



Ralston Hydrologic Services, Inc.

GROUND WATER CONSULTING AND EDUCATION

1122 East B Street, Moscow, ID USA 83843

Cell 208-699-3989 Fax 208-882-3334 ralston@moscow.com

**EVALUATION OF ALTERNATIVE GROUND-
WATER PUMPING SCHEMES AS AN APPROACH
TO MITIGATING PROBLEMS OF CRITICAL LOW
FLOW IN THE SPOKANE RIVER AT SPOKANE,
WASHINGTON**

Dale R. Ralston PhD PE PG and Gary S. Johnson PhD PE

Submitted to the Idaho Water Resource Board

April, 2015

TABLE OF CONTENTS

1. Introduction
2. Coeur d'Alene Lake and the Spokane River
 - 2.1. Coeur d'Alene Lake and Operation of the Post Falls Dam
 - 2.2. Spokane River from Coeur d'Alene Lake to the Spokane Gage
3. Spokane Valley – Rathdrum Prairie Aquifer
 - 3.1. Description of the Aquifer
 - 3.2. Ground-water Levels
 - 3.3. Ground-water Pumping
 - 3.4. Time Lag from Recharge Events
4. Description of the Bi-State SVRP Numerical Ground-Water Model
5. Evaluation of Model Application at Small Time and Space Scales
 - 5.1. Six Minute Study Analysis
 - 5.2. Comparison to the SAJB Finite Element Model
6. Spreadsheet Tool Utilizing the Bi-State Aquifer Model
 - 6.1. Spreadsheet Description
 - 6.2. Spreadsheet Use
7. River Flow Impacts from Decreased Pumping and Alternative Well Location Scenarios
 - 7.1. Introduction
 - 7.2. Alternative #1 Reduction in Pumping Quantities
 - 7.3. Alternative #2 Change in Well Locations
8. Conclusions and Recommendations
 - 8.1. Conclusions
 - 8.2. Recommendations
9. Appendices
 - a. Appendix A Development of Response Functions from the Bi-State Model
 - b. Appendix B Details of the Six Minute Study Comparisons

LIST OF FIGURES

- | | |
|------------|---|
| Figure 1-1 | Location map of the SVRP aquifer and the Spokane River |
| Figure 1-2 | Nature of the river/aquifer interconnection |
| Figure 2-1 | Hydrograph for Coeur d'Alene Lake for 2010 through 2014 |
| Figure 2-2 | Hydrograph for the Spokane River near Post Falls for 2010 through 2014 |
| Figure 2-3 | Average river flow and calculated river loss during the period of August 20-31, 2010, Coeur d'Alene gage to Greenacres gage |
| Figure 2-4 | Average river flow and calculated river loss during the period of August 20-31, 2010, Greenacres gage to Spokane gage |

- Figure 3-1 Locations of selected observation wells with long-term water level records
- Figure 3-2 Hydrograph for wells 51n 5w 33bba1 and 33cba1 near Post Falls, Idaho
- Figure 3-3 Hydrograph for well 25N 45E 16C01 located near Liberty Lake, Washington
- Figure 3-4 Hydrograph for well 53N 4W 28cab1 located near Spirit Lake, Idaho
- Figure 3-5 Hydrograph for well 25N 44E 19D02 located in Spokane Valley, Washington
- Figure 3-6 Taylor and others (2007) aquifer zones
- Figure 3-7 Analysis of impacts on the Spokane River at the Spokane gage from an annual one-month recharge event in area “s” representing overflow from Hayden Lake
- Figure 4-1 Bi-State aquifer model area and grid cells from the upper layer
- Figure 5-1 SVRP models finite-element mesh and finite-difference grid (from Porcello, 2014)
- Figure 5-2 Simulation results of moving pumping in Irvin Water District (after Porcello, 2014)
- Figure 6-1 Map of wells within the spreadsheet
- Figure 6-2 Example pumping data entry
- Figure 6-3 Results from the spreadsheet for changes in pumping at the two well locations
- Figure 7-1 Plot of cumulative river depletion resulting from reduction from summer to winter pumping rates versus the percent of pumping appearing as river depletion after 30 days
- Figure 7-2 Locations of wells that have a 40 percent or greater impact on the Spokane River at the Spokane gage
- Figure 7-3 Map showing well locations 69 and 76 in the Consolidated Irrigation District #1 example transfer scenario
- Figure 7-4 Spreadsheet estimated impacts on the Spokane River from the Consolidated Irrigation District #1 pumping relocation
- Figure 7-5 Map showing the locations of wells 22 and 84 in the example transfer scenario
- Figure 7-6 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd for 30 days from well 22 to well 84
- Figure 7-7 Map showing the locations of well 22 and well 3 in the example transfer scenario
- Figure 7-8 Spreadsheet estimated effect on flow of the Spokane River at the Spokane gage from shifting 10 mgd for 30 days from Well 22 to Well 3
- Figure 7-9 Map showing Well 22 and Well 112 in the example transfer scenario
- Figure 7-10 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd for 30 days from well 22 to well 112
- Figure 7-11 Map showing well 22 and well 93 in the example transfer scenario
- Figure 7-12 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd for 30 days from well 22 to well 93

CHAPTER 1 INTRODUCTION

The high hydraulic conductivity Spokane Valley – Rathdrum Prairie (SVRP) aquifer and the Spokane River form an interconnected water resource system in northern Idaho and eastern Washington (Figure 1-1). The Spokane River starts at the outlet of Coeur d’Alene Lake in Idaho and flows west into Washington to ultimately discharge into the Columbia River. About half of the recharge to the aquifer originates as losses from the Spokane River in the reach from the Coeur d’Alene gage near the lake outlet in Idaho to below the Greenacres gage in Washington, which is located about six miles west of the state line (Figure 1-1). The Spokane River is perched above the aquifer in this reach. Consequently, recharge from the river to the aquifer is independent of ground-water levels. Figure 1-2 illustrates the nature of a river/aquifer connection under perched, gaining and losing conditions.

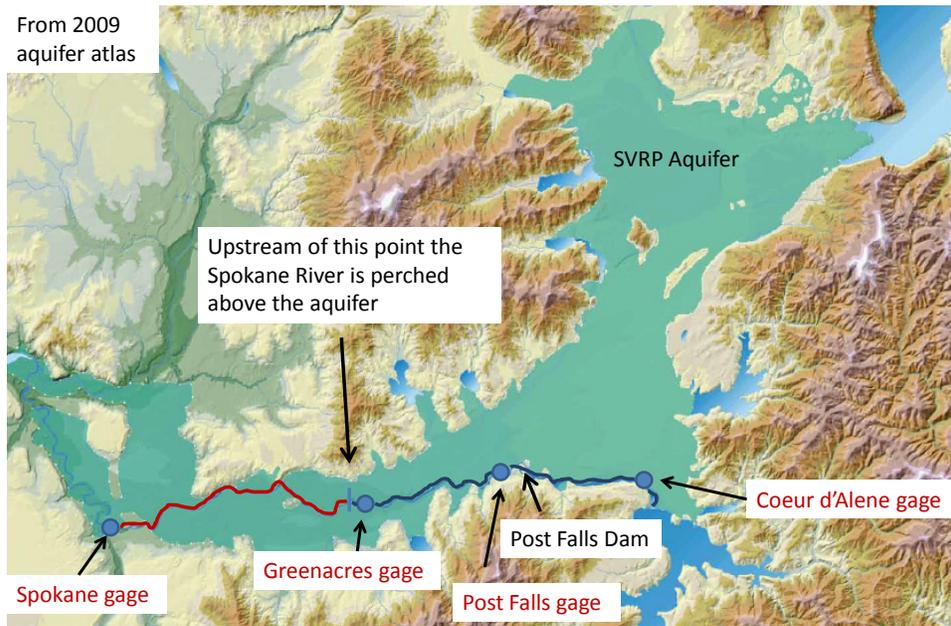
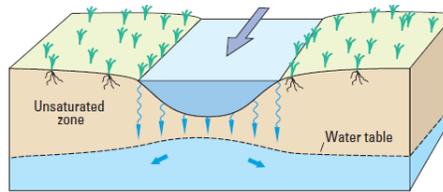


Figure 1-1 Location Map of the SVRP Aquifer and the Spokane River

Most of the aquifer discharge is to the Spokane River in the reach from below the Greenacres gage to the Spokane gage. There is a saturated connection between the river and the aquifer in this portion of the river with both gaining and losing reaches. The effects of ground-water pumping on the river in this reach include reduced gains and increased losses.

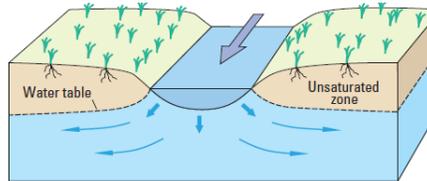
One of the primary water resource problems in the area is a period of low flow in the Spokane River at the Spokane gage that occurs for a few weeks to a month in August and September of many years. The low flow in the river results from three factors: 1) the temporal pattern of water release from the Post Falls Dam, 2) the timing of effects from aquifer recharge events and 3) the timing of effects from ground-water pumping from wells throughout the aquifer. The Post Falls dam, operated by Avista Corporation, controls lake levels and river flow from early summer to late fall. The dam does not control lake level or river flow from late fall to early summer.

Perched River – water table is below the bottom of the river channel – amount of aquifer recharge is controlled by the height of water in the river; it is independent of ground-water levels.



From USGS Circular 1376

Losing River -- river is in hydraulic connection with the aquifer – amount of aquifer recharge from the river is controlled by the difference between the river water level and the ground-water level.



Gaining River – river is in hydraulic connection with the aquifer – amount of ground-water discharge to the river is controlled by the difference between the river water level and the ground-water level.

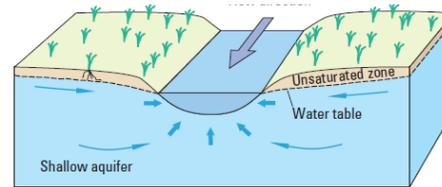


Figure 1-2 Nature of River/Aquifer Interconnection

The purpose of this project is to evaluate the feasibility of utilizing alternative ground-water pumping schemes from the SVRP aquifer in Washington and Idaho to reduce the severity of extreme low flow in the Spokane River as measured at the Spokane gage. The general objective of the project is to use the numerical ground-water model of the SVRP aquifer and Spokane River in conjunction with investigations of the surface water – ground water system to assess potential changes in the flow of the Spokane River at the Spokane gage that may result from a program of reductions or relocations in pumping from selected wells in both Washington and Idaho.

The Bi-State numerical ground-water model (Hsieh and others, 2007) was selected for use in this study because: 1) it is based on the best available spatial representation of the hydraulic properties of the aquifer and 2) because it has been calibrated to both historic ground-water levels and historic river flows. The Bi-State ground-water model was constructed as a joint effort of the U.S. Geological Survey, the Idaho Department of Water Resources, the Washington Department of Ecology, Washington State University and the University of Idaho. A spreadsheet interface to the Bi-State model, created by Taylor and others (2007), allows monthly analysis of pumping and/or recharge impacts in regions of the aquifer on the flow of the river at the Spokane gage. However, analysis of short term impacts of pumping on the river requires a daily based analysis.

This report is divided into the following sections after this introduction: 1) Coeur d’Alene Lake and the Spokane River, 2) SVRP aquifer, 3) description of the Bi-State numerical ground-water model, 4) evaluation of the model application at small time and space scales, 5) spreadsheet tool utilizing the Bi-State aquifer model, 6) river flow impacts from alternative operations and well locations scenarios, and 7) conclusions and recommendations.

CHAPTER 2 COEUR D'ALENE LAKE AND THE SPOKANE RIVER

The focus of this study is on the reach of the Spokane River from Coeur d'Alene Lake to the Spokane gage which is located in downtown Spokane (Figure 1-1). There are no surface water tributaries in this reach. There are long-term gaging stations on the Spokane River near Post Falls (below the Post Falls Dam) and at Spokane. Gaging stations have been operated for shorter periods of time near Coeur d'Alene, near Otis Orchards and at Greenacres. There is also a long-term record of the stage of Coeur d'Alene Lake at Coeur d'Alene.

Coeur d'Alene Lake and Operation of the Post Falls Dam

Most of the inflow to Coeur d'Alene Lake is from the Coeur d'Alene and St. Joe Rivers. There are gaging stations on both of these rivers. There are no impoundment structures on either of these rivers. Discharge from the lake is to the Spokane River with loss to ground water at the north end of the lake.

The following is a description of how the lake/river system is impacted by the operation of the Post Falls dam (www.avistautilities.com).

“A common assumption is that where there is a dam and a lake, the lake is a reservoir created by the dam.... Coeur d'Alene Lake is a natural lake that would exist regardless of Post Falls Dam. The Post Falls Dam affects the water surface elevation of Coeur d'Alene Lake for about half of any given year. The remainder of the time, during winter and spring, Coeur d'Alene Lake water elevations and outflow are controlled entirely by the natural outlet restriction.....

There are four principal operating time periods each year relating to operation of Post Falls Dam and Coeur d'Alene Lake....

Spring -- The extent and timing of spring runoff in the Coeur d'Alene Basin is determined by snowpack conditions, precipitation, and temperatures. During this time of the year, the Dam does not control the Coeur d'Alene Lake level or Spokane River flows. Both lake level and downstream river flows are controlled entirely by the Coeur d'Alene Lake outlet and the Spokane channel restriction, and both can fluctuate widely.... Avista takes control of the lake level by closing the spill gates. Because natural conditions vary, there is not a specific date each year that Avista begins this process. However, this typically occurs each year sometime between late May and early July. Initial control, by closing the dam's spill gates, reduces the outflow and begins to fill the nine-mile stretch of the Spokane River between Coeur d'Alene Lake and the dam.

Summer – As part of Avista's Federal Regulatory Commission license..., Avista is required to maintain the level of Coeur d'Alene Lake at summer full-pool-elevation of 2,128 from as early as practical to the Tuesday after Labor Day....

Fall – The water stored in the Lake during the summer increases available generation in the fall when Avista begins the fall drawdown on the Tuesday following Labor Day Weekend. Following Labor Day, depending on weather conditions, the lake is generally lowered to an elevation of about 2,122 feet by the end of December at a rate of about 1.5 feet per month.

Winter – During winter, inflows into Coeur d’Alene Lake vary widely due to fluctuating weather patterns.... Typically, near the end of December or first part of January, Post Falls is operated to pass all of the flow it is capable of passing, allowing Coeur d’Alene Lake to seek and achieve its natural level with no influence of Post Falls Dam. This free flow condition typically continues until late May, June or early July.”

The variation in the level of Coeur d’Alene Lake, shown on Figure 2-1 for years 2010 through 2014, reflects both hydrologic conditions within the watershed and the operational program of the dam. The lake level patterns in 2010 and 2013 are similar and represent years of typical spring runoff patterns within the lake watershed. Greater springtime flow in the Coeur d’Alene and St. Joe Rivers in 2011 and 2012 resulted in higher lake levels in the spring. There was a shorter duration of high lake levels in 2014.

Using 2013 as an example, the lake level varied from January through April because of variations in inflow from the Coeur d’Alene and St. Joe Rivers. The dam at Post Falls exerted no control over river flow during this period. High lake level occurred in early April 2013 at an elevation of about 2,128.5 feet. The dam was used to initiate control over river flow and lake level starting in the middle of April 2013 and maintained a lake elevation within 0.2 feet of 2,128 feet in June, July and August. The lake level decreased starting in early September to a low of about 2,122 feet at the end of December. The dam ceased control over the river near the end of December to start the cycle again.

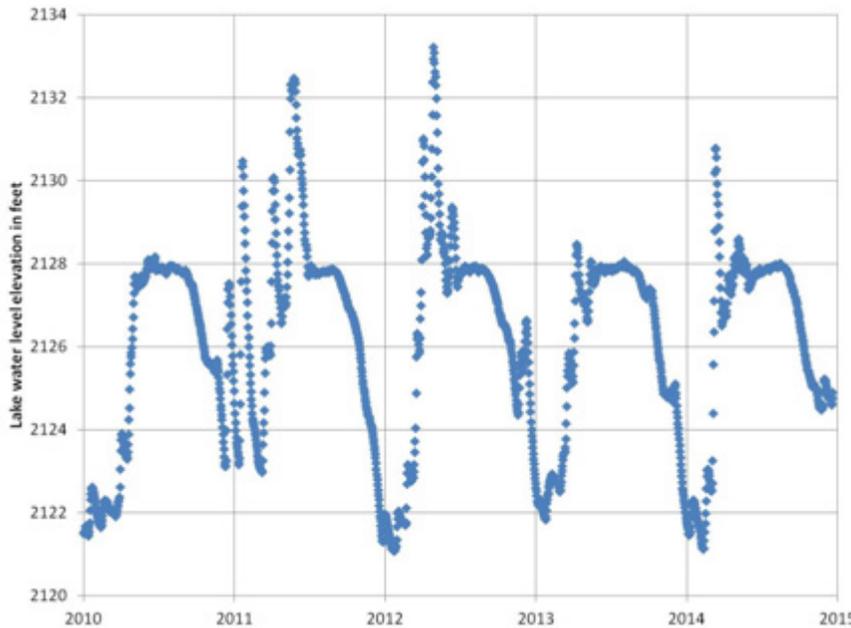


Figure 2-1 Hydrograph for Coeur d’Alene Lake for 2010 through 2014

Spokane River from Coeur d’Alene Lake to the Spokane Gage

The location of the Spokane River relative to the SVRP aquifer is important relative to river/aquifer interconnection. Both the thickness and average hydraulic

conductivity of the aquifer are greater near the center as compared to the margins. The Spokane River flows near the southern margin of the SVRP aquifer from the outlet of Coeur d'Alene Lake to midway between the Post Falls and Greenacres gages (Figure 1-1). Post Falls is located where the river flows over the metamorphic basement rocks along the south side of the SVRP aquifer. The river crosses from the southern margin to the northern margin of the aquifer in the vicinity of the Greenacres gage and then flows along the northern margin of the aquifer. The river then crosses back across the aquifer above the Spokane gage. Spokane Falls on the river is located where the river flows over basalt.

The river reach from Coeur d'Alene Lake to the Spokane gage can be divided into three major segments: 1) from the Coeur d'Alene gage near the outlet of the lake to the Post Falls gage, 2) from the Post Falls gage to below the Greenacres gage and 3) from below the Greenacres gage to the Spokane gage (Figure 1-1). The first two segments include the entire river reach in Idaho and the easternmost portion of the river reach in Washington. The Spokane River is perched above the SVRP aquifer for these two segments. Ground-water levels range from tens to hundreds of feet below the channel of the river. Changes in ground-water levels cannot impact river flow. The third river segment, from below the Greenacres gage to the Spokane gage, includes both gaining and losing reaches and the amount of gain or loss is dependent on ground-water levels.

The hydrograph for the Spokane River at the Post Falls gage for the years 2010 through 2014 reflects both hydrologic conditions within the watershed and the operational program of the dam (Figure 2-2). The peak flow in the river was greater in 2011 and 2012 than it was in 2010 and 2013. Using 2013 as an example, the annual maximum flow in the river at the Post Falls gage was 19,200 cfs on April 9th. The

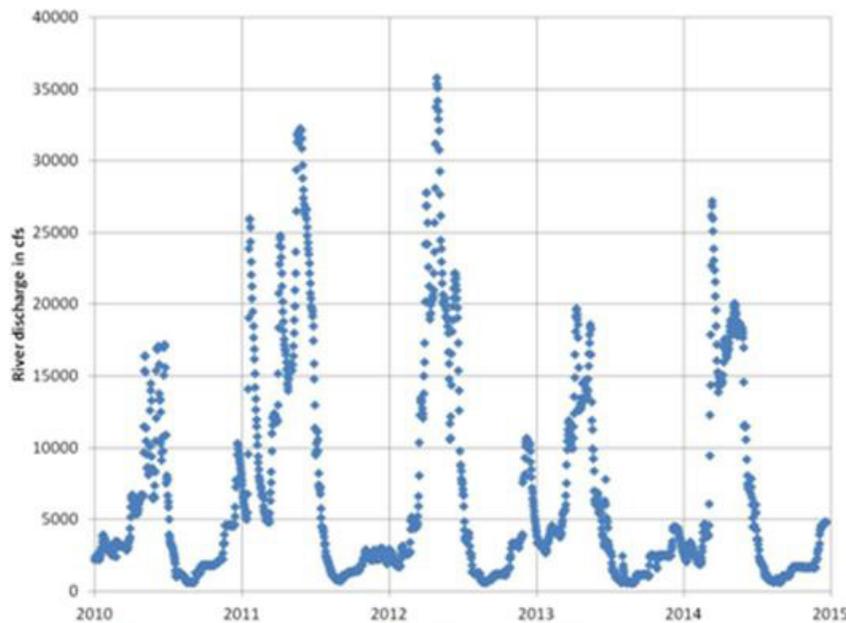


Figure 2-2 Hydrograph for the Spokane River near Post Falls for 2010 through 2014

annual minimum flow was 627 cfs on August 20, 2013. The maximum flow occurred prior to initiating control of the lake and river flow by the Post Falls Dam. A secondary flow peak occurred on May 14, 2013 (18,400 cfs) after control of the river/lake system was initiated at the Post Falls Dam. The dam in 2013 was operated to meet the required minimum flow of 600 cfs, which was initiated in 2009. The stepped up discharge rate starting on the Tuesday after Labor Day is evident in the hydrograph for the Post Falls gage.

