GSI Water Solutions, Inc.

TECHNICAL MEMORANDUM

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

To: Marcia Davis, City of Spokane Integrated Capital Management Department

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Attachments: Figures 1 through 20
Attachment A: Development of City Water Demand Scenarios
Attachment B: Development of Climate-Change Factors
Attachment C: Groundwater Flow Model Development and Application

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Introduction

On behalf of the City of Spokane (City), GSI Water Solutions, Inc. (GSI), has conducted a groundwater modeling analysis of the potential effects of future increased water demands and climate change on groundwater levels at each of the City's eight well station facilities that provide the sole source of municipal water supply to customers inside the City's water service area. The City commissioned this study with the recognition that future increases in demand due to growth, along with climate-driven changes to future water demands and to water recharge to the Spokane Valley-Rathdrum Prairie (SVRP) Aquifer, could affect groundwater levels in the aquifer and hence at each of the City's well stations. Using available 20-year and 50-year projections of future water needs, this study evaluates how changes in precipitation, temperatures, and other hydrologic variables (such as streamflows, inflows to the aquifer from lakes and tributary watersheds, and water demand requirements for agricultural crops and urban landscaping) can affect conditions in the Spokane River, the SVRP Aquifer, and hence at each City well station during the latter three decades of the 21st century (the years 2070 through 2099). While the groundwater modeling analysis simulated these potential effects for all months and seasons of a calendar year, the analysis focused on conditions during the summer months of July and August, when water demands are at their seasonal highs and groundwater recharge rates and Spokane River flows are at their seasonal lows. The analysis examined a range of future conditions for climate and for water demands and provides for the first time a quantitative, numerical modeling-based assessment of the general amounts of groundwater level changes at City wells that might arise in the future compared with recent historical conditions.

The locations of the City's well stations are shown in Figure 1. Following are summaries of the methodology for conducting the analysis, the simulated changes in groundwater levels at each well station, a comparison of these groundwater levels with the depths of caisson wells and pumping systems at each well station, the conclusions from this study, and a discussion of the limitations of the analysis.

Methodology

The study used a numerical three-dimensional groundwater flow model of the SVRP Aquifer and overlying and adjacent surface water bodies to simulate recent historical conditions in the aquifer followed by multiple scenarios of future changes in three variables: (1) groundwater pumping by the City, (2) inflows to the Spokane River from Coeur d'Alene Lake, and (3) inflows to the SVRP Aquifer from adjoining tributaries that bound the aquifer. For each of these three variables, an important element of the study was developing the climate-change factors to apply to these terms. The study evaluated six sets of climate scenarios for the latter three decades of the 21st century, expressed as averages during the period of calendar years 2070 through 2099. The six climate scenarios were based on (1) two different scenarios for greenhouse gas (GHG) emissions and (2) low, median, and high degrees of climate change under each of these future emissions scenarios during the last three decades of the 21st century. The two emissions scenarios are called Representative Concentration Pathways (RCPs) and are as follows:

- **RCP 4.5:** This scenario assumes that GHG emissions stabilize by the year 2050 and then decline steadily. This can be thought of as a somewhat optimistic scenario for future GHG emissions.
- **RCP 8.5:** This scenario assumes that GHG emissions do not decline and continue at their historical rates and result in continued accumulation of GHGs in the atmosphere. This can be thought of as a "business as usual" scenario for future GHG emissions.

Three separate water demand projections were each evaluated under all six of the climate-change scenarios, resulting in 18 future conditions that were evaluated using the groundwater model. For each of the 18 future conditions, the method for deriving future water demands and the climate-change-based changes in hydrologic conditions of the SVRP Aquifer and the Spokane River was as follows:

- **Groundwater Pumping by the City.** Changes in future pumping by the City were derived from published projections of water demands in 20 years (HDR, 2022) and 50 years (HDR, 2023), with additional adjustments to those demands to account for the effects of changing temperatures on the length of the growing season and changes in water needs on agricultural lands and urban landscapes requiring irrigation water supplies. Three future pumping scenarios were evaluated: a single scenario for the projected 20-year demand, and two 50-year demand projections that differ in their assumptions regarding growth and water conservation. The average-day demand (ADD) and maximum-day demand (MDD) for each of these three demand scenarios are summarized in Table 1 and are higher than the HDR-published projections because of different interpretations about future irrigation needs under a changing climate. For this study, GSI developed monthly estimates of system-wide demands using the HDR projections, the City's current seasonal variation in demands, and future projections of how demands might change in the future as temperatures change and the growing season lengthens (which affects outdoor watering needs). Figure 2 provides a visual comparison of these monthly distributions of system-wide demand.

Table 1. Water Demand Values for Recent Historical Usage and Future Demand Scenarios

Water Demand Scenario	ADD	MDD
Recent Historical Usage (Average for 2015 through 2020)	63.60	141.30
20-Year Projection with 2070–2099 Climate Change	91.47	186.42
50-Year Projection (Modest Level of Demand) ▪ Demographics: Baseline ▪ Conservation: Standard ▪ Climate Change: Aggressive (RCP 8.5, 2070–2099)	95.32	217.40
50-Year Projection (High Level of Demand) ▪ Demographics: High Growth/High Commercial ▪ Conservation: No Change from Current Conditions ▪ Climate Change: Aggressive (RCP 8.5, 2070–2099)	127.06	259.75

Notes

All values are in units of millions of gallons per day (mgd).
ADD = average-day demand MDD = maximum-day demand
RCP = Representative Concentration Pathway for future global greenhouse gas emissions

- **Surface Water Inflows to the Spokane River from Coeur d'Alene Lake.** Climate-model projections of changes in future flows of the Spokane River at Post Falls, Idaho (at the headwaters of the Spokane River) were obtained from an online data portal called The Climate Toolbox, which is accessible at https://climatetoolbox.org/. This data portal contains climate and streamflow projections that have been locally downscaled from multiple global-scale climate models by the research community and compiled into a geospatial viewer to facilitate data retrieval and analysis at specific locations of interest. Table 2 summarizes the average daily flow rates at Post Falls under average historical conditions (as available from The Climate Toolbox) and the future streamflow projections. Figure 3 compares the historical average values of monthly flows (as obtained from The Climate Toolbox) with future flow projections for each month under both GHG-emissions scenarios and the range of climate-change possibilities for those emissions scenarios. Table 3 provides the same information but expressed as a percentage change in flows. As shown in Table 3, climate change is expected to increase streamflows during the winter and early spring (December through March) and decrease streamflows during the remaining 8 months of the year (April through November). These values for flows at the headwaters of the Spokane River were programmed directly into the groundwater flow model, serving as inputs that were used by the model to evaluate how seepage rates through the bed of the Spokane River (i.e., recharge to the underlying aquifer from the river) might vary in the future downstream of Post Falls.

