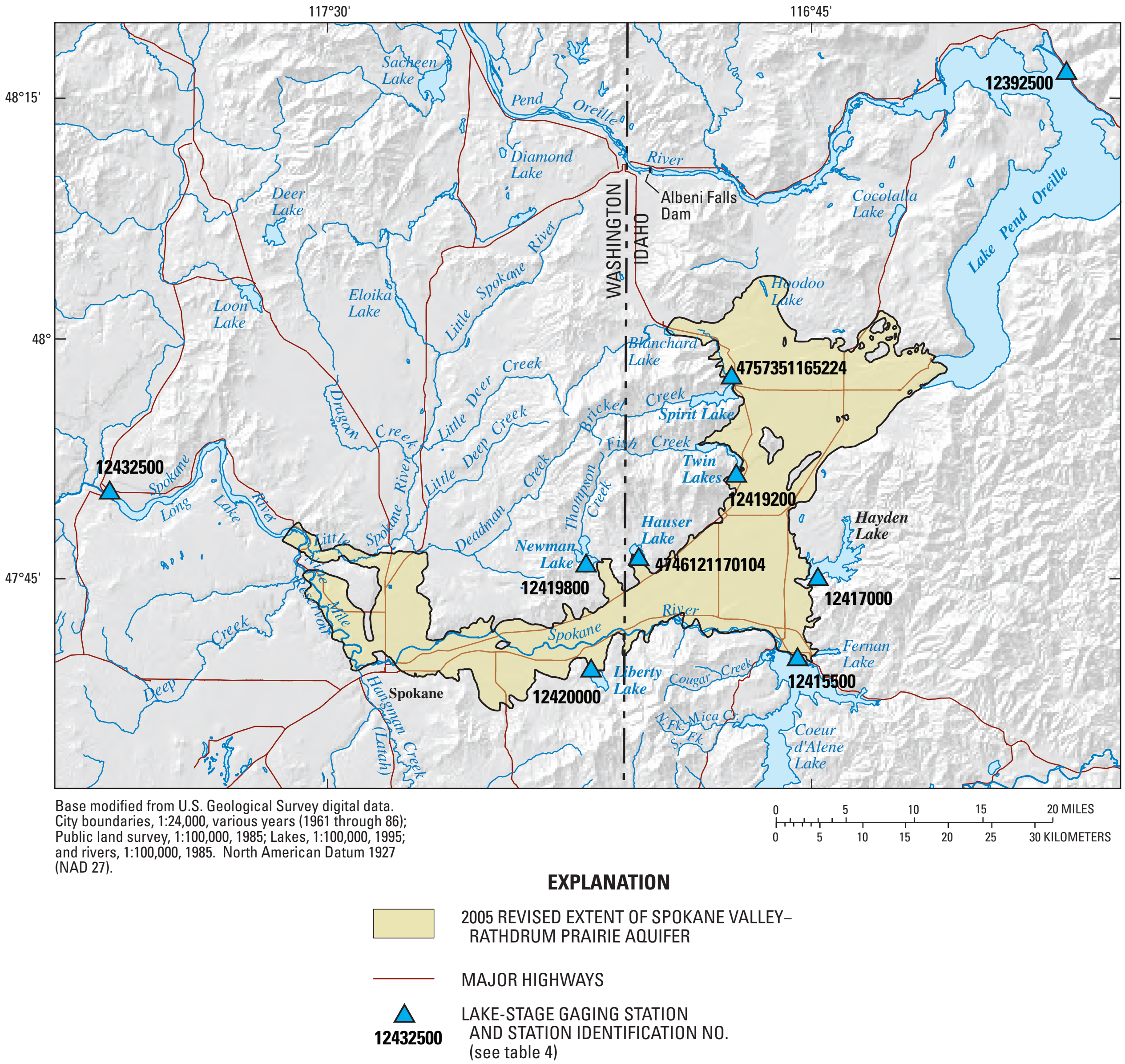


**Figure 6.** Locations of long-term and project-related lake-stage measurement sites, Washington and Idaho.

## Aquifer Boundaries

In most places, the Spokane Valley–Rathdrum Prairie aquifer is bounded laterally by bedrock and the lower or bottom aquifer boundary is mostly unknown except along the margins or in shallower parts of the aquifer where wells have penetrated the entire aquifer thickness and reached bedrock or silt and clay deposits. Reported ground-water divides approximately represent the aquifer boundary in the Hoodoo and Spirit Valleys and near Careywood, Idaho (Walker, 1964 and Parliman and others, 1980). Upgradient aquifer areas also are bounded by tributary lakes, including Pend Oreille, Spirit, Twin, Hayden, Coeur d'Alene, Hauser, Newman, and Liberty. Streams tributary to the aquifer include Lewellen, Sage, and Rathdrum Creeks in Idaho, and Chester and Saltese Creeks in Washington. Streams tributary to the Spokane River in the aquifer extent include Hangman (Latah) Creek near Spokane, Washington, and the Little Spokane River north of Spokane. The aquifer's lower discharge area is near Long Lake at the confluence of the Spokane and Little Spokane Rivers.

## Water-Budget Components

A water budget is an accounting of water and its movement in a hydrologic system. Water budgets can be as simple as a few numbers representing water added to and subtracted from the hydrologic system, or as complex as a numerical simulation of the hydrologic system. This hydrologic system can range in scale from global to site specific and could include only ground water, only surface water, or both. A water budget is a useful tool for helping water-resource scientists and managers conceptualize the hydrologic system. Because some of the inflows and outflows from the system cannot be measured directly, however, they must be estimated. Therefore, the resulting water budget is an approximation of the physical hydrologic system, and the measured inflow and outflow totals may not balance exactly.

Several investigators have compiled complete water budgets for large parts of the SVRP aquifer (table 5). These water budgets are not directly comparable because most studies have used different boundaries for the SVRP aquifer. More than 25 publications have addressed aspects of the water budget for the SVRP aquifer using different techniques. Water-budget component estimates from previous studies are summarized in tables 6 through 13.

Because of the long history of water development in the study area and the obscure nature of many reports on water-resource issues, numerous discrepancies exist between various reports. These discrepancies likely are due to the unavailability of original reports, resulting in investigators citing data referenced in subsequent reports. This potential source of error, compounded with misunderstandings and typographic mistakes, likely caused reported values to “drift” from the original. For this report, original sources were reviewed in nearly all cases; however, some documents were unavailable. These references are identified in the tables 6 through 13. How a particular value was obtained is not always known, but where possible, methods used by various investigators for their estimates have been identified. Finally, different investigators have defined or grouped measurement areas differently and estimates should be compared with caution. This report is intended as a review—the interested reader is urged to check original sources.

### Recharge and Underflow—How Ground Water Enters the Aquifer

Water enters an aquifer by many processes and settings and these processes and settings can be classified in numerous ways. In this report, recharge is discussed by the setting in which it occurs. Three main settings in which water enters the SVRP aquifer are: the valley floor over the aquifer, tributary basins, and adjacent uplands surrounding the aquifer, and the Spokane River itself (which also acts as a discharge setting in some reaches). Some investigators have included total recharge estimates to the aquifer without differentiating the source. These estimates are included in table 5.

**Table 5.** Published water budgets for the Spokane Valley–Rathdrum Prairie aquifer.

[**Method:** M, ground-water-flow model; R, referenced; SM, streamflow measurements; W, water balance; WY, watershed yield. **Abbreviations:** $ft^3/s$, cubic foot per second; –, not applicable or unknown]

| Area | Estimated total recharge/ discharge ($ft^3/s$) | Period calculated | Primary method | Reference |
|---|---|---|---|---|
| Aquifer above Spokane | [1,2]1,200 | 1959 | R, SM, WY | Thomas (1963) |
| | [1,2]1,100 | 1951–59 | R, SM, WY | Thomas (1963) |
| | [1,2]939 | 1951–54 | – | Bureau of Reclamation (1963)[3] |
| Aquifer above Otis Orchards | [1]1,000 | 1911–60 | SM, WY | Pluhowski and Thomas (1968) |
| | [1]1,000 | 1911–60 | SM, WY | Pluhowski (1970) |
| Approximate sole-source aquifer boundary | 1,320/1,320 | Average conditions | R | Drost and Seitz (1978b) |
| Report model area | 1,010 | May 1977–Apr. 1978 | M[4] | Bolke and Vaccaro (1981) |
| | 1,030 | May 1977–Apr. 1978 | M[5] | Bolke and Vaccaro (1981) |
| Aquifer, Idaho portion | [1]753 | Average conditions | R, W, WY | Painter (1991) |
| Report model area | 692/692 | Fall 1994[4] | M | CH2M HILL (1998) |
| | 730/730 | Spring 1995[4] | M | CH2M HILL (1998) |
| | 652/652 | Fall 1994[4] | M | CH2M HILL (2000a) |
| | 397/397 | Steady state conditions[4] | M | Buchanan (2000) |

[1] Recharge only.

[2] Does not include Lake Pend Oreille.

[3] From Frink (1964).

[4] Steady state.

[5] Transient.

### Valley Floor

The main source of recharge to ground water from the valley floor is infiltration from land surface: precipitation, applied irrigation water, canal-seepage loss, and septic-tank effluent. However, water loss to evapotranspiration decreases the amount of precipitation and irrigation water that reaches the saturated zone.

#### Precipitation

Direct recharge from precipitation on the valley floor was recognized early as a significant component of SVRP water budgets due to the scarcity of streams that reach the Spokane River. Recharge estimates from precipitation are more straightforward than many other water-budget components; however, previous estimates still range over an order of magnitude (table 6), partly due to differences in how areas are delineated—some investigators included the entire watershed while others included only the valley floor. Also, some investigators factored evapotranspiration losses directly into their recharge estimates while others subtracted evapotranspiration as a separate item.

A facet of precipitation recharge is the presence of numerous storm-water injection, or dry wells in the study area. These drain wells allow local disposal of storm water eliminating the need for extensive storm-water sewerage. Due to the long-standing use of these dry wells, it is unclear exactly how many exist, though McLeod (1991) reported about 2,500 in the "Panhandle area around Coeur d'Alene." Golder Associates, Inc. (2004) used Spokane County GIS coverages for the location of these wells and calculated that they recharge 83-87 percent of precipitation in the capture zone of the well and modeled them explicitly with a density of as many as 87 wells per square mile.

#### Applied Irrigation Water and Canal Seepage

Many early studies of the SVRP aquifer were related to irrigation projects, consequently several estimates have been made of irrigation seepage and canal leakage. These irrigation-related components are summarized in table 6.

#### Septic-System Effluent

Recharge from septic-system effluent was not included explicitly as a component in SVRP aquifer water budgets until around the advent of numerical simulation. This probably corresponds to rapid population growth and explains why previous investigators may not have considered it significant. Septic-system effluent recharge estimates are shown in table 6.

### Inflow from Tributary Basins, Adjacent Uplands, and Subsurface

Previous SVRP aquifer water budgets indicate that recharge from lakes and streams in tributary basins and adjacent uplands are the largest source of water to the SVRP aquifer. Traditionally, the quantity of such recharge has been difficult to measure and often has been calculated indirectly through water-budget or modeling methods.

Because of the SVRP aquifer's physical setting, many investigators have believed that Coeur d'Alene Lake and Lake Pend Oreille are among the largest sources of recharge to the aquifer. Consequently, much effort has gone into quantifying recharge contribution by these and other lakes using methods ranging from simple watershed-yield estimates to numerical simulation (table 7). Note that some estimates for a given lake may range over several orders of magnitude.

Tributary basins without major lakes and adjacent uplands, while individually small, collectively contribute a significant quantity of recharge to the SVRP aquifer (table 8). However, they have received less attention than other water-budget components possibly because quantifying such recharge is difficult or because study areas differ. Previous seepage estimate studies primarily used watershed-yield, streamflow measurement, or numerical simulation methods and are shown in table 8. Some estimates range over an order of magnitude. Of special interest is possible underflow from the Hoodoo Valley into the SVRP aquifer. Though surface-water drainage is to the north, several investigators suggested that ground water flows south, aided by the increased head of water behind Albeni Falls dam.

Underflow into the SVRP aquifer cannot be directly measured; therefore, these estimates tend to be the residual of other water-budget components in ground-water-flow models. Table 9 shows underflow recharge estimates by previous investigators.

### Spokane River

The direction and amount of water flowing between the Spokane River and the SVRP aquifer is one of the most important hydrologic issues in the study area. Not only do the volume and direction of flow between surface and ground water affect the amount of water in the river, they affect the volume of ground water available in the aquifer. Numerous studies have examined this interaction with a variety of techniques over different river reaches and have defined gaining (the river gains flow from ground-water discharge) and losing (the river loses flow to ground-water recharge). These often conflicting numbers result from different reach definition, seasonal and yearly precipitation variance, development in the study area, and study method. For instance, most investigators for most time periods have concluded that the Spokane River between Post Falls and Nine Mile Falls gains water from the aquifer, though shorter reaches lose water to the aquifer. Various estimates by previous investigators are shown in table 10 and are discussed in more detail in the Ground-Water/Surface-Water Interactions section.

**Table 6.** Estimates of total recharge, land-surface recharge, and evapotranspiration for the Spokane Valley–Rathdrum Prairie aquifer.

