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GEO476L Groundwater Hydrology Project

Topic: Review of the Spokane Valley–Rathdrum Prairie aquifer

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1. Introduction

The Spokane Valley–Rathdrum Prairie (SVRP) aquifer is located in the northwestern United States, across two states, Washington and Idaho. It is composed of unconsolidated Quaternary glaciofluvial deposits underlying an area of about 350 square miles (Drost and Seitz, 1977). The white space in figure 1 defines the boundary of SVRP Aquifer. In 2000 and 2004 Atlas reports, the extent of the aquifer was defined by United States Environmental Protection Agency (USEPA) in 1978, which was slightly smaller than the current one. The boundary was expanded by USGS based on hydrogeologic information and also to facilitate computer modeling (Boese et al., 2015). Water volume in the entire SVRP aquifer is estimated to be about 10 trillion gallons with an average of about 250 to 650 million gallon of water flowing through the aquifer daily at the Idaho–Washington border (MacInnis et al., 2000).

The thickness of the SVRP aquifer is still unknown because few wells extend more than 100 ft into the saturated zone (Kahle et al., 2005). The deepest well on record in the SVRP aquifer is 780 feet and yet it did not penetrate the full thickness of the glacial and flood deposits (Cline, 1969). At the Idaho-Washington State border, the aquifer is about 500 to 550 ft thick (Gerstel and Palmer, 1994). Overall, aquifer deposits are about 150-ft to more than 600-ft deep (MacInnis and others, 2000).

2. History of aquifer exploitation

The history of the SVRP aquifer presented below is a summary of Boese et al., 2015.

The SVRP aquifer was accidently discovered in 1894, by City of Spokane contractor during Upriver Dam construction. The workmen encountered the water in larger quantities than it could be pumped out while they were digging the channel above the water in 1894. In 1899, due to the discovery of SVRP aquifer, Spokane Valley Irrigation District formed, and Corbin ditch canal irrigation started.

In 1905, Modern Irrigation and Land Company formed to provide SVRP aquifer water to Spokane Valley farmers. The company set up a test plot, planted with every likely crop—and a few unlikely ones such as cotton and peanuts. They soon found out that the most profitable ones were the apples. As a result, acres of apple trees were planted on the newly irrigated fields of Spokane Valley. New railroads were built to provide a way to transport the apples to the markets, so after a few years, the demand was high. By 1922, there were more than 1.6 million apple trees in the Spokane Valley. However, because the company did not take risks into account seriously when deciding to grow apples, apple production started to decrease after 1922. The main factors were disease, insect infestations, low prices, untimely freezes, and competition from nearby valleys where the conditions were perfectly suited for apple growing. In 1926, about 200,000 apple trees were pulled out. In the same year, the upriver well construction project started in order to transport water more efficiently.

After 1945, the SVRP aquifer no longer supplied apple orchards, but instead supplied truck farms growing melons, berries, and vegetables. The Heart of Gold cantaloupe became a valley specialty. The major crops above the SVRP aquifer nowadays are grain, hay, pasture, and mint. Most of the large-scale agriculture occurs on the Rathdrum Prairie. Many smaller farms are rural home sites or are operated part-time to produce food for families and their animals. One large improvement that sustained the agriculture was the invention of water towers. By 1967, all large irrigation canals shut down. All the water used for agriculture and most other uses depended fully on drilled wells which pumped water from SVRP aquifer into water towers. The efficiency was largely increased due to less leaking, but large amounts of water is still lost to evaporation when sprinkled. Not until the 21st century were large agricultural sprinklers were changed to spray water down to reduce the evaporative losses before reaching the ground/crop.

Besides crop irrigation, the SVRP aquifer is also largely used as a drinking water source, but not until the early 1900s. In 1908, bacteriologist Frank Rose who was working at Spokane city at that time discovered that water in the SVRP aquifer was much purer than the drinkable water standard. By comparing bacteria concentration at the SVRP aquifer with other aquifers, he stated that the SVRP aquifer had the best water supply in the world. The aquifer then replaced the Spokane River as the City of Spokane’s primary source of drinking water in 1909. In 1978, USEPA designated SVRP aquifer as a “sole source aquifer”, meaning it is the only source of drinking water for over 500,000 residents and businesses in northern Idaho and eastern Washington, and there are no reasonably available alternative drinking water sources if the aquifer becomes contaminated.

Bolke and Vaccaro (1981) estimated total groundwater pumped from the SVRP aquifer in 1977 and compared the data with previous data. The authors stated that in 1977, the average pumping rate was 227 cubic feet per second during the year, which was much higher than 178 cubic feet per second in 1976 and 100 cubic feet per second in 1938. Most of the wells drilled and generated high pumping rates were close to Spokane County and in the middle of the aquifer. According to figure 2, Washington State largely uses water from SVRP aquifer for urban development. In comparison, those wells in Idaho were majorly used for irrigation/agriculture. Since groundwater generally enters from the east (Idaho) and leaves as discharge to Spokane and Little Spokane Rivers (Washington), groundwater in the SVRP aquifer in Washington State usually has a high concentration of nitrate and phosphate, which causes problems between states.

3. Geology/stratigraphy of the aquifer system

The summary that follows is based on descriptions contained in Kahle et al. (2005), Conners (1976), Molenaar (1998), (McKiness, 1988a), Hammond (1974), Hsieh et al. (2007) and Kahle and Bartolino (2007).

Kahle et al. (2005) simplified the geologic history of the SVRP area into three major time periods, the Quaternary geology, the pre-Tertiary geology and the Tertiary geology. According to figure 3, the SVRP aquifer is overlain on Glacial Lake Missoula flood deposits from the Quaternary. The pre-Tertiary and Tertiary sediments are underlain the glacial and interglacial deposits from the Quaternary. 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.

Among the pre-Tertiary rocks in the SVRP area, the oldest are metamorphosed, fine-grained sediments that were deposited during the Precambrian Era. Kahle et al. (2005) identified these rocks as “low-grade metasedimentary rocks including argillite, siltite, and quartzite, which grade locally into more highly metamorphosed schists and gneisses”. Conners (1976) found that as much as 20,000 ft of the Precambrian rocks were eroded before the Paleozoic Era began, following deposition and metamorphism.

In pre-Tertiary time, water drainage was from 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 (Kahle et al., 2005). Molenaar (1998) stated that the pre-Tertiary landscape was characterized by ridge crests and valley bottoms with considerable relief, probably 4,000 ft or more in places.

In the Tertiary period, due to active basalt flow, drainage systems that previously transported sediment out of the area, deposited the sediment at the margins of the basalt flows. Early Miocene basalt flows dammed drainages. As a result, lakes were created by deposition of sand, silt and clay of the Latah Formation (Kahle et al., 2005). Most of the Latah sediments consist of lacustrine silt and clay; the rest were sand and gravel units (McKiness, 1988a). Hammond (1974) studied the drillers' logs for wells in the northeastern Rathdrum Prairie and concluded that late Miocene basalt flows eventually overrode the entire Rathdrum Prairie region, creating alternating layers of basalt and Latah Formation interbeds.