Table 2. Future Estimates of Spokane River Streamflows (cfs) at Post Falls, Idaho

Month	Average Historical Streamflow (1950–2005)	Low Streamflow Under 2070–2099 Climate Change	Average Streamflow Under 2070–2099 Climate Change	High Streamflow Under 2070–2099 Climate Change
January	5,236	4,869 (RCP 4.5) 6,530 (RCP 8.5)	6,884 (RCP 4.5) 7,874 (RCP 8.5)	8,690 (RCP 4.5) 8,731 (RCP 8.5)
February	7,463	7,819 (RCP 4.5) 12,044 (RCP 8.5)	12,274 (RCP 4.5) 14,007 (RCP 8.5)	16,039 (RCP 4.5) 17,239 (RCP 8.5)
March	8,941	9,166 (RCP 4.5) 8,290 (RCP 8.5)	11,558 (RCP 4.5) 11,640 (RCP 8.5)	14,068 (RCP 4.5) 15,357 (RCP 8.5)
April	15,394	11,086 (RCP 4.5) 7,742 (RCP 8.5)	14,714 (RCP 4.5) 12,974 (RCP 8.5)	17,831 (RCP 4.5) 17,121 (RCP 8.5)
May	17,408	7,236 (RCP 4.5) 3,152 (RCP 8.5)	10,278 (RCP 4.5) 6,420 (RCP 8.5)	13,064 (RCP 4.5) 9,846 (RCP 8.5)
June	9,118	1,675 (RCP 4.5) 931 (RCP 8.5)	2,436 (RCP 4.5) 1,410 (RCP 8.5)	3,484 (RCP 4.5) 2,181 (RCP 8.5)
July	2,381	595 (RCP 4.5) 396 (RCP 8.5)	741 (RCP 4.5) 543 (RCP 8.5)	971 (RCP 4.5) 754 (RCP 8.5)
August	877	195 (RCP 4.5) 132 (RCP 8.5)	297 (RCP 4.5) 207 (RCP 8.5)	388 (RCP 4.5) 348 (RCP 8.5)
September	798	236 (RCP 4.5) 160 (RCP 8.5)	318 (RCP 4.5) 233 (RCP 8.5)	411 (RCP 4.5) 344 (RCP 8.5)
October	1,368	632 (RCP 4.5) 494 (RCP 8.5)	740 (RCP 4.5) 600(RCP 8.5)	886 (RCP 4.5) 793 (RCP 8.5)
November	2,903	1,999 (RCP 4.5) 1,953 (RCP 8.5)	2,824 (RCP 4.5) 2,529 (RCP 8.5)	3,642 (RCP 4.5) 3,600 (RCP 8.5)
December	4,646	4,869 (RCP 4.5) 5,327 (RCP 8.5)	6,414 (RCP 4.5) 7,194 (RCP 8.5)	9,570 (RCP 4.5) 9,984 (RCP 8.5)
Annual Average	6,361	4,173 (RCP 4.5) 3,876 (RCP 8.5)	5,744 (RCP 4.5) 5,412 (RCP 8.5)	7,361 (RCP 4.5) 7,124 (RCP 8.5)

Notes

All values are in units of cubic feet per second (cfs).

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

Table 3. Future Estimates of Percentage Changes in Spokane River Streamflows at Post Falls, Idaho

Month	Percentage Change (Low Streamflows in 2070–2099 versus Average Historical Streamflows)	Percentage Change (Average Streamflows in 2070–2099 versus Average Historical Streamflows)	Percentage Change (High Streamflows in 2070–2099 versus Average Historical Streamflows)
January	-7.0% (RCP 4.5) +24.7% (RCP 8.5)	+31.5% (RCP 4.5) +50.4% (RCP 8.5)	+66.0% (RCP 4.5) +66.8% (RCP 8.5)
February	+4.8% (RCP 4.5) +61.4% (RCP 8.5)	+64.5% (RCP 4.5) +87.7% (RCP 8.5)	+114.9% (RCP 4.5) +131.0% (RCP 8.5)
March	+2.5% (RCP 4.5) -7.3% (RCP 8.5)	+29.3% (RCP 4.5) +30.2% (RCP 8.5)	+57.3% (RCP 4.5) +71.8% (RCP 8.5)
April	-28.0% (RCP 4.5) -49.7% (RCP 8.5)	-4.4% (RCP 4.5) -15.7% (RCP 8.5)	+15.8% (RCP 4.5) +11.2% (RCP 8.5)
May	-58.4% (RCP 4.5) -81.9% (RCP 8.5)	-41.0% (RCP 4.5) -63.1% (RCP 8.5)	-25.0% (RCP 4.5) -43.4% (RCP 8.5)
June	-81.6% (RCP 4.5) -89.8% (RCP 8.5)	-73.3% (RCP 4.5) -84.5% (RCP 8.5)	-61.8% (RCP 4.5) -76.1% (RCP 8.5)
July	-75.0% (RCP 4.5) -83.4% (RCP 8.5)	-68.9% (RCP 4.5) -77.2% (RCP 8.5)	-59.2% (RCP 4.5) -68.4% (RCP 8.5)
August	-77.8% (RCP 4.5) -84.9% (RCP 8.5)	-66.1% (RCP 4.5) -76.4% (RCP 8.5)	-55.7% (RCP 4.5) -60.3% (RCP 8.5)
September	-70.4% (RCP 4.5) -80.0% (RCP 8.5)	-60.1% (RCP 4.5) -70.9% (RCP 8.5)	-48.5% (RCP 4.5) -56.9% (RCP 8.5)
October	-53.8% (RCP 4.5) -63.9% (RCP 8.5)	-45.9% (RCP 4.5) -56.1% (RCP 8.5)	-35.2% (RCP 4.5) -42.0% (RCP 8.5)
November	-31.2% (RCP 4.5) -32.7% (RCP 8.5)	-2.7% (RCP 4.5) -12.9% (RCP 8.5)	+25.5% (RCP 4.5) +24.0% (RCP 8.5)
December	+4.8% (RCP 4.5) 14.7% (RCP 8.5)	+38.1% (RCP 4.5) +54.8% (RCP 8.5)	+106.0% (RCP 4.5) +114.9% (RCP 8.5)
Annual Average	-34.4% (RCP 4.5) -39.1% (RCP 8.5)	-9.7% (RCP 4.5) -14.9% (RCP 8.5)	+15.7% (RCP 4.5) +12.0% (RCP 8.5)