Leakage from the Spokane River to the SVRP aquifer from the Spokane River in the reach from Coeur d'Alene Lake to below the Greenacres gage occurs throughout the year but can be quantified only during low flow periods. The river loss resulting from the subtraction of the daily average flow at one gage from the daily average flow at the another gage is meaningful only when the discharge rate at the Coeur d'Alene gage is less than about 1,500 cfs because of gage data uncertainty. Figure 2-3 shows that the average flow in the river during the period of August 20-31, 2010 decreased from 997 cfs at the Coeur d'Alene gage to 637 cfs at the Post Falls gage and to 249 cfs at the Greenacres gage. This represents a loss of about 75 percent of the flow in the river from near the mouth of the lake to the Greenacres gage. Calculations for the same period in 2009 and 2011 showed river losses between the Coeur d'Alene and Greenacres gages of 64 and 63 percent respectively. The amount of leakage from the river to the aquifer in the reach from the lake to Greenacres should be higher during high flow events due to higher river stage and greater river width, although the percentage loss as compared to the discharge rate likely decreases. Water-level data from wells near the river show that there is greater recharge to the aquifer during high flow events.

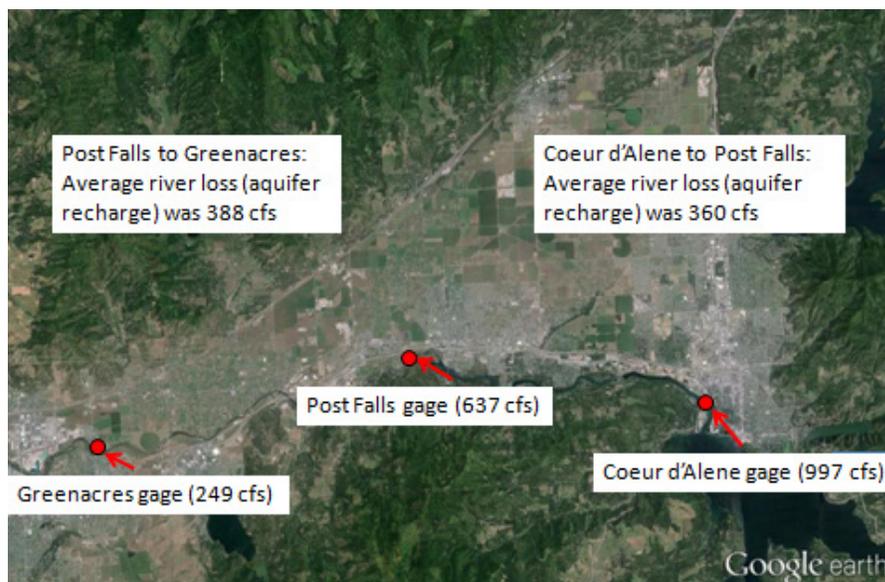


Figure 2-3 Average river flow and calculated river loss during the period of August 20-31, 2010, Coeur d'Alene gage to Greenacres gage

Ground water discharges back into the Spokane River in the river reach between the Greenacres gage and the Spokane gage. Figure 2-4 shows that the average flow in August 20-31, 2010 increased from 249 cfs at the Greenacres gage to 917 cfs at the Spokane gage, an increase in flow of 668 cfs. Calculations for the same period in 2009 and 2011 showed net gains between the two gaging stations of 745 and 957 cfs respectively.

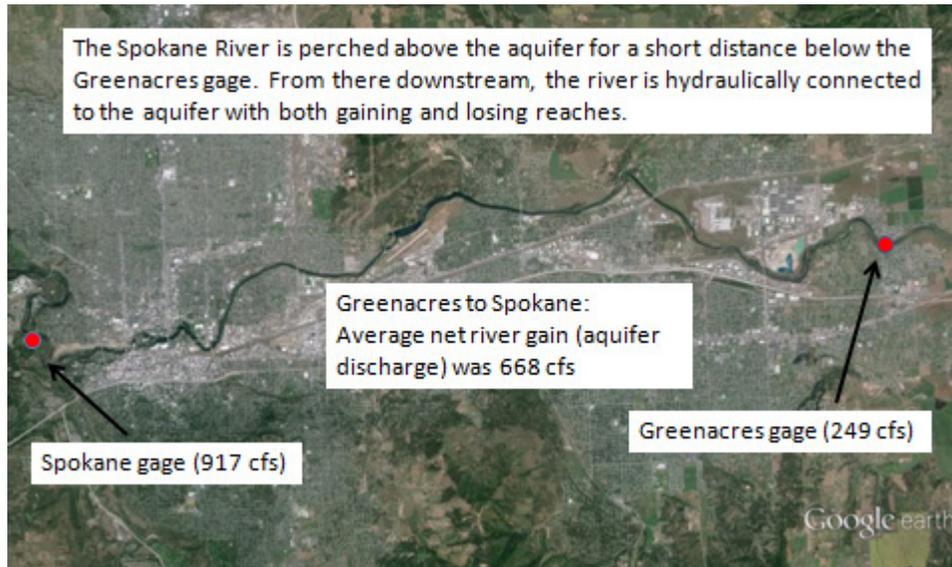


Figure 2-4 Average river flow and calculated river loss during the period of August 20-31, 2010, Greenacres gage to Spokane gage

Flow data taken at the USGS gaging station on the Spokane River at Spokane as analyzed by Barber and others (2011) show that the maximum and average flow of the river have not been impacted by development but the minimum flow of the river has been impacted. Barber and others (2011, page 6) describe the low-flow characteristics of the river as follows.

“As illustrated... summer low flows at the USGS gage near downtown Spokane are often less than 1,000 ft³/s, particularly in the last 40 years. It is this disturbing trend in low flows that raises concerns among water resource agencies. A regression analysis of the minimum annual daily flow data indicates a statistically significant ... decrease in low flow between 1900 and 2007. While the rate of decline was steepest from 1900 through 1950.....the downward trend has still continued since that time.....The combined effects of changes in reservoir operations associated with the Post Falls Dam, changes in water use patterns from irrigation of orchards and row crops to suburban residential uses, increases in municipal pumping as the regions’ populations has grown and changes in runoff patterns due to climate change... are creating severe low flow conditions that threaten water users and the environment.”

Hortness and Covert (2005) show that the annual 7-day low flow of the Spokane River near Post Falls (the discharge from the Post Falls Dam) and at Spokane both have a

downward trend for the period of 1968 – 2002. They state the following based on a comparison of the streamflow data from the Post Falls gage and the Spokane gage (page 14).

“Differences in monthly mean streamflow between the Post Falls and Spokane gaging stations for the months of July through December during 1968 – 2002 were analyzed for trends. Although the upper parts of this reach generally lose streamflow to the aquifer, the overall reach historically has gained streamflow. Trends detected for the months of September, October, and November were statistically significant. The analyses showed that the streamflow gains within this reach decreased over time during the period 1968-2002.”

CHAPTER 3 SPOKANE VALLEY – RATHDRUM PRARIE AQUIFER

Description of the Aquifer

The SVRP aquifer underlies a broad valley that extends from northern Idaho into eastern Washington (Figure 1-1). Recharge occurs in both Idaho and Washington although most of the recharge occurs in Idaho. Almost all natural aquifer discharge is to the Spokane and Little Spokane Rivers entirely within Washington.

The aquifer is composed of glacial outwash and flood sediments deposited in a valley eroded into older sediments, basalt and metamorphic rocks. Kahle and Bartolino (2007, page 12-13) describe the aquifer as follows.

“The SVRP aquifer consists of unconsolidated, coarse-grained gravel, cobbles, boulders, and some sand 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 and forms one of the most productive aquifers in the United States...The aquifer extends from Lake Pend Oreille through the Rathdrum Prairie and Spokane Valley to near Spokane where it is divided by Five Mile Prairie... On the west side of Five Mile Prairie, the Western Arm of the aquifer follows the course of the present-day Spokane River from near downtown Spokane to the community of Seven Mile. On the east side of Five Mile Prairie, the main body of the aquifer extends through the Hillyard Trough and then west through the Little Spokane River Valley to Long Lake...”

Natural recharge to the aquifer occurs via three primary mechanisms (Kahle and Bartolino 2007, page 21). First, aquifer recharge occurs as leakage from the Spokane River in the reach from Coeur d’Alene Lake to approximately Barker Road in Eastern Washington (about 49 percent). Second, recharge to the aquifer occurs as underflow from the surrounding tributary valleys and as leakage from the lakes that are present in many of these valleys (about 30 percent). Third, recharge occurs from precipitation and direct infiltration on the glacial sediments (about 16 percent). The remaining 5 percent is from landscape irrigation and septic systems.

Discharge from the aquifer occurs predominantly to the Spokane and Little Spokane Rivers and ground-water pumping. Kahle and Bartolino (2007, page 21) indicated that these percentages are approximately 59 percent, 16 percent and 22 percent

respectively. The remaining discharge is subsurface outflow and infiltration of ground water into sewers. All of the natural discharge from the aquifer occurs within Washington. The total estimated discharge from the aquifer is 1,468 cfs.

Ground-Water Levels

Ground-water levels reflect the water balance described above and the nature of the hydraulic connection with the river in the various portions of the aquifer. Four wells that have long-term water-level records represent the eastern and western portions of the aquifer (Figure 3-1). The wells located near Post Falls, Idaho (51N 5W 33bba1/33cba1) and near Liberty Lake, Washington (25N 45E 16C01) have the longest records, dating back into the 1920’s. Well 53N 4W 28cab1 located near Spirit Lake, Idaho has records

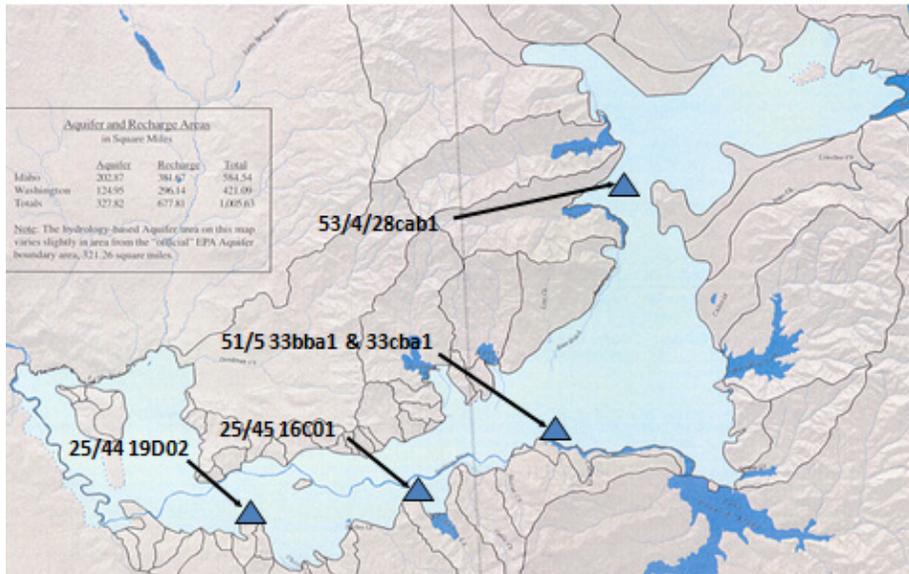


Figure 3-1 Locations of selected observation wells with long-term water level records

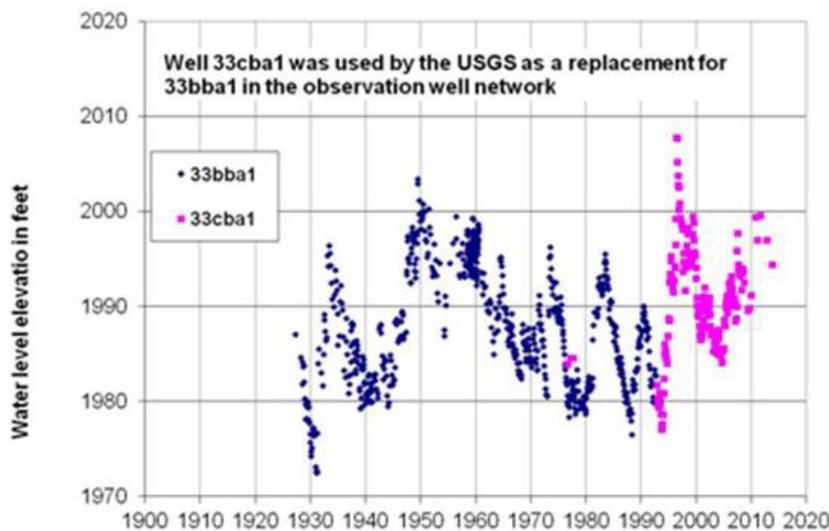


Figure 3-2 Hydrograph for wells 51N 5W 33bba1 and 33cba1 near Post Falls, Idaho

starting in the 1970's. Well 25N 44E 19D02, located along the southern boundary of the aquifer in Spokane Valley, has data starting in the 1920's but the record ends in the late 1970's. Hydrographs for these four wells are presented in Figures 3-2, 3-3, 3-4 and 3-5. Data were taken from the USGS websites for water resource data from Idaho and Washington with a limited number of additional data points obtained from the Idaho Department of Water Resources (IDWR website, 2014).

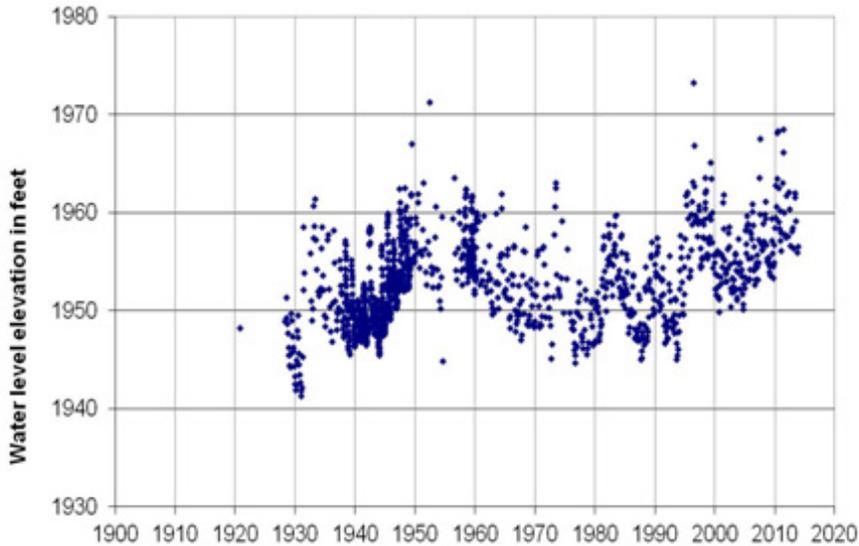


Figure 3-3 Hydrograph for well 25N 45E 16C01 located near Liberty Lake, Washington

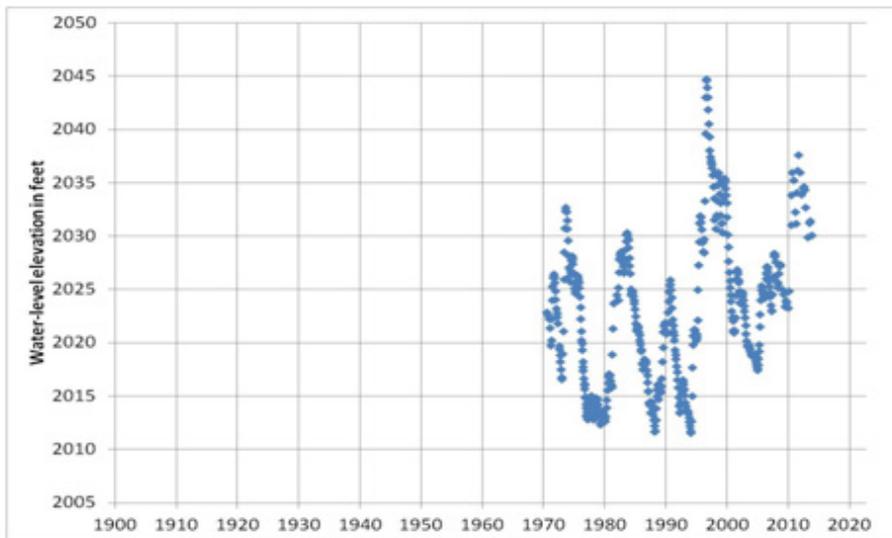


Figure 3-4 Hydrograph for well 53N 4W 28cab1 located near Spirit Lake, Idaho

The lowest levels on record for the wells near Post Falls and Liberty Lake were in the early 1930's with the highest records in the mid 1990's (Figures 3-2 and 3-3). The hydrograph for the well near Spirit Lake is similar in that the highest water level occurred in the 1990's (Figure 3-4). There is no evidence of long-term water-level decline in any of these three wells. These three observation wells are located in areas either away from

the Spokane River or where the Spokane River is perched above the aquifer. In all cases, high ground-water levels are associated with multiple years of above average precipitation within the watershed (as measured by precipitation and snow survey records). The hydrograph for well 25N 44E 19D02, located along the southern boundary of the aquifer in Spokane Valley, does not show the same apparent temporal pattern as the other wells (Figure 3-5). This well is located in an area where the Spokane River is hydraulically connected to the SVRP aquifer. Therefore, the hydrograph for well 25N 44E 19D02 represents the range of stage variation in the Spokane River in that portion of the basin.

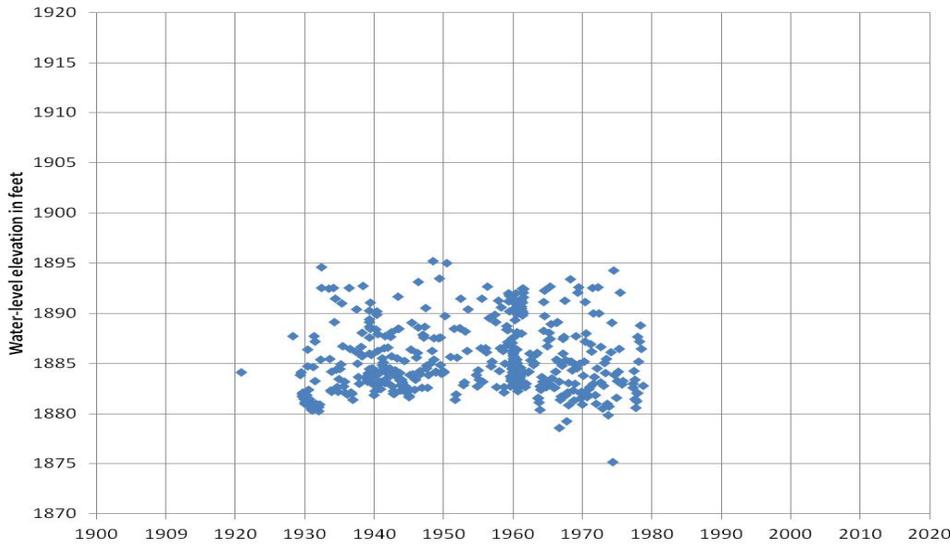


Figure 3-5 Hydrograph for well 25 N 44E 19D02 located in Spokane Valley, Washington

Ground-Water Pumping

Ground-water pumping impacts surface water systems via declining ground-water levels. Lower ground-water levels cause greater losses in hydraulically connected losing stream reaches and reduced gains in gaining reaches. Ground-water level changes only impact flow in streams where there is saturated hydraulic connection between ground water and the stream. Thus, ground-water pumping in Idaho and extreme eastern Washington cannot impact river flow in the reach in those immediate areas. However, ground-water pumping in Idaho and extreme eastern Washington does impact river flow starting downstream of the Greenacres gage.

The largest human impact on the hydrologic system stems from the withdrawal of ground water in both Idaho and Washington. The total ground-water withdrawal is composed mostly of pumpage by water purveyors' wells followed by irrigation wells. The average combined withdrawal rate is 317 cfs (Hsieh and others, 2007, page 23). The summer peaks of the combined withdrawal generally range from 600 to 800 cfs. Most of the water purveyors' wells are located in Washington. Almost all of the irrigated areas are in Idaho.

Time Lag from Recharge Events

The primary focus of this study is on the temporal effects of ground-water pumping on the Spokane River as measured at the Spokane gage. The temporal effects of

recharge events are of equal importance. The Taylor and others (2007) spreadsheet interface to the Bi-State model provides the opportunity to assess the temporal impacts of recharge events in various zones of the aquifer. Their spreadsheet allows multiple year analysis but is limited to monthly time steps. The example presented in this section of the report is intended to represent the recharge effects of overflow from Hayden Lake that occurs for a short period of time in most years.

Hayden Lake is located adjacent to area “s” on the Taylor and others (2007) spreadsheet map (Figure 3-6). For this analysis we assumed that the overflow recharge occurred each January for six years in a row. The assigned recharge rate is 100 acre-feet per month. This rate is not intended to represent actual recharge, but provides the convenience of viewing results on a percentage basis. The results of a ten-year analysis, presented on Figure 3-7, show that the maximum benefit to the river during the first year is about 6% of the recharge rate with a lag time of about three months. The effect of the first year recharge extends to the second year giving a maximum benefit to the river of about 7% of the recharge rate during the second year. Repeated recharge events results a cumulative maximum benefit to the river of about 9% of the recharge rate. This analysis represents any location in the “s” zone.

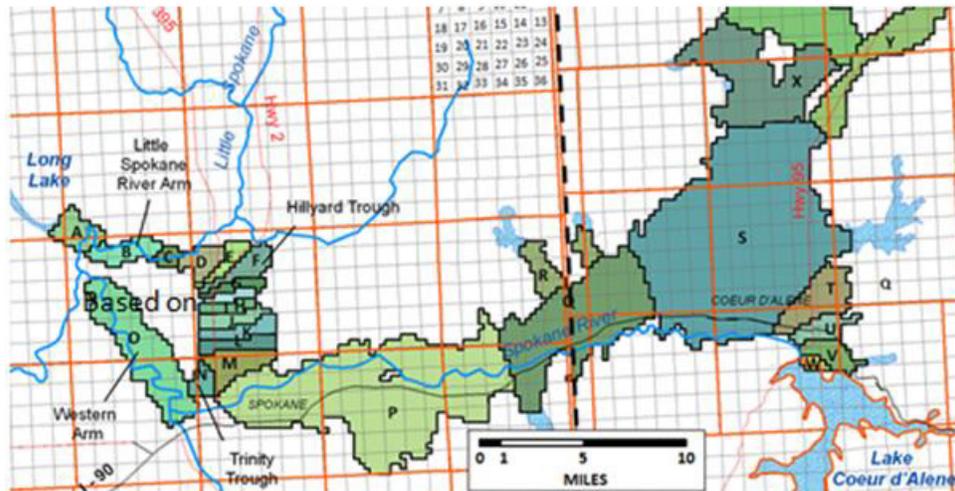


Figure 3-6 Taylor and others (2007) aquifer zones

The maximum percent benefit would be less with a greater lag time if the recharge occurred in a zone farther to the north such as near Spirit Lake. Similarly, the maximum percent benefit would be greater with a shorter lag time if the recharge occurred in a zone farther to the west such as near Post Falls.