The Quaternary geologic events contributed to the large amount of groundwater in the SVRP aquifer and thick, fine-grained sediments throughout much of the region. During the Pleistocene Epoch, the cooling climate caused sheets of ice to move southward from current day Canada. The uneven leading edges created two main lobes in the area, the Purcell Trench Lobe and the Okanogan Lobe (figure 4). Because the Purcell Trench lobe blocked the drainage in northwestern Montana, Glacial Lake Missoula was created (figure. 4). With a maximum elevation of 4200 feet and maximum depth of 2000 feet, Glacial Lake Missoula released as much as 500 cubic miles of water at a rate 10 times the combined flow of all the present-day rivers on earth during late Pleistocene (Kahle et al., 2005). The largest of the Missoula floods saturated all Spokane and even spilled southward towards Cheney and beyond. After the flood event ended, the ice lobe slowly moved southward, blocking the Clark Fork River once again. The dam would fail again, resulting in another flood. This repeated flooding formed Lakes Coeur d'Alene, Hayden, Pend Oreille, Spirit, Twin, Hauser, Liberty and Newman because eventually the large amounts of gravel and cobbles deposited in the SVRP area blocked the tributary valleys.

Hsieh et al. (2007) confirmed that the sands, gravels, cobbles, and boulders in the SVRP aquifer primarily deposited by a series of catastrophic glacial outburst floods from ancient glacial Lake Missoula during the Pleistocene Epoch. Kahle and Bartolino (2007) noted that the sediments deposited due to glacial melt are mostly coarse grained. However, they also noted that in the path of Missoula floods, fine-grained layers of clay and silt are scattered everywhere. From analysis of drillers' reports, Kahle and Bartolino (2007) found that "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 throughout the Rathdrum Prairie and Spokane Valley. In the Hillyard Trough, the deposits generally are finer grained and the aquifer consists of sand with some gravel, silt, and boulders."

Kahle and Bartolino (2007) described three distinct hydrogeologic units in the study area: the SVRP aquifer, the Basalt and fine-grained interbeds unit, and the Bedrock unit (Figure 5). The former two units were described earlier in this report. The bedrock unit, which includes metamorphic and intrusive igneous rocks from the Precambrian to Tertiary and Tertiary basalt and their interbeds, underlies and laterally bounds the SVRP aquifer (Kahle and Bartolino, 2007). Permeability in these rocks are low because of the crystalline structure in these metamorphic and igneous rocks, and therefore they are not considered major aquifers within the SVRP area. Only if the rocks are weathered and/or fractured, usable amount of water can move through them. Similarly, though the basalt and fine-grained interbeds can produce significant discharges, but they are not considered important aquifers because they are not continuous.

4. Hydrogeology

This section summarizes water balance/budget (recharge and discharge), groundwater-surface water interactions and important models of the SVRP aquifer.

Kahle et al. (2005) collected data from previous studies and summarized recharge rate in the SVRP aquifer (table 1). The estimated mean annual inflow and outflow to and from the aquifer is 1,471 and 1,468 cubic feet per second, respectively. Kahle and Bartolino (2007) described six main sources of recharge: the Spokane River, lakes, precipitation over the aquifer, tributaries, infiltration from landscape irrigation and septic systems, and subsurface inflow, and five sources of discharge: the Spokane River, the Little Spokane River, pumpage, subsurface discharge to Long Lake, and infiltration of ground water to sewers.

The Spokane River is the largest groundwater recharge source in the SVRP aquifer, with an average recharge rate of 718 cubic feet per second, almost half of the recharge rate of the entire aquifer. Besides the Spokane River, nine lakes also recharge the aquifer. These lakes constantly recharge the aquifer throughout the year, meaning the water table at the lakes are always higher than the surrounding. The uncertainty in calculating lake recharge rate is high because inflow to the aquifer from lakes cannot be measured directly. Kahle and Bartolino (2007) described three approaches to overcome the problem but still stated that there was significant uncertainty. The groundwater inflow from Coeur d’Alene Lake and Lake Pend Oreille to the SVRP aquifer estimated by Kahle et al. (2005) ranges from 35 to 300 cubic feet per second and 20 to greater than 1,000 cubic feet per second respectively. Kahle and Bartolino (2007) attributed this high uncertainty to poorly constrained hydraulic conductivity and cross-sectional area of the lake/aquifer interface around Coeur d’Alene Lake and Lake Pend Oreille. Besides the Spokane river and lakes, another important recharge sources to the SVRP aquifer is areal recharge due to precipitation. Bartolino (2007) calculated direct areal recharge to the SVRP aquifer to be 233 cubic feet per second using data from six active weather stations. Among the rest 16 percent of the recharge, tributaries counts for 8%, infiltration from landscape irrigation and septic systems counts for 5 percent, and subsurface inflow counts the other 3 percent.

Among all the outflow sources of the SVRP aquifer, more than 74 percent of such is distributed to The Spokane River and Little Spokane River. Since the Spokane River is also a major source of recharge, the seasonal change in flow direction must contribute to the river being a major factor of both recharge to and discharge from the SVRP aquifer. Another significant source of outflow is pumping. The estimated annual pumping rate from the aquifer is 312 cubic feet per second from 1990 to 2005, which is 37 percent higher than the pumping rate in 1977. Public supply, self-supplied industry, irrigation and domestic supply wells are the four major sources of pumping. Among such, more than 65 percent of pumping goes to public supply, which reflects the quick development of cities near/in the SVRP area. The outflow to Long Lake is another source of discharge. Drost and Seitz (1977) estimated such rate as 55 cubic feet per second. The last source, which only contributes 0.1 percent of the outflow is infiltration of groundwater into sewers.

Interactions between rivers and the aquifer is worth studying because the Spokane River by itself affected roughly 50 percent of inflow and outflow. MacInnis et al. (2004) characterized segments of the Spokane River as gaining, losing, transitional, or minimal. Such characterization was based on simultaneous streamflow measurements and estimated low-flow values based on historical data and computer modeling (Hsieh et al., 2007). Table 3 (Kahle et al., 2005) summarized the flow direction for most segments in the Spokane River and figure 6 showed the locations of the gaging stations in table 3. Within these gaging stations, Gregory and Covert (2005) noted that the gaining segment actually occurs downstream of the Sullivan Road site (figure 6) and the data indicated a net gain of 233 cubic feet per second instead of 360 cubic feet per second (table 3) from the Centennial Trail Bridge site to the site below Greene Street Bridge. By comparing the data from both paper, Gregory and Covert (2005) did not consider the losing stream at the gage Spokane River at Spokane, which counted for 112 cubic feet per second. The other 30 cubic feet per second might be due to monthly variations. Campbell (2005) and Hsieh et al. (2007) presented a map (figure 6) showing the groundwater levels and general flow direction in the SVRP aquifer, which can generally summarize the water budget.