Notes

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

- **Inflows to the SVRP Aquifer from Adjoining Tributaries.** Historical and future projections of precipitation and runoff were used to define the inflows to the SVRP Aquifer from 52 tributaries that drain to the outer boundary of the aquifer and infiltrate this runoff into the aquifer along its outer margins. The Climate Toolbox was used as the source of the future projections, providing future runoff estimates on a seasonal (rather than monthly) basis and for Spokane County as a whole. As shown in Table 4, these seasonal inflows into the aquifer are estimated to be higher than current flows during the fall and winter months (from approximately September or October through February or March) and lower during the remaining months of the year. (In Attachment B, see Table B-2 and Figure B-2 for the equivalent runoff depths in inches.)

Table 4. Future Estimates of Percentage Changes in Runoff (Tributaries Draining into the SVRP Aquifer)

Season	Percentage Change (Low Runoff in 2070–2099 versus Average Historical Runoff)	(Median Runoff in 2070–2099 versus Average Historical Runoff)	(High Runoff in 2070–2099 versus Average Historical Runoff)
December–February	+19.5% (RCP 4.5) +23.5% (RCP 8.5)	+23.9% (RCP 4.5) +29.6% (RCP 8.5)	+28.2% (RCP 4.5) +35.5% (RCP 8.5)
March–May	-11.9% (RCP 4.5) -15.1% (RCP 8.5)	-6.3% (RCP 4.5) -9.1% (RCP 8.5)	-1.2% (RCP 4.5) -3.6% (RCP 8.5)
June–August	-9.6% (RCP 4.5) -12.2% (RCP 8.5)	-6.5% (RCP 4.5) -8.6% (RCP 8.5)	-3.3% (RCP 4.5) -5.6% (RCP 8.5)
September–November	+10.6% (RCP 4.5) +15.6% (RCP 8.5)	+16.1% (RCP 4.5) +19.8% (RCP 8.5)	+22.6% (RCP 4.5) +22.2% (RCP 8.5)
Annual Average	+1.6% (RCP 4.5) +2.2% (RCP 8.5)	+6.4% (RCP 4.5) +7.4% (RCP 8.5)	+11.2% (RCP 4.5) +11.8% (RCP 8.5)

Notes

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

SVRP = Spokane Valley-Rathdrum Prairie

Details regarding the technical methodology for developing the water demand and climate-change scenarios and simulating them in the groundwater model are provided in the following attachments:

- **Attachment A:** Development of Monthly Distributions for Groundwater Pumping at City of Spokane Well Stations Under Future Water Demand Scenarios
- **Attachment B:** Development of Climate-Change Factors for the City of Spokane Climate-Change Study
- **Attachment C:** Groundwater Flow Model Development for the City of Spokane

The results of the modeling analyses are described below and are presented in terms of various degrees of climate change. As discussed in Attachment B, the correlation of low, average, and high streamflow and tributary inflow valleys to three degrees of climate change are as follows:

- The low degree of climate change involves the smallest reductions in projected dry-season Spokane River streamflows, the highest projected wet-season streamflows in the Spokane River, the smallest projected increases in wet-season tributary inflows, and the smallest projected reductions in dry-season tributary inflows.
- The median degree of climate change involves the median projected changes in Spokane River streamflows and tributary inflows in all months.
- The high degree of climate change involves the largest reductions in projected dry-season Spokane River streamflows, the lowest projected wet-season streamflows in the Spokane River, the largest projected increases in wet-season tributary inflows, and the largest projected reductions in dry-season tributary inflows.

Climate-Change Simulation Results

Peak water demands typically occur in July and August in the region. During the summer season, July is the month that will experience the greatest declines in groundwater levels due to climate-change influences. (Groundwater level declines will also occur in August but will be more modest because August is already the month with the lowest rainfall rates and lowest Spokane River streamflows.)

During July, groundwater elevations are expected to be lower at the City's well stations under each of the future scenarios that were simulated in the groundwater flow model. During the last three decades of the 21st century, future groundwater levels during July are estimated to be between 3 and 11 feet lower than under current conditions, depending on the demand scenario and the degree of climate change that occurs in the future.

- **RCP 4.5:** Under this somewhat optimistic scenario for future GHG emissions, Figure 4 shows that the July groundwater levels are estimated to be between 3.0 and 8.5 feet lower when considering the median degrees of climate change from the available global climate models. The 20-year demand projection and the modest level of 2072 demand have similar results, but the high level of 2072 demand reduces groundwater levels by 0.5 to 3.5 feet more than the two other demand scenarios.
- **RCP 8.5:** Under the "business as usual" scenario for future GHG emissions, Figure 5 shows that the July groundwater levels are estimated to be between 4.0 and 9.5 feet lower when considering the median degrees of climate change from the available global climate models. As with RCP 4.5, the 20-year demand projection and the modest level of 2072 demand have similar results for RCP 8.5, but the high level of 2072 demand under RCP 8.5 reduces groundwater levels by 0.5 to 3.5 feet more than the two other demand scenarios under RCP 8.5.