[**Recharge or discharge:** Negative values indicate discharge from the aquifer. **Method:** C, calculated; D, Darcy's Law; M, ground-water-flow model; MO, meteorological observations; R, referenced; SM, streamflow measurements; W, water balance; WY, watershed yield. **Abbreviations:** WRIA, Water Resource Inventory Area; ID, Idaho; WA, Washington; $ft^3/s$, cubic foot per second; –, not applicable or unknown]

| Type of recharge or discharge | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| All recharge | 1,000 | 1928–38 | D | Piper and La Rocque (1944) |
| | 1,000 | – | R | Piper and Huff (1943) |
| | 1,200 | 1959 | WB | Thomas (1963) |
| | 1,100 | 1951–59 | WB | Thomas (1963) |
| | 1,105 | – | – | Bureau of Reclamation (1966) |
| | 1,320 | Average conditions | – | Drost and Seitz (1978b) |
| All recharge-WA | 384 | 1951–54 | – | Bureau of Reclamation (1963)[5] |
| All recharge-ID except Lake Pend Oreille | 550 | 1951–54 | – | Bureau of Reclamation (1963)[4] |
| All recharge except Lake Pend Oreille | 939 | 1951–54 | – | Bureau of Reclamation (1963)[4] |
| All recharge except Lake Pend Oreille, Coeur d'Alene Lake, and Spokane River | 260–670 | Average year | – | Meneely (1951)[5] |
| | 40–390 | Dry year | – | Meneely (1951)[5] |
| | 260–670 | Average year | R | Bureau of Reclamation (1956) |
| | 40–390 | Dry year | R | Bureau of Reclamation (1956) |
| Precipitation, ID | 132 | 1959 | MO | Thomas (1963) |
| | 130 | Average conditions | R | Drost and Seitz (1978b) |
| | 250 | – | W | Painter (1991) |
| Precipitation, WA valley floor | 63 | 1959 | – | Thomas (1963) |
| Precipitation, WA | 50 | 1951–54 | – | Bureau of Reclamation (1963)[5] |
| Precipitation, lowlands | 120 | – | WY | Piper and Huff (1943) |
| | 381 | Average conditions | C | Nace and others (1970) |
| Precipitation, uplands | 45 | – | WY | Piper and Huff (1943) |
| Precipitation, total | 165 | 1950 | R | Anderson (1951) |
| | 250 | 1951–54 | R | Frink (1964) |
| | 50 | – | WY | Pluhowski and Thomas (1968) |
| | 530 | – | R | Pluhowski (1970) |
| | [1]209 | May 1977–April 1978 | MO | Bolke and Vaccaro (1981) |
| | [2]216 | May 1977–April 1978 | MO | Bolke and Vaccaro (1981) |
| Precipitation | 125 | Steady state conditions | M | Buchanan (2000) |
| | 25 | Fall 1994 | M | CH2M HILL (1998) |
| | 52 | Spring 1995 | M | CH2M HILL (1998) |
| | 25 | Fall 1994 | M | CH2M HILL (2000a) |
| Precipitation–evapotranspiration lowlands | 156 | Average conditions | C | Nace and others (1970) |
| Precipitation and runoff-total | 770 | 1959 | – | Thomas (1963) |
| | 640 | 1951–59 | – | Thomas (1963) |
| Irrigation seepage, WA | 28 | 1950 | R | Anderson (1951) |
| | 66 | May–Aug. | W | McDonald and Broom (1951) |
| | 54 | 1951–54 | – | Bureau of Reclamation (1963)[5] |
| Irrigation seepage-total | 113 | 1952 | C | Nace and others (1970) |
| Irrigation seepage (includes canals) | 55 | 1951–59 | – | Thomas (1963) |
| | 56 | 1959 | – | Thomas (1963) |
| Irrigation seepage | 280 | 1951–54 | R | Frink (1964) |
| | 50 | – | WY | Pluhowski and Thomas (1968) |
| | 50 | – | R | Pluhowski (1970) |
| Irrigation seepage, from surface water | 90 | 1952 | C | Nace and others (1970) |
| Irrigation seepage, from ground water | 23 | 1952 | C | Nace and others (1970) |
| Irrigation seepage, agriculture, 3,360 acres | 78 | Average conditions | C | Golder Associates, Inc. (2004) |
| Irrigation seepage, lawns, 15,260 acres | 8 | Average conditions | C | Golder Associates, Inc. (2004) |
| Canal Loss: Main Canal, Post Falls to State Line | 8 | 1953 | C | Bureau of Reclamation (1956) |

**Table 6.** Estimates of total recharge, land-surface recharge, and evapotranspiration for the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge or discharge:** Negative values indicate discharge from the aquifer. **Method:** C, calculated; D, Darcy's Law; M, ground-water-flow model; MO, meteorological observations; R, referenced; SM, streamflow measurements; W, water balance; WY, watershed yield. **Abbreviations:** WRIA, Water Resource Inventory Area; ID, Idaho; WA, Washington; $ft^3/s$, cubic foot per second; –, not applicable or unknown]

| Type of recharge or discharge | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Canal Loss: North Branch Canal, State Line to Pasadena Park | 10 | 1953 | C | Bureau of Reclamation (1956) |
| Canal Loss: South Branch Canal, State Line to Liberty Lake Road | 3 | 1953 | C | Bureau of Reclamation (1956) |
| Canal Loss: Liberty Lake Chute Outlet to Greenacres | 2 | 1953 | C | Bureau of Reclamation (1956) |
| Canal Loss: High lateral, Liberty Lake Chute Outlet to south of Greenacres | 1 | 1953 | C | Bureau of Reclamation (1956) |
| Land-applied water (from ground water) | 11 | Fall 1994 | C | CH2M HILL (1998) |
| | 2 | Spring 1995 | C | CH2M HILL (1998) |
| | 11 | Fall 1994 | C | CH2M HILL (2000a) |
| | [1]99 | May 1977–Apr. 1978 | C | Bolke and Vaccaro (1981) |
| | [2]108 | May 1977–Apr. 1978 | C | Bolke and Vaccaro (1981) |
| | 50 percent of pumpage from Spokane seasonal wells | 1977 | R | Bolke and Vaccaro (1981) |
| | 10 percent of pumpage from Spokane continuous wells | 1977 | R | Bolke and Vaccaro (1981) |
| | 100 percent of pumpage from non-Spokane wells | 1977 | R | Bolke and Vaccaro (1981) |
| | 100 percent of pumpage from irrigation wells | 1977 | R | Bolke and Vaccaro (1981) |
| | 0 percent of pumpage from industrial wells | 1977 | R | Bolke and Vaccaro (1981) |
| Septic systems | 34 | Average conditions | R | Drost and Seitz (1978b) |
| | 29 | 1976 | R | Drost and Seitz (1978b) |
| | [1,2]35 | May 1977–Apr. 1978 | – | Bolke and Vaccaro (1981) |
| | 16 | Fall 1994 | C | CH2M HILL (1998) |
| | 16 | Spring 1995 | C | CH2M HILL (1998) |
| | 16 | Fall 1994 | C | CH2M HILL (2000a) |
| Evapotranspiration, lowlands | -225 | Average conditions | C | McQueen (1970) |
| Evapotranspiration | No direct | Average conditions | R | Drost and Seitz (1978b) |
| | [1]-143 | May 1977–Apr. 1978 | C | Bolke and Vaccaro (1981) |
| | [2]-98 | May 1977–Apr. 1978 | C | Bolke and Vaccaro (1981) |
| Evapotranspiration, WRIA 55 | -972 | Average conditions | C | Golder Associates, Inc. (2004) |
| Evapotranspiration, WRIA 57 | -307 | Average conditions | C | Golder Associates, Inc. (2004) |
| Consumptive crop use, WA | -33 | May–August | W | McDonald and Broom (1951) |
| Land-surface infiltration, Rathdrum Prairie Valley | [3]42–276 | 1950 | | Lenz, 1950 |
| | 530 | 1911-60 | W | Pluhowski and Thomas (1968) |

[1] Steady-state.

[2] Transient.

[3] Range of monthly averages.

[4] From Frink (1964).

[5] From Anderson (1951).

**Table 7.** Estimates of seepage from lakes into the Spokane Valley–Rathdrum Prairie aquifer.

[**Method:** D, Darcy's Law; M, ground-water-flow model; R, referenced; W, water balance; WY, watershed yield. **Abbreviations:** $ft^3/s$, cubic foot per second; ≥, greater than or equal; ≤, less than or equal; –, not applicable or unknown]

| Lake | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Coeur d'Alene Lake | 300 | 1950 | R | Anderson (1951) |
| | 300 | 1951–54 | – | Bureau of Reclamation (1963)[1] |
| | 250 | Average conditions | R | Drost and Seitz (1978b) |
| | 35 | Steady state conditions | M | Buchanan (2000) |
| Coeur d'Alene Lake and Spokane River–Post Falls gaging station | ≤300 | – | R | Bureau of Reclamation (1956) |
| | 140 | 1959 | W | Thomas (1963) |
| | 170 | July 1959 | W | Thomas (1963) |
| | 120 | August 1959 | W | Thomas (1963) |
| | 270 | October 1959 | W | Thomas (1963) |
| | 250 | 1911–60 | W | Pluhowski and Thomas (1968) |
| Coeur d'Alene Lake and Spokane River–Post Falls | 380 | – | W | McQueen and Nace (1970) |
| | 225 | – | D | Sagstad (1977) |
| | 230 | – | R | Painter (1991) |
| Hauser Lake | 37 | 1959 | W | Thomas (1963) |
| | 37 | Average conditions | R | Drost and Seitz (1978b) |
| | 8.2 | | – | Entranco Engineering (1990)[5] |
| | 8.2 | – | R | Painter (1991) |
| | 2.5 | Steady state conditions | M | Buchanan (2000) |
| Hayden Lake | 50 | – | – | Meneely (1951)[2] |
| | 50 | 1951–54 | – | Bureau of Reclamation (1963)[1] |
| | 100 | 1959 | W | Thomas (1963) |
| | 80 | 1951–59 | W | Thomas (1963) |
| | 100 | | W | McQueen and Nace (1970) |
| | 80 | Average conditions | R | Drost and Seitz (1978b) |
| | 37.8 | | WY | Painter (1991) |
| | 27 | Steady state conditions | M | Buchanan (2000) |
| Liberty Lake | 16 | 1959 | W | Thomas (1963) |
| | 16 | Average conditions | R | Drost and Seitz (1978b) |
| Newman Lake drainage | 65 | 1959 | W | Thomas (1963) |
| Newman Lake | 65 | Average conditions | R | Drost and Seitz (1978b) |
| Lake Pend Oreille | 50–200 | 1911–60 | W | Pluhowski and Thomas (1968) |
| | 201–309 | – | – | Simons and others (1953)[3] |
| | ≥1,000 | Natural conditions | W | Piper and Huff (1943) |
| | "Several hundred" | 1950 | R | Anderson (1951) |
| | "Insignificant" | – | W | Thomas (1963) |
| | "Major source" | 1951–54 | – | Bureau of Reclamation (1956) |
| | 20–60 | – | D | Frink (1964) |
| | 50 | – | W | McQueen and Nace (1970) |
| | 46 | – | – | Hammond (1974) |
| | 20–50 | Average conditions | R | Drost and Seitz (1978b) |
| | [3]50 | – | R | Painter (1991) |
| | 61 | Steady state conditions | M | Buchanan (2000) |
| Spirit Lake watershed | 98 | 1959 | W | Thomas (1963) |
| | 93 | – | – | Hammond (1974) |
| | 100 | Average conditions | R | Drost and Seitz (1978b) |
| | 22 | – | W | Soltero and Hall (1985) |
| | 22 | – | W | Bellatty (1987)[4] |
| Spirit Lake | 22.3 | – | R | Painter (1991) |
| | 13 | – | M | Buchanan (2000) |

**Table 7.** Estimates of seepage from lakes into the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Method:** D, Darcy's Law; M, ground-water-flow model; R, referenced; W, water balance; WY, watershed yield. **Abbreviations:** $ft^3/s$, cubic foot per second; ≥, greater than or equal; ≤, less than or equal; –, not applicable or unknown]

| Lake | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Twin Lakes basin | 86 | – | W | Thomas (1963) |
| Twin Lakes | 85 | Average conditions | R | Drost and Seitz (1978b) |
| | 25 | – | R | Painter (1991b) |
| | 25 | – | – | Falter and Hallock (1987)[4] |
| | 6 | Steady state conditions | M | Buchanan (2000) |

[1] From Frink (1964).

[2] From Anderson (1951).

[3] From Hammond (1974).

[4] From Painter (1991).

**Table 8.** Estimates of recharge from tributary streams, drainages, and uplands into the Spokane Valley–Rathdrum Prairie aquifer.

[**Method:** M, ground-water-flow model; R, referenced; SM, streamflow measurements; WY, watershed yield. **Abbreviations:** $ft^3/s$, cubic foot per second; –, not applicable or unknown]

| Source area | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Bayview/Kelso drainage | 14.8 | – | WY | Painter (1991b) |
| Blanchard drainage | 89 | 1959 | SM | Thomas (1963) |
| | 62.2 | – | WY | Painter (1991) |
| | 3 | Steady state conditions | M | Buchanan (2000) |
| Blanchard Creek and Spirit Valley | 77 | – | – | Hammond (1974) |
| Cable Creek | 11 | 1959 | SM | Thomas (1963) |
| | 11 | Average conditions | R | Drost and Seitz (1978b) |
| Canfield drainage area | 11 | 1959 | SM | Thomas (1963) |
| Canfield drainage | 11 | Average conditions | R | Drost and Seitz (1978b) |
| | 4.6 | – | WY | Painter (1991) |
| Coulee Creek | 5 | – | R | Drost and Seitz (1978b) |
| Chilco Channel area | 43 | 1959 | SM | Thomas (1963) |
| | 40 | Average conditions | R | Drost and Seitz (1978b) |
| Chilco Channel | 40.6 | – | WY | Painter (1991) |
| | 4 | Steady state conditions | M | Buchanan (2000) |
| Deep Creek | 2 | Average conditions | R | Drost and Seitz (1978b) |
| Dishman Hills | 31 | 1959 | SM | Thomas (1963) |
| | 31 | Average conditions | R | Drost and Seitz (1978b) |
| Hangman (Latah) Creek | 15 | Average conditions | R | Drost and Seitz (1978b) |
| Hidden Valley area | 30 | 1959 | SM | Thomas (1963) |
| | 30 | Average conditions | R | Drost and Seitz (1978b) |
| Hidden Valley | 7.3 | – | WY | Painter (1991) |
| Hoodoo Valley | 90 | Average conditions | R | Drost and Seitz (1978b) |
| Indian Canyon | 2 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Indian Canyon–Deep Creek | 2 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Orchard Prairie area | 5 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Peone Prairie area | 18 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Pleasant Prairie area | 9 | 1959 | SM | Thomas (1963) |
| | 9 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Saltese Flats area | 24 | 1959 | SM | Thomas (1963) |
| | 24 | Average conditions | R | Drost and Seitz (1978b) |
| Uplands: Scalan Creek area | 13 | 1959 | SM | Thomas (1963) |
| | 13 | Average conditions | R | Drost and Seitz (1978b) |

**Table 9.** Estimates of non-tributary underflow into and out of the Spokane Valley–Rathdrum Prairie aquifer.

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** M, ground-water-flow model; R, referenced. **Abbreviation:** $ft^3/s$ cubic foot per second]

| Inflow and outflow | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Subsurface inflow, north, east, south model boundaries | 668[1] | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | 656[2] | May 1977–Apr. 1978 | M[2] | Bolke and Vaccaro (1981) |
| Subsurface outflow, west model boundary | -105 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | -102 | May 1977–Apr. 1978 | M[2] | Bolke and Vaccaro (1981) |
| Ground-water outflow at Nine Mile Dam | 0 | Fall 1994 | M | CH2M HILL (1998) |
| | 0 | Spring 1995 | M | CH2M HILL (1998) |
| | -55 | Average conditions | R | Drost and Seitz (1978b) |
| | 0 | Fall 1994 | M | CH2M HILL (2000a) |
| | 0 | Average conditions | M | Golder Associates, Inc. (2004) |

[1] Steady-state.

[2] Transient.