Two main models have been applied to the SVRP aquifer since the beginning of this century. One is done by Oldow and Sprenke (2006) to model depth to basement by gravity acquisition; the other is constructed by Hsieh et al. (2007) on groundwater flow modeling.

Oldow and Sprenke (2006) expanded an existing model of depth to basement of the SVRP aquifer to better understand the change in depth throughout the whole aquifer. Previous works (Sprenke, 2006) only focused in the eastern Spokane Valley and southern Rathdrum Prairie and lack understanding of the regional geophysical pattern. Oldow and Sprenke (2006) collected more gravity data not only from north to east as previous works had done, but also north to south data and more data points outside the aquifer (figure 8). The researchers combined and analyzed the existing and new gravity data sets to calculate a complete Bouguer anomaly for the region, which was the main achievements of the new model.

Previous works did good estimates on the unsaturated gravel thickness and the densities of unsaturated gravel, saturated gravel, and bedrock. Specifically, Sprenke (2006) reviewed probable rock and sediment bulk densities in the aquifer area. The depth to basement and thickness of the saturated aquifer can therefore be computed from the residual gravity based on the existing data (Oldow and Sprenke, 2006). The U.S. Geological Survey has monitored water level in the SVRP aquifer since 1990, using data from many wells drilled to the water table throughout the study area. To calculate the thickness of the unsaturated aquifer, Oldow and Sprenke (2006) subtracted the interpolated water table from the USGS's data from the elevation of the gravity station for each gravity station within the aquifer. For the gravity modeling, Oldow and Sprenke (2006) used the Parker-Oldenburg algorithm which is based on two-dimensional Fourier Transforms (Oldenburg, 1974; Sprenke and Kanasewich,1982).

Figure 8 was the primary result of Oldow and Sprenke (2006). According to the figure, the maximum depth to the basement in the SVRPP aquifer exceeds 400 m in the Rathdrum Prairie. In general, the thickness decreases from Coeur d'Alene Lake (Southeastern SVRP) north toward Lake Pend Oreille (Northeastern SVRP). Oldow and Sprenke (2006) attributed the reason for such gradual change in the basement surface and the high thickness in the southern half of the Rathdrum Prairie to the consequence of "erosion as Missoula Flood waters emerged from the narrow channels on the sides of Round Mountain or a glacial trough similar that below Lake Pend Oreille where glacial sediments extend to well below sea level."

Hsieh et al. (2007) used MODFLOW-2000 (Harbaugh et al., 2000) to construct a groundwater flow model for the SVRP aquifer. The researchers defined boundary conditions and applied six packages based on the boundary conditions: Recharge Package, Well Package, Flow and Head Boundary Package, River Package, Streamflow-Routing package and General-Head Boundary Package. The main advantage of this model is its generality. It considered most boundary conditions and did good projection on streamflow gain and loss for almost every segment of the SVRP aquifer (figure 10). The researchers also analyzed five additional models and modified the calibration curve based on each additional model. Table 5 compares values from the calibrated SVRP model (Hsieh et al., 2007) with those from all five additional models. The SVRP model shows similar results in most projections with the average of additional models.

5. Current status and issues confronting it

Since the Spokane Valley-Rathdrum Prairie Aquifer is the sole source of drinking water for more than 500,000 people in Washington and Idaho, it is well studied and monitored by both states. Since 2004, Washington, Idaho and the USGS have collaborated to produce a groundwater budget and numerical groundwater flow model for the cross-border SVRP aquifer, with the intention of enabling the states to evaluate management tools for the water system. Kahle et al. (2005), Hsieh et al. (2007) and Kahle and Bartolino (2007) are the products of such collaboration and both reports are detailed and conclusive. According to table 2 constructed by Kahle and

Bartilino (2007), recharge is slightly higher/similar with discharge each year in the SVRP aquifer, meaning the aquifer is sustainable, unlike the Ogallala Aquifer.

Although the current status of the SVRP aquifer is much better than other large aquifers in the United States such as the Ogallala, problems still exist. One of the major issues is its dependence on the Spokane River. Nguyen et al. (2013) stated that since the SVRP aquifer is highly connected to the Spokane River and responds very fast to natural and human perturbations, it is relatively vulnerable to climate and anthropogenic changes in future decades. Studies by the department of Ecology of Washington state have shown that minimum daily flow of the Spokane River decreased in the last 100 years. Researchers in Washington also projected an increase in cool-season precipitation in the future. Table 2 indicated that the steady increase/relatively no change in the storage of the SVRP aquifer highly depends on the Spokane River. In order to fully understand the potential problems of the SVRP aquifer, extensive researches should also be done on the Spokane River.

A major problem of the Spokane River is the water conflict between Washington and Idaho states. Significant amount of “water fight” happened in the last 20 years. In 2014, Washington stated that the Spokane river was shrinking and attributed such to Idaho controlling the level of Lake Coeur d'Alene, which feeds the Spokane River. With the increasing demand in water due to the expansion of Spokane, and the enormous amount of water needed in Idaho agriculture, water level in the Spokane River will continuously decrease, which could be a potential issue of the SVRP aquifer when its level is no longer stable.

The second issue of the SVRP aquifer is constant increase in water demand. Based on Rathdrum Prairie Aquifer (only in Idaho) water demand projections, if a low-population growth rate of 1.6% per year happens in 50 years and aggressive water conservation policies are implemented, water demand by the year 2060 would rise about 4%. If on the other hand that population grows at a rate of 3%, and water is used without conservation, then a 200% increase of the current water withdrawals would be expected. The water consumption is projected to increase 47.5% to 90% in 2060, assuming moderate population and employment growth. The range reflects different water conservation levels. Moreover, urbanization in Idaho will lead to a decrease in water use for agricultural irrigation and an increase in urban and suburban land uses. The Idaho Water Resource Board (2010) indicated that the development of new residential and municipal irrigation on land that is currently non-irrigated will likely lead to an overall increase in total irrigation demand.