Lesser degrees of climate change will result in less change in groundwater levels, while the highest degrees of climate change obtained from the Climate Toolbox will cause greater lowering of groundwater levels than under the median level of change shown in Figures 4 and 5. For example, at the Nevada Well Station, the median level of RCP 8.5 climate change is estimated to cause a 9.5-foot water level decline as shown in Figure 5, but the highest degree of RCP 8.5 climate change presented in the Climate Toolbox is estimated to cause an 11-foot water level decline at this well station. To help illustrate the effects of both increased water demands and various degrees of climate change, Figures 6 through 13 each compare the changes in groundwater levels for all 18 simulated scenarios at a specific well station. These figures are presented in a sequence starting with the northernmost well station (Central; Figure 6) and progressing southwards to other well stations located north of the Spokane River (Hoffman in Figure 7, which is southeast of the Central well station; and the Nevada and Grace well stations further to the south [Figures 8 and 9]). These are followed by the well stations that are located south and east of the Spokane River (Well Electric, Parkwater, Ray Street, and Havana Street; Figures 10, 11, 12, and 13, respectively). In each figure, the left-hand graphic groups the changes in future summer-season groundwater levels according to the level of water demand inside the City of Spokane, while the right-hand graphic shows the changes in a progressive sequence (from the least change to the greatest change).

The left-hand plots show that some of the climate scenarios produce very similar changes in summer-season groundwater levels for a given level of demand. For example, the summer groundwater level change under the low degree of climate change for RCP 8.5 is equal to (or within 0.5 feet of) the summer groundwater level change that occurs under the median degree of climate change for RCP 4.5. Similarly, the summer groundwater level change under the median degree of climate change for RCP 8.5 is equal to (or within 0.5 feet of) the summer groundwater level change occurring under the high degree of climate change for RCP 4.5. The high degree of climate change under RCP 8.5 stands out from the other simulations as producing the notably greatest declines in groundwater levels.

The right-hand plots show that the declines at some wells are somewhat more controlled by the level of water demand, while the declines at other wells are more controlled by the degree of climate change. For example, the Grace and Nevada well stations show that the orange bars are generally clustered together on the right side of the plot, which indicates that the greatest declines in water levels are for the high level of 2072 demand, regardless of the degree of climate change. In contrast, the orange bars for the Ray Street and Havana Street well stations are interspersed across the plots, which suggests that the level of demand is not as dominant an influence on the water levels as occurs at the Grace and Nevada well stations.

Comparison of Future Projected Groundwater Levels with Well Construction and Pumping Systems at Each Well Station

To date, the City has conducted formal assessments of the conditions of seven of its eight well stations (GSI et al., 2017; GSI et al., 2019a, 2019b, and 2019c; GSI and Murraysmith, 2020; GSI et al., 2023). These assessments have included comparisons of historical groundwater levels over multi-year periods against the depths of specific physical characteristics that govern each water station's ability to meet target pumping capacities and to sustain pumping through variable background hydrologic conditions. The critical factors for maintaining pumping pertain to (1) the height of the groundwater level above pump intakes and (2) the position of the groundwater level relative to the total depth of each well and the depths of either the well screen (for the vertical wells at the Havana Street well station) or the perforations/weep holes (for the caisson wells that are present at the other well stations).

For each well station except Parkwater, which has not yet been evaluated, Figures 14 through 20 display schematic diagrams with vertical scales showing the positions (i.e., elevations) of the historical low groundwater level, the projected range of future low groundwater levels in 2070–2099, the bottom of the well, the position of each pump intake inside the well, and the submergence requirements for each pump. Blue shading is used to show the position of the water column in the well for (1) historical conditions (the left-most panel on each figure), (2) the future scenario with the smallest projected decline in 2070–2099 groundwater levels (the middle panel on each figure), and (3) the future scenario with the largest projected decline in 2070–2099 groundwater levels (the right panel on each figure). Each figure is constructed to not only display the physical positions (i.e., elevations) of the water levels, wells, and pumps, but also the height of the water column that is critical for maintaining operation of each pump (which is labeled as the "required submergence depth" on each figure). Observations for each of the seven well stations that have been evaluated to date are as follows (starting with the northern-most well stations and progressing to the eastern-most and southern-most well stations):

- **Central Well Station (Figure 14):** The historical and projected 2070–2099 low groundwater levels at this well station are substantially higher than the required submergence depths for the two existing pumps. This indicates that modifications to the pumping system and the caisson are likely not necessary to maintain current pumping rates/volumes at the Central well station.
- **Hoffman Well Station (Figure 15):** The historical and projected 2070–2099 low groundwater levels at this well station are substantially higher than the required submergence depth for Pump 2, but are below the required submergence depth for Pump 1. This indicates that (1) modifications to Pump 2 and the caisson are likely not necessary to maintain current pumping rates/volumes from Pump 2, and (2) deepening Pump 1 to a similar depth as Pump 2 would be necessary (and feasible) for sustaining pumping from Pump 1. The concept plan for improvements at the Hoffman well station (GSI et al., 2019d) called for improvements to the caisson structure housing Pump 2 and reinstalling the pump to a depth of 7 feet above the bottom of the well. The concept plan did not contemplate changes to the depth of Pump 1.

- **Nevada Well Station (Figure 16):** Although the historical low groundwater level at this well station is higher than the required submergence depth for each of the four pumps in this caisson well, the projected 2070–2099 low groundwater levels are below the required submergence depth for all four pumps. Because the pump intakes are less than 10 feet above the bottom of the caisson, require between 4 and 7 feet of submergence, and must be as much as 5 feet above the bottom of the caisson for proper operation, it is not possible to further lower the pumps to accommodate the 7- to 11-foot declines that could occur for future low groundwater levels compared with historical levels, unless the caisson were to be deepened and/or pump chambers were to be drilled and installed below the existing floor of the caisson (GSI et al., 2023). The City is currently evaluating options for modifying the existing caisson and/or installing a new water supply source consisting of vertical wells at this well station.
- **Grace Well Station (Figure 17):** Conditions at the Grace well station are similar to the Nevada well station, except the two pumps at Grace are shallower than at Nevada, and the caisson at Grace is slightly deeper (by 4 feet) than the caisson at Nevada. Hence, it may be feasible to lower the two pumps in Grace to accommodate future water level declines. (Further study would be required to evaluate this possibility.)
- **Well Electric Well Station (Figure 18):** For Pump 1 and Pump 3, which are vertical line-shaft turbine pumps installed in the Well 5 caisson, the projected 2070–2099 low groundwater levels are projected to drop to depths just above or just below the required pump submergence depths. Lowering these pumps is likely infeasible due to the depth of the Well 5 caisson. For Pump 2 and Pump 4, which are centrifugal pumps placed inside the Well 5 and Well 4 caissons, respectively, their significant submergence requirements cause the historical and projected future low groundwater levels to be below the critical threshold depths for maintaining their pumping under low groundwater level conditions. As discussed by GSI et al. (2019a), deepening the two caissons and/or installing pump chambers through and below the bottoms of the caissons could allow the pumps to be deepened; however, as discussed by GSI et al. (2019e), these options are not included in the concept plan for this well station because they would not eliminate the current need to shut down the well station when river flows are high and hence would not meet the City's objectives for resiliency at this well station.
- **Ray Street Well Station (Figure 19):** Although the historical low groundwater level at this well station is higher than the required submergence depth for each of the three pumps in this caisson well, the projected 2070–2099 low groundwater levels are below the required submergence depth for all three pumps. As discussed by GSI et al. (2019f), the City is planning to lower the intakes of the three existing pumps by 5 to 7 feet and add a fourth pump to optimize production from this well station.
- **Havana Street Well Station (Figure 20):** For the six recently-constructed vertical wells at this well station, the historical low and projected 2070–2099 low groundwater levels at this well station are higher than the required submergence depth for the well screen. At each well, the pump will be installed in a sump that is below the well screen. Accordingly, the depths of the well screens and the placement of each pump below the well screen are expected to continue providing sufficient submergence in the future, so as to not require modifications to the wells or pumps to maintain pumping.