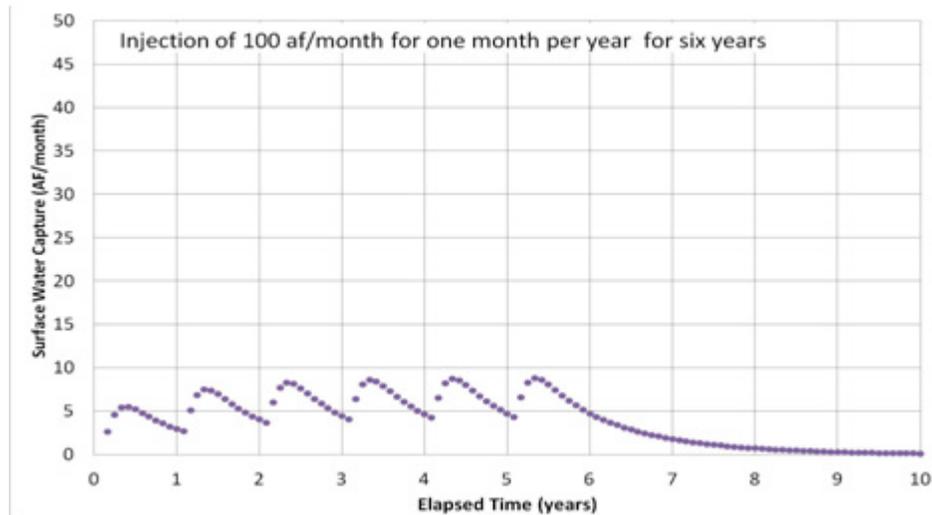


Figure 3-7 Analysis of impacts on the Spokane River at the Spokane gage from an annual one-month recharge event in area “s” representing overflow from Hayden Lake

The combined effects of recharge events throughout most of the Idaho portion of the aquifer provide a relatively constant supply of water to the gaining portion of the river in Washington. The seasonal changes in recharge rate are important only in the western portion of the aquifer in Idaho and the extreme eastern portion of the aquifer in Washington. The recharge source of primary importance in this area is the Spokane River.

CHAPTER 4 DESCRIPTION OF THE BI-STATE SVRP AQUIFER MODEL

This project relies on quantitative estimates of the magnitude and timing of ground water pumping effects on flows of the Spokane River. Those values cannot be physically measured because: a) effects of an individual well are confounded by temporal variations in aquifer recharge and the many other wells operating simultaneously, b) errors in measurement of Spokane River flows are larger than the effects of any single well on the river, and c) temporal changes in river flow from other causes complicate identification of effects resulting from aquifer pumping. Because the effects of aquifer pumping on the river cannot be directly measured, a computational estimation method is needed. In this case, the most reliable method was determined to be application of the Bi-State SVRP Aquifer model developed by Hsieh and others (2007). The model is applied repeatedly to estimate the proportion of ground water pumping at individual locations that is depleted from the hydraulically connected reach of the Spokane River above the Spokane gage. A detailed description of the process to estimate these relationships and incorporate them in the spreadsheet tool is provided in Appendix A. The purpose of this section is to provide a general description of the model. A more complete description of the model and calibration process can be found in Hsieh and others (2007).

The Bi-State SVRP aquifer model was developed in the 2004 to 2007 period by a

group of scientists and engineers representing the U.S. Geological Survey, Washington Department of Ecology, Idaho Department of Water Resources, Washington State University, and the University of Idaho. The group was led by Paul Hsieh of the U.S. Geological Survey, a nationally known expert in aquifer modeling. The model was developed as part of a program to respond to “concerns about the impacts of increased ground-water withdrawals resulting from recent and projected urban growth...” (Hsieh and others, 2007, p. 1). The primary purpose of the model was to “serve as a tool for analyzing SVRP aquifer inflows and outflows, simulating the effects of future changes in ground-water withdrawals from the aquifer, and evaluating aquifer management strategies” (Hsieh and others, 2007, p. 2). Decisions on the modeling approach, design, and interpretations were reached by consensus (Hsieh and others, 2007).

The model employed the frequently used Modflow-2000 finite-difference modeling code developed by the U.S. Geological Survey (Harbaugh and others, 2000). The model calculates ground water flow between a network of rectangular (square in the case of the SVRP model) grid cells and the exchange of water with head-dependent boundaries including surface water sources. These fluxes vary in response to spatially and temporally varying aquifer recharge and discharge inputs such as percolation from precipitation and ground water pumping. In the SVRP model, the aquifer is represented using a square grid, ¼ mile on a side. More than 5000 cells are used to represent the 326 square mile aquifer area in eastern Washington and Northern Idaho. The grid is superimposed on a base map in Figure 4-1 to illustrate the scale. In performing calculations, the finite-difference model is limited to representing all aquifer recharge, withdrawals, and exchanges with surface water as occurring at the center of each grid cell. Similarly, each cell is represented as having internally homogeneous aquifer properties such as hydraulic conductivity and storativity. In the case of the SVRP, homogeneous conditions are assigned to groups of multiple cells (zones) because of our inability to reliably identify the properties at a smaller continuous scale.

The model represents the aquifer as a single layer except in the Hillyard trough near the City of Spokane. The presence of a relatively thick and continuous clay layer in this area resulted in dividing the aquifer into upper and lower units, separated by a low permeability confining layer. The model represents the upper and lower aquifer units as merging in the southern portion of the Hillyard Trough where the confining layer thins and disappears. This project evaluated effects of only wells in the upper model layer, mostly east of the City of Spokane.

Model development included calibration of the model to a 10-year period from October 1995 through September 2005. During model calibration aquifer properties were adjusted within reasonable limits to obtain an acceptable match between: a) observed water level measurements in wells and simulated water levels at respective locations in the model, and b) estimated surface water gains and losses and those simulated in the model. Estimates of river gains and losses were made by differencing inflow and outflow at gaging stations. This produces moderately reliable results when gains and losses are a significant proportion of river flow. When river flows are large however, errors in measurement become too large to produce reliable estimates of gains and losses. Gains to, and losses from, the lakes are largely unknown; however, the model was constrained

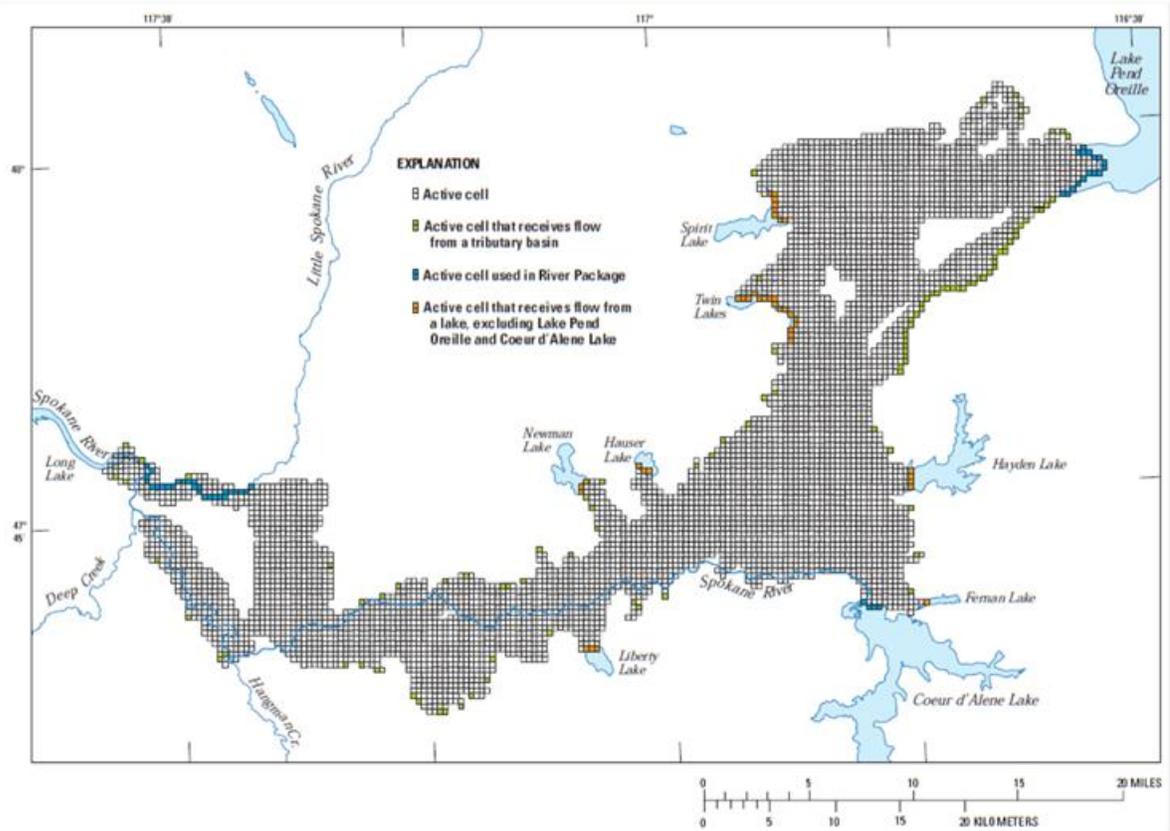


Figure 4-1 Bi-State aquifer model area and grid cells from the upper layer

to keep these values within what the modeling team believed was a reasonable range.

The Bi-State SVRP model represents five surface water bodies as head dependent. These include: the Spokane River below the Greenacres gage to Long Lake, Long Lake, the Little Spokane River, Pend Oreille Lake, and Coeur d'Alene Lake. In this work, the Spokane River gage location was used to subdivide the head dependent length of the Spokane River into two reaches; one above and one below the Spokane gage. All results are presented for the head-dependent reach above the Spokane gage and below the Greenacres gage. Other lakes around the perimeter of the SVRP aquifer are modeled as head independent, resulting in seepage losses independent of ground water levels and pumping.

The simulated rate of ground water exchange between head dependent surface water bodies and the aquifer is controlled by the head difference between them, the surface area of the water body in each cell, the hydraulic conductivity of the bed materials, and the thickness of the bed materials. In the case of the SVRP, the thickness of bed materials was unknown, so a uniform thickness was applied and spatial variations in bed hydraulic conductivity determined during calibration were allowed to compensate for variations in thickness. Although the area of head dependent surface water bodies may vary as stage rises and falls, estimates of pumping effects on the river (in this project) are not specific to a given time period with known river stage or width.

Insufficient data were available to incorporate this level of refinement into the model. Consequently the area of each water body is simulated as remaining constant in time in each cell using the average area used in the Bi-State model calibration period.

All characteristics of the model that affect the calculation of ground water pumping effects on the hydraulically connected surface water bodies were unchanged in this work. The specific modifications to the data files needed to determine changes in Spokane River gains and losses for individual wells is described in Appendix A.

CHAPTER 5 EVALUATION OF MODEL APPLICATION AT SMALL TIME AND SPACE SCALES

The Bi-State SVRP model was constructed with a finite-difference grid interval of $\frac{1}{4}$ mile by $\frac{1}{4}$ mile. Although this results in more than 5,000 active model cells, the grid spacing can misrepresent distances between wells and the Spokane River when the wells of interest are in close proximity to the river. The model was also calibrated by Hsieh and others (2007) to monthly increments of water level, river gain and loss, and recharge and pumping data. Daily time increments are needed in this application to evaluate short term responses of the Spokane River to changes in groundwater pumping. Use of daily time increments is an application of the model beyond the scale of its calibration. A perfect model should perform correctly at any time scale. However, errors and approximations in model development and parameterization have unknown impacts at scales outside of those used in calibration.

The two above concerns resulted in efforts to determine the degree to which model predications are impacted by application to smaller space and time scales than used in its development. The evaluation was performed by a) comparing hourly and daily simulation results to field data obtained by the Washington Department of Ecology (WDOE) in their “Six-Minute Study”, and b) by comparing results of the Bi-State Model to a comparable simulation by a finite-element model with much denser node spacing. These two evaluations are described in more detail below.

Six-Minute Study Analysis

The data base for the WDOE Six-Minute study consists of data logger readings from 51 wells and 5 river stations (Covert, 2014). All of the sites were in Washington with north-south transects along Idaho Road just west of the state boundary near where the river is perched above the aquifer and along Sullivan Road in an area of major ground-water discharge to the river. The data loggers at all sites obtained readings every six minutes or 240 readings per day.

The Bi-State aquifer model was used in an attempt to replicate the aquifer water level changes that resulted from a change in stage in the Spokane River resulting from opening of the gates at the Post Falls dam in September of 2005. The depth of stage change varied as the effect propagated down the Spokane River and that variation was approximated as input to the model. Hourly stress periods were used to replicate the stage change and simulate changes in aquifer head in 24 selected wells that resulted from the stage change. All other simulated recharge and discharge was treated as time-constant to assure that all simulated water level changes at the approximate well locations (to the nearest $\frac{1}{4}$ mile spaced nodes) was only caused by the change in modeled river

stage. A more detailed description of the simulation conditions is provided in Appendix B.

Simulated water level changes in the wells were graphically compared to observed water level changes for a period of 10 days. The results are presented for all 24 wells in Appendix B. The match between simulated and observed heads varied substantially among the wells. The fit was determined as “good” in the authors’ judgment in about 45% of the well locations. In about 30% of the locations the fit was judged as “fair”, and in about 25% of the wells the fit was considered “poor”. A more explicit definition of the rating scheme is provided in Appendix B. The locations of poor model fits tended to be in the upper portion of the reach where the river is perched and continuously losing water. This is reasonable because the head change near this reach is related to the rate of river losses and river losses are affected by the river width which changes with stage, but was represented as constant in the simulation. Overall, the Bi-State model was judged to be adequate to provide assessments of ground water pumping effects on the river. This conclusion includes consideration of both time and space scale issues since wells and the river were only represented to the nearest model node point.

In only 7 of the 24 well locations did the model overestimate the head change resulting from the change in the stage of the river. In the other 17 locations the model underestimated. This indicates that the model likely is biased to underestimate river responses (i.e. responses may be more rapid than simulated) from pumping at locations relatively near the river.

Comparison to the SAJB Finite Element Model

A finite element aquifer model of the Washington portion of the SVRP aquifer was originally developed for the purpose of assessing source water protection areas for community water supplies. Recently an expanded version of the model has been applied to evaluate the effects of pumping individual wells on the Spokane River (Porcello, 2014). The evaluation of pumping effects was performed for the Spokane Aquifer Joint Board (SAJB) which is comprised of 21 water purveyors in the Washington portion of the aquifer. This application of the finite element (SAJB) model is documented at <http://www.spokaneaquifer.org/wp-content/uploads/2014/05/SAJB-GSI-Presentation-04-24-2014-1-slide-per-page.pdf>.

The SAJB model differs from the Bi-State model in many ways. Most notable is the fact that the SAJB model employs a proprietary finite-element code (MicroFEM) that allows more flexibility in model node spacing than the rectangular grid used in the Bi-State model. The grid spacing in the SAJB model is highly variable and in key areas of interest the grid spacing is much less than the ¼ square grid used in the Bi-State Model (Figure 5-1). This greater grid density allows the model to more closely approximate the configuration of the river and the true distance between wells and the Spokane River. Distance is one of the important factors controlling the quickness of the response of the river to well pumping. The greater grid density does not, however, imply that spatial variability in aquifer properties is defined to a higher degree. Even in the coarser grid of the Bi-State model, aquifer properties such as transmissivity and storativity are represented as uniform across groups of many grid cells (zones) because present knowledge and data are insufficient to refine the distribution of these estimates. In most

areas, the uncalibrated SAJB model has assumed aquifer properties similar to those of the calibrated Bi-State model (Porcello, verbal communication, 2014).

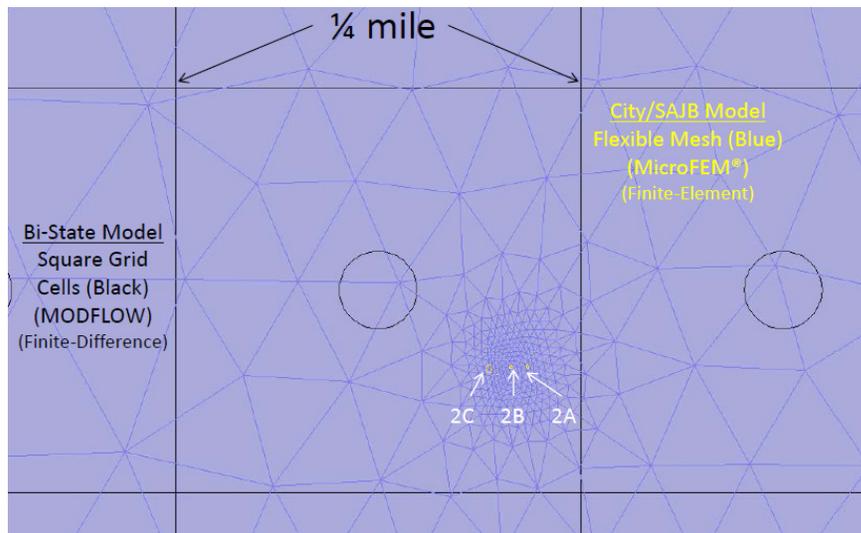


Figure 5-1 SVRP models finite-element mesh and finite-difference grid (from Porcello, 2014)

The Bi-State model and the SAJB model were developed somewhat independently and contain different features and representations of the real system. Results of both models are only approximations to the responses of the real system. Comparison of their results can provide a subjective understanding of the reliability of the models. In cases where the model results compare well, one gains a greater confidence in the reliability of both models. One or both models may be questioned in cases where model results differ. The cursory analysis presented here is for a single scenario evaluating aquifer pumping effects on the Spokane River.

The spreadsheet tools developed using the Bi-State model were used to replicate a scenario evaluated using the SAJB model and presented by Porcello (2014). That scenario involved moving part of the pumping rate from one well in the Irvin Water District to a second well in the District that was farther from the Spokane River. John Porcello of GSI Water Solutions assisted in the translation of the SAJB simulation data to the Bi-State model based spreadsheet. In this scenario, pumping was transferred from well 48 to well 39 in the spreadsheet. The transferred pumping rate was simulated as the following: 0.12 cfs in June, 0.34 cfs in July, and 0.29 cfs in August and zero at all other times. SAJB model results for this scenario are presented in Figure 5-2 as red and blue lines (representing a range of aquifer properties); the results from the Bi-State model spreadsheet are superimposed on the same figure as a black line. The simulation performed with the SAJB model repeated the transfer each year for multiple years, and two annual cycles of the effects are presented. The Bi-State model simulation was limited to a period of 180 days and the results are superimposed on the graph of the GSI model response at the appropriate time period (Figure 5-2).

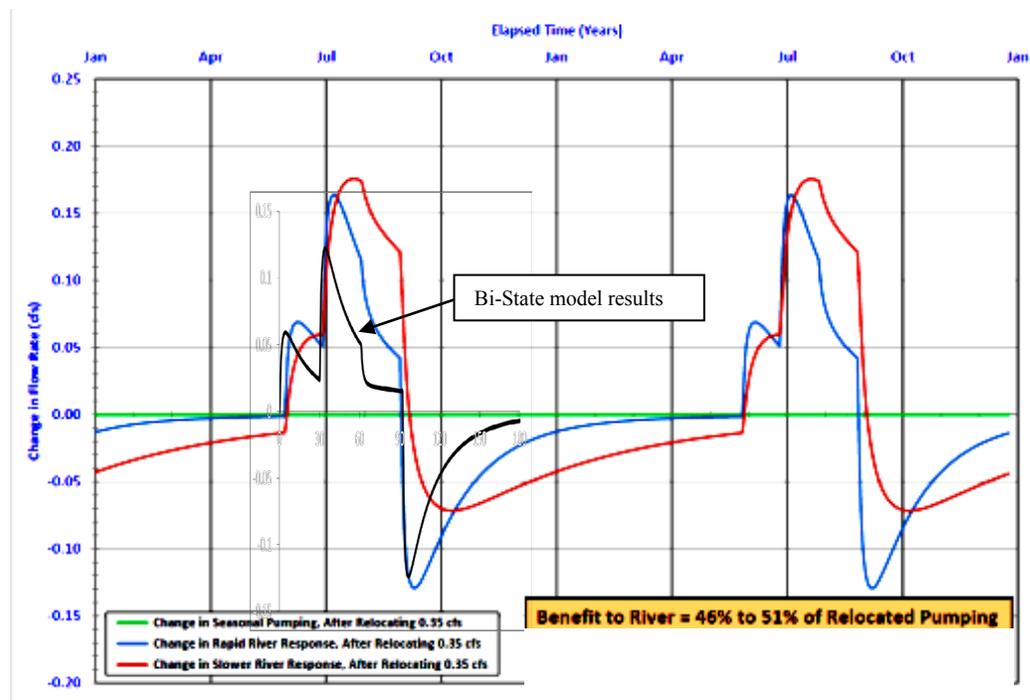


Figure 5-2 Simulation results of moving pumping in Irvin Water District (after Porcello, 2014)

The results of the transfer of pumping on the Spokane River show a benefit (increased river gain) during the months of the shift in pumping followed by a depletion of the river in the following months. Both models predict this response. The magnitude of the beneficial impact is somewhat greater with the SAJB model, but the depletion effects extend over greater time periods than exhibited with the Bi-State model. This response would be expected if the river connection at the receiving well (pumping shifted to this location) is more dampened in the SAJB model. This may be due to differences between the models in representation of distances, river properties, or aquifer properties. The relatively similar river responses, both in magnitude and in timing, predicted by the two models is reassuring and adds to the confidence in use of both of these models to provide evaluation of aquifer pumping effects on the Spokane River at the time and distance scales used in this project.