The third issue of the SVRP aquifer is contamination. The water in the aquifer itself is more than clean based on the USGS data. However, water quality in the Spokane River is not that good. One of the issues with the Spokane River is that it is originated from Coeur d'Alene Lake, Idaho. From the 1880s to the 1980s, the mining industry in the South Fork Coeur d'Alene River produced the largest amount of silver, zinc, lead and other heavy metals in the nation. Tons of waste materials such as cadmium, zinc and lead discharged directly to the Coeur d'Alene River and its tributaries and continues to pollute Coeur d'Alene Lake and the Spokane River (Wood and Beckwith, 2008). Since the implementation of the Clear Water Act, the contaminants were largely degraded, but still significant amounts of heavy metals remained dormant in the sediments. Those metals were thought to be directly related with dissolved oxygen level in the river. Wood and Beckwith (2008) stated that the increase in phosphate level in Coeur d'Alene Lake can change the lake's trophic status—or level of biological productivity—which could result in secondary releases of metals from contaminated lakebed sediments. Caldwell et al. (2002) presented that on average 20,000 kg/yr of whole-water lead (particulate plus dissolved), 2,100 kg/yr of whole-water cadmium, and 450,000 kg/yr of whole-water zinc flowed out of Coeur d'Alene Lake into the Spokane River during 1999 and 2000. With that amount of heavy metal flowing in, even though the SVRP aquifer should not be affected because the Spokane River recharges the Spokane Valley/Rathdrum Prairie aquifer along a 35-km reach between Coeur d'Alene Lake and Spokane, long enough that the groundwater chemistry will not be affected (Caldwell et al., 2002), the risks of heavy metal diffusing into groundwater should not be ignored. Barber et al. (2009) gathered contaminants concentration in the past several decades and stated that even though the Spokane River carries mining waste and has elevated concentrations of PCBs and dioxins/furans, the groundwater quality was not shown to be adversely affected by the contaminants in the Spokane River.

6. Prognosis for the aquifer

The Spokane Valley-Rathdrum Prairie Aquifer seems to be a sustainable aquifer. The groundwater budget is healthy and water quality is continuously good for the past decades and not easily affected by contaminants in the Spokane River. Water use policies in both Washington and Idaho need to be studied if one wants to take advantage of the aquifer. For the future, it is still unclear how the Spokane River and the SVRP aquifer will be affected by climate change. One cannot be optimistic about the SVRP aquifer even if it looks like the decrease in minimum daily flow rate in the Spokane River and the pollutants do not affect the aquifer much. The SVRP aquifer is still stable right now. If the balance is broken, it will be hard to infer what could happen.

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Figures:

Figure 1. Aquifer extent used in SVRP Aquifer Atlas 2015 (USGS, 2005; Boese et al., 2015).

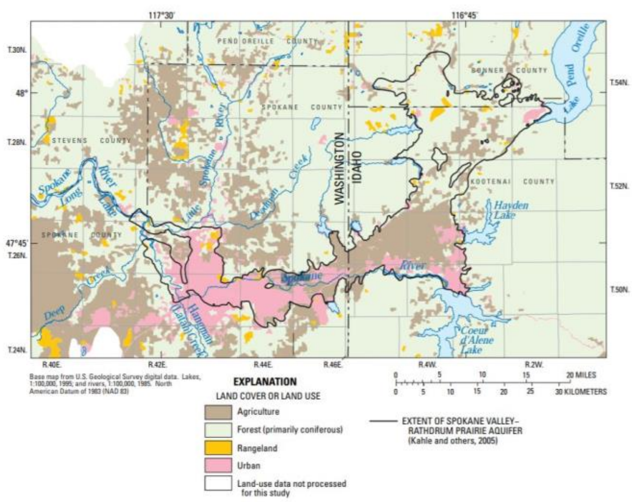

Figure 2. Generalized land cover and land use in the Spokane Valley-Rathdrum Prairie aquifer study area, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho (Kahle, Bartolino, 2007)

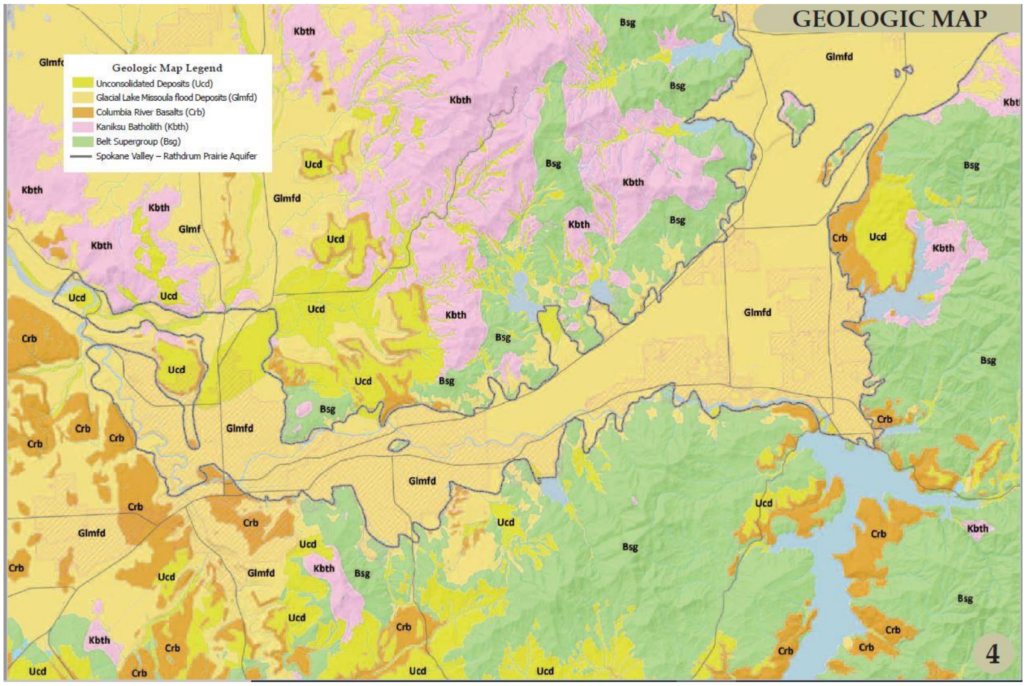

Figure 3. Geological Map of the SVRP area (Boese et al., 2015)