In summary, modifications are likely to be required at five of the seven well stations that have been evaluated to date, in order to address the lowering of groundwater levels that is projected by this study as being likely to occur during the latter three decades of the 21st century. Modifications are likely not needed at the two other well stations (Central and Havana Street). The need for modifications at the eighth well station (Parkwater) is unknown at this time.

Conclusions

The primary conclusion from the study is that future changes in groundwater levels at the City's well stations are expected to be less than 10 feet in many of the future scenarios evaluated with the model. Only one simulation resulted in a water level decline of more than 10 feet, which was a model-estimated 11-foot decline at the Nevada Well Station for the greatest degree of climate change under RCP 8.5. As discussed above, the projected declines in groundwater levels in the aquifer are estimated to result in operational limitations for the existing caisson wells and pumping systems at five or six of the City's eight well stations.

One important observation from the family of simulations is that climate change generally has more influence than increasing water demands on the amount of groundwater level change that could occur in the future. This is noted by comparing the simulation results for the 20-year and 50-year projections. Specifically, the high degree of climate change for RCP 8.5 under the 20-year water demand projection simulates significant climate change under only a modest increase in water demands, thereby providing an estimate of changes that reflects climate-change effects in the SVRP Aquifer more so than the effects of changing demands. The difference between that simulation and the simulation of a high degree of climate change for RCP 8.5 under the most aggressive 50-year water demand projection shows the effect of future water demands alone. As indicated in Table 5, these two simulations show that most of the total projected future groundwater level decline in July arises from the amount of climate change that is projected to occur during the latter three decades of the 21st century. The increase in demands between the 20-year and most aggressive 50-year projections only accounts for 1 to 2 feet of the total change that is projected in the future (though this demand-driven change is slightly greater at the Parkwater [2.5 feet], Grace [3.5 feet], and Nevada [4.0 feet] well stations).

Table 5. Estimates of Future Groundwater Level Changes in July at City Well Stations

Well Station	Total Change in Summer Water Levels Under the 20-Year Demand Projection and High RCP 8.5 Climate Change for 2070–2099	Total Change in Summer Water Levels Under the Aggressive 50-Year Demand Projection and High RCP 8.5 Climate Change for 2070–2099	Change in 2070–2099 Summer Water Level Due to the Difference Between the 20-Year and 50-Year Demand Projections
Central	-6.5	-8.5	-2.0
Hoffman	-5.5	-6.5	-1.0
Nevada	-7.0	-11.0	-4.0
Grace	-6.5	-10.0	-3.5
Well Electric	-7.0	-8.5	-1.5
Parkwater	-7.5	-10.0	-2.5
Ray Street	-5.5	-6.5	-1.0
Havana Street	-6.5	-7.5	-1.0

Notes

All values are in units of feet.

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

In summary, climate change is likely to contribute more than future changes in water demands to the water level declines that are projected by this study to occur in the future, with changes in Spokane River flows at Post Falls being the largest climate-change influence. This finding is similar to what has been observed to occur in the region during the past few decades. A phased study conducted by the Spokane Aquifer Joint

Board (SAJB) from 2014 through 2016 (Porcello et al., 2017) examined the historical decreases in the seasonal low flows of the Spokane River since the early 1900s, with particular focus on evaluating why the seasonal low flows at the stream gage in downtown Spokane were continuing to decrease in recent decades. The study found that an approximately 40 percent reduction in summer-season water use in the Spokane/Coeur d'Alene metropolitan region had occurred by the late 1980s compared with summer-season water uses during the 1940s and 1950s. The reduction in peak-season regional water uses began when surface water diversions for agricultural water use ended in the 1960s, The SAJB study found that despite the reductions in water use, river flows were still declining, and other changes over the footprint of the SVRP Aquifer (such as changes in stormwater management, wastewater discharges, and irrigation water use) were found to have little influence on the continued declines in the river's seasonal low flows during the rest of the 20th century and the first 15 years of the 21st century. The last phase of the SAJB study examined data on snowpack conditions in the watersheds contributing flow into Coeur d'Alene Lake and found that notable shifts in the magnitudes and timing of snow accumulation and melt had occurred during the first 15 years of the 21st century compared with conditions during the last two decades of the 20th century. The SAJB study found a correlation between recent historical changes in April snowpack conditions and the continuation of historical decreases in August low flows in the Spokane River in downtown Spokane. The projections from climate models of future climate-driven changes in Spokane River flows are consistent with the findings of SAJB's historical study of the changes in Spokane River flows.