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Spokane River | -282 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | -338 | May 1977–Apr. 1978 | M[2] | Bolke and Vaccaro (1981) |
| | [3]-700–470 | May 1977–Apr. 1978 | M[2] | Bolke and Vaccaro (1981) |
| | 120 | Steady state conditions | M | Buchanan (2000) |
| Coeur d'Alene Lake to Post Falls gaging station | 120 | 1949–59 | R | Crosthwaite and others (1970) |
| | ≤1,000 | – | R | Bureau of Reclamation (1956) |
| Coeur d'Alene Lake to Sullivan Road | [9]207 | – | CM | Miller (1996)[5] |
| | [6]303 | – | CM | Miller (1996)[5] |
| | [7]319 | – | CM | Miller (1996)[5] |
| Coeur d'Alene Lake to 4 mi west of the State Line | 0 | – | SM | Piper and La Rocque (1944) |
| Post Falls to Otis Orchard gaging stations | 280 | 1951–54 | SM | Bureau of Reclamation (1956) |
| | 150 | 1959 | SM | Thomas (1963) |
| | 180 | 1951–59 | SM | Thomas (1963) |
| | 120 | 1911–60 | W | Pluhowski and Thomas (1968) |
| | [8]8–1,130 | 1951–59 | SM | Crosthwaite and others (1970) |
| | 180 | 1951–59 | SM | Crosthwaite and others (1970) |
| | [9]69–810 | 1999–2001 | SM | Caldwell and Bowers (2003) |
| | 255 | 1999–2001 | SM | Caldwell and Bowers (2003) |
| | [10]37–78 | 1929–83, 1999–2004 | SM | Hortness and Covert (2005) |
| | 177 | Sept. 2004 | SM | Hortness and Covert (2005) |
| Post Falls to Greenacres gaging stations | 5.7 | Dec. 1948–Sept. 1949 | | Anderson (1951) |
| | Minimal | 1947–50 | SM | McDonald and Broom (1951) |
| | 78 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-529–757 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | 80 | Average conditions | R | Drost and Seitz (1978b) |
| | 50 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | 144 | July 1984–Sept. 1984 | SM | Patmount and others (1985) |
| | [9]-42–770 | 1999–2001 | SM | Caldwell and Bowers (2003) |

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Post Falls to Greenacres gaging stations—Continued | 288 | 1999–2001 | SM | Caldwell and Bowers (2003) |
| | 292–919 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 655 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 287 | Sept. 2004 | SM | Hortness and Covert (2005) |
| Post Falls to Trent Bridge gaging stations | -357 | Dec. 1948–Sept. 1949 | SM | Anderson (1951) |
| Post Falls to Greene Street gaging stations | -807 | Dec. 1948–Sept. 1949 | SM | Anderson (1951) |
| Post Falls to Spokane gaging stations | -322– -1,383 | Dec. 1948–Mar. 1950 | SM | Lenz (1950) |
| | -787 | Dec. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -467 | 1920–48 | SM | Anderson (1951) |
| | [9]-881– -77 | 1920–48 | SM | Anderson (1951) |
| | -753 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -467 | – | – | Bureau of Reclamation (1954) |
| | -460 | 1914–53 | SM | Bureau of Reclamation (1956) |
| | 268 | Sept. 12, 1994 | SM | CH2M HILL (1998) |
| | 153 | Sept. 13, 1994 | SM | CH2M HILL (1998) |
| | 103 | Sept. 14, 1994 | SM | CH2M HILL (1998) |
| | 43 | Sept. 15, 1994 | SM | CH2M HILL (1998) |
| | 103 | Apr. 9, 1995 | SM | CH2M HILL (1998) |
| | 3 | Apr. 10, 1995 | SM | CH2M HILL (1998) |
| | 3 | Apr. 11, 1995 | SM | CH2M HILL (1998) |
| | -247 | Apr. 12, 1995 | SM | CH2M HILL (1998) |
| Post Falls gaging station to Seven Mile | -878 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Post Falls gaging station to Nine Mile | -1,014 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | 224 | Sept. 12, 1994 | SM | CH2M HILL (1998) |
| | 29 | Sept. 13, 1994 | SM | CH2M HILL (1998) |
| | -104 | Sept. 14, 1994 | SM | CH2M HILL (1998) |
| | -39 | Sept. 15, 1994 | SM | CH2M HILL (1998) |
| | -1,080 | Apr. 09, 1995 | SM | CH2M HILL (1998) |
| | -1,207 | Apr. 10, 1995 | SM | CH2M HILL (1998) |
| | -1,099 | Apr. 11, 1995 | SM | CH2M HILL (1998) |
| | -1,381 | April 12, 1995 | SM | CH2M HILL (1998) |
| Stateline to Barker Road | 45 | Fall 1994 | M | CH2M HILL (1998) |
| | 71 | Spring 1995 | M | CH2M HILL (1998) |
| | 45 | Fall 1994 | M | CH2M HILL (2000a) |
| | 76–444 | – | D | Gearhart (2001) |
| | 142–660 | Aug. 20, 1998–July 6, 1999 | SM | Gearhart (2001) |
| Stateline to Harvard Road | 168–591 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004) |
| | 406 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004) |
| 4 mi west of State Line to a few miles below Spokane | -600– -800 | Late summer-fall | SM | Piper and La Rocque (1944) |
| Otis Orchard to Greenacres gaging stations | Minimal | 1951–59 | SM | Crosthwaite and others (1970) |
| | Minimal | 1948–52, 1999–2004 | SM | Hortness and Covert (2005) |
| Harvard Road to Barker Road | 28.7–137 | – | D | Gearhart (2001) |
| | 5.7–16.6 | Annual range, 1994–99 | M | Golder (2004)[13] |
| | 11.8 | Annual mean, 1994–99 | M | Golder (2004)[13] |
| Harvard Road to E. Trent Bridge | -404 | July 1984–Sept. 1984 | SM | Patmount and others (1985) |
| Greenacres to Trent Bridge gaging stations | -363 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -370 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-1,140– -39 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | -330 | Average conditions | R | Drost and Seitz (1978b) |
| | -240 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | [10]-754– -330 | 1948–54 | SM | Hortness and Covert (2005) |

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; ft$^3$/s, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer (ft$^3$/s) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Greenacres to Greene Street gaging stations | -813 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Greenacres to Spokane gaging stations | -793 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | ≤-1,500 | 1948–52 | SM | Bureau of Reclamation (1956) |
| | -720 | 1951–59 | SM | Crosthwaite and others (1970) |
| | [8]-995– -576 | 1951 | SM | Crosthwaite and others (1970) |
| | -557 | Sept. 2004 | SM | Hortness and Covert (2005) |
| Greenacres to Spokane gaging stations, Little Spokane River | -900 | – | R | Piper and Huff (1943) |
| Greenacres gaging station to Seven Mile | -885 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Greenacres gaging station to Nine Mile | -1,021 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Greenacres to Long Lake gaging stations | -1,286 | 1951 | SM | Crosthwaite and others (1970) |
| | [8]-1,009– -1,642 | 1951 | SM | Crosthwaite and others (1970) |
| Greenacres gaging station to Sullivan Road | -273– -172 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -211 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -284– -202 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -232 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Barker Road to Sullivan Road | 91 | Fall 1994 | M | CH2M HILL (1998) |
| | 100 | Spring 1995 | M | CH2M HILL (1998) |
| | 75 | Fall 1994 | M | CH2M HILL (2000a) |
| | -241–423 | – | D | Gearhart (2001) |
| Barker Road to Plante's Ferry footbridge | -493– -110 | Aug. 20, 1998–July 6, 1999 | SM | Gearhart (2001) |
| Sullivan Road to Kaiser–Trentwood WWTP | 7 | Fall 1994 | M | CH2M HILL (1998) |
| | 5 | Spring 1995 | M | CH2M HILL (1998) |
| | -1 | Fall 1994 | M | CH2M HILL (2000a) |
| Sullivan Road to East Trent Bridge | -164–288 | – | D | Gearhart (2001) |
| | -116– -82.3 | Annual range, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| | -94.1 | Annual mean, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| Sullivan Road to Plante's Ferry footbridge | -117– -81.2 | Annual range, 1994-99 | M | Golder Associates, Inc. (2004)[12] |
| | -93.6 | Annual mean, 1994-99 | M | Golder Associates, Inc. (2004)[12] |
| | [9]-206 | – | CM | Miller (1996)[5] |
| | [6]-315 | – | CM | Miller (1996)[5] |
| | [7]-160 | – | CM | Miller (1996)[5] |
| Kaiser–Trentwood WWTP to E. Trent Bridge | -22 | Fall 1994 | M | CH2M HILL (1998) |
| | -64 | Spring 1995 | M | CH2M HILL (1998) |
| | -63 | Fall 1994 | M | CH2M HILL (2000a) |
| East Trent Bridge to Plante's Ferry footbridge | -1 | Fall 1994 | M | CH2M HILL (1998) |
| | -12 | Spring 1995 | M | CH2M HILL (1998) |
| | -12 | Fall 1994 | M | CH2M HILL (2000a) |
| | -69–121 | – | D | Gearhart (2001) |
| | .0-.4 | Annual range, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| | .1 | Annual mean, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| East Trent Bridge to Upriver Dam | 13.1–15.7 | Annual range, 1994-99 | M | Golder Associates, Inc. (2004)[12] |
| | 16.2 | Annual mean, 1994-99 | M | Golder Associates, Inc. (2004)[12] |
| East Trent Bridge to Greene Street | -321 | July 1984–Sept. 1984 | SM | Patmount and others (1985) |
| Trent Bridge gaging station to Upriver Dam | 40 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| Trent Bridge gaging station to Greene Street gaging station | -273 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -566 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-1,650–12 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [10]447– -229 | 1949–52 | SM | Hortness and Covert (2005) |

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Trent Bridge gaging station to Spokane gaging station | -430 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -230 | – | R | Drost and Seitz (1978b) |
| Trent Bridge gaging station to Seven Mile | -522 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Trent Bridge gaging station to Nine Mile | -658 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Plante's Ferry footbridge to Argonne Road | 12 | Fall 1994 | M | CH2M HILL (1998) |
| | 4 | Spring 1995 | M | CH2M HILL (1998) |
| | 11 | Fall 1994 | M | CH2M HILL (2000a) |
| | 2.8–3.9 | Annual range, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| | 3.3 | Annual mean, 1994-99 | M | Golder Associates, Inc. (2004)[13] |
| Plante's Ferry footbridge to Upriver Dam | Possible gain[9] | – | CM | Miller (1996)[5] |
| | Indeterminate[6] | – | CM | Miller (1996)[5] |
| | Possible gain[7] | – | CM | Miller (1996)[5] |
| Argonne Road to Upriver Dam | 6 | Fall 1994 | M | CH2M HILL (1998) |
| | 4 | Spring 1995 | M | CH2M HILL (1998) |
| | 6 | Fall 1994 | M | CH2M HILL (2000a) |
| | 18.0–20.1 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 19.1 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| Upriver Dam to Upriver Drive (RM 79.1) | -102– -77.4 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -90.8 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Upriver Dam to Greene Street | -270 | May 1977-–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | [9]-209 | – | CM | Miller (1996)[5] |
| | [6]-264 | – | CM | Miller (1996)[5] |
| | [7]-377 | – | CM | Miller (1996)[5] |
| | -149 | Fall 1994 | M | CH2M HILL (1998) |
| | -194 | Spring 1995 | M | CH2M HILL (1998) |
| | -174 | Fall 1994 | M | CH2M HILL (2000a) |
| | -82.3– -38.9 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -66.8 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| Upriver Drive (RM 79.1) to Greene Street | 19.4–43.2 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 29.8 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Greene Street to Mission Street | 38 | Fall 1994 | M | CH2M HILL (1998) |
| | 32 | Spring 1995 | M | CH2M HILL (1998) |
| | 26 | Fall 1994 | M | CH2M HILL (2000a) |
| | 104–166 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 132.9 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| Greene Street to Upper Falls Dam | 200 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | 142–224 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 177.0 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Greene Street to Monroe Street | [9]-63 | – | CM | Miller (1996)[5] |
| | [6]0 | – | CM | Miller (1996)[5] |
| | [7]-122 | – | CM | Miller (1996)[5] |
| Greene Street to Spokane gaging stations | 20 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | 39 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-216–428 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | 75 | July 1984–Sept. 1984 | SM | Patmount and others (1985) |
| | Minimal | 1949–52 | SM | Hortness and Covert (2005) |
| Greene Street to Seven Mile | -72 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Greene Street to Nine Mile | -208 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| Mission Avenue to Trent Avenue Bridge at SIRTI | 22 | Fall 1994 | M | CH2M HILL (1998) |
| | 9 | Spring 1995 | M | CH2M HILL (1998) |
| | 11 | Fall 1994 | M | CH2M HILL (2000a) |

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Trent Avenue Bridge at SIRTI to Monroe Street | 15 | Fall 1994 | M | CH2M HILL (1998) |
| | 1 | Spring 1995 | M | CH2M HILL (1998) |
| | 8 | Fall 1994 | M | CH2M HILL (2000a) |
| | 35.3–57.9 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 43.7 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| Upper Falls Dam to Monroe Street | 0.0 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 0.0 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -130 | May 1977–Apr. 1978 | M1 | Bolke and Vaccaro (1981) |
| Monroe Street to Spokane gaging station | [9]57 | – | CM | Miller (1996)[5] |
| | [6]19 | – | CM | Miller (1996)[5] |
| | [7]80 | – | CM | Miller (1996)[5] |
| | 42 | Fall 1994 | M | CH2M HILL (1998) |
| | 41 | Spring 1995 | M | CH2M HILL (1998) |
| | 41 | Fall 1994 | M | CH2M HILL (2000a) |
| | 46.6–62.9 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 56.2 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 46.5–58.1 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 56.0 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Spokane gaging station to T.J. Meenach Bridge | 110 | Fall 1994 | M | CH2M HILL (1998) |
| | 80 | Spring 1995 | M | CH2M HILL (1998) |
| | 91 | Fall 1994 | M | CH2M HILL (2000a) |
| | -24.0– -23.7 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -30.4 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -37.8– -24.2 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -30.4 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Spokane gaging station to 1 mi above T.J. Meenach Bridge | 50 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| Spokane gaging station to Seven Mile | -92 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -126 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-427–184 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | -120 | Average conditions | R | Drost and Seitz (1978b) |
| Spokane gaging station to Nine Mile | -853– -60 | Dec. 1948–Mar. 1950 | | Lenz (1950) |
| | -138 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -115 | July 1984–Sept. 1984 | SM | Patmount and others (1985) |
| | -43 | Sept. 12, 1994 | SM | CH2M HILL (1998) |
| | -123 | Sept. 13, 1994 | SM | CH2M HILL (1998) |
| | -206 | Sept. 14, 1994 | SM | CH2M HILL (1998) |
| | -81 | Sept. 15, 1994 | SM | CH2M HILL (1998) |
| | -1,183 | Apr. 9, 1995 | SM | CH2M HILL (1998) |
| | -1,210 | Apr. 10, 1995 | SM | CH2M HILL (1998) |
| | -1,102 | April 11, 1995 | SM | CH2M HILL (1998) |
| | -1,134 | Apr. 12, 1995 | SM | CH2M HILL (1998) |
| Spokane gaging station to Long Lake | -220 | Oct. 1948–Mar. 1952 | SM | Bureau of Reclamation (1956) |
| | [8]-207– -11 | Oct. 1948–Mar. 1952 | SM | Bureau of Reclamation (1956) |
| | -564 | 1951–59 | SM | Crosthwaite and others (1970) |
| | [8]-713– -352 | 1951–59 | SM | Crosthwaite and others (1970) |
| 1 mi above T.J. Meenach Bridge to T.J. Meenach Bridge | -5 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| T.J. Meenach Bridge to Bowl and Pitcher Bridge | -50 | Fall 1994 | M | CH2M HILL (1998) |
| | -56 | Spring 1995 | M | CH2M HILL (1998) |
| | -49 | Fall 1994 | M | CH2M HILL (2000a) |
| | -51.2– -48.4 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -52.1 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |

**Table 10.** Estimates of seepage between the Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.—Continued

[**Recharge:** Negative values indicate discharge from the aquifer. **Method:** D, Darcy's Law; M, ground-water-flow model; CM, chemical mass balance; R, referenced; SM, streamflow measurements. **Abbreviations:** RM, river mile; SIRTI, Spokane Intercollegiate Research and Technology Institute; WWTP, wastewater treatment plant; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| T.J. Meenach Bridge to Seven Mile | 40 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | -169– -159 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -165.4 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Bowl and Pitcher Bridge to Seven Mile | -50 | May 1977–Apr. 1978 | M[1] | Bolke and Vaccaro (1981) |
| | -77 | Fall 1994 | M | CH2M HILL (1998) |
| | -82 | Spring 1995 | M | CH2M HILL (1998) |
| | -71 | Fall 1994 | M | CH2M HILL (2000a) |
| | -101– -80.2 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | -94.8 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| Seven Mile to Nine Mile | -136 | Oct. 1948–Sept. 1949 | SM | Anderson (1951) |
| | -21 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-653–1,028 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | -100 | Average conditions | R | Drost and Seitz (1978b) |
| | -40 | May 1977–April 1978 | M[1] | Bolke and Vaccaro (1981) |
| | -6 | Fall 1994 | M | CH2M HILL (1998) |
| | -9 | Spring 1995 | M | CH2M HILL (1998) |
| | -5 | Fall 1994 | M | CH2M HILL (2000a) |
| | 1.1–38.9 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 9.6 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[13] |
| | 59.4–77.4 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | 71.0 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Nine Mile to Little Spokane River confluence | -62.4– -51.6 | Annual range, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| | -63.9 | Annual mean, 1994–99 | M | Golder Associates, Inc. (2004)[12] |
| Nine Mile to Long Lake | -507– -343 | Dec. 1948–Mar. 1950 | | Lenz (1950) |
| | -157 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | [11]-1,422–603 | Oct. 1948–Sept. 1950 | SM | Broom (1951) |
| | -100 | 1951–59 | SM | Crosthwaite and others (1970) |

[1] Steady-state.