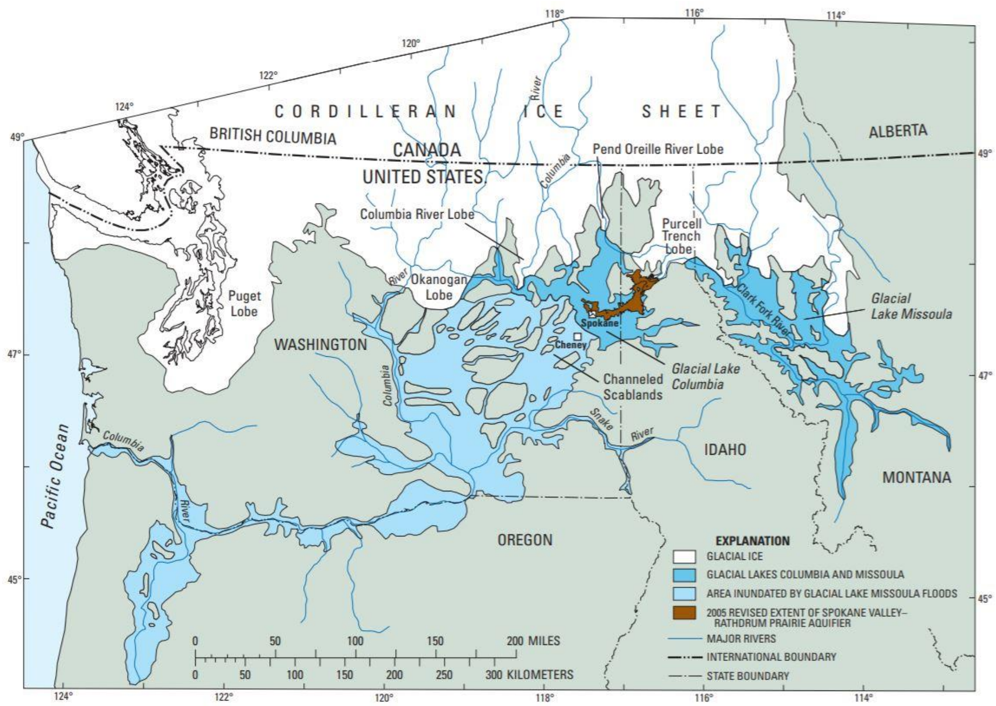

Figure 4. Extent of glacial ice and glacial lakes in northern Washington, Idaho, and parts of Montana. (Kahle et al., 2005).

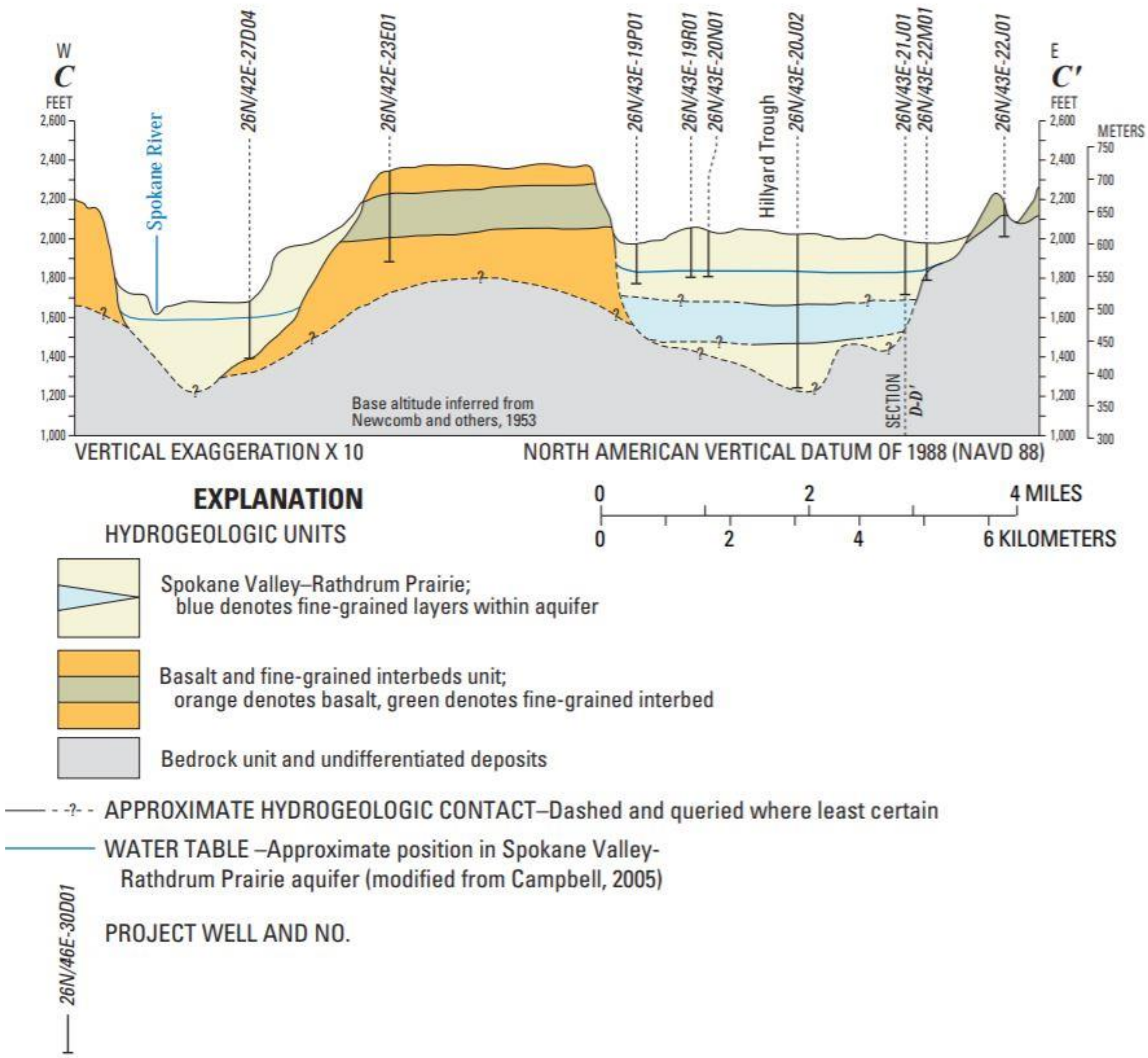

Figure 5. Generalized hydrogeologic section of the Spokane Valley-Rathdrum Prairie aquifer along hydrogeologic section C-C' (from Kahle and Bartolino, 2007).