Limitations of this Study

The study described in this technical memorandum used a detailed process for (1) identifying and studying a range of climate-change scenarios that are projected to affect the SVRP Aquifer and the surrounding watershed in which it resides; (2) carefully constructing water demand scenarios that consider a range of future water demand needs at two different time frames in the future (20 years and 50 years); and (3) evaluating the influences of changing climate and changing demands on the City's well stations by using a three-dimensional numerical groundwater flow model of the SVRP Aquifer. Nonetheless, despite the detail and the in-depth nature of this study, the supporting data and analyses provides a simplification of a complex climatic and hydrogeologic system, and also contains certain built-in assumptions pertaining to these systems and the nature of future water demands. Accordingly, the interpretations and conclusions presented in this study should not be viewed as absolute results and could change in the future as new climate and demand projections become available and as the groundwater model is refined in the future (which is anticipated to occur in coming years for the portions of the SVRP Aquifer lying outside the City).

In addition to the general limitations described above, the study presented in this memorandum has some specific limitations:

- The study did not account for changes in future water demands (and hence increases in future pumping from the SVRP Aquifer) that would occur outside of the City of Spokane. Increased future pumping by municipal water suppliers east of the City in both the Washington and Idaho portions of the SVRP Aquifer could further lower groundwater levels inside the City. However, this additional decrease in groundwater levels at the City's well stations would likely be only a small percentage beyond the water level decreases described in this study. GSI understands that the Spokane Aquifer Joint Board (SAJB) and the Idaho Washington Aquifer Collaborative (IWAC) intend to fund similar studies in upcoming years that will focus on their municipal water supply wells; if conducted, those studies would provide clarity on this question for the City's well stations.
- This study also did not simulate climate-change-based variations in two aspects of the natural hydrologic system:
    - **Subsurface Recharge from Lakes.** The subsurface inflow rates from lakes that bound the SVRP Aquifer are simulated as being generally similar in the future as under present conditions, meaning

that no lake-derived climate-change influences on the SVRP Aquifer are simulated in the model. Prior studies provide a significant range of estimates for the annual water being recharged to the SVRP Aquifer from the bounding lakes. The lowest and highest published estimates range from 185 mgd (287 cubic feet per second [cfs]) by the U.S. Geological Survey (USGS) (Kahle and Bartolino, 2007) to 280 mgd (435 cfs) as reported in *The Spokane Valley-Rathdrum Prairie Aquifer Atlas, 2015 Edition*. The groundwater flow model developed for the study described in this technical memorandum predicts that under current-day conditions, combined recharge from all bounding lakes is seasonal, ranging from approximately 80 mgd (124 cfs) to 200 mgd (465 cfs), and averaging approximately 125 mgd (193 cfs) over the course of a full year.

- **Recharge over the Footprint of the SVRP Aquifer.** In the groundwater model, this recharge (which varies spatially and arises from precipitation, agricultural irrigation, urban irrigation, and septic systems) is based on land use information that is on the order of 20 years old (or older). As a result, these rates do not reflect current or projected future land and water uses.

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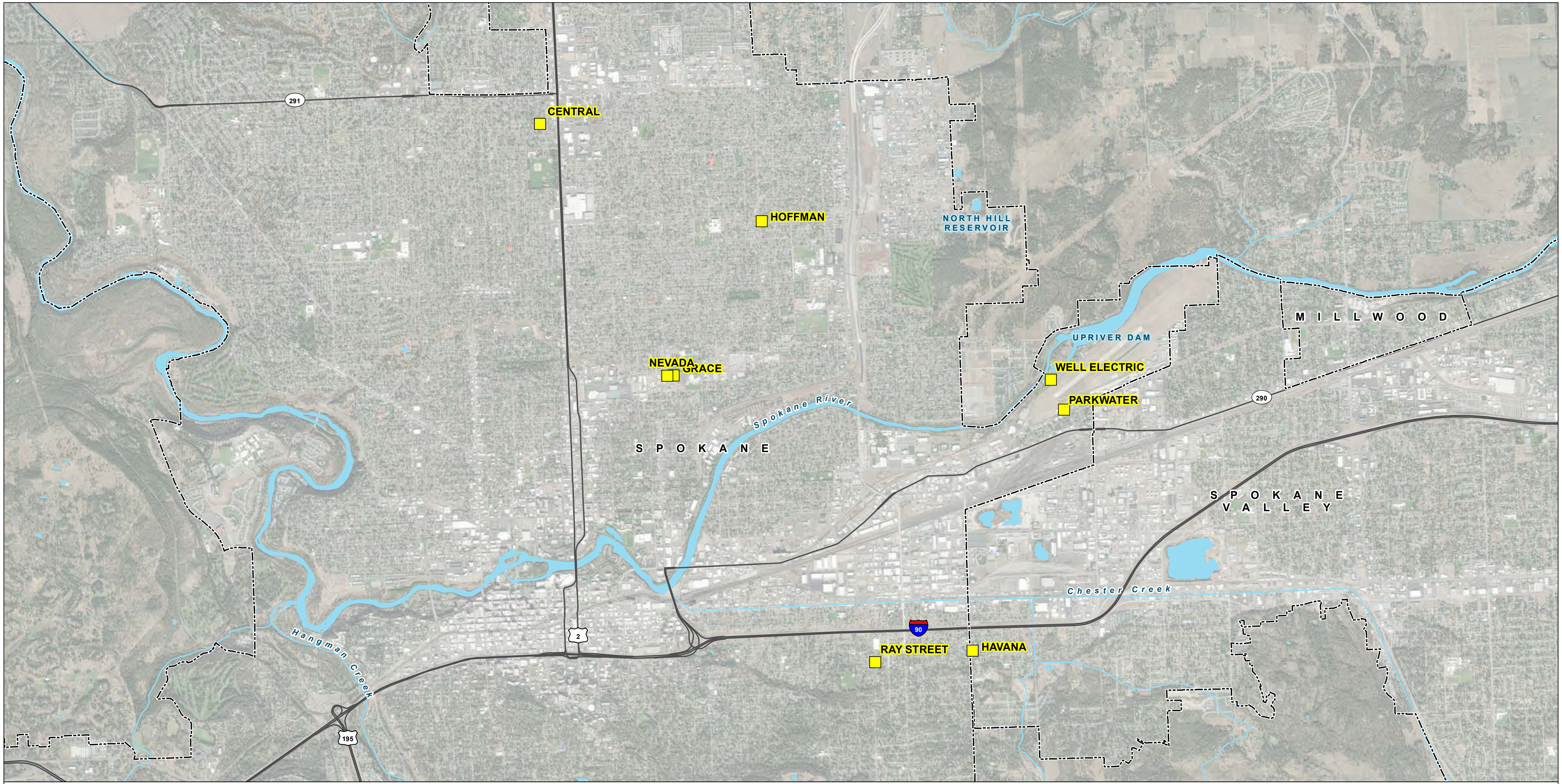
Figures



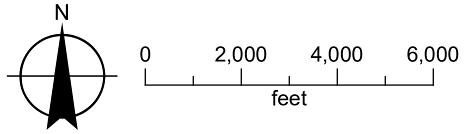
LEGEND

- 🟨 Well Station
- ⬚ City Boundary
- Major Road
- Watercourse
- Waterbody

FIGURE 1

Location Map for City Well Stations

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System



GSI Water Solutions, Inc.