[2] Transient.

[3] Range in 5-day recharge periods.

[4] Flow at 347 cubic feet per second.

[5] From Gearhart (2001).

[6] Flow at 1,190 cubic feet per second.

[7] Flow at 2,030 cubic feet per second.

[8] Range in yearly averages.

[9] Range in monthly averages.

[10] Range in monthly averages, July–December.

[11] Range in weekly averages.

[12] Golder Associates, Inc., 2004 (table 9.3, revised).

[13] Golder Associates, Inc., 2004 (table 9.5).

## Discharge—How Ground Water Leaves the Aquifer

Ground water leaves the SVRP aquifer in several ways: through pumpage from wells; seepage into the Spokane and Little Spokane Rivers; and outflow to Long Lake.

### Withdrawals From Wells

Monthly ground-water withdrawal data for 1990 through 2004 currently (2005) are being compiled for this study, and generally are available from almost all public-supply water systems with varying degrees of completeness. Data quality differs from system to system and the limitations include:

Larger supply systems are metered, but many smaller systems either are unmetered or are not recorded in monthly increments.

Some public-supply systems combine withdrawals from multiple wells into one measurement.

Withdrawals from irrigation, industrial, and self-supplied domestic wells typically are not reported, therefore pumpage must be estimated using ancillary data like per-capita domestic use or crop consumptive-use coefficients to estimate annual or seasonal withdrawals.

Estimates of ground-water withdrawals by previous investigators are shown in table 11. Two types of irrigation pumpage are shown in table 11: irrigation pumpage and irrigation pumpage consumptive loss. The former is strictly ground water pumped for irrigation. The latter is ground water pumped for irrigation that is used consumptively, that is, lost to evapotranspiration or plant growth and not returned to the aquifer. Ground-water withdrawal estimates used in previous models are discussed in more detail in the Previous Ground Water Flow Modeling section.

Much of the ground water pumped by municipal or industrial users is returned to the Spokane or Little Spokane Rivers through wastewater-treatment plants. Though not strictly an input or withdrawal from ground water, estimates are included in table 12 to show (in addition to evapotranspiration and recharge) the destination of ground-water withdrawals.

### Spokane River

As discussed above, the Spokane River gains and loses flow along its length, depending upon the particular reach. See table 10 and the Ground-Water/Surface-Water Interactions section for more information.

### Little Spokane River

The Little Spokane River primarily gains flow from the SVRP aquifer. Loss estimates primarily are from streamflow measurements and vary much less than other SVRP water budget components (table 13).

### Evapotranspiration

Evapotranspiration in the study area primarily is by crop irrigation and lawn and landscaping vegetation. Previous evapotranspiration estimates have been either subtracted from precipitation, irrigation, or general land-application volumes or explicitly included as an item in water budgets. Both estimate types are included in table 6. Previous investigators rejected evapotranspiration directly from the saturated zone as a significant water-budget component.

### Underflow to Long Lake

As with ground-water underflow to the SVRP aquifer, underflow out of the aquifer cannot be directly measured and estimates usually are the residual of other water-budget components. Previous underflow estimates are shown in table 9.

**Table 11.** Estimates of ground-water withdrawals from the Spokane-Valley–Rathdrum Prairie aquifer.

[**Withdrawal:** shown as negative for consistency with other water-budget components (negative values indicate discharge from the aquifer). **Method:** C, calculated; R, referenced; **Abbreviations:** SW, surface water; ID, Idaho; WA, Washington; $ft^3/s$, cubic foot per second; ≤, less than or equal; –, not applicable or unknown]

| Pumpage | Withdrawal from aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Pumpage, total | -138 | – | – | Bureau of Reclamation (1954) |
| | -227 | 1977 | R | Bolke and Vaccaro (1981) |
| | [1]-119– -465 | 1977 | R | Bolke and Vaccaro (1981) |
| | -234 | Fall 1994 | C | CH2M HILL (1998) |
| | -129 | Spring 1995 | C | CH2M HILL (1998) |
| | -234 | Fall 1994 | C | CH2M HILL (2000a) |
| Pumpage, total, WA | -100– -250 | 1928–38 | R | Piper and La Rocque (1944) |
| | -178 | 1972 | R | U.S. Army Corps of Engineers and Kennedy-Tudor Engineers (1976) |
| Industrial pumpage | -14 | 1950 | R | Anderson (1951) |
| | -14 | 1955 | R | Bureau of Reclamation (1956) |
| Industrial pumpage[2] | -19 | 1964 | R | Cline (1969) |
| Industrial pumpage | -19 | 1976 | R | Drost and Seitz (1978b) |
| Irrigation pumpage | -33 | 1977 | R | Bolke and Vaccaro (1981) |
| Irrigation pumpage, WA | -44 | 1950 | R | Anderson (1951) |
| | -31 | 1976 | R | Drost and Seitz (1978b) |
| Irrigation pumpage, ID | -61 | 1976 | R | Drost and Seitz (1978b) |
| Irrigation pumpage consumptive loss, WA | -21 | 1976 | R | Drost and Seitz (1978b) |
| Irrigation pumpage consumptive loss, WA | -17 | 1950 | R | Anderson (1951) |
| Irrigation pumpage consumptive loss, ID | -41 | 1976 | R | Drost and Seitz (1978b) |
| Irrigation pumpage | -48 | – | R | Bureau of Reclamation (1954) |
| | -48 | 1955 | R | Bureau of Reclamation (1956) |
| Irrigation pumpage[2] | -3 | 1964 | R | Cline (1969) |
| Municipal pumpage | -90 | – | R | Anderson (1951) |
| Municipal pumpage[2] | -15 | 1964 | R | Cline (1969) |
| Municipal pumpage | -128 | 1976 | R | Drost and Seitz (1978b) |
| | -160 | 1977 | R | Bolke and Vaccaro (1981) |
| Municipal pumpage, city of Spokane | -83 | 1950 | R | Anderson (1951) |
| | -82 | 1951 | R | Broom (1951) |
| | -84 | 1949 | R | Bureau of Reclamation (1954) |
| | -93 | 1955 | R | Bureau of Reclamation (1956) |
| Municipal and domestic pumpage | ≤-117 | 1955 | R | Bureau of Reclamation (1956) |
| Rural domestic pumpage[2] | -1 | 1964 | R | Cline (1969) |
| Stock pumpage[2] | -1 | 1964 | R | Cline (1969) |
| Pumpage discharged to SW, WA | -62 | Average conditions | R | Drost and Seitz (1978b) |
| Pumpage discharged to SW, ID | -2 | Average conditions | R | Drost and Seitz (1978b) |
| Irrigation pumpage consumptive loss | -14 | 1955 | R | Bureau of Reclamation (1956) |
| Pumpage consumptive loss, WA | -17 | 1950 | R | Anderson (1951) |
| | -65 | Average conditions | R | Drost and Seitz (1978b) |
| Pumpage consumptive loss, ID | -46 | Average conditions | R | Drost and Seitz (1978b) |
| Pumpage consumptive loss, exempt users | -14 | – | R | Golder Associates, Inc. (2004) |

[1] Range in monthly averages.

[2] Primarily the Little Spokane River Valley.

**Table 12.** Estimates of discharges to surface water in the Spokane Valley–Rathdrum Prairie aquifer study area.

[**Method:** R, referenced. **Abbreviations:** ID, Idaho; WA, Washington; WWTP, wastewater-treatment plant; ft$^3$/s, cubic foot per second]

| Discharges | Discharge/diversion (ft$^3$/s) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Wastewater discharge, WA | 62 | 1976 | R | Drost and Seitz (1978b) |
| Wastewater discharge, ID | 2 | 1976 | R | Drost and Seitz (1978b) |
| Coeur d'Alene WWTP | 3.58 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| Liberty Lake WWTP | 0.7–.8 | Monthly range | R | Golder Associates, Inc. (2004) |
| | .7 | Annual average | R | Golder Associates, Inc. (2004) |
| | .4 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| Spokane Industrial Park | 1.46 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| Kaiser Trentwood | 37.5 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| | 29.7–34.6 | Monthly range | R | Golder Associates, Inc. (2004) |
| | 32 | Annual average | R | Golder Associates, Inc. (2004) |
| Inland Empire Paper | 3.38 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| | 5.9–6.7 | Monthly range | R | Golder Associates, Inc. (2004) |
| | 6.1 | Annual average | R | Golder Associates, Inc. (2004) |
| Avista heating wastewater | .5 | Monthly range | R | Golder Associates, Inc. (2004) |
| | .5 | Annual average | R | Golder Associates, Inc. (2004) |
| Spokane WWTP | 63 | 1951 | R | Broom (1951) |
| Spokane Advanced WWTP | 56.5–75.0 | Monthly range | R | Golder Associates, Inc. (2004) |
| | 58.2–67.8 | Range, July–Sept. 1984 | R | Patmount and others (1985) |
| | 62.6 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| | 63.9 | Annual average | R | Golder (2004) |
| Northwest Terrace WWTP | .13 | Mean, July–Sept. 1984 | R | Patmount and others (1985) |
| Colbert Landfill east and west systems | 1.4 | Monthly range | R | Golder Associates, Inc. (2004) |
| | 1.4 | Annual average | R | Golder Associates, Inc. (2004) |
| Colbert Landfill south system | .1 | Monthly range | R | Golder Associates, Inc. (2004) |
| | .1 | Annual average | R | Golder Associates, Inc. (2004) |
| Fish hatchery (to Little Spokane River) | 14 | Monthly range | R | Golder Associates, Inc. (2004) |
| | 14 | Annual average | R | Golder Associates, Inc. (2004) |
| Total wastewater discharge to surface water | 64 | 1976 | R | Drost and Seitz (1978b) |
| Wastewater discharge to surface water | 50 percent pumpage from Spokane seasonal wells | 1977 | R | Bolke and Vaccaro (1981) |
| | 90 percent pumpage from Spokane continuous wells | 1977 | R | Bolke and Vaccaro (1981) |

**Table 13.** Estimates of seepage between the Little Spokane River and the Spokane Valley–Rathdrum Prairie aquifer.

[**Recharge:** Negative values indicate discharge from the aquifer into the stream. **Method:** M, ground-water-flow model; R, referenced; SM, streamflow measurements; WY, watershed yield. **Abbreviations:** $ft^3/s$, cubic foot per second; –, not applicable or unknown; <, less than]

| Stream and reach | Recharge to aquifer ($ft^3/s$) | Period calculated | Method | Reference |
|---|---|---|---|---|
| Little Spokane River | < -249 | – | – | Bureau of Reclamation (1954) |
| | -336– -223 | Sept. 1955-70, 1973, 1977 | SM | Bolke and Vaccaro (1981) |
| | [1]-267 | Sept. 1955-70, 1973, 1977 | SM | Bolke and Vaccaro (1981) |
| | -250 | May 1977-Apr. 1978 | M[2] | Bolke and Vaccaro (1981) |
| | -263 | May 1977-Apr. 1978 | M[3] | Bolke and Vaccaro (1981) |
| | [4]-280– -250 | May 1977-Apr. 1978 | M[3] | Bolke and Vaccaro (1981) |
| | -300 | Fall 1994 | M | CH2M HILL (1998) |
| | -335 | Spring 1995 | M | CH2M HILL (1998) |
| | -182 | Fall 1994 | M | CH2M HILL (2000a) |
| | -281 | 1994-99 | M | Golder Associates, Inc. (2004) |
| Lower Little Spokane River | "A few hundred"[5] | 1931-32 | R | Piper and La Rocque (1944) |
| Above at Dartford gaging station | -160 | – | R | Cline (1969) |
| Above near Dartford gaging station | -130 | – | SM, WY | Pluhowski (1970) |
| At Dartford–Near Dartford gaging stations | [6]-251– -218 | Oct. 1948-Sept. 1952 | SM | Broom (1951) |
| | [7]-279– -46 | Oct. 1948-Sept. 1952 | SM | Broom (1951) |
| | -230 | Mean, Apr. 1948–Mar. 1952 | SM | Bureau of Reclamation (1956) |
| | [6]-251– -216 | Apr. 1948-Mar. 1952 | SM | Bureau of Reclamation (1956) |
| | [7]-264– -172 | Apr. 1948-Mar. 1952 | SM | Bureau of Reclamation (1956) |
| 4-mile reach below Dartford | -60 | -- | R | Cline (1969) |
| At Dartford–Near Dartford gaging stations | -235 | Oct. 1948-Mar. 1952 | SM | Crosthwaite and others (1970) |
| | [6]-250– -218 | Oct. 1948-Mar. 1952 | SM | Crosthwaite and others (1970) |
| Dartford–3 mi above mouth | -310 | Average conditions | R | Drost and Seitz (1978b) |
| At Dartford–Near Dartford gaging stations | -255 | Sept. 2004 | SM | Hortness and Covert (2005) |
| | [4]-249– -244 | 1947-52, 1998-2003 | SM | Hortness and Covert (2005) |
| At Dartford–mouth | -318– -236 | Dec. 1976-Sept. 1977 | SM | Bolke and Vaccaro (1981) |
| | [1]-266 | Sept. 1955-70, 1973, 1977 | SM | Bolke and Vaccaro (1981) |

[1] Mean value.

[2] Steady state.

[3] Transient.

[4] Range in monthly means, June-December.

[5] Ground-water discharge to the river.

[6] Range in yearly means.

[7] Range in monthly means.

## Ground-Water/Surface-Water Interactions

Spokane River interacts dynamically with the SVRP aquifer acting as a ground-water recharge source in some places and as a ground-water discharge area in other places. An adequate understanding of the Spokane River and the SVRP aquifer interaction is essential for managers and scientists when making water resource decisions for the area.

### Conceptual Model of Ground-Water/ Surface-Water Interactions

Streams interact with ground water in three basic ways: a stream can gain water from inflow of ground water through the streambed, a stream can lose water to the aquifer by outflow through the streambed, or a stream can do both by gaining in some reaches and losing in other reaches (Winter and others, 1998). When the stream-water surface altitude is higher than ground-water levels in the nearby area, water potentially flows to the aquifer from the river (a losing reach). Conversely, when the stream-water surface altitude is less than the nearby ground-water levels, water flows from the aquifer to the river (a gaining reach). Since ground-water levels and stream stage can change temporally with various factors such as precipitation, water use, and streamflow changes (natural or human-caused), stream reaches may temporally alternate from gaining to losing.