CHAPTER 6 –SPREADSHEET TOOL UTILIZING THE BI-STATE AQUIFER MODEL

Spreadsheet Description

A spreadsheet was developed following the work of Taylor and others (2007) to allow water users and water purveyors in the SVRP aquifer to estimate changes in flow of the Spokane River on a daily basis that would result from alternative aquifer pumping schemes. The spreadsheet provides the opportunity to develop a common and hydrologically sound understanding of impacts from ground-water pumping among conflicting groups of water users. The water users may experiment with the spreadsheet individually or in group settings. The spreadsheet provides an avenue for a broad

audience to utilize the technical capabilities of the Bi-State Aquifer Model without having any modeling expertise.

The spreadsheet is designed to estimate *changes* in the flow of the Spokane River resulting from *changes* in ground water pumping rates at any of 131 locations where there are existing or proposed public supply wells. For example, the spreadsheet can be used to evaluate the effects of ceasing or reducing pumping at a specific location for a selected period of time. The results would portray the difference in Spokane River discharge at the Spokane gage that would result from changing from full discharge to no discharge or reduced discharge. Similarly, if there was interest in increasing pumping by 20% at a given well, then the “pumping rate” should be set at a value equal to 20% of the previous pumping rate. The corresponding results would show the change in Spokane River flow resulting from the increase (not the total effect of pumping). The sign convention used in the spreadsheet is that decreased pumping is expressed as a positive pumping rate and increased ground water extraction is expressed as negative pumping values. The effects of changes in pumping at as many as 10 wells can be evaluated simultaneously. The spreadsheet also determines the net or total effect of the wells that are used in the analysis.

The spreadsheet is specifically designed to aid evaluation of mitigation alternatives for low-flow periods of a few weeks duration in the Spokane River at the Spokane gage. It is anticipated that alternative aquifer pumping schemes would be of one month duration or less because the low-flow problem only exists for a few weeks to a month and does not occur every year. Consequently, the spreadsheet provides the opportunity to evaluate changes in pumping rate over different periods of time ranging from 1 to 180 days. A pumping rate may be entered for every day during a 180 day period. That rate may be constant from day to day, or may vary according the scheme proposed by the user. The spreadsheet provides an estimate of the resulting changes in river flow at the Spokane gage for each day in the 180 day period and displays the results in graphical form.

Spreadsheet Use

The five tabs on the spreadsheet are titled as follows: 1) explanation, 2) well map, 3) well description, 4) river effect graph (mgd) and 5) river effect graph (cfs). Spreadsheet users can select from one to ten well locations based on identification numbers shown on the well map (Figure 6-1). The owner/operator of the well can be determined from the well description tab.

The two wells circled on Figure 6-1 (#57 and #62) are owned by Consolidated Irrigation District #1 and Vera Irrigation District #15 respectively and are used as a demonstration of the spreadsheet. Well #57 is located near a reach of the river that is hydraulically connected to the river. Well #62 is located along the southern edge of the aquifer in the same general portion of Spokane Valley. The data entry formats are explained within the spreadsheet and in a narrated power point presentation available on-line at the Idaho Department of Water Resources. Figure 6-2 shows the pumping data entry for decreasing the pumping from well #57 by 10 mgd for 20 days and increasing the pumping from well #62 by the same amount and time period. The impacts on the Spokane River at the Spokane gage are displayed in graphical form on Figure 6-3. The

results are shown for changes in pumping rate at the two well locations. The collective change in pumping rate (zero) is shown by the dashed green line, and the changes in river flow resulting from each of the wells are shown as red and solid green colored lines. The heavy black line shows the net change in flow of the Spokane River at the Spokane gage from changes in pumping in the two wells. Negative values represent depletion of river flow; positive values indicate an increase in Spokane River flow at the Spokane gage.

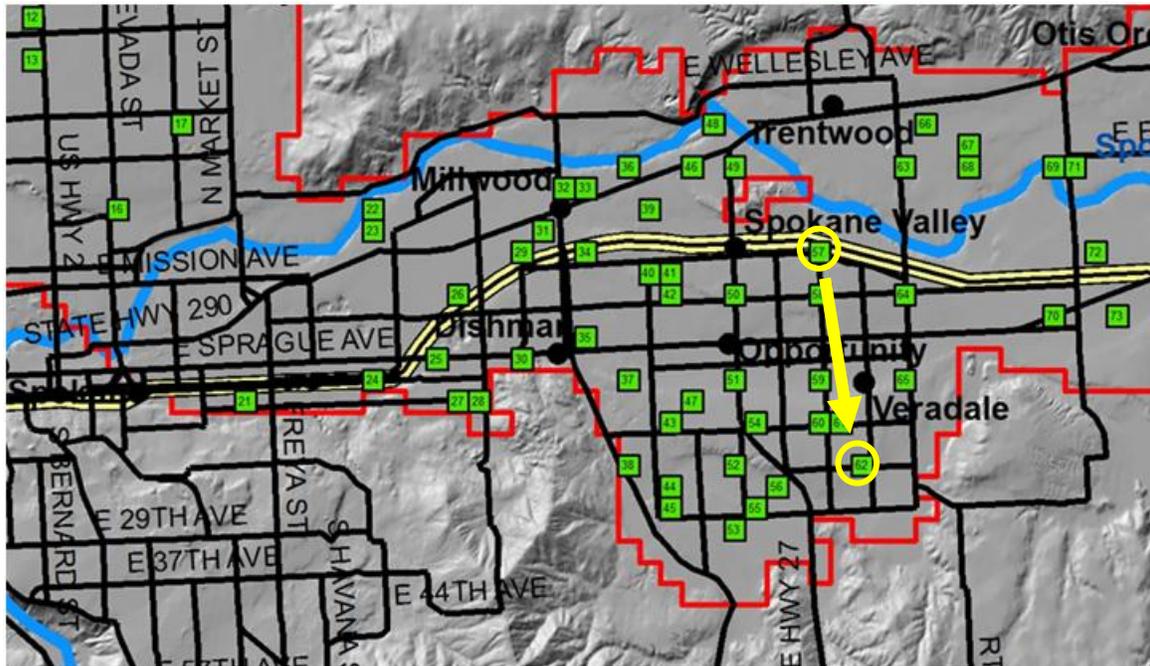


Figure 6-1 Map of wells within the spreadsheet

The graph in Figure 6-3 shows that the river flow increases (black line) from 0 to 20 days because the effects from reduced pumping from well #57 (red line) are greater than the effects of increased pumping in well #62 (green line). The river has reduced flow in the period from 20 to about 100 days because of the time lag effects from well #62. The net impact from this action is beneficial if the extreme low-flow period in the river is during the 20 days of changed pumping patterns.

The spreadsheet integrates capabilities of the Bi-State aquifer model by including a generic form of model results (response functions) for each of the 131 specific well locations. The response functions express the percent or proportion of aquifer pumping that appears as depletion of Spokane River flow above the Spokane gage. The proportion changes over time and with location. The response function array (180 days by 131 pumping locations), determined by a series of Bi-State Aquifer model runs, is incorporated into the spreadsheet. That array of values cannot be altered by users. A more complete description of response functions can be found in Cosgrove and Johnson (2004), and more detail on the development of the response functions for this project is provided in Appendix A.

Reduction in Daily Pumpage (mgd)							
Location	57	62	0	0	0	0	0
System	Consolidated Irrigation Distric	Vera Irrigation District #15	NOT USED				
Well	NA	Well 4	NOT USED				
Day							
1	10	-10	0	0	0	0	0
2	10	-10	0	0	0	0	0
3	10	-10	0	0	0	0	0
4	10	-10	0	0	0	0	0
5	10	-10	0	0	0	0	0
6	10	-10	0	0	0	0	0
7	10	-10	0	0	0	0	0
8	10	-10	0	0	0	0	0
9	10	-10	0	0	0	0	0
10	10	-10	0	0	0	0	0
11	10	-10	0	0	0	0	0
12	10	-10	0	0	0	0	0
13	10	-10	0	0	0	0	0
14	10	-10	0	0	0	0	0
15	10	-10	0	0	0	0	0
16	10	-10	0	0	0	0	0
17	10	-10	0	0	0	0	0
18	10	-10	0	0	0	0	0
19	10	-10	0	0	0	0	0
20	10	-10	0	0	0	0	0
21	0	0	0	0	0	0	0

Figure 6-2 Example pumping data entry

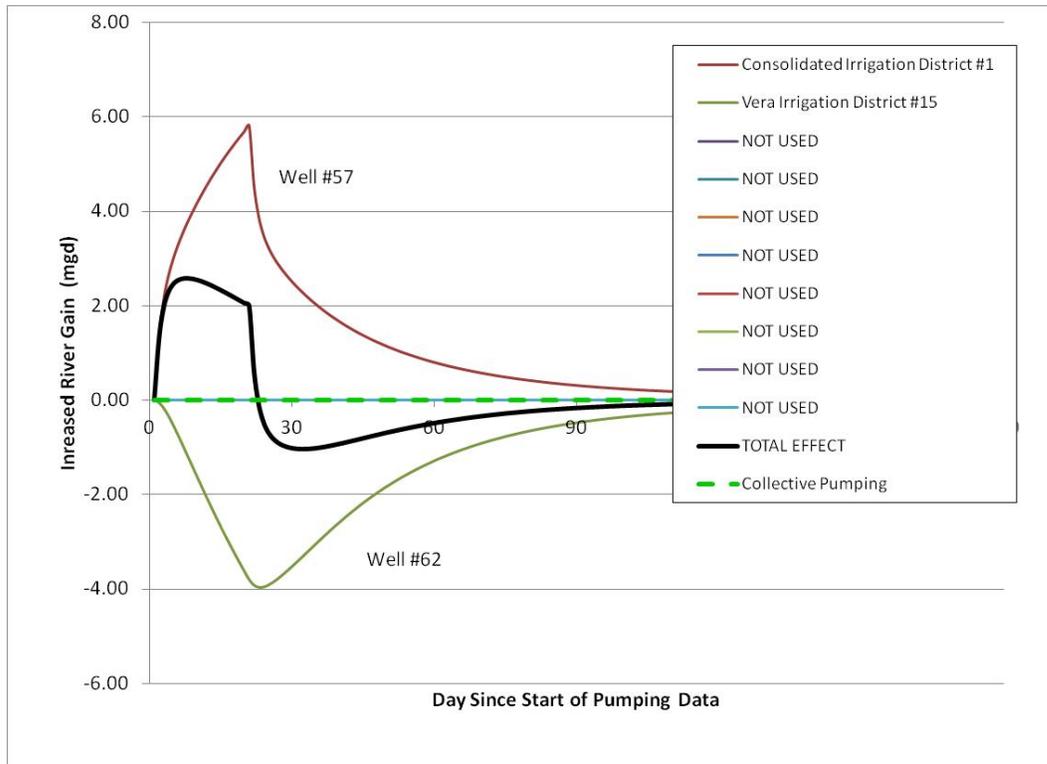


Figure 6-3 Results from the spreadsheet for changes in pumping at the two well locations

CHAPTER 7 – RIVER FLOW IMPACTS FROM DECREASED PUMPING AND ALTERNATIVE WELL LOCATION SCENARIOS

Introduction

The purpose of this project is to evaluate the feasibility of utilizing alternative ground-water pumping schemes from the SVRP aquifer in Washington and Idaho to reduce the severity of short-term low flow events in the Spokane River as measured at the Spokane gage. Selection of the alternative ground-water pumping scenarios was based on the following hydraulic characteristics of the river/aquifer system: 1) wells near the hydraulically connected reach of the river have the fastest response with the greatest percentage impact on the river; 2) wells more distant from the hydraulically connected reach of the river have a more delayed response with a smaller percentage impact on the river; and 3) the problem of low flow in the river is short duration from a few days to a month. The scenario selection was also based on the assumption that short-term solutions should be used since the critical low-flow periods in the river are usually of short-term duration (one to five weeks).

Two alternative ground-water pumping approaches are addressed in this section of the report: 1) reduction in pumping quantities from wells selected based on their hydraulic impact on river flow; and 2) transfer pumping demand from wells that are near the reach of the river that is hydraulically connected to the aquifer to wells that are more distant from this reach. Both approaches are designed to achieve greater flow in the Spokane River as measured at the Spokane gage during critical low flow periods.

Analysis of alternative scenarios within the two approaches is based on river/aquifer hydraulics without consideration of legal, physical, economic and social constraints. The dominant disregarded legal constraint is selection of wells based on impact on river flow rather than application of the prior appropriation doctrine (first in time in first in right) either within one state or between states. The primary physical constraint is the lack of infrastructure (predominantly pipelines) for transferring water from an alternative well located away from the river to the water distribution system supplied by the original well located near the river. Economic constraints include funding for necessary distribution system modifications that would be needed for the water-supply transfer approach. The social constraints include acceptance by water users of reduced water supply during critical landscape demand periods in order to increase river flow.

Approach #1 Reduction in Pumping Quantities

The spreadsheet interface to the Bi-State model facilitates assessing the magnitude and timing of impacts on the flow of the Spokane River at the Spokane gage from individual wells (on a node by node basis). Each node has a unique response function and thus a unique pattern of impact on the river. Wells within nodes nearer the hydraulically reaches of the river have a higher percent impact on river flow than more distant wells.

One scenario is presented for reduction of pumping based on impact on river flow. The scenario was developed in the following steps.

- First, a tabular list was created of the percent depletion of the river after 30 days

for the nodes where the 131 wells included in the spreadsheet are located. The 30-day period was selected because it best represents the length of time of critical low flow within the river.

- Second, the difference between average summer pumping rate (July-Sept) and average winter pumping rate (Dec-Feb) was selected as the amount of withdrawal reduction for this scenario. This effectively means the reduction of pumping is approximately equivalent to a ban of outside water use. Monthly pumpage data for both summer and winter months were obtained from input files used for calibration of the Bi-State model. These data were compiled for use in the spreadsheet as input to calculate the benefit to the river after 30 days. Response functions from the spreadsheet were used to calculate river depletion for all of the 131 wells in the spreadsheet. Fourth, the list was sorted based on the percent depletion after 30 days with the greatest percent impact at the top of the list and the least percent at the bottom of the list.
- Fifth, a plot of cumulative river depletion versus percent of pumping appearing as river depletion after 30 days was prepared (Figure 7-1). Each data point on the plot represents a node. Each node includes one to several wells.

The first data point on Figure 7-1 represents a node that includes several wells that are located adjacent to the Spokane River in the reach where the aquifer is hydraulically connected to the river. The node has about 92 percent impact on the river after 30 days. The benefit to the river from a reduction from summer to winter pumping rates at this node is about 10 cfs. The cumulative benefit of pumping reduction from wells represented by the first four nodes is about 80 cfs. The “stair step” pattern of data points on Figure 7-1 reflects the locations of wells and the differences between summer and winter pumping rates for these wells. Including wells in the pumping reduction program that have 40 percent or greater impact on the river after 30 days would result in an increased flow in the river of about 135 cfs. Including all 131 wells would do little to further increase river flow as the maximum cumulative impact is only slightly more than 140 cfs. Figure 7-2 shows the locations of the wells that would be included in this pumping reduction program. The graph presented in Figure 7-1 could be used to select the scope of pumping reductions that would be needed to meet a selected mitigation target.

The alternative approach relative to reduction of pumpage is to select wells based on priority under the appropriation doctrine of first in time is first in right. This alternative was considered but not included in the study for several reasons: 1) lack of water right information since water right adjudications have not been completed in either Washington or Idaho (an adjudication in Idaho is underway but not completed at the time of this report); and 2) the work is beyond the scope of this project.

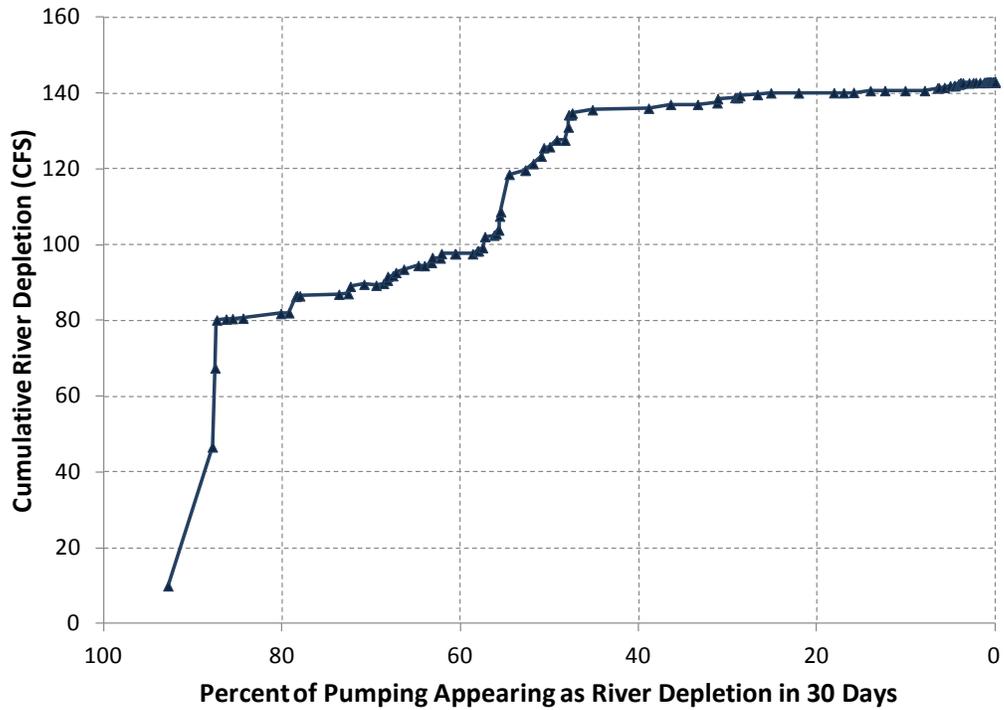


Figure 7-1 Plot of cumulative river depletion resulting from reduction from summer to winter pumping rates versus the percent of pumping appearing as river depletion after 30 days

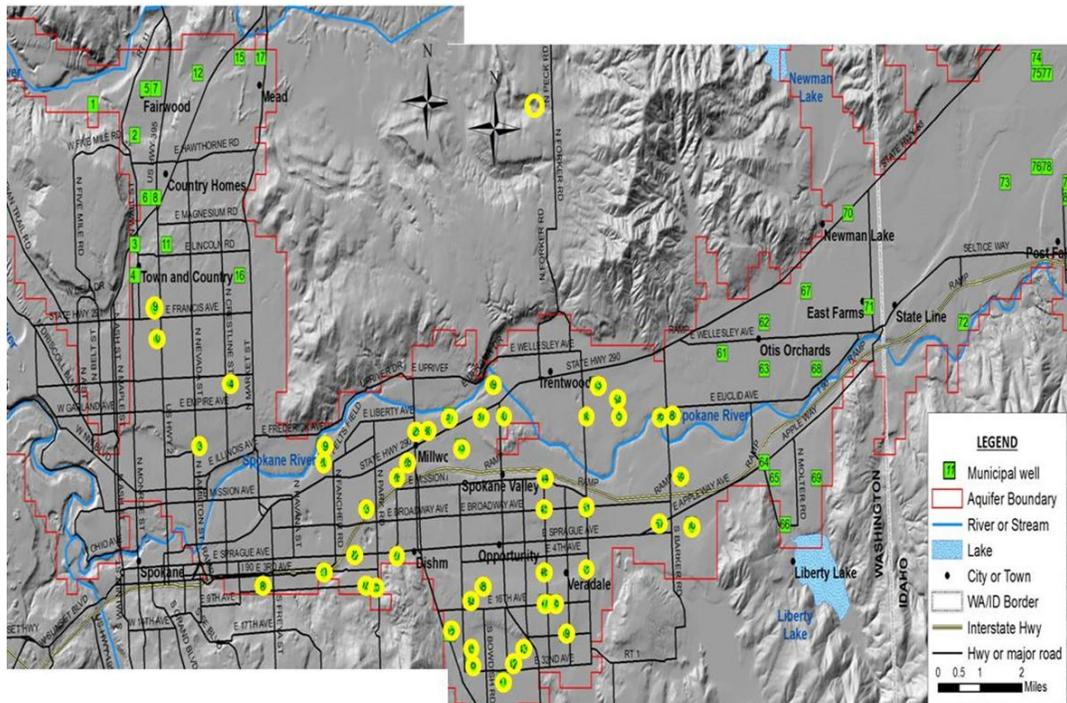


Figure 7-2 Locations of wells that have a 40 percent or greater impact on the Spokane River at the Spokane gage (yellow circled locations)

Approach #2 Transfer Withdrawal Locations

The second approach is to maintain pumping amounts but transfer withdrawal locations from wells near the hydraulically connected reach of the river to more distant locations. The change in withdrawal location alters the timing and magnitude of impacts on the river and has the potential to benefit river flows during critical time periods. Five scenarios are included in this analysis. The locations of the wells and the amount of the transfers were selected to illustrate how the river/aquifer systems function and are not recommendations for implementation.

- Scenario 2-1 -- Transfer in Washington; both wells are part of the same water district with some existing infrastructure
- Scenarios 2-2 and 2-3 -- Transfer in Washington; pumping locations are not connected by existing infrastructure
- Scenarios 2-4 and 2-5 -- Transfer across the state line; pumping locations are not connected by existing infrastructure

All of the scenarios represent theoretical changes in pumping amounts with no consideration of the characteristics of the existing wells and the demands on the associated water systems. Names of water purveyors are shown but they have not been involved with the data analysis or interpretation. The pumping rate of 10 mgd was selected so that the results, although labeled as mgd, also can be readily converted to the percentage of pumping change that appears in river flow.