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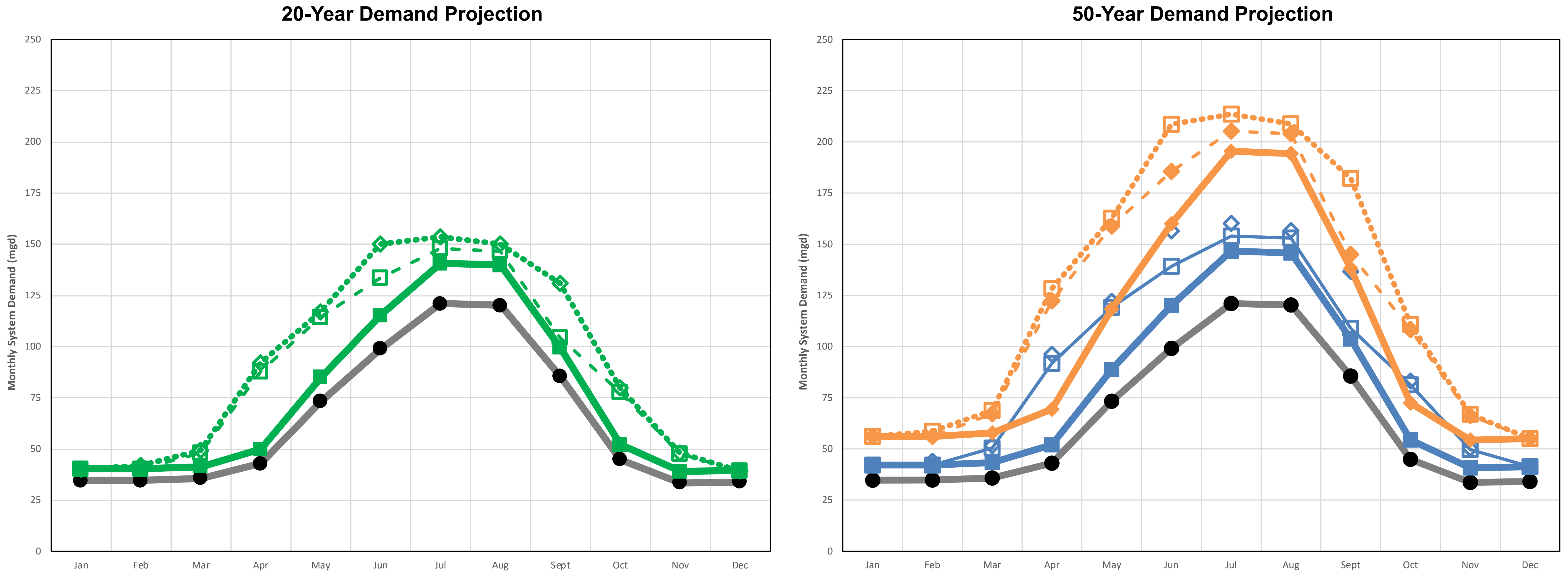

Average-Day Demands (ADD) and Maximum-Day Demands (MDD)

2015–2020:
ADD = 63.60 mgd, MDD = 141.30 mgd

2042:
ADD = 91.47 mgd, MDD = 186.42 mgd

Average-Day Demands (ADD) and Maximum-Day Demands (MDD)

2015–2020:
ADD = 63.60 mgd, MDD = 141.30 mgd

2072 Modest Level of Demand:
ADD = 95.32 mgd, MDD = 217.40 mgd

2072 High Level of Demand:
ADD = 127.06 mgd, MDD = 259.75 mgd

LEGEND

- 2015–2020 Avg. Demands
- 2042 Demands, No Climate Change
- 2042 Demands, RCP 4.5 Avg. Emissions Scenario
- 2042 Demands, RCP 8.5 Avg. Emissions Scenario
- 2072 Modest Level of Demand, No Climate Change
- 2072 Modest Level of Demand, RCP 4.5 Avg. Emissions Scenario
- 2072 Modest Level of Demand, RCP 8.5 Avg. Emissions Scenario
- 2072 High Level of Demand, No Climate Change
- 2072 High Level of Demand, RCP 4.5 Avg. Emissions Scenario
- 2072 High Level of Demand, RCP 8.5 Avg. Emissions Scenario

FIGURE 2

Historical and Projected Water Demands

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.

NOTES

RCP: Representative Concentration Pathway for future global greenhouse gas emissions.

The City's water rights are for an instantaneous pumping rate of 241,100 gallons per minute (gpm), which is equivalent to 347.184 million gallons per day (mgd). The annual pumping allowed under the City's water rights is 147,570 acre-feet per year.