The rate at which water flows from stream to aquifer depends on several factors including hydraulic properties of the streambed and adjoining aquifer, depth of stream penetration into the aquifer, and the hydraulic gradient between the stream and aquifer. Generally, for a losing reach, increased leakage from the river will result as the stream level increases (increasing hydraulic gradient) and as more streambed area is submerged. When unsaturated conditions exist below a stream (the water table is below the stream bottom), leakage from the stream is unaffected by the hydraulic head in the aquifer. When saturated conditions exist below a stream, leakage from the stream will decrease as the hydraulic head in the aquifer approaches the stream level.

### Spokane River

The Spokane River is the only surface outflow of Coeur d’Alene Lake in northern Idaho (pl. 1). The river flows out of the northern end of Coeur d’Alene Lake and then westward into the glacial and flood deposit filled valley and through the city of Spokane, Washington (pl. 2). Between Lake Coeur d’Alene and the Washington–Idaho state line, the river flows adjacent to bedrock uplands to the south or through narrow bedrock channels. The river flows through a relatively narrow valley incised in valley deposits from the Washington–Idaho state line and westward through Spokane. A short reach of the river in downtown Spokane flows over basalt.

Water discharge from Coeur d’Alene Lake into the Spokane River is regulated by a set of dams at Post Falls. Therefore, streamflow does not always represent the runoff from the watershed. During normal years, the gates are usually open between December and June and streamflow increases during the spring snowmelt and decreases in June. During most of summer, flow is regulated to maintain levels in Coeur d’Alene Lake. From late September through December, the gates are incrementally opened to lower the lake to its natural level (Box and Wallis, 2002.) Streamflow has been measured by USGS since 1913 at Spokane River near Post Falls, Idaho, (table 14).

**Table 14.** Continuous streamflow gaging stations in the extent of the Spokane Valley–Rathdrum Prairie aquifer.

[**Abbreviations:** ID, Idaho; WA, Washington]

| Gaging station name | Gaging station No. | Period of record (water years) |
|---|---|---|
| Spokane River near Post Falls, ID | 12419000 | 1913–present |
| Spokane River above Liberty Bridge, near Otis Orchards, WA | 12419500 | 1929–83, 1999–present |
| Spokane River at Greenacres, WA | 12420500 | 1948–52, 1999–present |
| Spokane River at Trent, WA | 12421000 | 1912–13 |
| Spokane River below Trent Bridge, near Spokane, WA | 12421500 | 1948–54 |
| Spokane River below Greene Street, at Spokane, WA | 12422000 | 1949–52 |
| Spokane River at Spokane, WA | 12422500 | 1891–present |
| Hangman (Latah) Creek at Spokane, WA | 12424000 | 1948–present |
| Little Spokane River at Dartford, WA | 12431000 | 1929–32, 1947–present |
| Little Spokane River near Dartford, WA | 12431500 | 1948–52, 1998–present |

## Previous Investigations of SVRP Aquifer and Spokane River Interactions

Several investigations (including Piper and La Rocque, 1944; Broom, 1951; McDonald and Broom, 1951; Drost and Seitz, 1978b; Bolke and Vaccaro, 1981; CH2M HILL, 1998; Gearhart and Buchanan, 2000; Marti and Garrigues, 2001; Caldwell and Bowers, 2003; Hortness and Covert, 2005) have determined that the Spokane River loses water to the SVRP aquifer in some places and gains water from the aquifer in other places. As early as 1944, Piper and La Rocque noted that the upper reach of Spokane River from at least Post Falls, Idaho, to a point 4 mi west of the Washington–Idaho state line appeared to be insulated from and higher than the regional water table. They also noted that ground-water level fluctuations were similar to river water-level fluctuations. Later studies corroborated their results.

Broom (1951) and McDonald and Broom (1951) analyzed data from 11 gaging stations on the Spokane and Little Spokane Rivers for water years 1948-50. They concluded that not only did the amounts of gains and losses vary throughout the year, but also that the locations of the gains and losses varied. For example, the reach of the Spokane River between Post Falls, Idaho, and the Barker Road Bridge near Greenacres, Washington (fig. 1), ranged from gaining as much as 529 $ft^3/s$ to losing as much as 757 $ft^3/s$, with an average annual loss of about 78 $ft^3/s$.

Based on data from Broom (1951) and McDonald and Broom (1951), Drost and Seitz (1978b) provided estimates of average gains and losses between the SVRP aquifer and the Spokane and Little Spokane Rivers. They estimated an average annual loss of about 80 $ft^3/s$ in the reach of the Spokane River between Post Falls, Idaho, and near Barker Road Bridge in Washington (fig. 1). They also estimated that about 250 $ft^3/s$ recharged the aquifer from Coeur d'Alene Lake and the Spokane River between the lake and Post Falls. It was estimated that the remainder of the Spokane River between the Barker Road Bridge and its confluence with the Little Spokane River gained an annual average of 780 $ft^3/s$. Drost and Seitz (1978b) separated the gaining reach of the Spokane River into four segments and provided estimates of annual gains for each. They also estimated that the Little Spokane River gains about 310 $ft^3/s$ from the aquifer below Dartford, Washington (fig. 1). Overall, Drost and Seitz (1978b) estimated a net annual discharge of 1,010 $ft^3/s$ from the SVRP aquifer to the Spokane and Little Spokane Rivers.

Bolke and Vaccaro (1981) presented gains and losses of the Spokane River based on a numerical flow model. The Spokane and Little Spokane Rivers were divided into 13 reaches. In contrast to earlier studies, several gaining and losing stream reaches were determined based on the May 1977 to April 1978 modeled period. Previous studies reported that the Spokane River was entirely a gaining reach below Barker Road Bridge in Greenacres, whereas, Bolke and Vaccaro (1981) reported five losing reaches and five gaining reaches below Barker Road Bridge.

The consulting firm CH2M HILL (1998) constructed a finite-element ground-water flow model of the Washington part of the SVRP aquifer for the city of Spokane. Riverbed leakage rates were specified in the model for 16 Spokane River reaches. Results of two model simulations based on two data-collection periods (autumn 1994 and spring 1995) indicated that the Spokane River had a net streamflow loss of about 83 $ft^3/s$ during autumn and a net gain of 80 $ft^3/s$ during spring. The river fluctuated several times from losing to gaining along its course on the Washington part of the aquifer in both modeling scenarios. Ten reaches were reported as losing and six were reported as gaining. However, CH2M HILL (1998) reported considerable uncertainty in quantifying magnitudes and locations of the streamflow gains and losses.

Gearhart and Buchanan (2000) examined the hydraulic connection between the Spokane River and the aquifer from the Washington–Idaho state line to Spokane, Washington, and also described the results of previous studies. The river was divided into five reaches and each reach was specified as unsaturated, saturated, or transitional (combination of saturated and unsaturated) based on ground-water levels and river stage. Consistent with earlier studies, they concluded that the river was a losing reach between Post Falls, Idaho, and the Barker Road Bridge west of Spokane (fig. 1) with unsaturated flow conditions between the river and aquifer. Gearhart and Buchanan (2000) also concluded that the river is transitional downstream between the Barker Road and Sullivan Road Bridges as it varies from losing to gaining with changes in the water table and river stage (fig. 1). Flux values were calculated for each reach using Darcy's equation with riverbed areas estimated from aerial photographs and field observations at high and low streamflow conditions.

Caldwell and Bowers (2003) monitored the Spokane River and ground water between Post Falls and the Sullivan Road Bridge (fig. 1) over various hydrologic conditions at a streamflow-gaging station and at 25 monitoring wells ranging from 40 to 3,500 ft from the river. River stage, ground-water level, water temperature, and specific conductance were measured hourly to biweekly. Hydrologic and chemical data corroborated with earlier studies, which indicate that the Spokane River recharges the SVRP aquifer along an 18-mi reach between Post Falls, Idaho, and Barker Road Bridge (fig. 1). However, ground-water levels in the near-river aquifer (less than 300 ft from the river) indicated that saturated conditions could exist below the river where a steep hydraulic gradient is between the river and the aquifer. Therefore, the conceptual model for the river's losing section between Post Falls and Spokane shows that the river either is separated from the ground-water system by an unsaturated zone or a steep hydraulic gradient exists from the river to aquifer. Caldwell and Bowers (2003) describe the streambed of Spokane River along this reach as being composed of coarse gravel, pebbles, and cobbles, with interstitial fine silt and clay between the larger materials below the surface. The fine-grained material, some of which may have been transported with the leaking water from the river, likely decreases the permeability of the streambed and underlying adjacent substrate. This low permeability material acts as a leaky layer between the river and the underlying aquifer.

Caldwell and Bowers (2003) used water levels from about 70 wells to construct a generalized water-table map of the area between Post Falls, Idaho, and Spokane, Washington (fig. 7). A hydraulic gradient of about 0.001 (5.4 ft/mi) characterizes the regional flow system in the central part of the valley, which supports the reported high transmissivity for the aquifer. However, the hydraulic gradient determined using monitoring wells near the losing reach of the river is more than an order of magnitude larger at 0.08 (422 ft/mi). This large gradient results from localized recharge from the river and the hydraulic properties of the shallow, near-river aquifer material.

Spokane River mean annual flow measured at Post Falls over the period of record from 1913 through 2001 was about 6,200 $ft^3/s$. Caldwell and Bowers (2003) calculated streamflow differences between the Post Falls and Otis Orchards gaging stations from water years 2000-01 to determine the leakage between Post Falls, Idaho, and the eastern city limits of Spokane, Washington. This section of the river potentially always loses water to the underlying aquifer because the water-table altitude in the area is below the river stage. Based on mean monthly streamflow values from the Post Falls and the Otis Orchards gaging stations from water years 2000-01, Caldwell and Bowers (2003) calculated net losses ranging from 69 to 810 $ft^3/s$ with a median of 255 $ft^3/s$. Losses generally increased with increased streamflow. As

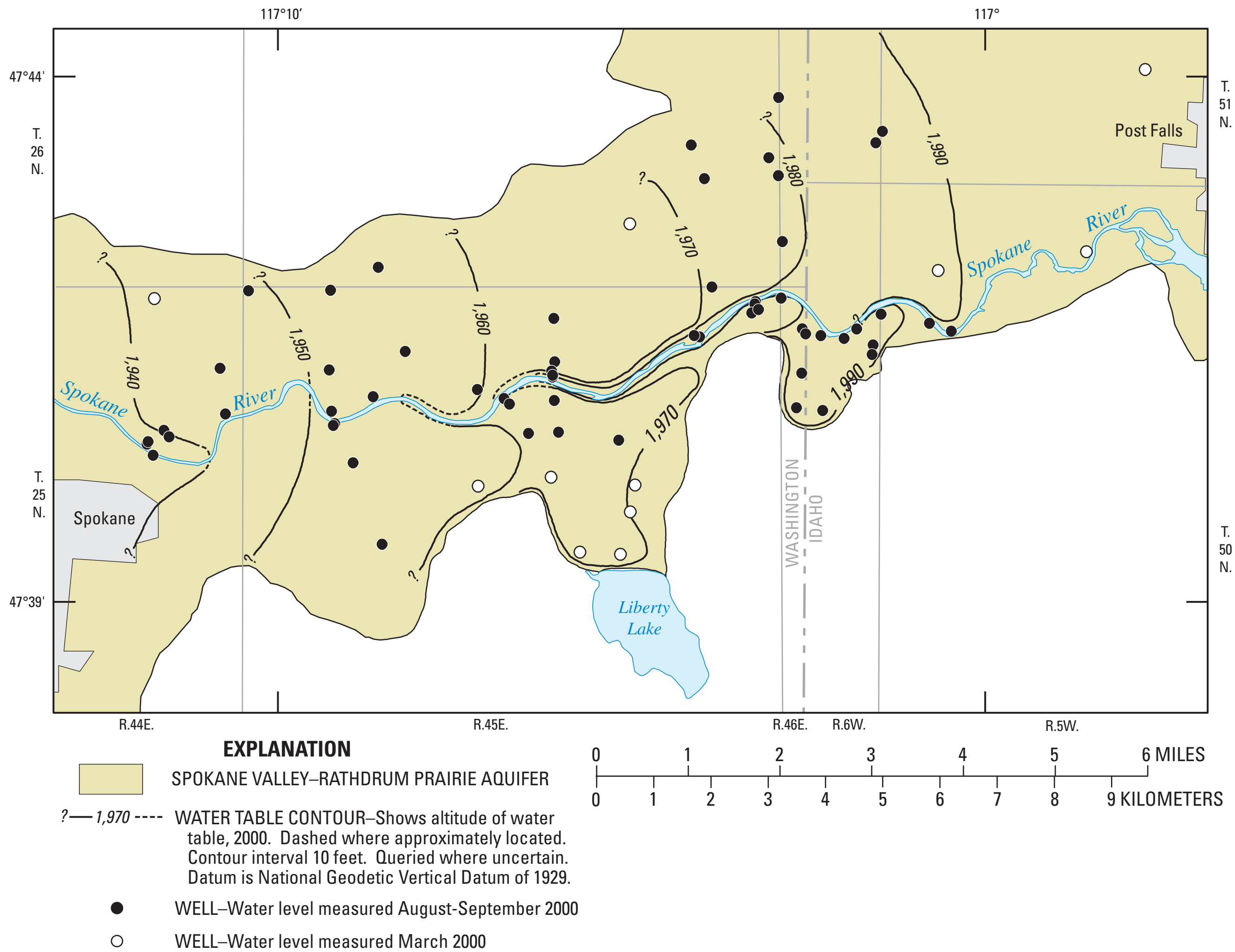


**Figure 7**. Water-table altitude and monitoring wells in part of the Spokane Valley–Rathdrum Prairie aquifer between Post Falls, Idaho, and Spokane, Washington.
(Modified from Caldwell and Bowers, 2003.)

stream levels increase with increased flows, leakage generally increases because of the increase in both the hydraulic gradient between the surface water and ground water and the amount of streambed area submerged by the stream. However, late summer warm water temperatures also appear to be a factor with increased losses due to lower viscosity as water temperatures increased. Losses determined from this study are similar to those calculated by Gearhart and Buchanan (2000) using riverbed areas and Darcy's Law to calculate losses for the reach between the Washington–Idaho state line and the Sullivan Road Bridge (losses of 104 $ft^3/s$ during low flow conditions to 571 $ft^3/s$ during high flow conditions).

Golder Associates, Inc. (2004) constructed computer models of the Little Spokane and Middle Spokane watersheds, which includes the SVRP aquifer in Washington. Initial streambed leakage values were compiled from previous studies and adjusted during the calibration process. Model calibration included the attempted matching of measured weekly discharges at three gaging stations on the Spokane and Little Spokane Rivers. The final model matched the Spokane River streamflow values quite well, but not as well for the Little Spokane River. Average annual gains and losses were calculated for 1994-99 for 13 Spokane River reaches based on modeled base flows for those years.

Hortness and Covert (2005) examined streamflow data for 10 gaging stations on the Spokane River and its tributaries (fig. 8, table 14). Trend analyses were computed using streamflow data from 4 of the 10 gaging stations with complete records from 1968 through 2002 (a period most likely representing current conditions after ceasing operation of a canal system in the area). Only a few statistically significant trends in the July through December monthly mean streamflow data and annual 7-day low streamflows were observed. Statistically significant decreasing trends in the monthly mean streamflow were determined at the gaging stations: Spokane River near Post Falls, Idaho (August and September); Spokane River at Spokane, Washington (September); and Little Spokane River at Dartford, Washington (September and October). Decreasing annual 7-day low streamflows were detected at the Spokane River near Post Falls, Idaho, and Spokane River at Spokane, Washington, gaging stations.