Scenario 2-1 The first scenario involves transferring pumping from a well located near the east end of the reach of the river that is hydraulically connected to the aquifer to a second well located about 2.5 miles farther to the east. Both wells are operated by Consolidated Irrigation District #1. This analysis did not consider the characteristics of the pipeline network within the district and the degree to which this transfer is feasible.

In this example, one month of pumping at 10 mgd is shifted from well 69 to well 76 (Figure 7-3). In the spreadsheet, the transferred pumping rates were entered in as positive values in well 69 and as negative values in well 76 resulting in no net change in overall pumping. The spreadsheet results are displayed in Figure 7-4. The dashed green line which represents the net change in pumping rate (considering both wells) is continuously zero. The changes in river flow at the Spokane Gage resulting from the pumping changes at the well 69 and well 76 are shown by the patterns of the red and olive green lines, respectively. The reduced pumping at well 69 produces a positive flow benefit in the river while the increased extraction at well 76 results in reduced flow in the river. The net change in river flow from both actions, represented by the black line, is positive during the transfer period which means that there would be additional flow in the river, relative to what would have occurred if the transfer did not take place.

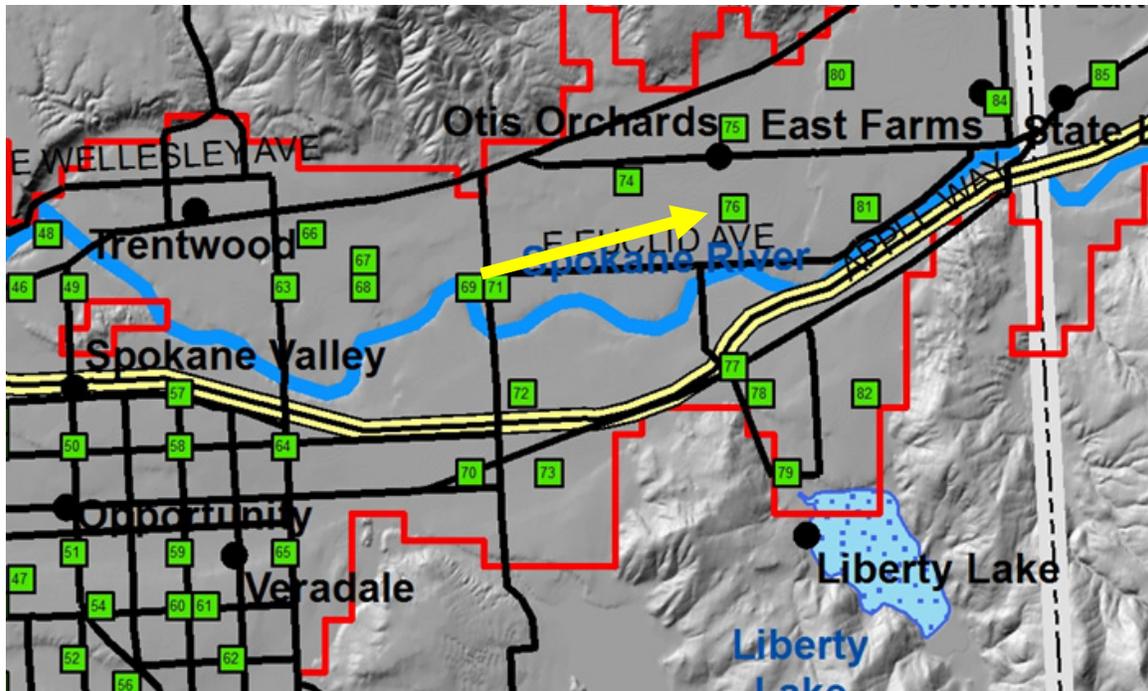


Figure 7-3 Map showing well locations 69 and 76 in the Consolidated Irrigation District #1 example transfer scenario

The pumping conditions revert to the original situation after the transfer period of 30 days. This is represented in the input by entering values of zero for all days after day 30. Despite pumping conditions returning to the original rate, there is a residual effect from the completed transfer. The black line shows a flow benefit to the river for an additional 15 days but an adverse impact on the river from about 45 days through the end of the 180-day analysis. This transfer scenario would have helped river flow if it was timed to coincide with the low-flow period. The negative aspects of this transfer would not be important if the delayed decrease in river flow coincided with greater river flow associated with increased discharge from Post Falls Dam after the end of the critical low-flow period.

This pumping transfer scenario demonstrates some important points.

- The benefit to the river of a transfer of pumping depends on the distance of each well to the river where it is hydraulically connected to the aquifer. Well 69 is located adjacent to a reach of the river that is hydraulically connected to the aquifer whereas well 76 is north of the river where it is perched above the aquifer.
- Typically a transfer from a well near the river to a well more distant from the river will result in a temporary increase in river flow followed by a temporary decrease in river flow. The duration of these periods depends on the duration of the transfer and upon the distance of the wells from the hydraulically connected section of the river. The timing of the increased flow must be synchronized with the occurrence of low river flow in order to provide a meaningful benefit for low periods in the river.

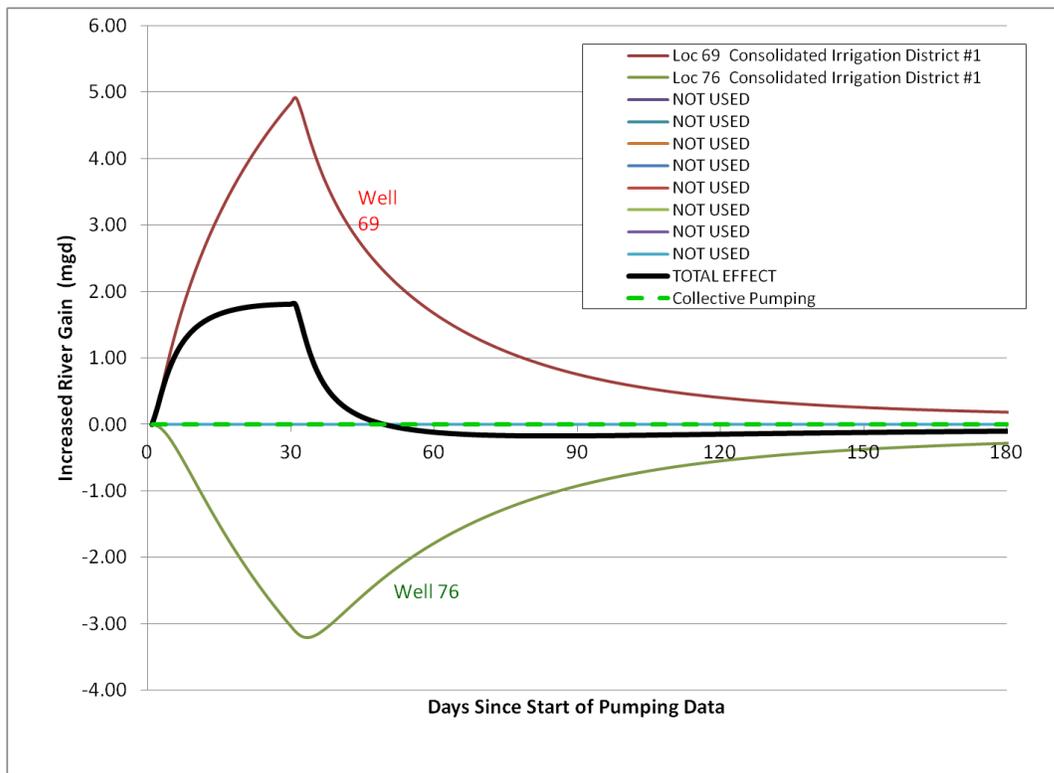


Figure 7-4 Spreadsheet estimated impacts on the Spokane River from Consolidated Irrigation District #1 pumping relocation

The following scenarios involve pumping transfers that are not located within a single existing water supply network; construction of new pipelines would be required. The locations of the wells and the amount of the transfers were selected to illustrate how the river/aquifer systems function and are not recommendations for implementation.

Scenario 2-2 In this example, pumping at well 22, which is located near the hydraulically connected section of the Spokane River, is decreased by 10 mgd and the water demand is satisfied by an equivalent increase in pumping at well 84 (Figure 7-5). The change in pumping rate is simulated for a period of one month, after which pumping returns to the previous condition. A pumping shift from well 22 to well 84 moves the transferred pumping about 13 miles to the east. Both wells are within Washington but serve different communities. A pipeline would need to be constructed for this transfer scenario to occur.

The red line in Figure 7-6 represents the spreadsheet estimated increase in Spokane River flow at the Spokane gage resulting from 10 mgd of reduced ground water extraction from well 22 for 30 days. The solid olive green line shows the decrease in Spokane River flow resulting from 10 mgd of increased extraction at well 84 for the same 30-day period. The effects of increased pumping at well 84 are smaller in magnitude and lagged in time because of the greater distance to the hydraulically connected reach of the river. The black line shows that the net effect is an increase in flow at the Spokane gage

of about 7 mgd after about 30 days. The increase in river flow diminishes rapidly once

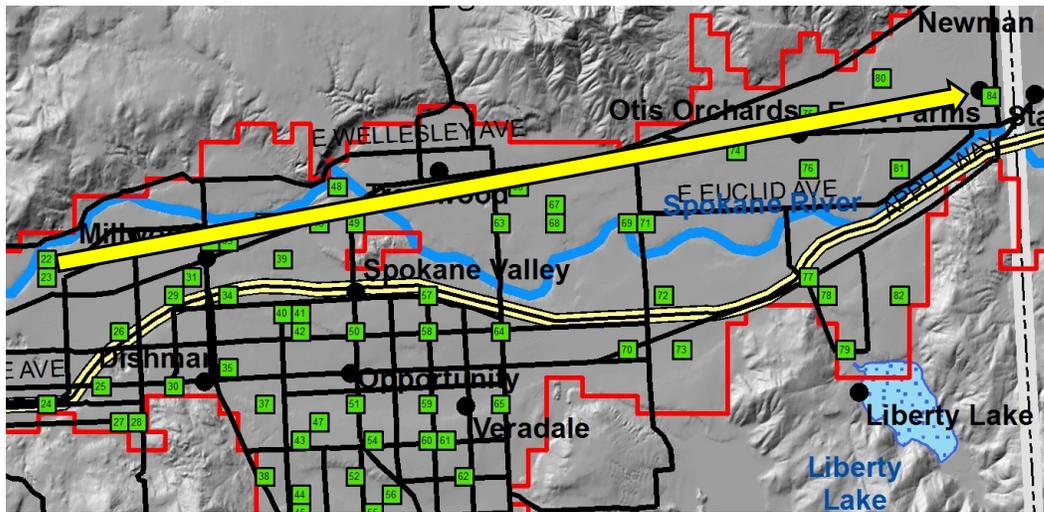


Figure 7-5 Map showing the location of wells 22 and 84 in the example transfer scenario

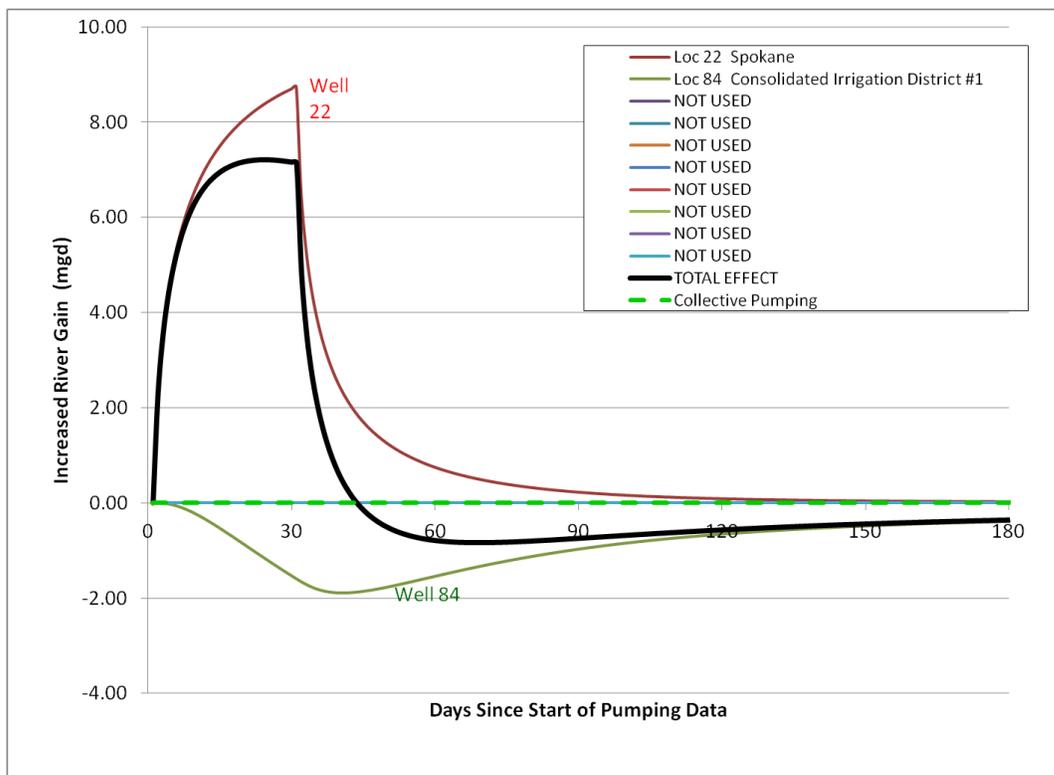


Figure 7-6 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd for 30 days from well 22 to well 84

the original pumping regime returns (after 30 days). After about 45 days, the transfer has a depleting effect on the river which continues to beyond the end of the analysis at 180 days. Again, this mitigation program has benefit if the increased river flow occurs during the critical low-flow period and the period of decreased river flow occurs later in the fall

when discharge from the Post Falls dam is greater. If infrastructure and agreement issues can be resolved, such a transfer could become part of a larger scheme to mitigate periods of extreme low flow in the river.

Scenario 2-3 This scenario is similar to scenario 2-2 except the pumping shift is from well 22 to well 3 as shown in Figure 7-7. Again, an arbitrary pumping rate of 10 mgd is shifted for the period of one month. Well 3 is a location for a proposed well in the Western Arm of the aquifer (John Covert, 2015). The Western Arm is largely hydraulically isolated from the main aquifer containing well 22 connected by only a narrow alluvial channel at Trinity Trough.

The spreadsheet estimated effects on the Spokane River above the Spokane gage from shifting well 22 pumping to well 3 are shown in Figure 7-8. The pumping at well 3 has no visible effect on the Spokane River above the Spokane gage due to the aquifer constriction at Trinity Trough. The effects of increasing pumping at well 3 are likely will impact the Spokane River below the Spokane gage. The plotted red dashed line in Figure 7-8 which represents a decrease in pumping at Well 22 lies under the black line representing the total effect. The spreadsheet estimates that after 30 days of reduced pumping, the increase in Spokane River flow at the Spokane gage is between 8.5 and 9 mgd. The transfer of pumping from well 22 to well 3 results in a shift in the effects on the Spokane River from above to below the Spokane gage. This may or may not be desirable depending on the objectives of the pumping management program.

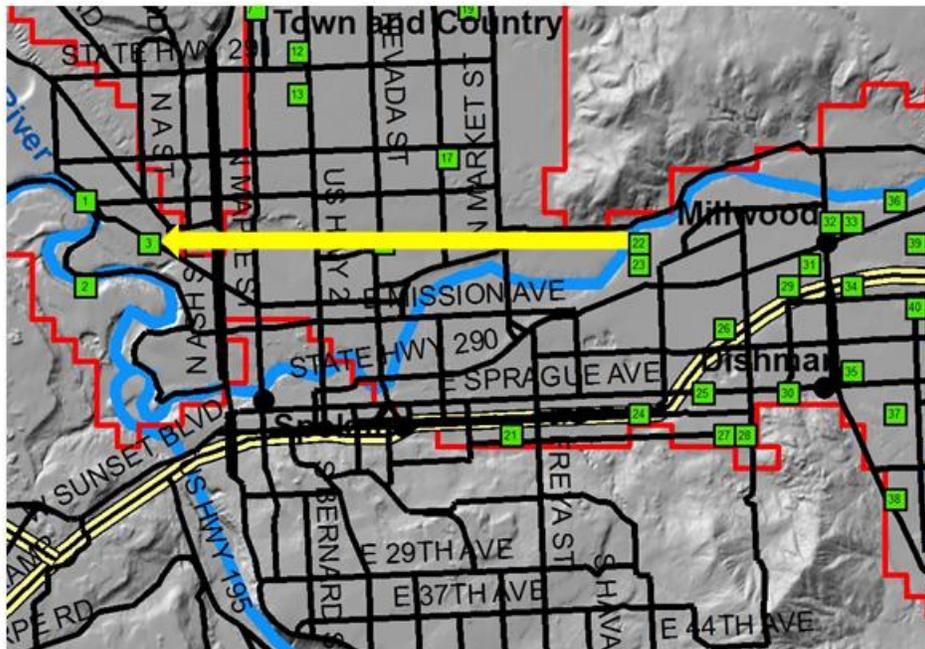


Figure 7-7 Map showing Well 22 and Well 3 in the example transfer

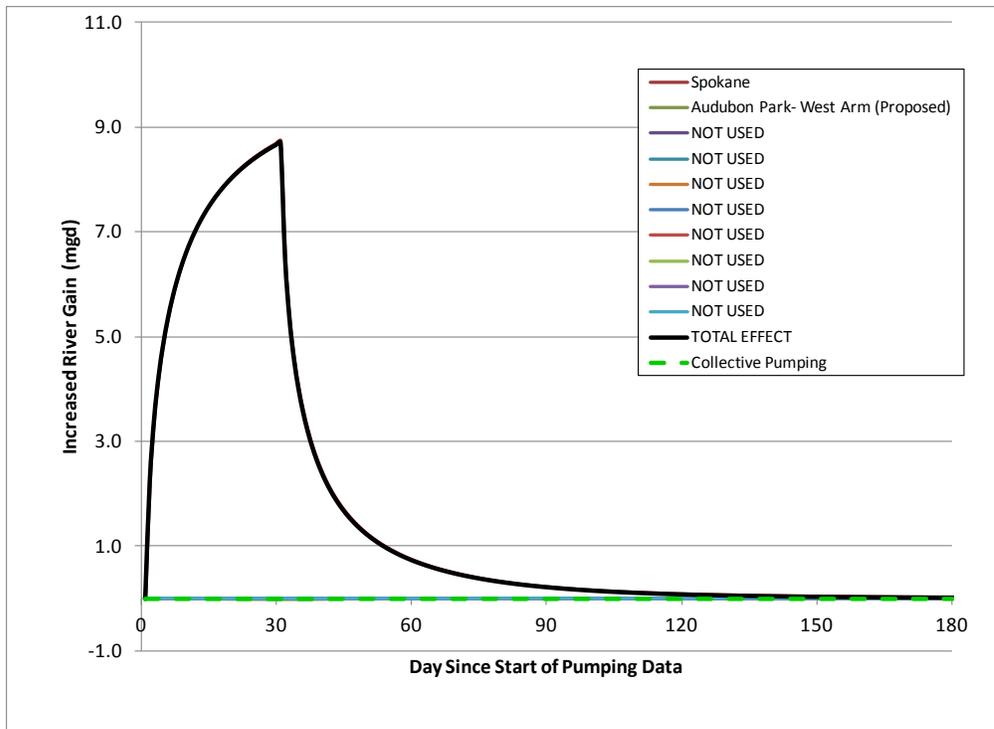


Figure 7-8 Spreadsheet estimated effect on flow of the Spokane River at the Spokane gage from shifting 10 mgd for 30 days from Well 22 to Well 3

Scenario 2-4 The maximum benefit from transferring pumping locations likely would occur by consideration of sites in Idaho. This example scenario describes a transfer of 10.0 mgd (arbitrarily selected rate) for 30 days from well 22 in Spokane to well 112 near Coeur d’Alene (Figure 7-9). In practice, such a water transfer across the state line

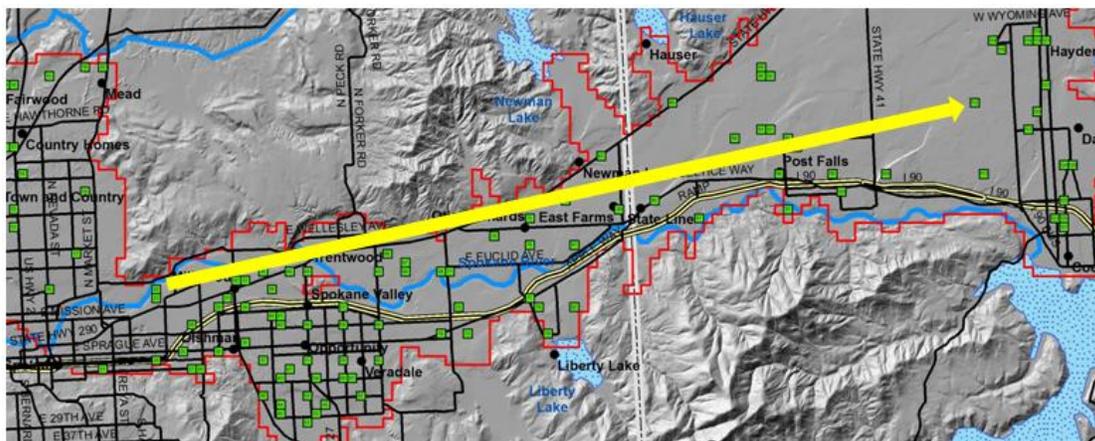


Figure 7-9 Map showing Well 22 and Well 112 in the example transfer scenario

would be legally complex. The transfer would also be very expensive because the pipeline to connect these two sites would be very long.