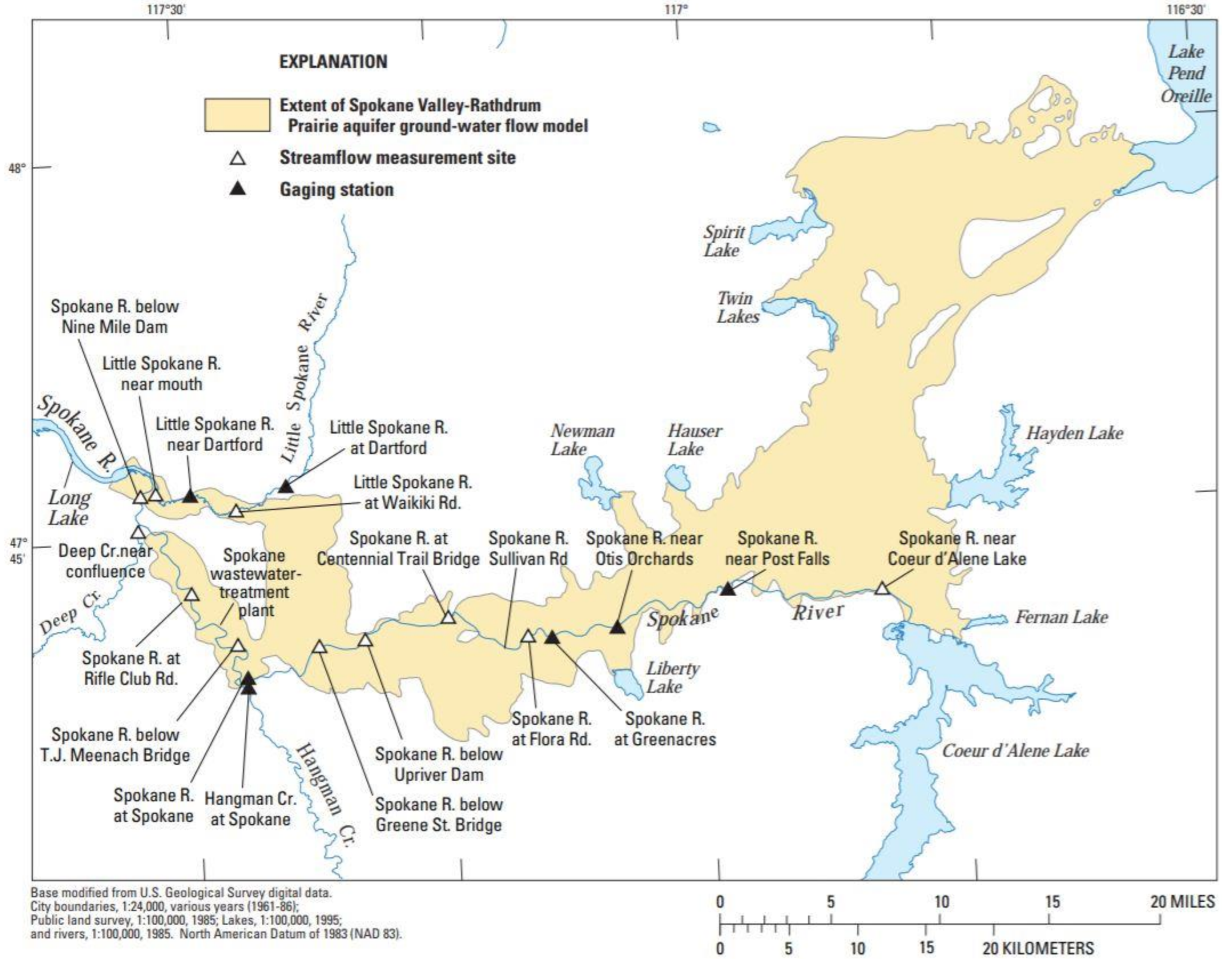

Figure 6. Locations of gaging stations and streamflow measurement sites on the Spokane and Little Spokane Rivers, Spokane ValleyRathdrum Prairie aquifer, Washington and Idaho (Hsieh et al., 2007).

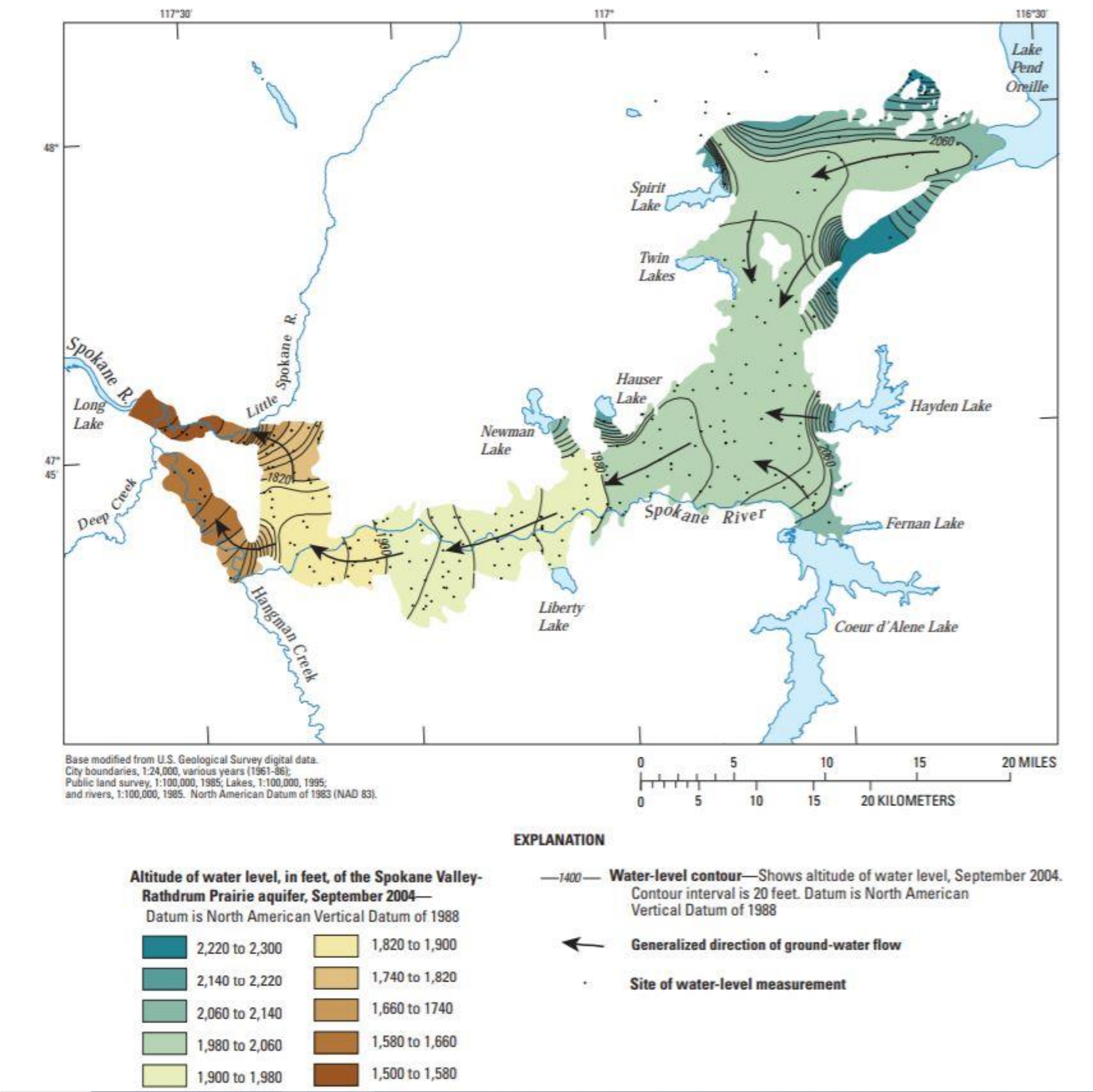

Figure 7. Ground-water levels for the Spokane Valley-Rathdrum Prairie aquifer, Washington and Idaho, September 2004 (Hsieh et al., 2007).