Hortness and Covert (2005) calculated ground-water/surface-water exchanges on the Spokane and Little Spokane Rivers based on July through December (1968-2002) monthly mean streamflow data from adjacent gaging stations (table 14). However, several analyses were based on data from gaging stations with limited periods of record. Median losses ranged from 37 to 78 $ft^3/s$ for the Spokane River reach between Post Falls, Idaho, and near Otis Orchards, Washington. Analysis of available data for the Spokane River reach between the Otis Orchards and Greenacres gaging stations indicated that no calculated gains or losses were outside the range of measurement error. Median gains between the Spokane River at Greenacres, Washington and the Spokane River below Trent Bridge gaging stations ranged from 330 $ft^3/s$ to 754 $ft^3/s$ and gains between the Trent Bridge and Greene Street gaging stations ranged from 259 $ft^3/s$ to 447 $ft^3/s$. Differences in monthly mean streamflow values for the area between gaging stations on the Little Spokane River at Dartford and near Dartford (a distance of about 6 river miles) ranged from an average gain of 244 $ft^3/s$ in July to an average gain of 249 $ft^3/s$ in October and December.

Hortness and Covert (2005) also did trend analyses on the differences in monthly mean streamflow between the Spokane River near Post Falls, Idaho, and the Spokane River at Spokane, Washington, gaging stations for July through December, 1968-2002. While the upper portions of this reach are known to lose streamflow to the aquifer, the overall reach historically has a net gain in streamflow. However, the trend analysis indicated that streamflow gains significantly decreased over time during September, October, and November.

A seepage study of the Spokane and Little Spokane Rivers was completed by the USGS during September 2004 (table 15). Streamflow measurements from selected sites are included in figure 8. Streamflow measurements indicated that the upper reach of the Spokane River between the gaging station at Post Falls and downstream at Flora Road lost 321 $ft^3/s$. A gain of 736 $ft^3/s$ was calculated between the Flora Road measurement site and downstream at the Greene Street Bridge. A loss of 124 $ft^3/s$ was calculated for the reach between the Greene Street Bridge and the Spokane River at Spokane gaging station. The river gained about 87 $ft^3/s$ (after subtracting inflow from Hangman Creek and springs above T.J. Meenach Bridge) between the Spokane River at Spokane gaging station and the T.J. Meenach Bridge. Overall, the Spokane River gained about 376 $ft^3/s$ between the Post Falls, Idaho, gaging station and just below the T.J. Meenach Bridge. Spokane River streamflow was not measured further downstream because of the effects of the Nine Mile and Long Lake Reservoirs. Estimated gains of 254 $ft^3/s$ (after measured inflow from springs and tributaries were subtracted) were calculated for the reach between the Little Spokane River gaging stations at Dartford and near Dartford (a distance of about 7 river miles). Differences in streamflow measured at the Little Spokane River near Dartford gaging station and on the Little Spokane River near the mouth were within the error of the measurements.

MacInnis and others (2004), included the September 2004 USGS seepage data and estimated low flow values based on historical data and computer modeling of additional sites to further delineate and quantify Spokane and Little Spokane Rivers reach characteristics (fig. 8). Their interpretation included the determination of gaining, losing, and transitional reaches of the Spokane River between Flora Road and the Spokane gaging station in addition to determinations made using the USGS seepage data. MacInnis and others (2004) also

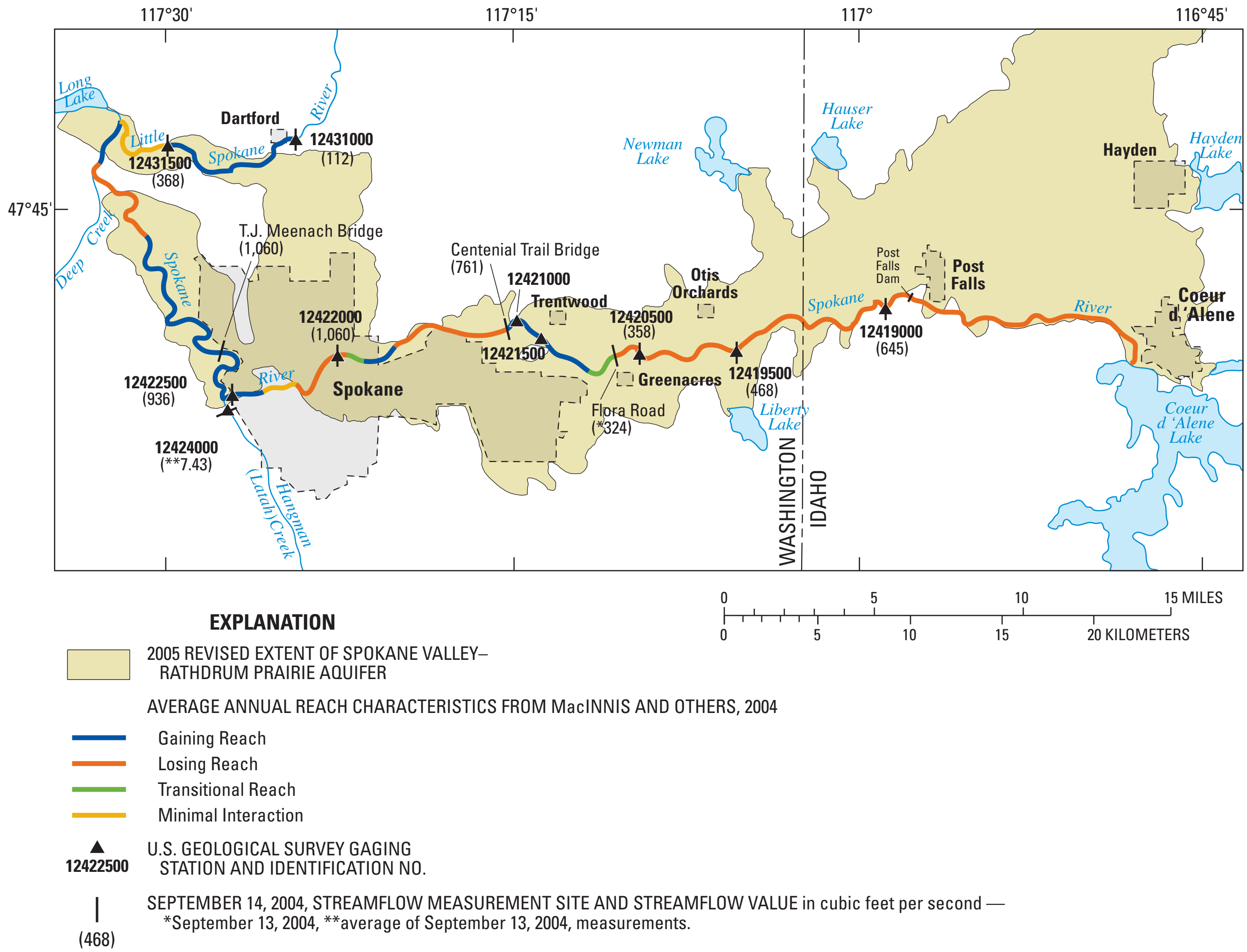


**Figure 8.** Location of gaging stations, streamflow measurement sites in September 2004, and reach characteristics in the Spokane Valley–Rathdrum Prairie, Washington and Idaho.

delineated gaining and losing reaches of the Spokane River from the T. J. Meenach Bridge (the most downstream site measured during the USGS seepage study) to its confluence with the Little Spokane River.

Zheng (1995), Marti and Garrigues (2001), and Caldwell and Bowers (2003) examined water quality aspects of the area. In 1994, Zheng (1995) investigated ground-water quality and Spokane River water quality. Zheng noted that trace metal concentrations in ground water generally were at low concentrations, but also noted consistently high zinc concentrations in the river. Zheng suggested that the river is unlikely to pose significant contamination to the aquifer. Marti and Garrigues (2001) and Caldwell and Bowers (2003) determined that water-chemistry data indicated that Spokane River does lose water to the aquifer along its upper reaches and that it does affect the aquifer's water quality. Cadmium, lead, and zinc concentrations in the near-river aquifer were elevated and similar to the Spokane River, but all were well below drinking-water standards. Chemical data indicated that river recharge may influence ground-water chemistry as far as 3,000 ft from the river, but ground water is most affected within a few hundred feet of the river (Caldwell and Bowers, 2003). Major ions, stable isotopes, and temperature of the river and ground water from near-river wells were similar and exhibited similar temporal trends, whereas, ground water from wells farther from the river generally had higher major ion concentrations and more stable temperatures and chemistry.

Although it is known that interaction occurs between the SVRP aquifer and the Spokane and Little Spokane Rivers, additional information still is needed for increased

**Table 15.** Discharge measurements made on the Spokane River and some tributaries to study seepage gains and losses, September 13–16, 2004.

[Modified from Kimbrough and others, 2005; **Abbreviations:** mi, mile; ft³/s, cubic foot per second; °C, degrees Celsius. –, no data]

| River mile | Stream | Location | Measured discharge (ft³/s) | Date | Gain or loss (ft³/s) | Water temperature (°C) |
|---|---|---|---|---|---|---|
| 100.7 | Spokane River | Gaging station near Post Falls (12419000) | [1]645 | 09-14-04 | – | – |
| 93.9 | Spokane River | Gaging station above Liberty Bridge (12419500) | [1]468 | 09-14-04 | -177 | – |
| 90.5 | Spokane River | Gaging station at Greenacres (12420500) | [1]358 | 09-14-04 | -110 | – |
| 89.1 | Spokane River | At Flora Road NW¼SW¼ sec.7, T.25 N., R.44 E. | 324 | 09-13-04 | -34 | 16.2 |
| 84.2 | Spokane River | At Centennial Trail pedestrian bridge below Plantes Ferry Park, NW¼SE¼ sec.4, T.25 N., R.44 E. | 761 | 09-13-04 | +437 | – |
| 77.3 | Spokane River | 0.5 mi below Greene Street bridge, NW¼SE¼ sec.9, T.25 N., R.43 E. (0.5 mi below former gaging station 12422000) | 1,060 | 09-14-04 | +299 | 12.5 |
| 72.8 | Spokane River | Gaging station at Spokane (12422500) | [1]936 | 09-14-04 | -124 | – |
| 73.2 | Hangman Creek | Gaging station at Spokane (12424000) | [2]7.43 | 09-13-04 | – | 13.8 |
| 72.2 | Confluence of Hangman Creek and Spokane River | | | | | |
| 70 | Springs | NW¼SW¼ sec.12, T.25 N., R.42 E., above T.J. Meenach Bridge | 1.88 | 09-16-04 | – | 11.4 |
| 69.6 | Spokane River | SE¼NW¼ sec.11, T.25 N., R.42 E., below T.J. Meenach Bridge | 1,030 | 09-14-04 | +85 | 13.2 |
| 69.7 | Little Spokane River | SE¼NW¼ sec.33, T.27 N., R.43 E., below Little Spokane Drive bridge, above Deadman Creek | 99.2 | 09-14-04 | – | 12.8 |
| 69.7 | Little Deep Creek | SW¼NE¼ sec.33, T.27 N., R.43 E., below Shady Slope Road bridge, near mouth | .67 | 09-14-04 | – | 10.7 |
| 69.8 | Deadman Creek | NW¼SE¼ sec.33, T.27 N., R.43 E., at Shady Slope Road bridge, near mouth (South tributary) | .14 | 09-14-04 | – | 11.1 |
| 69.8 | Deadman Creek | NW¼SE¼ sec.33, T.27 N., R.43 E., at Shady Slope Road bridge, near mouth | 10.3 | 09-14-04 | – | 10.5 |
| 67.7 | Little Spokane River | SE¼SW¼ sec.32, T.27 N., R.43 E., below foot bridge, at Pine River Park | 105 | 09-14-04 | -5.3 | 13.7 |
| 67.2 | Little Spokane River | Gaging station at Dartford (12431000) | [1]112 | 09-15-04 | +7 | – |
| 66.8 | Dartford Creek | NW¼NE¼ sec.6, T.26 N., R.43 E., above Hazard Road bridge, near mouth | 2.37 | 09-14-04 | – | 11.3 |
| 63.9 | Little Spokane River | NE¼NE¼ sec.11, T.26 N., R.42 E., at Waikiki Road/Rutter Parkway bridge | 302 | 09-15-04 | +188 | – |
| 60.2 | Little Spokane River | Gaging station near Dartford (12431500) | [1]368 | 09-15-04 | +66 | – |
| 57.4 | Little Spokane River | SE¼NW¼ sec.5, T.26 N., R.42 E., at State Route 291 bridge, near mouth | 349 | 09-15-04 | -19 | 11.4 |
| 56.3 | Confluence of Little Spokane River and Spokane River | | | | | |

[1] Discharge from gaging station rating.

[2] Average of multiple measurements.

understanding of the hydrologic system and to enable more accurate construction and calibration of the ground-water flow model. Previous studies reported ground- and surface-water interaction, but several discrepancies exist among the studies regarding location, direction of flow (to or from rivers), and quantity of streamflow gains or losses.

For a computer model to most accurately represent a hydrologic system, the model needs to adequately match real-world water-level measurements in the aquifer and streamflow in the rivers. Not only is it important to match these measurements under assumed steady-state (approximate equilibrium) conditions, but also under transient conditions as the hydrologic system responds to changing stresses (examples: pumping increases, changing river stage, and varying precipitation). Several gaging stations are on the Spokane and Little Spokane Rivers and ground-water levels have been monitored at various locations, over a range of time periods, and at a variety of frequencies ranging from a few miscellaneous measurements to continuously recorded measurements. A significant amount of data currently are available from near-river monitoring wells between Post Falls and the Sullivan Road Bridge (fig. 1), but more data are needed elsewhere along the Spokane and Little Spokane Rivers.

# Previous Ground-Water Flow Modeling

Several numerical computer models have been constructed to represent the ground-water flow system in at least part of the SVRP aquifer. At least four of these computer models have been published since the early 1980s (Bolke and Vaccaro, 1981; CH2M HILL, 1998; Buchanan, 2000; and Golder Associates, Inc., 2004).

## Bolke and Vaccaro (1981)

Bolke and Vaccaro (1981) constructed a two-dimensional (plan view) computer flow model of the Washington part of the SVRP aquifer from near Post Falls, Idaho, on the east to near Nine Mile Falls, Washington on the west. This part of the SVRP aquifer was termed the Spokane Aquifer. The finite-element model was developed by USGS and simulated ground-water flow by solving a set of linear equations derived by J.V. Tracy (U.S. Geological Survey, written commun., 1977). A two-dimensional model was deemed adequate since vertical flow or gradients in the aquifer were thought to be insignificant.

The model indicated that pumping at the current rate (1977) had little effect on water levels in the Spokane aquifer. The model was used to forecast increased pumping effects on aquifer heads and streamflow. During a one-year simulation, pumping at twice the 1977 rate of 227 $ft^3/s$ resulted in calculated water-level declines of about 3 ft. Spokane River streamflow was calculated to decline 150 $ft^3/s$ in the summer and about 50 $ft^3/s$ during the rest of the year. Flow to the Little Spokane River was modeled to decrease about 10 $ft^3/s$. The increased pumping rate had a more significant effect on the discharge of the Spokane River than on the change in water levels in the aquifer.