The spreadsheet estimated effects on flow of the Spokane River at Spokane of the example transfer are shown in Figure 7-10 for 180 days. The dashed green line remains at zero throughout the 180 day graphed period indicating no net change in aquifer

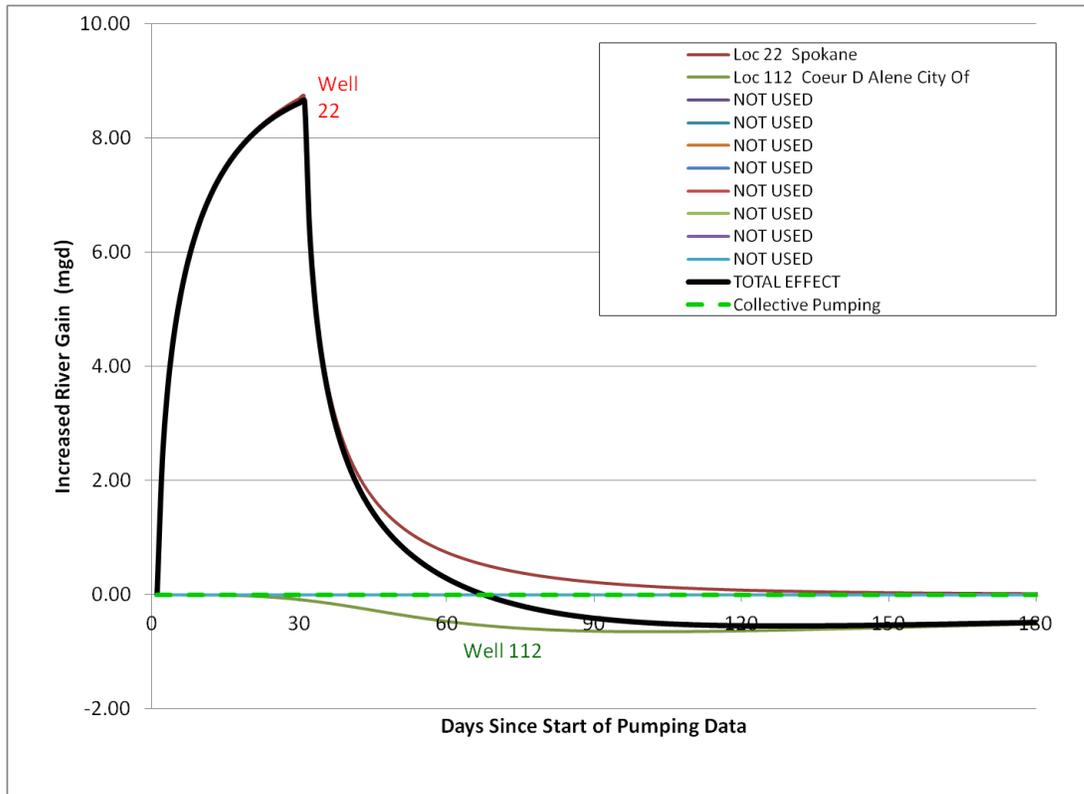


Figure 7-10 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd from well 22 to well 112

extraction. The red line represents the effect of decreased extraction at well 22 for 30 days. The effect of decreased extraction at well 22 causes an increase in flow of the Spokane River of 8.5 to 9.0 mgd after about one month. Following the peak, the benefit of that reduced extraction gradually recedes to zero. The effects of increased extraction at well 112 are shown by the olive green line. The peak reduction in the flow of the Spokane River caused by well 112 is a relatively small (0.5 to 1.0 mgd) and the peak does not occur until about 90 days after the start of the program. The effects of this 30 day increase in pumping in well 122 in Idaho will result in less flow in the Spokane River beyond the 180-day limit of the spreadsheet and may exceed one year. The net effect, illustrated by the black line is for a positive benefit (increased river flow) for about the first 70 days, after which the adverse consequences of the increased extraction at Well 112 dominate.

Scenario 2-5 A second example of an interstate transfer of pumping is less distant, but nearly as effective as scenario 2-4. This involves a pumping transfer from well 22 in Spokane to well 93 which is located north of Post Falls (Figure 7-11). This type of transfer again would involve the legal complications of an interstate move, but would be less costly than the previous alternative because of the smaller distance required for a pipeline.

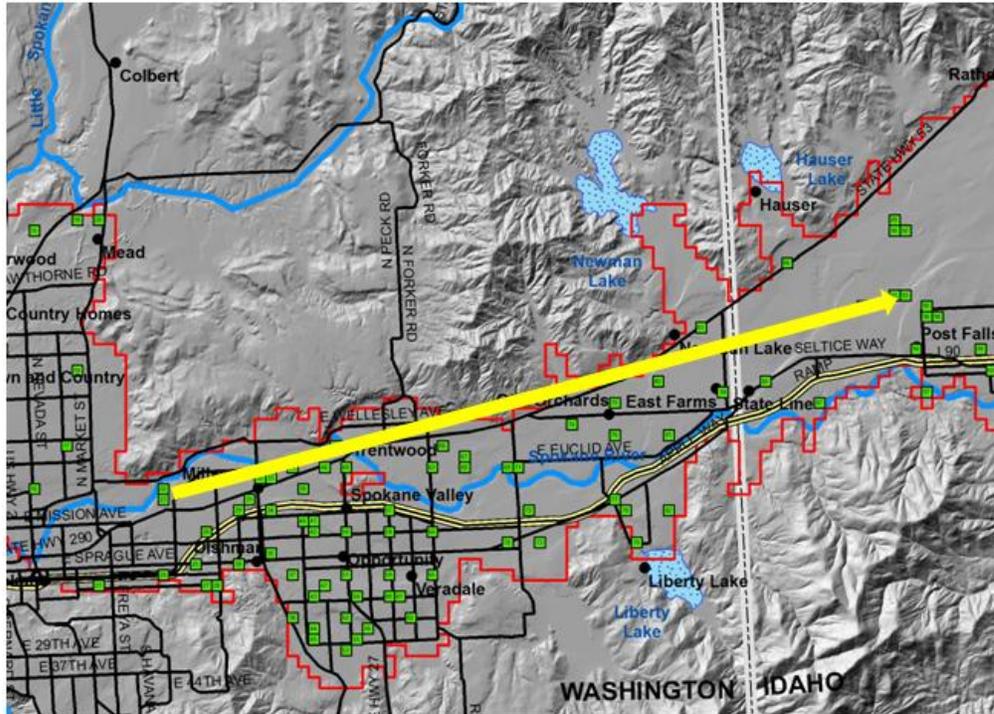


Figure 7-11 Map showing well 22 and well 93 in the example transfer scenario

The spreadsheet estimated effects on flow of the Spokane River at the Spokane gage of the transfer from well 22 to well 93 are similar to those of the previous example when transferring the greater distance to well 112 (Figure 7-12). The red line is identical to that of the previous example because again pumping is assumed to decrease by 10 mgd at well 22. In the first 30 or 40 days the net benefit, shown by the black line, is only slightly less than the effect of the reduced extraction at well 22. During this time, the effects of increased extraction at well 93 have not yet fully propagated to the hydraulically connected reach of river. The maximum net benefit appears to be 8.0 to 8.5 mgd after about 30 days of transfer. Again the depletion effects of increased extraction at well 93 continue beyond the 180 days of estimate provided by the spreadsheet.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The primary product of this project is the spreadsheet interface that allows ready access to the Bi-State model for analysis of pumping impacts on the Spokane River at the Spokane gage. The spreadsheet is user friendly and allows for input of increases in pumping (negative input values) or decreases in pumping (positive input values) for 131 well sites in the aquifer. The inputs can vary on a daily basis for a maximum of 180 days. Graphical outputs show the impact of each well on the river plus the sum of impacts from as many as ten wells.

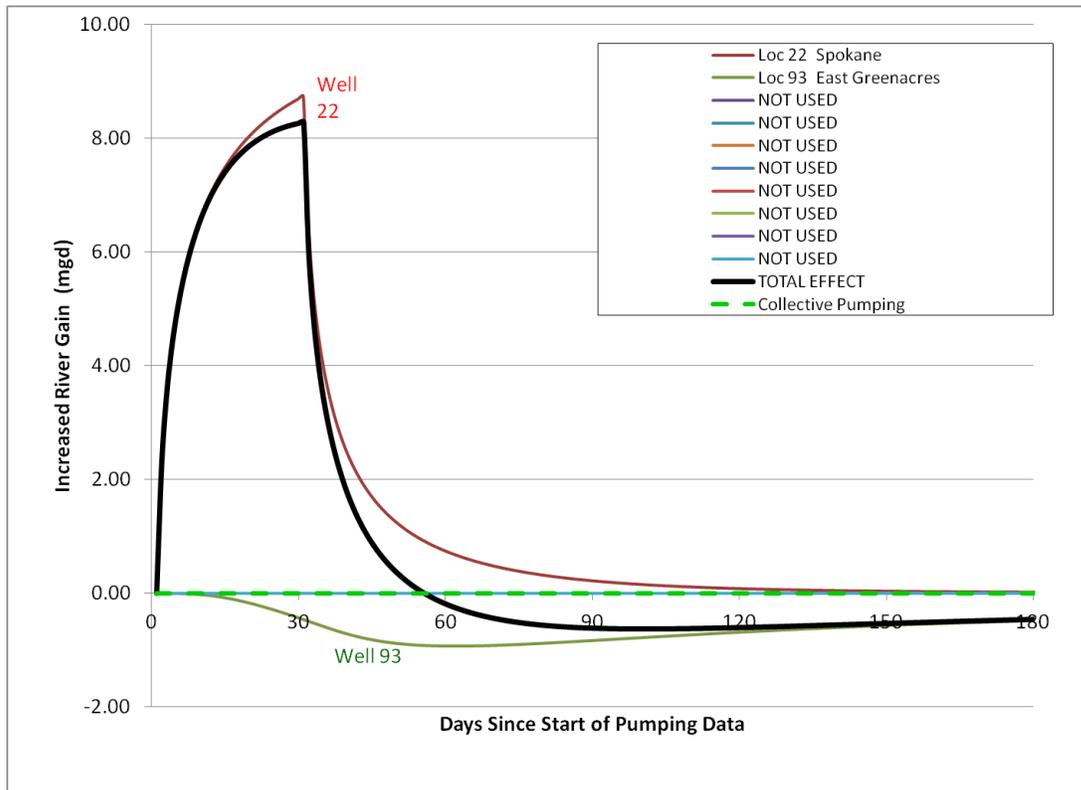


Figure 7-12 Spreadsheet estimated impacts on the Spokane River from shifting 10 mgd for 30 days from well 22 to well 93

The magnitude and timing of ground-water pumping impacts on the Spokane River at the Spokane gage are dependent mostly on the distance from the wells to the reach of the river that is hydraulically connected to the aquifer. The hydraulically connected reach starts west of the Greenacres gage in Washington and continues downstream with gaining and losing reaches to beyond the Spokane gage. Thus, production wells located in and near the cities of Spokane and Spokane Valley have a higher percentage and more immediate impact on the flow of the Spokane River than wells near the cities of Post Falls and Coeur d'Alene. The spreadsheet interface to the Bi-State model can be used to test this statement at any of the 131 sites where wells are located or planned.

The problem of low flow in the Spokane River at the Spokane gage typically occurs in late August and early September and is of short duration (a few days to a month). The two approaches to mitigate the low flow problem evaluated in this study are: 1) to reduce pumping in selected wells and 2) to relocate pumping from wells that have a rapid and large percentage impact on the river to wells more distant that have smaller and time-lagged impacts on river flow. The focus of both of these approaches was on identifying short-term solutions to the short-term problem of flow in the river. It is likely that neither of these approaches, by themselves, will resolve low flow conditions in all years. Either approach, however, may find application to partially mitigate low

flows or as part of a larger mitigation scheme.

Recommendations

The spreadsheet interface to the Bi-State model is intended to serve as the starting point for discussions of alternative approaches for water resource management for the SVRP aquifer and the Spokane River. We recommend that individuals and groups use the spreadsheet interface either independently or in collaborative settings to investigate a wide range of water resource management alternatives.

Advance knowledge of low-flow conditions is vital to successful implementation of mitigation procedures. Further work should be focused on methods for forecasting the occurrence of low-flow conditions.

The availability of water-resource data is important to development of alternative management approaches. Gaging stations on the Spokane River must continue to be maintained along with monitoring of ground-water levels in the aquifer in both states.

REFERENCES

Avista Utilities, 2014, www.avistautilities.com

Barber, M.E., M.A. Hossain, C.J. Poor, C. Shelton, L. Garcia and M. McDonald, 2011, Spokane Valley – Rathdrum Prairie Aquifer Optimized Recharge for Summer Flow Augmentation of the Columbia River; State of Washington Water Research Center, Washington State University, Prepared for the Washington State Department of Ecology.

Barlow, P.M., and Leake, S.A., 2012, Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow: U.S. Geological Survey Circular 1376, 84 p. (Also available at <http://pubs.usgs.gov/circ/1376/>).

Cosgrove, D.S. and G.S. Johnson, 2004, Transient Response Functions for Conjunctive Management of the Snake River Plain, Idaho; Journal of the American Water Resources Association, December, Pages 1469-1482.

Cosgrove, D.M. and G.S. Johnson, 2005, Aquifer Management Zones Based on Simulated Surface-Water Response to Aquifer Stress (Response Functions). ASCE Journal of Water Resources Planning and Management, Vol. 131, No. 2, pp. 89-100.

Covert, J.J., 2014, Personal communication relative to the “Six-Minute Study”; Washington Department of Ecology

Covert, J.J., 2015, Personal communication relative to the location of production wells in Washington; Washington Department of Ecology.

Harbaugh, A.W., E.R. Banta, M.C. Hill, M.C., and M.G. McDonald, 2000, MODFLOW-2000, the U.S. Geological Survey Modular Ground-water Model -- User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hortness, J.E. and J.J. Covert, 2005, Streamflow Trends in the Spokane River and

Tributaries, Spokane Valley/Rathdrum Prairie, Idaho and Washington; U.S. Geological Survey Scientific Investigations Report 2005-5005.

Hsieh, P.A., M.E. Barber, B.A. Contor, M.A. Hossain, G.S. Johnson, J.J. Jones and A.H. Wylie, 2007, Ground-Water Flow Model for the Spokane Valley – Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho; U.S. Geological Survey Scientific Investigations Report 2007-5044.

Johnson, G.S., B.A. Contor, and D.M. Cosgrove, 2007, Efficient and Practical Approaches to Ground Water Right Transfers under the Prior Appropriation Doctrine and the Snake River Example. *Journal of the American Water Resources Association*, vol 44, no 1, pp 27-36.

Johnson, G.S., B.A. Contor, and S.L. Taylor, 2009. Evaluation of Potential Errors Resulting from Imposing Linearity in the Development of Capture Response Functions for the Spokane Valley-Rathdrum Prairie Aquifer. Idaho Water Resources Research Institute Technical Completion Report 2009-04.

Kahle, S.C. and J.R. Bartolino, 2007, Hydrogeologic Framework and Ground-Water Budget of the Spokane Valley – Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho; U.S. Geological Survey Scientific Investigations Report 2007-5041.

MacInnis, J.D., Jr., B.B. Lackaff, R.M. Boese, G. Stevens, S. King, R.C. Lindsay, 2009, The Spokane Valley-Rathdrum Prairie Aquifer Atlas 2009 Update: Spokane, Washington, City of Spokane, 30p.

Neely, K., 2013, Personal communication, Idaho Department of Water Resources.

Porcello, John, 2014, Presentation at Spokane Aquifer Joint Board April 2014 meeting: <http://www.spokaneaquifer.org/wp-content/uploads/2014/05/SAJB-GSI-Presentation-04-24-2014-1-slide-per-page.pdf>

Taylor, S.L., B.A. Contor, and G.S. Johnson, 2007, Spokane Valley – Rathdrum Prairie Capture Spreadsheet. An on-line and interactive spreadsheet for evaluation of surface and ground water interaction available at http://www.if.uidaho.edu/%7Ejohnson/ifiwri/research_and_education.html

APPENDIX A: DEVELOPMENT OF RESPONSE FUNCTIONS FROM THE BI-STATE MODEL

The spreadsheet to estimate SVRP aquifer pumping effects on the Spokane River resulting from this project depends upon mathematical relationships, expressed as a matrix of coefficients (response functions) and generated by the Bi-State SVRP aquifer model. Those coefficients represent the proportion of a one-day aquifer stress (ground water pumping event), expressed as a rate, that is manifested as a daily change in flow rate of the Spokane River between the Greenacres and Spokane gages for a period of 180 days. The values of the coefficients were determined by executing one simulation for each of 131 potential pumping well locations (model grid cell) for 180 daily time steps (365 days were generated, but only 180 days imported to the spreadsheet). This appendix describes the procedure that was used in quantifying those relationships. This process resulted in a matrix of 131 x 180 response coefficients that are used in combination with a convolution procedure to achieve temporal superposition of pumping effects from multiple days. A description of the convolution procedure is available in Cosgrove and Johnson (2004).

General Procedure

The general procedure is very similar to that described in Johnson and others (2008) and includes the following basic steps.

1. An *average conditions* data set was developed that represents the average a) aquifer recharge and pumping and b) interconnected surface water stage and physical dimensions during the October 1995 through September 2005 period.
2. A series of 5269 simulations (one for each active cell) were performed to determine the capture response functions at each model cell on the hydraulically connected reach of the collective cells representing the Spokane River above the Spokane gage. These simulations were performed by running the 1995-2005 average conditions in steady state, then running these same conditions with an additional stress of 10,000 cfs/day added to a specific cell for a 180 day-long transient stress period subdivided into daily time steps. Streamflow gain and loss differences between the initial steady state period and the subsequent 180 days represent the effects of continuous individual well pumping on Spokane River gains and losses.
3. The table of resulting response functions was subsequently imported into an Excel spreadsheet where a compilation of the selected 131 cells representing identified wells was created. The data for these locations were then further processed to obtain 180 daily responses for a single day stress event rather than continuous. This process involved superimposing identical magnitude but negative response functions with a one-day lag. The resulting values were subsequently entered into the spreadsheet used to compute effects of pumping on the Spokane River.

The rest of this document is organized into sections associated with the above

general procedure steps.

Original Data Sets and Model

This work involved modifying the data sets that were created during the calibration of the Bi-State SVRP model. Those data sets were downloaded from the website: <http://pubs.usgs.gov/sir/2007/5044/>. This data set includes the use of the pcg solver. These files are referred to in this report as the original model files. Modflow 2000 Version 1.15.01 was used in the model development. Previous work had determined that a double precision version of Modflow 2000 was needed to provide the desired level of accuracy (Johnson and others., 2008). A double precision executable code, acquired from Stanley Leake of the U.S. Geological Survey and used for previous work (Johnson and others., 2008) was also used in this evaluation.

The Average Conditions Data Set

Simulation conditions for the average conditions data set use an unconfined model representation with the same basic characteristics as the original model. That is, model geometry, aquifer layers, thickness, horizontal and vertical hydraulic conductivity, stream and river conductance, aquifer storativity and specific yield, and boundary types are unchanged. Time variant characteristics such as lake and river stage, stream width, aquifer recharge and discharge and boundary flux were determined as average values for the 120 months of the original model calibration period (October 1995 through September 2005). Use of this period implies that these conditions will be similar to conditions for which the spreadsheets will be applied.

Simulations for generating response functions

The specific changes made to the original model input files are described below on a file-by-file basis.

Unchanged files Sy.dat, hk_1.dat, hk_2.dat, hk_3.dat, ibound_1.dat, ibound_2.dat, ibound_3.dat, wetdry_1.dat, bot_1.dat, bot_2.dat, bot_3.dat, vka_2.dat describe non-time variant properties and were all unchanged.

.nam file The name file was changed to reflect new names of input and output files used in generating response functions.

Output files (.lst, .hds, .bgt, .strmflow) The output files identified in the .nam file have different names, but represent the same content as those of the original model, except for the .bgt file. The .bgt file contents are controlled by the output control file (.oc). This has been altered from the original model such that the .bgt file will only contain budget contents for the stream flow routing, river package, and general head boundary package for stress periods needed for determining response functions (the initial steady state period and 180 daily transient steps).

.dis file The discretization file was altered to perform first a steady state period followed by a 365 day transient stress period divided into 365 daily timesteps. Only the first 180 days were used in the spreadsheets. The first stress period is steady state and represents the average 1995-2005 conditions without any additional stress. The 365 daily timesteps are transient and include the additional stress (10,000 cf/day) at a specific cell (the cell for which response functions are being generated) for the entire duration of the 365 day stress period. Response functions are determined by differencing results of the

first steady state stress period (no added stress) from results of each transient time step which include the added stress representing pumping at a single cell.

.bas file The .bas file was unchanged from the original model file except that head at inactive cells was set to -999 for convenience in post processing.

.lpf file The .lpf file was unchanged from that of the original model files

.riv file The .riv file was changed so that temporally varying characteristics were represented by an October 1995 through September 2005 average value. The average values are listed for the first stress period, then flagged as repeated for each subsequent stress period. Non-time dependent characteristics are unaltered from the original model file. These include the number and location of river cells, and hydraulic river bed conductance, and river bottom. River or lake stage was determined as the average value for the October 1995 through September 2005 period.

.rch file Average values of monthly recharge rates for each cell were determined for the October 1995 through September 2005 period. These values were included in the .rch file for the first stress period and transient time steps of the second stress period were flagged to repeat the use of these values in the second stress period.

.wel file There are 5204 cells with a well representation that is comprised of the 5203 well cells in the original model and an added cell that is at the stressed location. The .wel file lists well data for two stress periods. The first is the steady state period representing average conditions (October 1995 through September 2005) with no added stress. In this stress period the added cell has a stress set to zero. The second stress period used initial steady state rates plus the added stress of 10,000 cubic feet per day at a selected cell. The location of that selected cell is varied by a preprocessing fortran executable file.