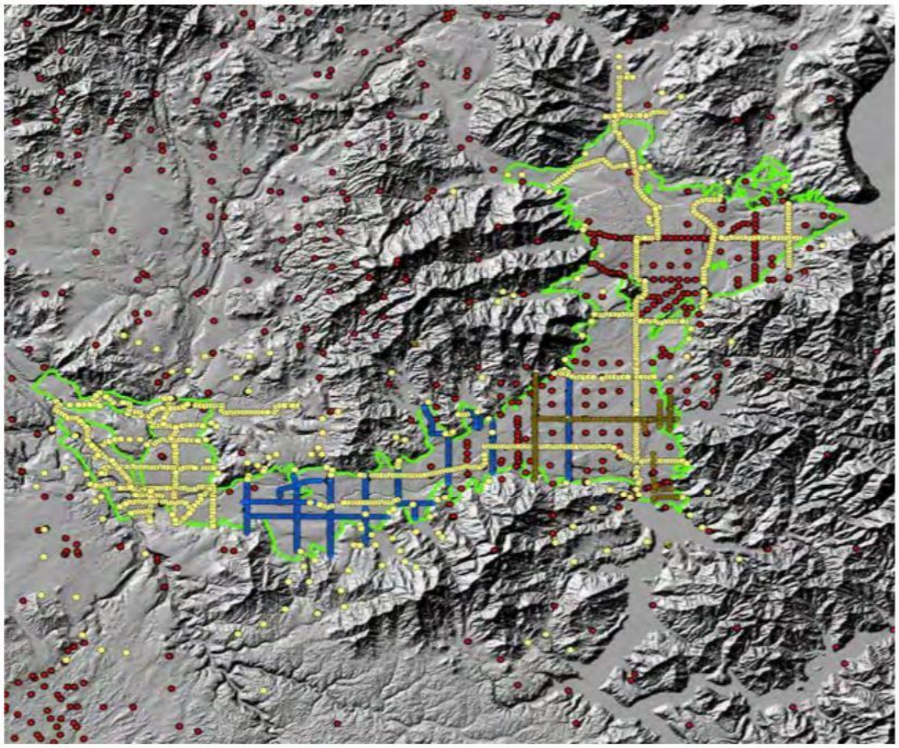

Figure 8. Terrain map of the SVRP showing the distribution of all gravity data used (Oldow and Sprenke, 2006).

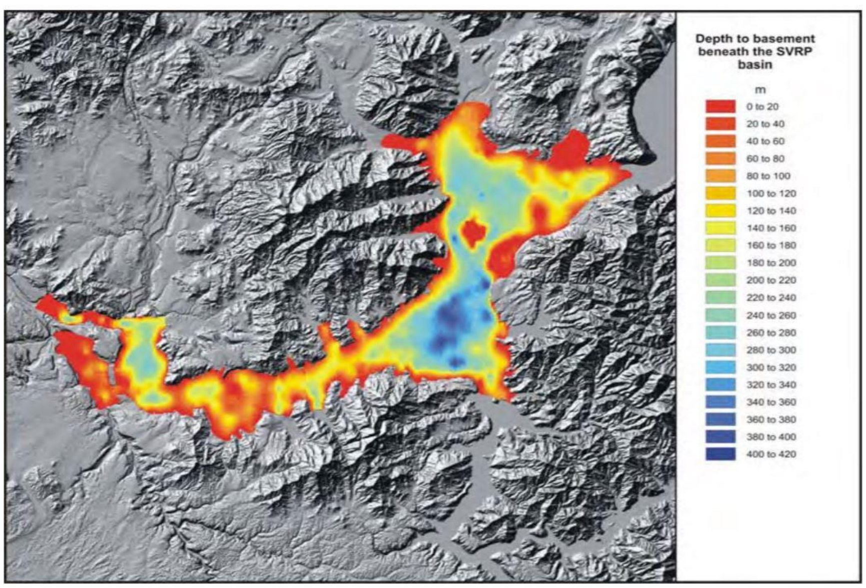

Figure 9. Terrain map showing depth to basement beneath the Spokane Valley – Rathdrum Prairie basin (Oldow and Sprenke, 2006).

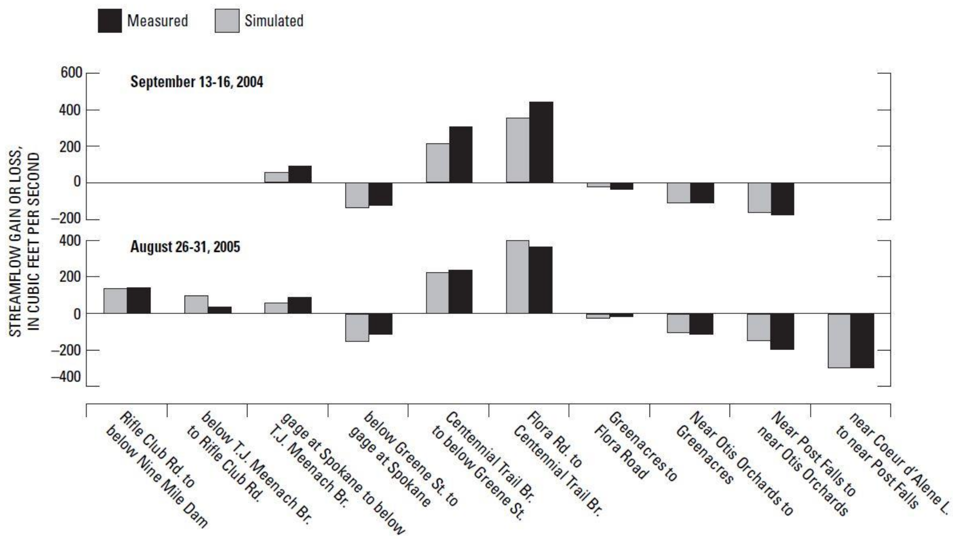

Figure 10: Simulated and measured streamflow gains (positive values) and losses (negative values) on various segments of the Spokane River during seepage runs of September 13-16, 2004, and August 26-31, 2005 (Hsieh et al., 2007).

Tables:

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.