### Model Boundaries

The eastern boundary basically was an approximate north-south line near Post Falls, Idaho, that split the “Spokane Aquifer” from the rest of the SVRP aquifer to the east. This boundary was assigned a specified head value determined from an average of heads in nearby monitoring wells. The specified head value was held constant during simulation. The western part of the model between where the Spokane and Little Spokane Rivers exit the model was classified as specified head boundary to simulate constant ground-water outflow. Ground-water inflow was specified and held constant in areas where surrounding drainage areas entered the modeled area. The ground-water inflow estimates for these areas were obtained from Drost and Seitz (1978b). The remaining external boundaries represented the contact between the aquifer and the surrounding bedrock. These boundaries were specified as no-flow boundaries. The bottom of the aquifer also was specified as a no-flow boundary.

### Aquifer Properties

Lateral hydraulic conductivity values were estimated from specific-capacity data. Values ranged from about 0.07 ft/s (6,048 ft/d) in the eastern part of the aquifer to about 0.01 ft/s (864 ft/d) in other parts of the aquifer to the west. Values in the Five Mile Prairie area and other areas where bedrock exists in the modeled domain ranged from 0.001 to 0.00001 ft/s (86.4 to 0.86 ft/d). Available data indicated an absence of vertical stratification in the aquifer lithology. Therefore, the lateral and vertical hydraulic conductivity was interpreted as equal (no anisotropy).

Saturated thickness values were determined from the difference between a water-table map of 1977-78 data and the estimated bottom of the unconsolidated sand and gravel deposits. The basal altitude was based mainly on drillers' logs and on two seismic profiles by Newcomb and others (1953). Transmissivity values were computed by multiplying estimated saturated thickness by lateral hydraulic conductivity. Specific yield initially was estimated by comparing lithologic information with grain size/specific yield tables from Johnson (1967).

### Ground-Water/Surface-Water Interaction

Initially, gains and losses of Spokane and Little Spokane Rivers were obtained from previous work by Broom (1951). Broom (1951) divided the rivers into 7 reaches and computed values for water year 1950. During subsequent model analysis, the Spokane and Little Spokane Rivers were divided into 13 gaining and losing reaches based on the May 1977 to April 1978 modeled period. Previous studies reported that the Spokane River was an entirely gaining reach below the bridge at Barker Road; whereas Bolke and Vaccaro (1981) reported 5 losing reaches and 5 gaining reaches below the bridge at Barker Road (fig. 1).

Within each of the 13 reaches, leakage coefficients were assigned a uniform value based on streambed lithology and whether the river was gaining or losing. Relative differences between head in the river and heads in the adjacent aquifer, leakage coefficients, and the streambed area were used in a form of Darcy's Law to quantify flow to or from the river. Water level altitudes in reservoirs were treated as specified heads for the model simulation.

### Ground-Water Withdrawal

Ground-water withdrawals were determined from a water-use inventory of all major water purveyors in the study area. Total ground water withdrawal in the modeled area during 1977 was about 164,000 acre-ft (about 227 $ft^3/s$). Based on the percentage of water pumped each month, the total withdrawal was distributed monthly for the transient simulation.

The percentage of water pumped from the aquifer and applied at land surface or discharged to sewers was estimated based on information from purveyors. The estimates were: 50 percent of the water pumped from seasonally used city of Spokane wells was applied to the land surface and 50 percent was discharged to sewers; 10 percent of the water from continuously used city of Spokane wells was applied at land surface and 90 percent was discharged to sewers; 70 percent of the water from other municipalities was applied at land surface and 30 percent was estimated to directly recharge the aquifer through septic systems; 100 percent of the water pumped for agricultural irrigation was applied at land surface; and none of the water pumped for industry was applied at land surface.

### Precipitation

Precipitation was set to be uniformly distributed in the modeled area based on data from weather stations at the Spokane International Airport and at Spokane (fig. 3). An average precipitation rate was set at 1.72 in/mo for the steady-state simulation. Actual monthly values were used for transient simulation.

### Evapotranspiration

Depth to water in nearly all parts of the modeled area was thought to be too great to allow for transpiration by plants, except near the Spokane and Little Spokane Rivers. Evaporation also was known to occur from the surface-water bodies. These transpiration and evaporation values were considered negligible. However, estimates of evapotranspiration (ET) were needed to calculate the amount of water that reaches the aquifer from precipitation and water applied at land surface.

Potential evapotranspiration or consumptive use by crops was estimated by the Blaney and Criddle (1962) method. This method assumed total availability of water to the crops and was dependent on air temperature and length of growing season. Estimates of actual ET were made by assuming that some or all precipitation falling during the crop-growing season was available to meet the water requirements (actual ET) of the crops. This precipitation (effective rainfall) was about the same as the actual ET. Actual ET or effective rainfall was estimated by a method developed by the U.S. Department of Agriculture (1967). Effective rainfall was calculated on a monthly basis, which provided an actual ET estimate that was used in the model to determine the amount of precipitation reaching the ground-water table. The amount of water that infiltrated to ground water was calculated as the difference between the sum of the precipitation and applied irrigation water and the amount of ET, where ET was the lesser of either the actual ET or the potential ET. An average potential ET was set at 1.31 in. for the steady-state simulation; monthly values of potential ET and actual ET were used for the transient simulation.

### Model Calibration

Initial estimated transmissivity values were adjusted upwards by a factor of 1.9 and specific yield values were uniformly halved (ranging from 0.1 to 0.2 in the unconsolidated material and less than 0.05 in the Five Mile Prairie area) during model calibration.

Model sensitivity analysis indicated that the model was most sensitive to changes in transmissivity. Therefore, potential errors in transmissivity would have a greater effect on the model-predicted heads and discharges than would errors in boundary flows or specific yields.

## CH2M HILL (1998)

CH2M HILL (1998) constructed a 3-dimensional numerical flow model of the Spokane Aquifer (Washington part of the SVRP aquifer) as part of the city of Spokane Wellhead Protection Program. The modeling was designed to represent two scenarios (conditions in September 1994 and April 1995). The software MicroFem (Hemker and van Elburg, 1986) was used for modeling steady-state conditions. MicroFem is a finite-element model capable of simulating horizontal and vertical anisotropy.

The calibrated model was used to estimate ground-water capture zones using particle tracking procedures. Particle tracking was conducted for eight existing and two planned well fields in the city of Spokane. Particle tracking results then were used to develop wellhead protection areas for each of the well fields.

### Model Boundaries

A specified flux boundary was used at the Washington–Idaho state line (eastern extent of the model). Flux was initially estimated from the hydraulic gradient in the area, the cross-sectional area, and the initial estimate of transmissivity. The flux was adjusted manually whenever transmissivity values were altered at the state line.

Specified flux boundaries also were defined where tributary valleys and creeks intersected the aquifer margins and infiltrated the aquifer. The flux at these sites was allowed to vary during model calibration.

Specified heads were used along the model's downgradient boundaries at Nine Mile Reservoir and Little Spokane River. Specified head values were based on an autumn 1994, ground-water altitude map.

Areas with very low transmissivity, essentially no flow boundaries, were set around Five Mile Prairie and other bedrock highlands. Low transmissivity values also were set in areas where the aquifer was not present in layer 2 or layer 3, but was present in an overlying layer.

## Aquifer Properties

The ground-water system was modeled with 3 layers designed to simulate ground-water withdrawals at different depths: Layer 1 represented the upper 100 ft of the saturated zone; Layer 2 represented depths from 100 to 200 ft below the water table; and Layer 3 represented variable depths from 200 ft below the water table to the bottom of the aquifer.

Hydraulic conductivity was simulated with 20 different zones and was allowed to vary in most of the zones during calibration. Hydraulic conductivities of the zones ranged from <20 to 7,000 ft/d in the calibrated model. The vertical anisotropy was set to 10:1 and was fixed during calibration.

## Ground-Water/Surface-Water Interaction

The Spokane River was modeled with specified water-surface elevations measured at 23 stations along the river. Equal elevations were specified for river nodes in Nine Mile Reservoir and Upriver Pool based on stage measurements at each site. Stages in areas between measurement sites were adjusted to incorporate riverbed elevation variations shown in Federal Emergency Management Agency maps. The remaining nodes representing the river were assigned elevations based on interpolation between the stations.

Riverbed leakage rates were specified for 16 river reaches based on the locations of stage measurements. Initial riverbed leakage coefficients of Bolke and Vaccaro (1981) were used and varied during calibration. Rates were varied according to the assumption that coefficients would be higher in areas where ground water discharges to the river than in areas where the river recharges the aquifer. The model simulated leakage rates based on the leakage coefficients and the difference between the water table altitude and river stage. The WADI package of MicroFem (an environment where surface water is separated from ground water) also allowed for leakage simulation from a streambed that is separated from the water table by an unsaturated zone. In those cases, the model recognized that the leakage rate was independent of the depth to the water table.

## Ground-Water Withdrawal

Withdrawal rates in the model were determined from field observations and from information supplied by purveyors. For many purveyor wells, withdrawal estimates were determined from pumping logs for the September 1994 and April 1995 periods. Withdrawal estimates for other wells were based on the well's capacity and the estimated pumping duration. Pumping primarily was assigned to Layer 1, with some pumping in Layer 2, and no pumping in Layer 3. Withdrawal rates were not adjusted during calibration.

## Precipitation

Recharge from precipitation was based on previous work by Bolke and Vaccaro (1981) and Olness (1993). Bolke and Vaccaro (1981) estimated that a uniform rate of 66 $ft^3/s$ percolated to the water table after evapotranspiration. Olness (1993) determined that spatial variations of precipitation existed across the modeled area. An initial rate of 66 $ft^3/s$ was set across the model area, but the spatial distribution determined by Olness (1993) also was used. Recharge from precipitation was allowed to vary during calibration.

## Irrigation

Recharge from land-applied water, which includes the percolation of water used outdoors in urban and suburban areas and irrigation on agricultural lands, was included in the model. Recharge from land-applied water was not allowed to vary during calibration.

Recharge from outdoor water use in urban and suburban areas within the city of Spokane was specified from pumpage estimates and effluent discharge volumes. The analysis indicated that about 45 percent of Spokane's annual water use consisted of outdoor use. Recharge to the water table was assumed to be about 30 percent of the total outdoor use, resulting in an average recharge of 2.5 in/yr within Spokane city limits.

Recharge rates from outdoor use outside Spokane city limits were estimated from pumpage rates supplied by purveyors and by estimates of population densities. The pumping rates and population densities were compared with those within the city limits. Recharge rates were assigned 2.5 in/yr in areas with the highest densities (about 6,000 persons per square mile), 1.0 in/yr in areas with moderate population densities (about 1,000 persons per square mile), and 0.25 in/yr in areas with the lowest population densities (about 100 persons per square mile). Recharge from urban and suburban outdoor use was set equal to zero elsewhere, including agricultural and undeveloped fallow lands.

Recharge for agricultural lands was set at 2.0 in/yr. This rate was set for areas outside the city limits where irrigation is known to occur.

### Septic Systems

Recharge from septic systems was assigned to urban and suburban areas outside the city limits. Recharge rates were based on an assumed discharge rate of 75 gallons per capita per day to septic drain lines and population densities used to quantify recharge from land-applied water. The resulting recharge rate was set at 16 $ft^3/s$ and was not allowed to vary during calibration.

### Model Calibration

The model was calibrated using September 1994 conditions, which were considered to represent short-term steady-state conditions. The following parameters were adjusted during calibration: transmissivity; river leakage coefficients; recharge from precipitation; inflow from tributary valleys; and ground-water flow rates across the state line. The objective of the calibration process was to obtain reasonable simulations of ground-water altitudes, ground-water flow directions, and the aquifer water budget including river gains and losses.

The model was "verified" by simulating conditions measured in April 1995. All values for the April 1995 simulation were the same as the September 1994 simulation except for the pumping rates, river stages, ground-water altitudes at the downgradient fixed-head boundaries, areal recharge rates, and recharge from tributary boundaries. Simulated ground-water altitude contours in most areas of the model were within 5 ft of ground-water altitude contours based on September 1994 measurements. The 5-ft maximum residual value equals about 1 percent of the total observed ground-water altitude difference in the model area. Ground-water flow directions were closely simulated by the calibrated model throughout the model area. Simulated river gains and losses generally were in agreement with historical streamflow records and other independent estimates.

## Buchanan (2000)

John Buchanan, a professor of geology at Eastern Washington University, constructed the first ground-water flow model of the entire SVRP aquifer. The finite-difference, single-layer, steady-state model was designed as a tool for understanding the overall water balance. The numerical simulation utilized MODFLOW code (McDonald and Harbaugh, 1988). Results of the model indicated that (1) less recharge to the aquifer occurred on the Idaho side of the aquifer than previously estimated and (2) the calculated ground-water flux at the Washington–Idaho state line (390 $ft^3/s$) was about one-half that of earlier estimates made during the sole source aquifer designation process.

### Model Boundaries

The SVRP aquifer is bounded by lakes and hillslopes around the periphery of the Rathdrum Prairie in Idaho, and downgradient by the Columbia River basalts and the Little Spokane River. Constant head nodes were used to represent peripheral lakes and the Little Spokane River to provide appropriate inflow/outflow to and from the bounding sides of the model. Model data for inflows was from Bolke and Vaccaro (1981) and Painter (1991b). Lateral boundaries were defined geologically with the bedrock contacts and were specified as no-flow boundaries.

### Aquifer Properties

Estimates of hydraulic conductivity were derived from previous modeling and are based on field data and calibrated model values. Vertical and horizontal hydraulic conductivity were set to be equal, therefore no anisotropy. Hydraulic conductivity values decreased from east to west ranging from about 10 to 50,000 ft/d. The porosity of the aquifer was set at 20 percent throughout the model domain.

Aquifer thickness was estimated using the seismic reflection profiling by CH2M HILL (1998) in Washington and another seismic line surveyed near Twin Lakes on the Rathdrum Prairie. However, the depth to the aquifer base remains unknown throughout much of the Rathdrum Prairie.

### Ground-Water/Surface-Water Interaction

The Spokane River was represented as river nodes using the "Rivers" module in MODFLOW. In each river node, the bed elevation, bed thickness, bed conductance, and river stage were specified.

### Ground-Water Withdrawal

Since there was no comprehensive source of water usage statistics in the Rathdrum Prairie part of the aquifer, water withdrawal through pumping wells was not included in the model.

### Recharge

Recharge due to precipitation was applied to the top surface of each active cell in the model and was estimated at 25 percent of the rainfall volume. Recharge rates ranged from 0.0014 to 0.0023 ft/d. Additional recharge from hillslopes and small basins adjacent to the aquifer were applied to appropriate cells. These values were from Bolke and Vaccaro (1981) and Painter (1991b).

### Model Calibration

The model was calibrated with measured heads in the aquifer reported by CH2M HILL (1998) and Brian Painter (Buchanan, 2000). Hydraulic conductivity values were repeatedly changed near the "lake nodes" until the calculated heads approached measured heads. However, it was noted that the calibrated model by no means presents a unique solution.