.ghb file The .ghb file is used only to represent the boundary conditions of Long Lake. For these four cells, the same time-constant conductance value was used as in the original model files, but the stage values were determined as the average of the October 1995 through September 2005 values and held constant for all stress periods. This was accomplished by entering the values for the first stress period and flagging the second stress period to repeat these values.

.fhb file The flow and head boundary file was altered from the original model such that none of the flows at boundary cells are time variant. The time constant flows for each cell were determined as the average of the monthly flows for the October 1995 through September 2005 period.

.sfr file The streamflow routing file contains some time-constant and some time variable data. The time-constant data that were not changed from the original model file includes: stream-bed conductance, channel length, and channel bottom elevation. Time variant data that were averaged for the October 1995 through September 2005 period includes river width and river depth.

.pcg file Model calibration was originally performed using the .lmg solver, but the final model was converted to run with the .pcg solver to be accessible to all potential users (.lmg was proprietary). The .pcg file was altered from the original in that closure criteria on the water budget and on hydraulic head were both reduced by an order of magnitude with the response function files.

.oc The output control file of the response function data set was altered so that only the budget terms were saved and these were saved for all stress periods and

timesteps (two stress periods, and 365 timesteps in the second stress period). This provides the opportunity to determine head dependent fluxes for the average conditions (initial steady state stress period) and the 365 day-long timesteps that include the additional stress. Subtracting the results of the first stress period from any of the subsequent stress periods provides the response to the added stress.

Running Response Functions and Summarizing Results

The files identified above can be used to create a run with Modflow, however, the .wel file will contain an added stress for only one well. In order to generate response functions for different cell locations one must reset the location of the additional stress in the .wel file and use post-processing to determine the response of the Spokane River above the Spokane gage. A series of custom made pre- and post-processing routines (Fortran executables) are used and a DOS batch file has been created to run the sequence of programs and Modflow for each active cell in the SVRP.

The DOS batch file (Rundaily.bat) includes the following statements:

```
:start
nextcell
if exist endflag goto end
welmod
mf2kdbl <fname1.in
rch1response
massbal
goto start
:end
del endflag
```

The function of these statements are as follows:

:start

This statement identifies the beginning of the loop that is repeated to determine response functions for each active cell in the SVRP model grid.

nextcell

This statement executes the Fortran program nextcell.exe that identifies the next active cell in the model grid and outputs the grid coordinates of that cell to a temporary file.

if exist endflag.out goto end

If the program nextcell.exe determined that all model cells were completed then a file is created named endflag.out. If that step has been completed then the entire process is terminated by jumping to the :end statement.

welmod

This statement executes a Fortran program welmod.exe that rebuilds the file welfile.wel for input to Modflow. This executable builds the .wel file so that the stresses in the first stress period (steady state average conditions) are unchanged, but in stress period 2 an additional stress of 10,000 cubic feet per day is simulated at all 365 timesteps at the cell location identified and output from the program nextcell.exe.

mf2kdbl <fname1.in

This statement executes the double precision version of Modflow 2000 provided by Stanley Leake of the U.S. Geological Survey. The fname1.in file identifies the name of the Modflow .nam file used in the run (in this case SVRP_RFd.nam).

rch1response

This statement executes the rch1response.exe Fortran program. This program reads the double precision binary budget file (SVRP_RFd.bgt) and sums the flows for the Spokane River above the Spokane gage for each timestep. Reaches are identified in the file Reaches2.txt. The model generated flows (surface water gains and losses) are used to calculate response functions by differencing gains and losses of each timestep in stress period 2 with that of the first stress period (in which there was no added stress). These results are expressed as a response percentage (percentage of the stress) for each stressed cell in the file RF1.out.

Massbal

This statement executes the massbal.exe Fortran program. This program reads the Modflow .lst file and saves the mass balance residual (cubic feet per day) for each of the stress periods in each of the simulations in a file named Residual.out. This file can then be searched for high residuals that may cause problems in the determination of response functions.

goto start

This statement loops the process back to the :start statement which will identify and simulate response functions at a new model cell.

:end

This statement is an exit point that is accessed only when all cells in the active model grid have been simulated.

del endflag.out

This statement deletes the end flag so that if the batch file is run again the process will not immediately terminate.

Spreadsheet Determination of Effects of a Pumping Event of One Day Duration

The spreadsheet uses responses from a one day duration stress while the response functions calculated in the process described above determine response to a continuous stress. The responses to a one day stress were determined from the continuous stress response functions by subtracting a one-day lagged response from each daily response value:

$$RF(\text{day})_i = RF(\text{continuous})_i - RF(\text{continuous})_{i-1}$$

Where:

$RF(\text{day})_i$ is the response function from a stress of one day duration at time i ,

$RF(\text{continuous})_i$ is the response function from a continuous stress at time i ,

$RF(\text{continuous})_{i-1}$ is the response function from a continuous stress one day prior.

This is consistent with superposition concepts as often applied in image well and pumping test analyses. Response functions were determined for all active cells in the model; cells containing wells to be included were extracted from this larger set.

Appendix References

Cosgrove D.M. and G.S. Johnson, 2004, Transient Response Functions for Conjunctive Water Management in the Snake River Plain, Idaho. *Journal of the American Water Resources Association*, vol 40, no 6: 1469-1482.

Johnson, G.S., B.A. Contor, and S.L. Taylor, 2008, Procedure for Development of Surface Water Capture Response Functions for the Spokane Valley-Rathdrum Prairie Aquifer. University of Idaho Water Resources Research Institute.

APPENDIX B: DETAILS OF THE SIX-MINUTE STUDY COMPARISONS

Background

In August of 2005, the Washington Department of Ecology performed a field investigation to better understand the characteristics of the connection between the Spokane River and the aquifer and to possibly refine estimates of aquifer properties (Covert and others, 2005). A controlled release of water from Post Falls dam was used to raise the stage of the Spokane River. Aquifer water levels in a series of wells were measured at six-minute intervals to determine aquifer response to the increased stage. Most wells exhibited a water level increase within a day or two of the increased stage. Interpretation of the results of the “Six-Minute Study” is provided in two memos by Hiesh (2006a; 2006b).

Observations of the rapid response of aquifer water levels to change in Spokane River stage provide an opportunity to evaluate the ability of the Bi-State SVRP aquifer model to simulate events at time scales less than one month. The model can be used to predict water level changes at approximate locations within the aquifer resulting from input values of river stage change. These predicted, or simulated, aquifer water level changes can be compared to the observed values to gain a sense of accuracy of the model for short time and distance scales. This is important because the Bi-State SVRP aquifer model was developed using monthly time intervals and to our knowledge has not been tested for shorter periods. Although the governing equations of the model should be applicable at these times, it is possible that use of longer term data in model development (i.e. calibration) could result in biased estimates at shorter periods.

Many of the observation wells used in the Six-Minute Study were in close proximity to the Spokane River, at distances not well approximated by the ¼ mile model grid spacing. The comparison of simulated to observed results also reflects the effects of spatial discretization (grid spacing effects) on model results. Differences between simulated and observed values reflect the combined effects of a) approximations in the conceptual model, b) inaccuracies in calibrated estimates of aquifer properties, and c) the effects of spatial discretization.

Simulation Description

The Six-Minute Study conducted in August 2005 by the Washington Department of Ecology involved a controlled increase in stage of the Spokane River by increasing releases from Post Falls Dam. Numerous well water levels and river stage were monitored at six-minute intervals to identify the rate at which the stage change propagated into the aquifer system. The Washington Department of Ecology made these data available for development of this simulation and for comparison to simulation results.

The simulation does not attempt to exactly replicate the conditions at the time of the Six-Minute Study, but instead evaluates the effect of an identical increase in Spokane River stage under average flow and aquifer conditions. Initial conditions for the simulation (prior to stage change) were determined as average river stage, recharge, discharge, and boundary conditions that were developed for the October 1995 through

September 2005 calibration period in the SVRP aquifer model developed by Hsieh and others (2007). These conditions were simulated in a steady-state stress period to generate the initial (prior to stage change) aquifer water levels and river gains and losses. This representation is adequate because the model represents the exchange of water between the river and aquifer as a near linear relationship to the river-aquifer hydraulic gradient. The only nonlinear elements are the intermittent perching of a relatively small number of river cells caused by variations in aquifer water level and time-varied river width estimated in the input data set. The linear representation means that changes in simulated aquifer water levels and river gains and losses are insensitive to the initial conditions, whether average steady state, or specifically representing August of 2005 (with the exception of intermittent perching).

The simulation consisted of an average (average for 1995 through 2005) steady state stress period followed by a series of transient stress periods where recharge and discharge were held constant and only river stage varied. Simulated stage mimicked the pattern of change implemented in the Six-Minute Study which is shown in Figure B1 for the river observation locations. Locations of the river stations and observation wells are shown in the map of Figure B2. Stage remained constant after 35 hours for the duration of the simulation. Stage observations at the known locations shown in Figure B1 were linearly interpolated to estimate changes at all river model cells between these locations. Hourly model stress periods for the first 48 hours of the test were used to represent the rapidly changing river conditions. This was followed by a single stress period of 58 days (no further change in stage), subdivided into daily timesteps for a total transient simulation period of 60 days.

All model inputs except Spokane River stage were held constant throughout the duration of the simulation. Those inputs were identical to the conditions of the initial steady state period. Consequently, any transient changes in aquifer water levels or river gains and losses are a result of the input changes in river stage. In the real situation aquifer water levels would be responding to multiple other events including pumping and precipitation that are not included in the simulation. Therefore the match between simulated and observed values is not expected to be exact. Other conditions that affect the match include a) inaccuracies in estimates of aquifer and river properties, b) discretization of the aquifer system as a system of $\frac{1}{4}$ by $\frac{1}{4}$ mile square and homogeneous grid cells, c) not representing changes in river losses resulting from changes in river width that accompany stage change, and d) other model simplifications (e.g. a single layer in most locations).

Hsieh (2006a) applied a correction for antecedent trends in observation wells in the Six-Minute Study to account for generally declining water levels immediately prior to the test. That correction was not applied in this analysis; consequently, it is possible that the observations slightly underestimate true aquifer water level changes in the observation wells.

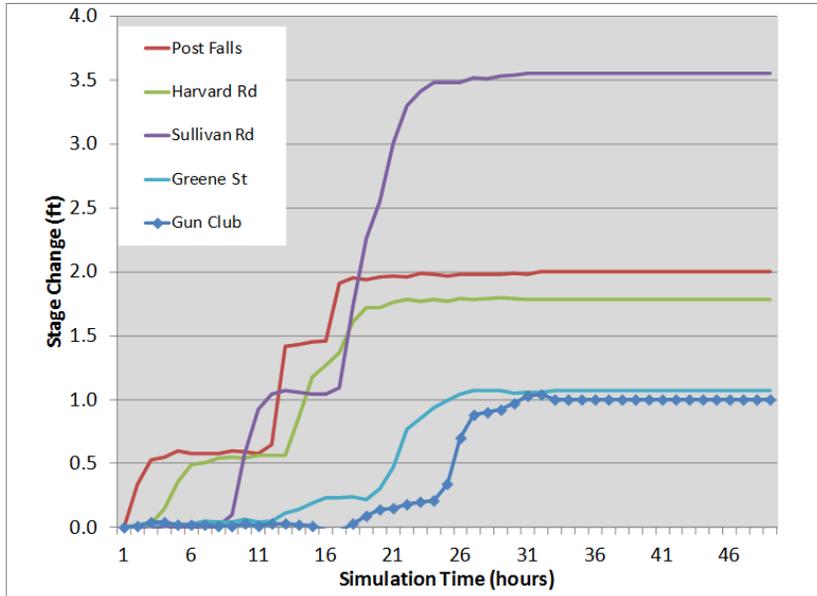


Figure B1. Simulated stage change at stations along the Spokane River.

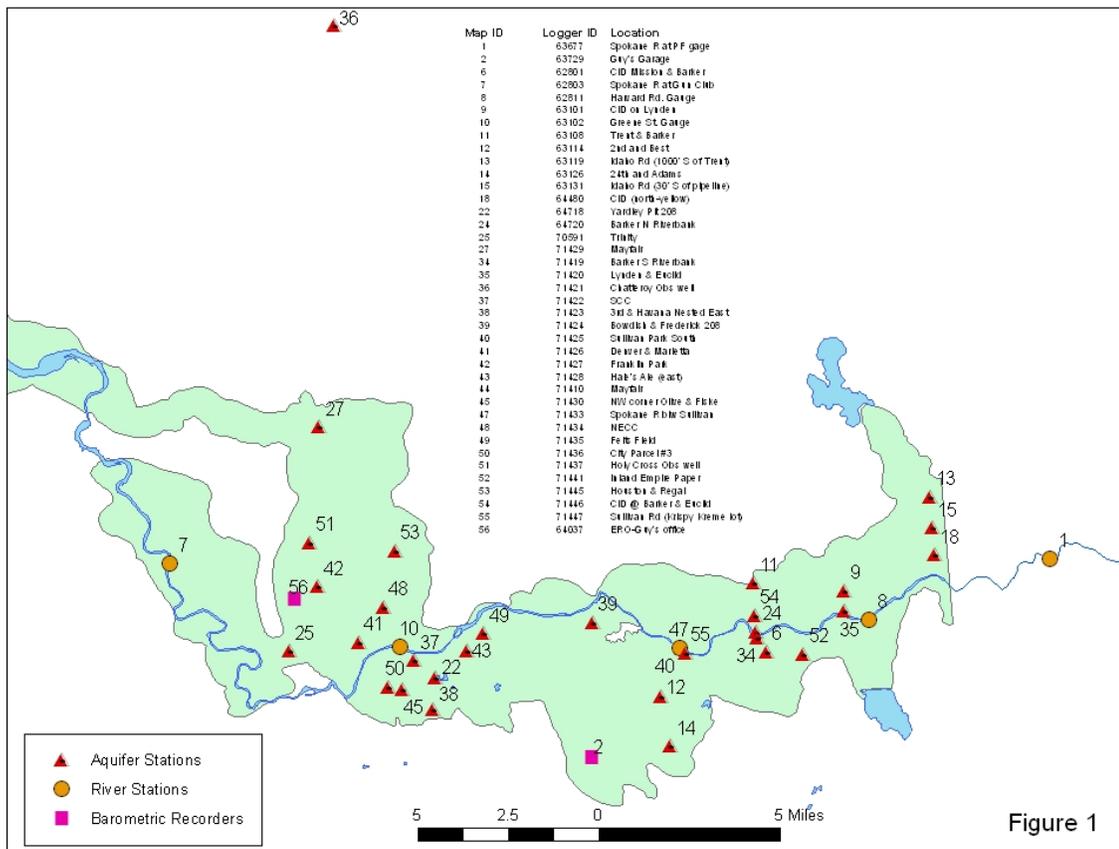


Figure 1

Figure B2. Locations of Spokane River stage observations and well observations (from

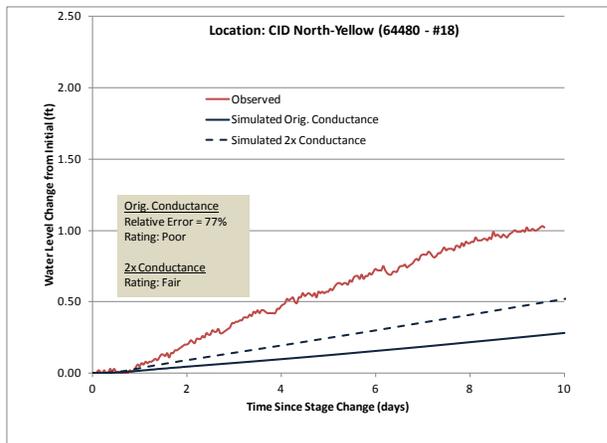
Covert and Gregory, 2005).

Comparison of Model Results to Observations

Simulated aquifer water level changes resulting from the stage change are compared to measured values at 24 well locations in the aquifer west of Post Falls. In general, simulated water level changes were smaller than observed values, but results varied by location. Graphs comparing observed and simulated water level changes at four selected locations (identified in Figure B2) are presented in Figure B3. Similar comparisons for the remaining 20 locations are presented at the end of this appendix.

There appears to be little pattern in the spatial distribution of the models ability to match observed changes in aquifer water level. Figure B4 shows a map of a measure of closeness of simulation fit to observations. A “good” fit is described when the mean relative difference between simulated and average water levels is less than 40 percent of the mean observed water level change. A “fair” fit is identified when the mean relative difference is within 40 to 60 percent of the mean observed water level change. A “poor” fit is defined as when the mean relative difference is more than 60% of the mean observed change. The ranges of good, fair, and poor are subjective and are based on the authors’ judgement. The fit ratings for all wells are identified in the graphs at the end of this appendix.

The model’s ability to replicate the aquifer’s response to Spokane River stage change is subjectively rated as “fair” overall in the authors’ opinion. This rating is not a reflection on the model development, but on the ability of the model to perform in time frames and distances smaller than those for which it was designed. The model tends to underestimate the actual changes in aquifer water level change at many locations but it does show a response in a reasonable time scale relative to observations. The model seldom overestimates aquifer water level change (Figure B4).



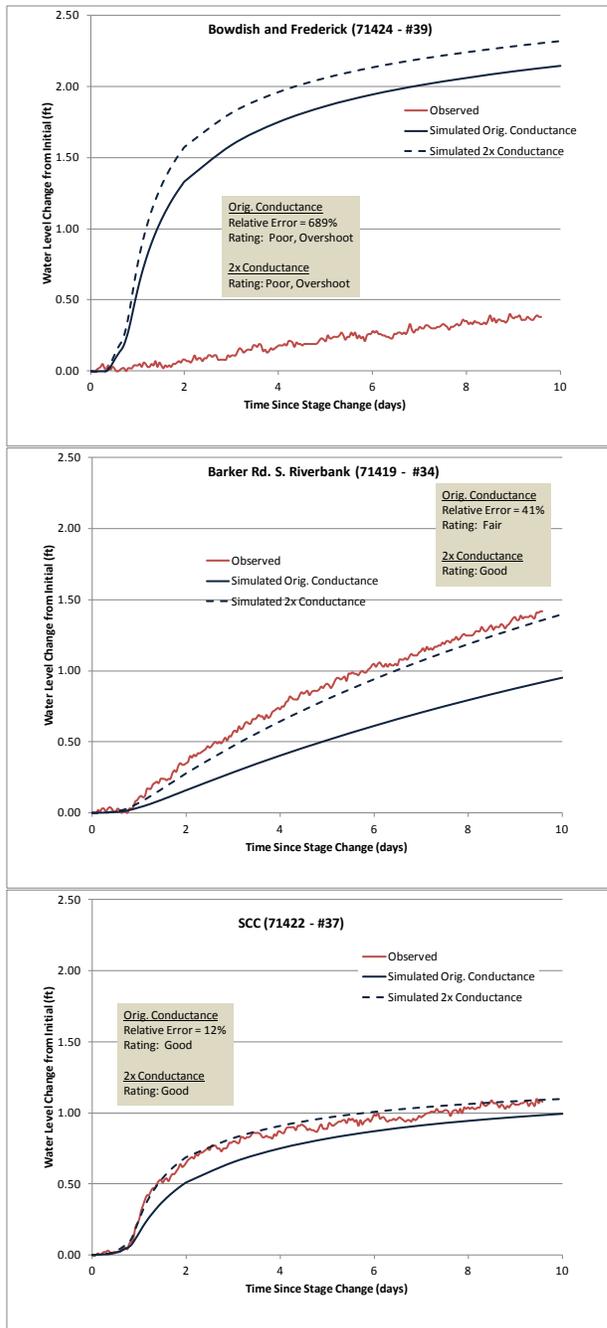


Figure B3. Simulated and observed aquifer water levels in four selected wells. Dashed lines show simulation results for an experimental doubling of all model river conductance values.

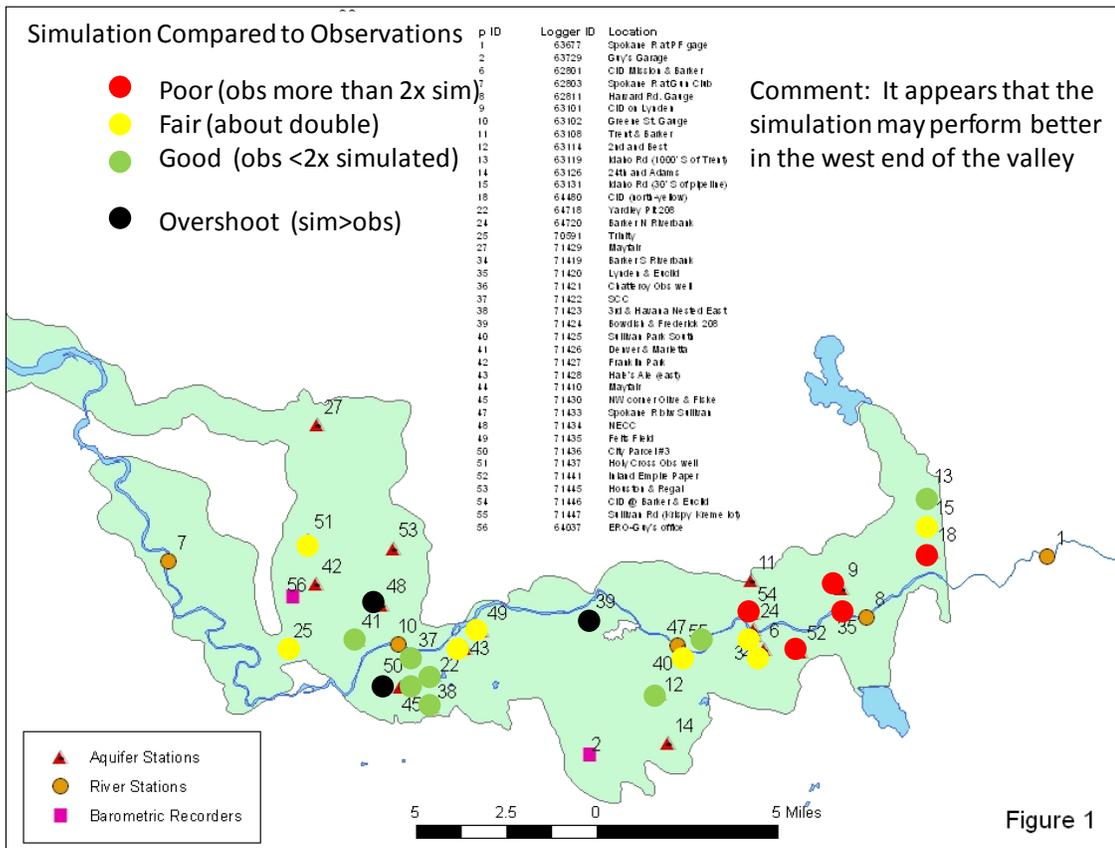


Figure B4. Color coded subjective rating of simulated water level change to observed.