Table 1. Published water budgets for the Spokane Valley–Rathdrum Prairie aquifer (Kahle et al., 2005) (Method: M, ground-water-flow model; R, referenced; SM, streamflow measurements; W, water balance; WY, watershed yield. Abbreviations: cubic feet per second, cubic foot per second; –, not applicable or unknown)

Component	Rate (ft^3/s)	Subcomponent or description	Rate (ft^3/s)	Source
		Inflow to aquifer		
Spokane River	718	Spokane River near Coeur d'Alene Lake to Flora Road	606	Aug. 27–Sept. 1, 2005 streamflow measurements
		Spokane River below Greene Street at Spokane gage	112	
Lakes	287	Hayden	62	L. Murray (University of Idaho, written commun., March 3, 2006)
		Pend Oreille	50	Frink (1964), Pluhowski and Thomas (1968), McQueen and Nace (1970), Drost and Seitz (1978), Painter (1991)
		Spirit	48	L. Murray (University of Idaho, written commun., March 3, 2006)
		Coeur d'Alene	37	Sagstad (1977)
		Twin	35	L. Murray (University of Idaho, written commun., March 3, 2006)
		Newman	20	
		Hauser	17	
		Fernan	13	
		Liberty	5	
Areal recharge	233	Total	–	B.A. Contor (Idaho State University, written commun., April 20, 2006 and July 19, 2006); P.A. Hsieh (U.S. Geological Survey, written commun., December 6, 2006); Bartolino (2007)
Tributary recharge	112	Total	–	Hortness (this volume)
Infiltration of ground water applied at land surface	77	Landscape irrigation	54	B.A. Contor (Idaho State University, written commun., January 15, 2007)
		Septic systems	23	
Spirit Valley	44	Total	–	L. Murray (University of Idaho, written commun., March 3, 2006)
Total inflow:	1,471			
		Outflow from aquifer		
Spokane River	861	Spokane River at Flora Road to below Greene Street	593	Aug. 27–Sept. 1, 2005 streamflow measurements
		Spokane River at Spokane gage to below Nine Mile Dam	268	
Pumpage	318	Public supply	205	M.A. Maupin (U.S.Geological Survey, written commun., January 4, 2006),
		Self-supplied Industrial	34	
		Irrigation (outside purveyor service areas)	51	B.A. Contor (Idaho State University, written commun., January 15, 2007)
		Domestic supply wells (outside purveyor service areas)	28	
Little Spokane River	232	Little Spokane R. below "At Dartford" gaging station		Aug. 27–Sept. 1, 2005 streamflow measurements
Subsurface outflow	55	Flow to Long Lake		Drost and Seitz (1978)
Infiltration of ground water into sewers	2.3	Total		L. Brewer (City of Spokane, written commun., February 8, 2006)
Total outflow:	1,468			
		Totals		
Total inflow:	1,471			
Total outflow:	1,468			
Difference:	-2.7	0.2 percent		

Table 2. Estimated ground-water budget for the Spokane Valley-Rathdrum Prairie aquifer for average conditions 1990–2005, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho (gathered by Kahle and Bartolino., 2007).

Measurement site or gaging station	August 26-31, 2005		August 8, 2006	
	Discharge (ft^3/s)	Gain or loss (ft^3/s)	Discharge (ft^3/s)	Gain or loss (ft^3/s)
Spokane River near Coeur d'Alene Lake	738	--	—	--
Spokane River near Post Falls	447	-291	—	--
Spokane River near Otis Orchards	256	-191	—	--
Spokane River at Greenacres	146	-110	—	--
Spokane River at Flora Road	132	-14	—	--
Spokane River at Centennial Trail Bridge	492	360	579	--
Spokane River below Upriver Dam	—	--	525	-54
Spokane River below Greene Street Bridge	725	233	869	344
Spokane River at Spokane	613	-112	767	-102
Hangman Creek at Spokane	1.5	--	—	--
Spokane River below T.J. Meenach Bridge	703	88.5	—	--
Spokane Wastewater Treatment Plant discharge[1]	56	--	—	--
Spokane River at Rifle Club Road	797	38	—	--
Deep Creek near confluence	0	--	—	--
Spokane River below Nine Mile Dam	938	141	—	--

[1]Spokane Wastewater Treatment Plant discharge value provided by John Convert, Washington State Department of Ecology, written. commun., 2005.

Table 3. Streamflow measurements made on the Spokane River (Kahle et al., 2005)

Spokane area	Inflow	eastern Spokane Valley	**1,280**	**1,227**	**1,319**	**1,270**	**1,312**	**1,288**
		recharge from precipitation	*30*	*30*	*30*	*30*	*30*	*30*
		tributary basins	*4*	*4*	*4*	*4*	*4*	*4*
	Outflow	net water use	*-133*	*-133*	*-133*	*-133*	*-133*	*-133*
		Spokane River	**-623**	**-616**	**-620**	**-618**	**-625**	**-628**
		Hillyard Trough	**-293**	**-293**	**-349**	**-293**	**-293**	**-293**
		Western Arm	**-264**	**-218**	**-249**	**-260**	**-295**	**-268**
	Decrease in Storage		0	0	0	0	0	0
Western Arm	Inflow	Spokane area	**264**	**218**	**249**	**260**	**295**	**268**
		recharge from precipitation	*7*	*7*	*7*	*7*	*7*	*7*
		tributary basins	*16*	*16*	*16*	*16*	*16*	*16*
	Outflow	net water use	*-3*	*-3*	*-3*	*-3*	*-3*	*-3*
		Spokane River	**-283**	**-238**	**-269**	**-280**	**-314**	**-287**
	Decrease in Storage		0	0	0	0	0	0
Hillyard Trough	Inflow	Spokane area	**293**	**293**	**349**	**293**	**-293**	**293**
		recharge from precipitation	*14*	*14*	*14*	*14*	*14*	*14*
		tributary basins	*3*	*3*	*3*	*3*	*3*	*3*
	Outflow	net water use	*-28*	*-28*	*-28*	*-28*	*-28*	*-28*
		Little Spokane River Arm	**-254**	**-254**	**-254**	**-254**	**-254**	**-254**
		Lower Unit	**-27**	**-27**	**-84**	**-27**	**-27**	**-27**
	Decrease in Storage		0	0	0	0	0	0
Little Spokane River Arm	Inflow	Hillyard Trough	**254**	**254**	**254**	**254**	**254**	**254**
		recharge from precipitation	*5*	*5*	*5*	*5*	*5*	*5*
		tributary basins	*6*	*6*	*6*	*6*	*6*	*6*
	Outflow	net water use	*0*	*0*	*0*	*0*	*0*	*0*
		Little Spokane River	**-257**	**-257**	**-257**	**-257**	**-257**	**-257**
		Spokane River/Long Lake	**-8**	**-8**	**-8**	**-8**	**-8**	**-8**
	Decrease in Storage		0	0	0	0	0	0
Lower Unit	Inflow	Hillyard Trough	**27**	**27**	**84**	**27**	**27**	**27**
	Outflow	net water use	*0*	*0*	*0*	*0*	*0*	*0*
		Long Lake	**-27**	**-27**	**-84**	**-27**	**-27**	**-27**
	Decrease in Storage		0	0	0	0	0	0

Table 4. Simulated 10-year average water budget for subregions of the Spokane Valley-Rathdrum Prairie aquifer (Hsieh et al., 2007). [Values are in cubic foot per second. Value in italic indicates flow component is specified; value in bold indicates flow component is not specified]