## Golder Associates, Inc. (2004)

Golder Associates, Inc., constructed computer models of the Little Spokane River and Middle Spokane River watersheds for Spokane County, Washington. The project's objective was to simulate all major hydrologic processes in the watersheds and was intended for use in planning and management of watershed hydrologic resources. Components in the model included subsurface flow in terms of ground water and unsaturated flow, surface water in terms of overland and river flow, and coupling between the surface water and ground water. The integrated model included the MIKE 11 HD one-dimensional model to simulate surface-water flow and the MIKE SHE finite-difference, three-dimensional ground-water flow model. The modeling effort represented water years 1994–99.

### Model Boundaries

Surface water discharge measurements from the USGS Post Falls gaging station were used to provide a time-varying flow boundary for the Spokane River on the eastern part of the model at Post Falls. A constant head boundary was assigned along the Long Lake section of the Spokane River. Impermeable or no-flow boundaries were assigned to all lateral boundaries for Layer 1 except on the eastern boundary near the Washington–Idaho state line where a time-varying head boundary (constant head for 3-month intervals) was established. An impermeable boundary was assigned to the model base. Internal surface-water boundary conditions included inflows from Hangman (Latah) Creek to the Spokane River and several wastewater discharge locations. Discharge data from a USGS gaging station were used for the boundary at Hangman (Latah) Creek. Monthly discharge data were used for each wastewater discharge point.

### Overland Flow

Topography and a spatial roughness coefficient map were used to model overland flow in the watersheds. Topography was obtained from USGS Digital Elevation Models (DEM). Roughness coefficients were assigned to each of the 21 land cover classes in the USGS National Land Cover Data (NLCD) grid coverage for the area.

### Unsaturated Flow

Unsaturated zone data needed for the model included depth, distribution, and hydrologic characteristics of soils within the model domain and drywells. The soils were divided into one of four Natural Resources Conservation Service hydrologic groups. Vertical saturated hydraulic conductivity and moisture retention curves were assigned to each soil group.

Drywells, or infiltration pits, were simulated with a "bypass" function which recharges a specified percentage of ground water to the saturated zone when water content in the unsaturated zone is greater than a minimum value. Recharge volume resulting from a dry well was decreased linearly when water content fell below the minimum water content value and was discontinued when water content fell to a set "stop" value. Dry wells were only assumed to exist in unsewered areas. The number of dry wells in a cell was estimated by the amount of impervious area like roadways or parking lots in a cell. The percentage of recharge above the estimated natural recharge was assigned to each cell based on the estimated number of dry wells in each cell.

### Saturated Flow

The ground-water flow model included two aquifer layers, a low conductivity lens in the Hillyard Trough area, and an impermeable basal boundary. Layer 1 was defined by the extent of the highly permeable, glaciofluvial deposits of sands and gravels. The clay lense divides the unconsolidated glaciofluvial deposits into confined and unconfined components. The clay layer was modeled as a lens in Layer 1. Layer 2 was defined by the extent of Tertiary basalt and the Latah Formation. The impermeable basal boundary was defined by the upper surface of the crystalline basement rock.

Spatial distribution and hydraulic conductivity values estimated by CH2M HILL (1998a, b) and Buchanan (2000) for the SVRP aquifer were used to develop initial values for the model. Conductivity values were adjusted during model calibration. A horizontal to vertical anisotropy ratio of hydraulic conductivity of 3:1 was initially used. These values also were refined during calibration. Hydraulic properties of the Grande Ronde basalt were used to represent the Tertiary unit in Layer 2. Boese and Buchanan (1996) provided estimates of hydraulic conductivity for the Tertiary basalts. A hydraulic conductivity of 0.5 ft/d initially was used to represent the layer, but was adjusted to 15.9 ft/d after model calibration. Whiteman and others (1994) and Boese and Buchanan (1996) provided vertical hydraulic conductivity estimates of the basalts ranging from 0.0005 ft/d to 3.5 ft/d. A vertical hydraulic conductivity of 1.59 ft/d initially was used in the model.

## Channel Flow

Only the primary lakes and rivers were modeled in the watersheds. The MIKE 11 HD model required data on surface-water channels including altitude, length, blocking structures, cross sections, roughness, and leakage coefficients. The cross sections provided altitude and channel shape for the model. An average range of Mannings roughness values was used depending on the population density, slope, and land cover in the basin. Structures within the Spokane River were modeled as weirs. Estimates of leakage between the Spokane and Little Spokane Rivers and the aquifer developed in previous modeling efforts were used for the initial leakage values in this model where possible, these values were adjusted during calibration.

## Ground-Water Withdrawal

Ground water withdrawal included purveyor, industrial, commercial, irrigation, and residential uses. Abstraction rates for purveyor, industrial, and commercial wells were obtained from Spokane County. A total of 191 wells were modeled with a total annual withdrawal of 52,663 Mgal/yr. Abstraction rates for exempt wells were modeled at estimated consumptive use rates to account for lawn or agricultural irrigation. Abstraction or consumptive use associated with the exempt wells was modeled in the same cell as where the irrigation occurred.

## Meteorological Data

Precipitation and temperature data were input into the model as daily, 4 km gridded data using a method outlined in Bauer and Vaccaro (1987). This method involves the comparison of point measurements and PRISM (Parameter-elevation Regressions on Independent Slopes Model) data (http://www.ocs.oregonstate.edu/index.html). A degree-day snow melt factor of 2.0 mm snow/day/ºC and a snowmelt threshold of 1.0ºC were used to simulate snowmelt within the model.

## Evapotranspiration

Evapotranspiration was calculated using spatial and time varying components of potential evapotranspiration (PET) along with relative evapotranspiration potential of vegetative cover, unsaturated zone characteristics, water surfaces, snow coverage, and saturated zone characteristics. Monthly PET estimates were calculated using the Blaney Criddle (Doorenboos and Pruit, 1977) method. Monthly temperature estimates were obtained from PRISM (http://www.ocs.oregonstate.edu/index.html).

## Irrigation

Irrigation estimates were based on previous work from Golder Associates, Inc. (2003). Irrigation was modeled to take place during the months of April through October. Lawn irrigation was estimated at 3.69 ft/yr and agricultural irrigation in the Middle Spokane River watershed was estimated at 1.58 ft/yr. Coverages of irrigated lawns and agricultural lands were provided by Spokane County. The use of wastewater discharge for irrigation purposes (such as for golf courses) also was included as irrigated areas. The source of irrigation water was assumed to be municipal if the area was in current water district boundaries and from a shallow well in the same cell if the area was outside of the water district boundaries.

## Model Calibration

The model was calibrated using ground water levels available throughout the Spokane Valley and discharge data available from four points along the Spokane River. Data were more limited for the Little Spokane River watershed. Parameters that were adjusted during model calibration included: vertical and horizontal hydraulic conductivity of the aquifer layers; unsaturated zone saturated hydraulic conductivity; unsaturated zone moisture retention and hydraulic conductivity curves; river bed lining leakage coefficients, snow melt degree-day coefficient and melting point temperature; overland run-off parameters; and drainage time constants. Spokane watershed model calibration primarily was done through aquifer property modifications.

## Data Needs

Data needs were identified during the review of information available for the Spokane Valley–Rathdrum Prairie aquifer. These data needs are presented in no particular order, but the completion of each would provide for a more complete data set for construction of a flow model of the aquifer. Prioritization would involve considering the most critical data needs for an improved regional ground-water flow model, as well as timing and funding constraints for their completion.

- Quantification of the ground-water inflow from the surrounding bedrock boundaries and peripheral watersheds.
- Estimation of recharge from precipitation.
- Quantification of losses from Coeur d'Alene, Hauser, Hayden, Liberty, Newman, Pend Oreille, Spirit, and Twin Lakes to the aquifer and determination of the conditions (saturated or unsaturated) beneath the lakes.
- Characterization of the cross sectional area and hydrostratigraphy of the aquifer at the following locations:
    - West of Lake Pend Oreille near Athol;
    - Across Hoodoo Valley;
    - Across the West (Main), Middle (Ramsey), and Chilco Channels near Round Mountain;
    - From near Rathdrum to near Hayden Lake;
    - Near the Washington–Idaho state line, downgradient from Newman and Liberty Lakes;
    - Near the southern part of the Hillyard Trough; and
    - Near the aquifers' discharge area near Long Lake.
- Updated ground-water withdrawal estimates, especially for the Idaho part of the aquifer.
- Updated estimates of the consumptive use of water.
- Definition of the river-aquifer interchange, especially downstream from the Sullivan Road Bridge. Additional aquifer-head measurements near the rivers in conjunction with stage and discharge measurements are a possible approach. Drilling near-river monitoring wells downstream of the Sullivan Road Bridge may be needed.
- Additional temporal aquifer-wide head measurements.
- Investigation and quantification of possible ground water discharge out of the basin beneath the Spokane and Little Spokane Rivers.
- Frequent measurement of ground-water levels in existing and new monitoring wells along the entire length of the Spokane and Little Spokane Rivers.
- Continued measurement of streamflow and (or) river stage at existing and (or) additional river locations.
- Determine direction of flow of water to or from the rivers using chemical tracers.

## Summary

The Spokane Valley–Rathdrum Prairie (SVRP) aquifer is the sole source of drinking water for over 400,000 residents in Spokane County, Washington, and Bonner and Kootenai Counties, Idaho. Recent and projected urban, suburban, and industrial/commercial growth has raised concerns about potential future effects on water availability and water quality in the SVRP aquifer and the Spokane and Little Spokane Rivers. This report presents geologic, hydrologic, and ground-water flow modeling information compiled by the U.S. Geological Survey, in cooperation with the Idaho Department of Water Resources and Washington Department of Ecology for the SVRP aquifer. Descriptions of the geologic history, hydrogeologic framework, surface geophysical studies, water-budget components, ground- and surface-water interactions, computer flow models, and further data needs are provided.

The SVRP aquifer consists primarily of thick layers of coarse-grained sediments—gravels, cobbles, and boulders—deposited during a series of outburst floods resulting from repeated collapse of the ice dams that impounded ancient Glacial Lake Missoula. Sources of recharge to the aquifer include infiltration from precipitation, return flow from water applied at land surface, seepage from the Spokane and Little Spokane Rivers and adjacent lakes, and surface- and ground-water inflow from tributary basins. The aquifer discharges into the Spokane and Little Spokane Rivers and through withdrawals from wells.

A simplified geologic model of the Rathdrum Prairie and Spokane Valley includes the ancient Rathdrum-Spokane River valley being filled with generally unknown amounts of Miocene basalts and interbedded sediments followed by a period of downcutting, repeated cycles of glacial and interglacial sedimentation, and finally the repeated and catastrophic cycles of outburst flooding from Glacial Lake Missoula. The Missoula Floods eroded much of the existing basalt and older sediments, significantly altering the geologic features that developed during the Miocene. To date, relatively little is known about the thickness of the flood deposits or the location and extent of older deposits beneath them, including the location of the buried bedrock surface. Depth to bedrock estimates are available at selected locations in the aquifer from surface geophysical studies that were conducted over 50-years beginning in the early 1950s. Methods used include seismic refraction and reflection, gravity, and microgravity.

In most places, the SVRP aquifer is bounded by bedrock of pre-Tertiary granite or metasedimentary rocks, or Miocene basalt and associated sedimentary deposits. The lower or bottom boundary of the aquifer is largely unknown except along the margins or in shallower parts of the aquifer where wells have penetrated the entire aquifer thickness and reached bedrock or silt and clay deposits. Reported ground-water divides approximately represent the aquifer boundary within Hoodoo and Spirit Valleys and near Careywood, Idaho. Upgradient areas of the aquifer also are bounded by tributary lakes, including Pend Oreille, Spirit, Twin, Hayden, Coeur d'Alene, Hauser, Liberty, and Newman. Streams tributary to the aquifer include Lewellen, Sage, and Rathdrum Creeks in Idaho and Chester and Saltese Creeks in Washington. Streams tributary to the Spokane River in the aquifer extent include Hangman (Latah) Creek and the Little Spokane River, both in Washington. Subsurface outflow occurs at the lower end of the aquifer near Long Lake at the confluence of the Spokane and Little Spokane Rivers.

Recharge to the SVRP aquifer occurs through precipitation, irrigation, canal leakage, septic tank effluent, inflow from tributary basins, and flow from the Spokane River. Discharge from the aquifer occurs through withdrawals from wells, flow to the Spokane and Little Spokane Rivers, evapotranspiration, and underflow to the Long Lake area. A compilation of estimates indicates that these estimated values should be compared with caution due to variability in the area boundaries and time period of interest, as well as the methods used to make the estimates.

Numerous studies have documented the dynamic ground- and surface-water interaction between the SVRP aquifer and the Spokane and Little Spokane Rivers. Gains and losses vary throughout the year, as well as the locations of gains and losses. Analysis of historical and recent streamflow data illustrates the magnitude and variability of these relations. September 2004 streamflow measurements indicated that the upper reach of the Spokane River between Post Falls and downstream at Flora Road lost 321 $ft^3/s$. A gain of 736 $ft^3/s$ was calculated between the Flora Road site and downstream at the Greene Street Bridge. A loss of 124 $ft^3/s$ was calculated for the reach between the Greene Street Bridge and the Spokane River at Spokane gaging station. The river gained about 87 $ft^3/s$ between the Spokane River at Spokane gaging station and the T.J. Meenach Bridge. Overall, the Spokane River gained about 376 $ft^3/s$ between the Post Falls, Idaho gaging station and the T.J. Meenach Bridge. Estimated gains of 254 $ft^3/s$ were calculated for the reach between the Little Spokane River gaging stations at Dartford and near Dartford (a distance of about 7 river miles).

Four regional ground-water flow models have been constructed for the aquifer, three on the Washington part of the aquifer and one for the entire aquifer. In the early 1980s, a two-dimensional computer flow model of the Washington part of the SVRP aquifer indicated that pumping at the current rate (1977) had little effect on water levels in the Washington part of the SVRP aquifer. During a one-year simulation, pumping at twice the 1977 rate of 227 $ft^3/s$ resulted in calculated water-level declines of about 3 feet. Spokane River streamflow was calculated to decrease about 150 $ft^3/s$ in the summer and about 50 $ft^3/s$ during the rest of the year. The increased pumping rate had a more significant effect on Spokane River discharge than on the change in water levels in the aquifer. In the late 1990s, a 3-dimensional flow model of the Washington part of the SVRP aquifer was constructed as part of a wellhead protection program and designed to represent scenarios for September 1994 and April 1995. The calibrated model was used to estimate ground-water capture zones using particle tracking. Also in the late 1990s, the first ground-water flow model of the entire SVRP aquifer was constructed. The finite-difference, single-layer, steady-state model was designed as a tool for understanding the overall water balance. In 2004, a modeling report was completed for the Little Spokane River and Middle Spokane River watersheds, Spokane County, Washington. The model, representing water years 1994–99, was constructed for use in planning and management of watershed hydrologic resources.

Data are needed that would provide a more comprehensive data set for the construction and calibration of a regional flow model and better understanding of the SVRP aquifer. These data needs include, but are not limited to: quantification of the ground-water inflow from the surrounding bedrock boundaries and peripheral watersheds; an understanding of the surface-water/ground-water interaction of lakes adjacent to the aquifer; characterization of the cross sectional area and hydrostratigraphy of the aquifer at key locations; updated ground-water withdrawal values and estimates of the consumptive use of water; additional and frequent aquifer-head measurements near the rivers in conjunction with stage and discharge measurements; additional temporal and regional aquifer-wide head measurements; an understanding of possible ground water discharge out of the basin; the continued measurement of streamflow and (or) river stage at existing and (or) additional river locations; and determine the flow direction of water to or from the rivers using chemical tracers.

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