Interpretation of Results

The rated “fair” ability of the model to replicate the aquifer water level changes may be a result of several factors. These include the following.

- Inexact quantification of the stage change at locations between stage observations on the Spokane River (cell-wise linear interpolation was used).
- At small distances model grid cell averaging (discretization error) may produce different results than would be observed at exact well locations. The averaging problem occurs both in identifying aquifer water level changes at specific locations and in representation of the Spokane River, where river gains and losses are represented at the cell centers rather than the exact geographic location.
- Aquifer properties determined during model calibration are neither exact, nor are they sufficiently refined to represent the true heterogeneity that exists in the aquifer. Smaller-scale simulations may be more sensitive to the inexact representation of these heterogeneities.

- During the test period, water levels in observation wells are responding to influences such as changes in pumping and recharge, that are not represented in the simulation. This is not a model flaw, but is merely a limitation in the developing an observation data set.
- The model is an inexact representation of the real system.

Despite these limitations, the model probably represents the best tool for performing quantitative assessments of the interchange of water between the Spokane River and the SVRP aquifer. The systematic trend of the model to underestimate response to the Spokane River stage change implies that short term analyses in the Spokane River corridor, such as needed in this project, are likely underestimates of actual system responses. That is, actual short term impacts on the Spokane River from municipal pumping are likely greater than those determined using the model.

Alternative Model Representation

The systematic underestimation of simulated aquifer water level change suggests that improvement to matching short term results may be achieved by a universal adjustment to a single model property. In this case, the underestimation of the amplitude of the water level change suggests that modeled river bed conductance of the Spokane River may need to be increased. River bed conductance is a model term that controls the rate of flow between the river and aquifer and includes characteristics such as hydraulic conductivity and thickness of the bed materials (Prudic et al., 2004).

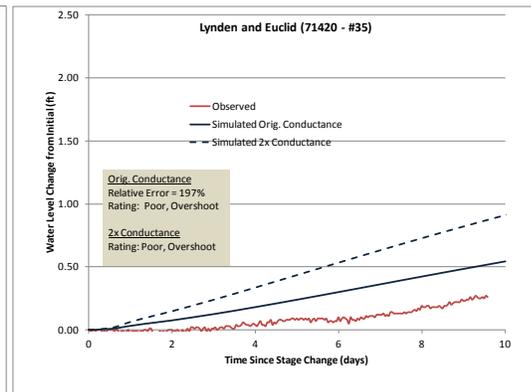
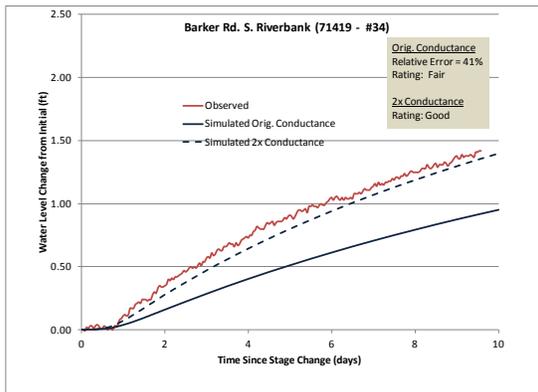
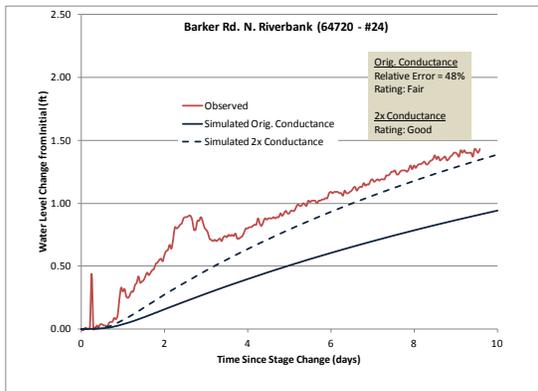
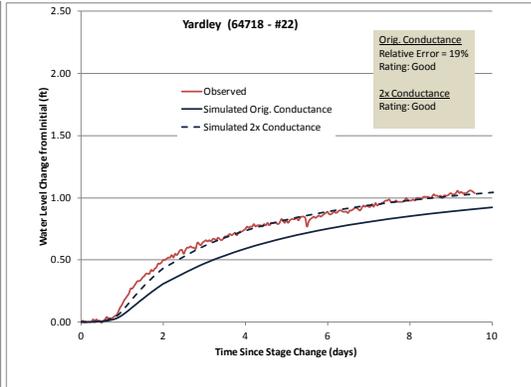
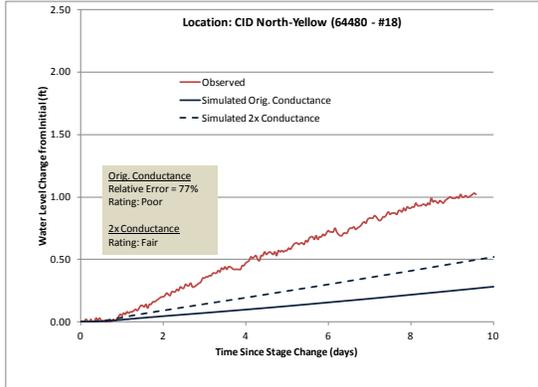
In the Streamflow Routing Package used in the SVRP aquifer model, values of bed hydraulic conductivity and thickness are individually input for each cell representing the Spokane River. A test was conducted where the ability of the river bed to transmit water was doubled by decreasing the bed thickness to one half of the values (at all cells representing the Spokane River) used in the calibrated SVRP aquifer model. The simulation with the adjusted thickness was then used to repeat the simulation to match aquifer water level change resulting from the stage change. Since stage above Post Falls Dam was not altered in the simulation, and that section of the river is perched above the aquifer, the change had no effect on the change in river losses above the dam (change in river losses are zero).

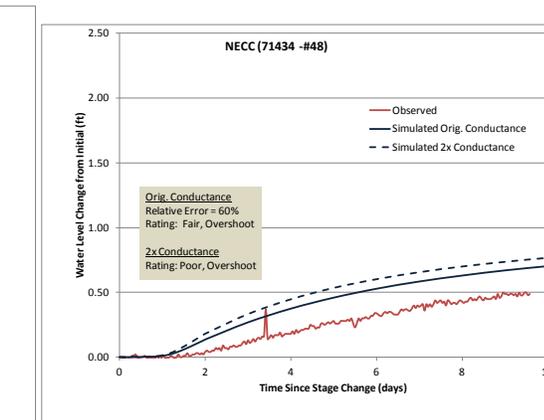
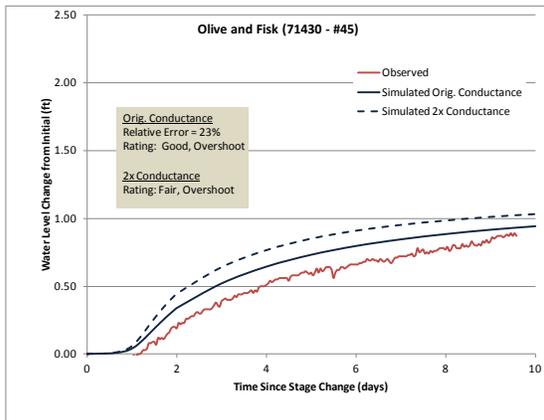
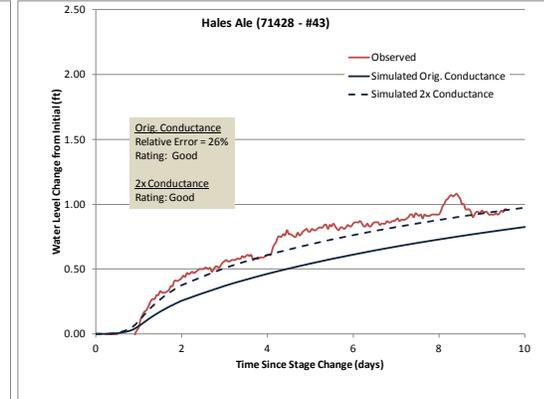
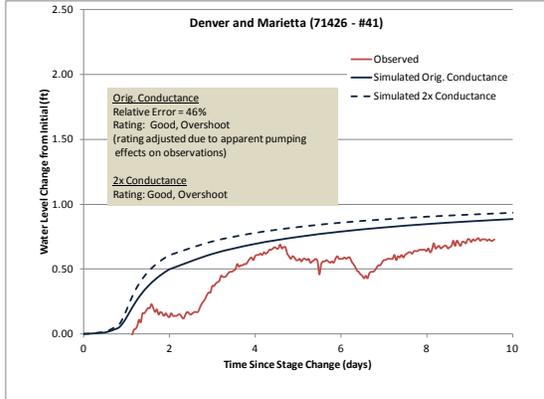
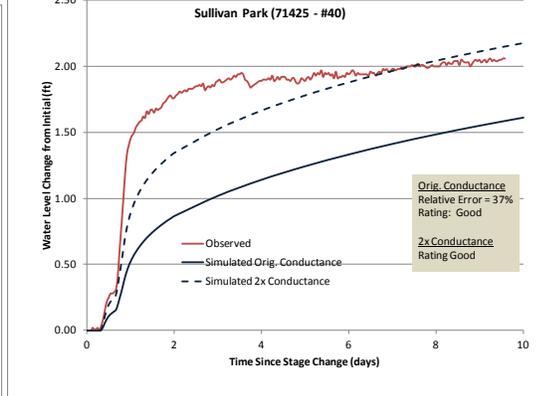
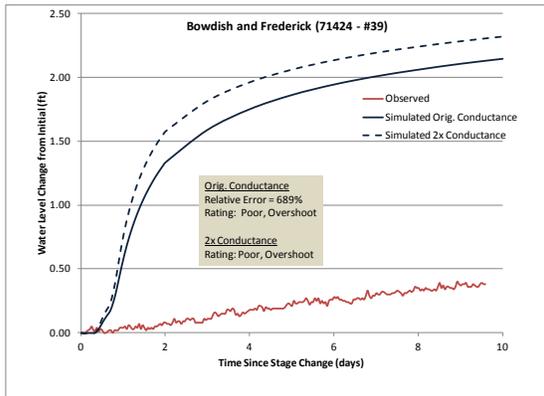
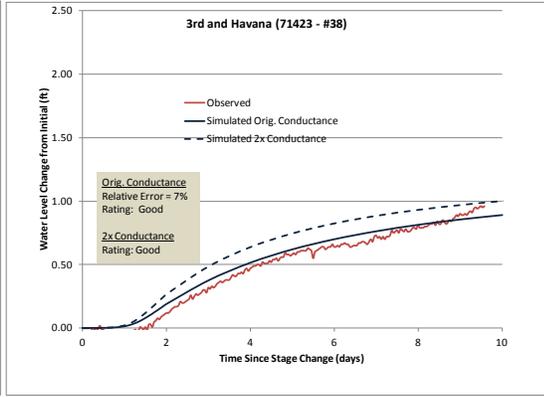
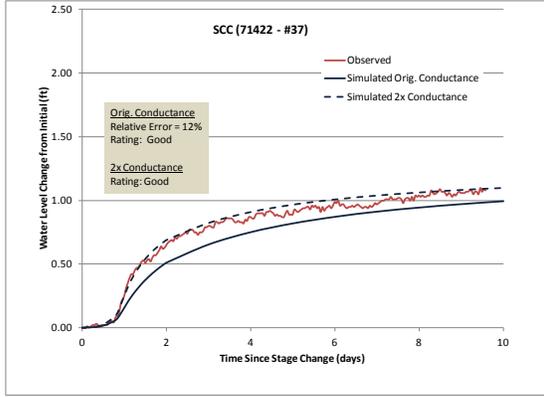
The simulation results with increased river conductance are shown in Figure B3 and in figures at the end of this appendix along with the results from the original model conductance. The model run with doubled river conductance sometimes produced simulated water levels that are nearer to observed values. In locations where simulation results overestimated water level change, the increased conductance usually resulted in a poorer fit to observations. Using the same criteria for good, fair, and poor matches, this simulation resulted in good matches in 13 out of 24 locations. Some of the fits between simulated and observed values are excellent.

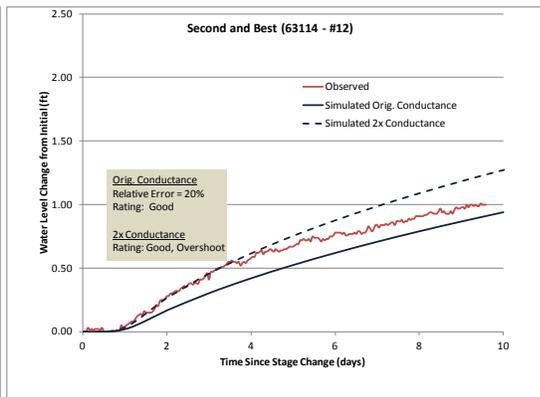
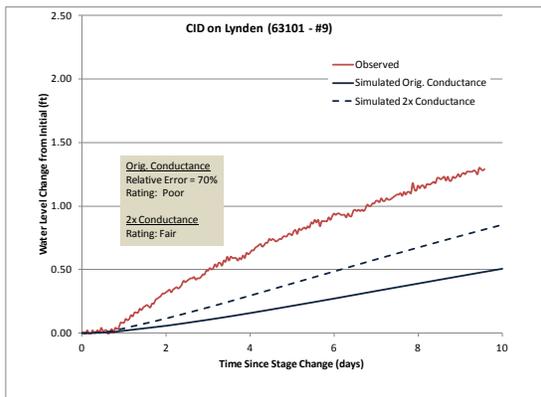
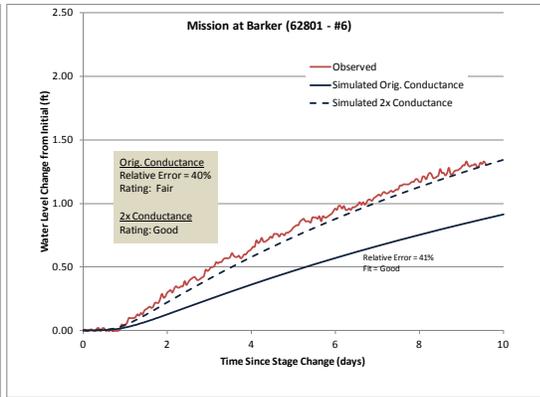
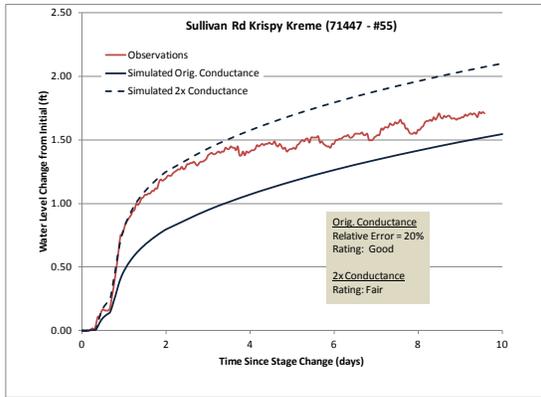
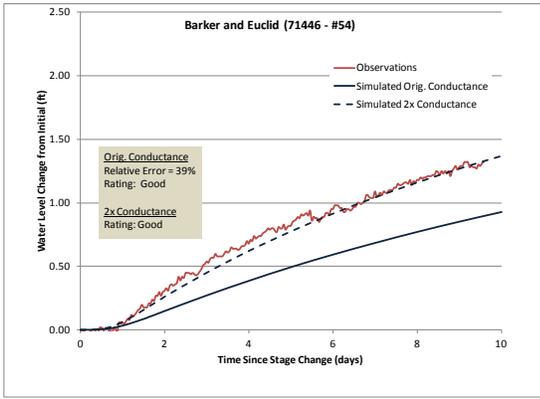
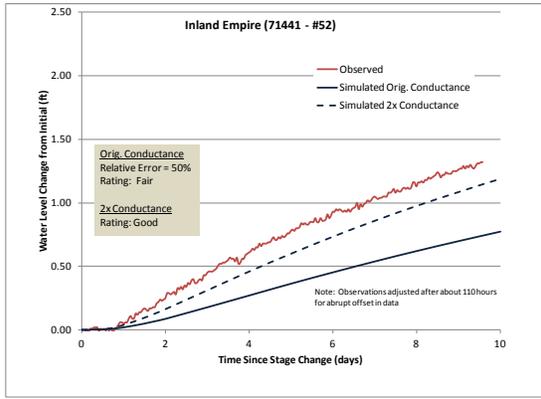
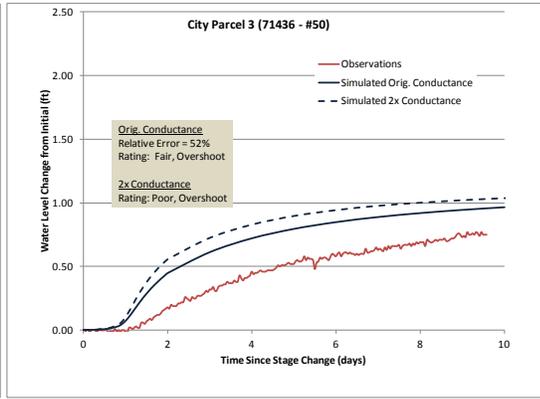
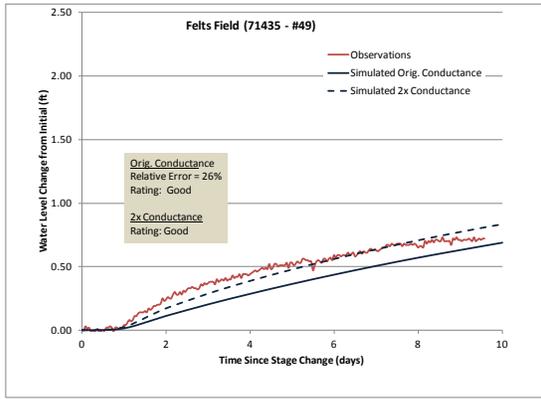
Increasing the values of Spokane River conductance may slightly improve the fit to short-term water level observations in the Spokane River corridor. This does not, however, necessarily mean this is an overall improvement to the model. It was not determined if the simulated matches to other longer term water level and river gain and loss data used in the original model calibration deteriorated as a result of the adjustment

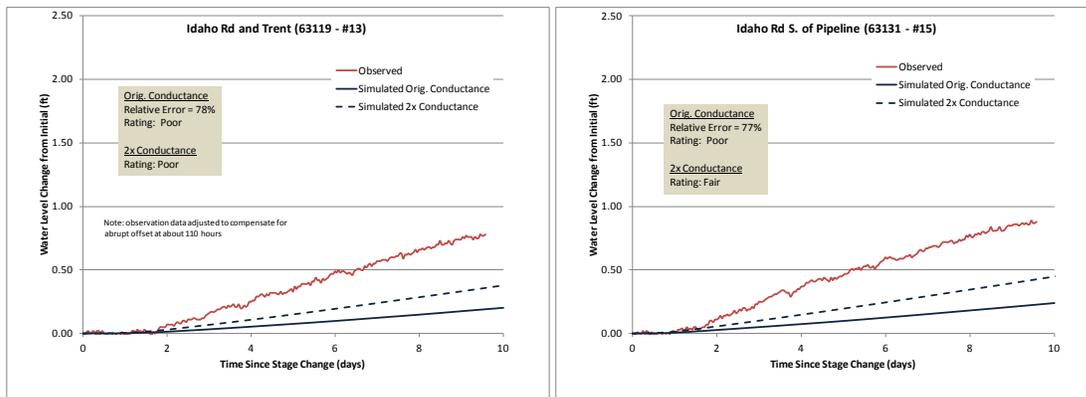
to conductance. This analysis was performed only as an experiment, and the doubled conductance values were not used in further analysis of Spokane River gains and losses.

GRAPHS OF SIMULATED AND OBSERVED AQUIFER WATER LEVELS IN THE SIX-MINUTE STUDY









Appendix B References

Covert, John J., T. L. Band, and G.J. Gregory, 2005, Data Report, 2005 “Six minute” Study, Spokane Valley Rathdrum Prairie Aquifer Area; Washington Department of Ecology memorandum.

Hsieh Paul, 2006a, Preliminary Analysis of wells 13, 15, and 18 of the “Six-Minute” Data; Memorandum to Modeling Team, John Covert, Guy Gregory, Jim Bartolino, Sue Kahle.

Hsieh, Paul, 2006b, General observations and additional analysis of the “Six-Minute” Study; Memorandum to Modeling Team, John Covert, Guy Gregory, Jim Bartolino, Sue Kahle.

Hsieh, P., M.E. Barber, B.A. Contor, Md. Akram Hossain, G.S. Johnson, J.L. Jones, and A.H. Wylie, 2007, Ground-Water Flow Model for the Spokane Valley-Rathdrum Prairie Aquifer, Spokane County, Washington, and Bonner and Kootenai Counties, Idaho. U.S. Geological Survey Scientific Investigations Report 2007-5044.

Prudic, D.E., L.F. Konikow, and E.R. Banta, 2004, A new streamflow-routing (SFR-1) package to simulate stream-aquifer interaction with Modflow -2000. U.S. Geological Survey Open-File Report 2004-1042.