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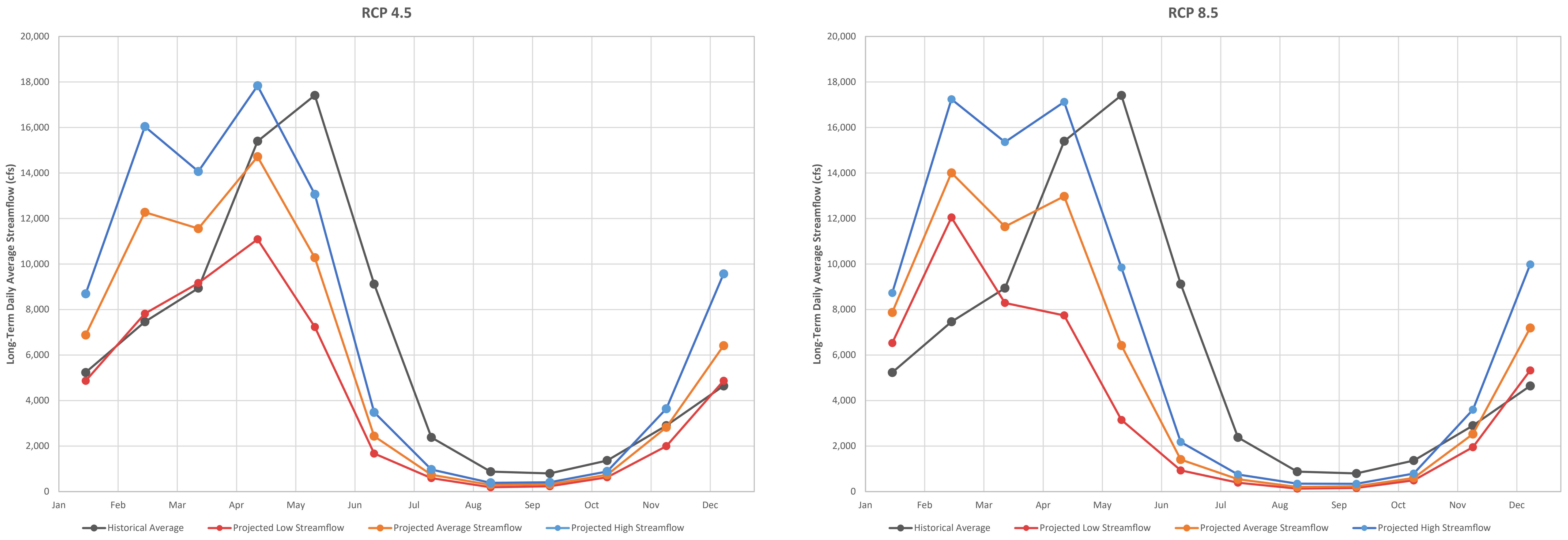

NOTE

RCP = Representative Concentration Pathway for global greenhouse gas emissions

FIGURE 3

Projected Monthly Streamflows in 2070–2099 for the Spokane River at Post Falls, Idaho

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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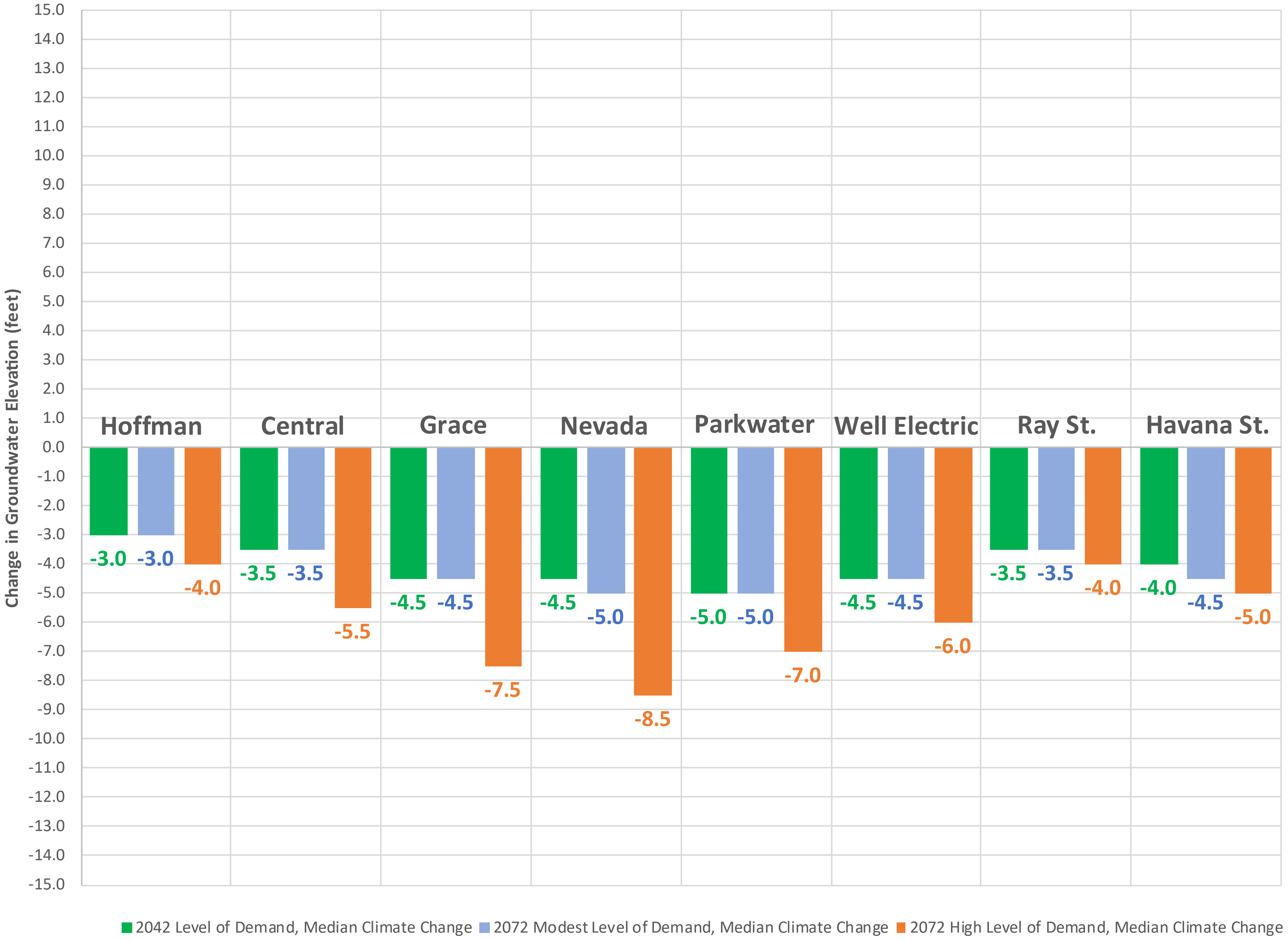

FIGURE 4

Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099
at City of Spokane Well Stations for the Median Projected Degree of RCP 4.5 Climate Change

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.

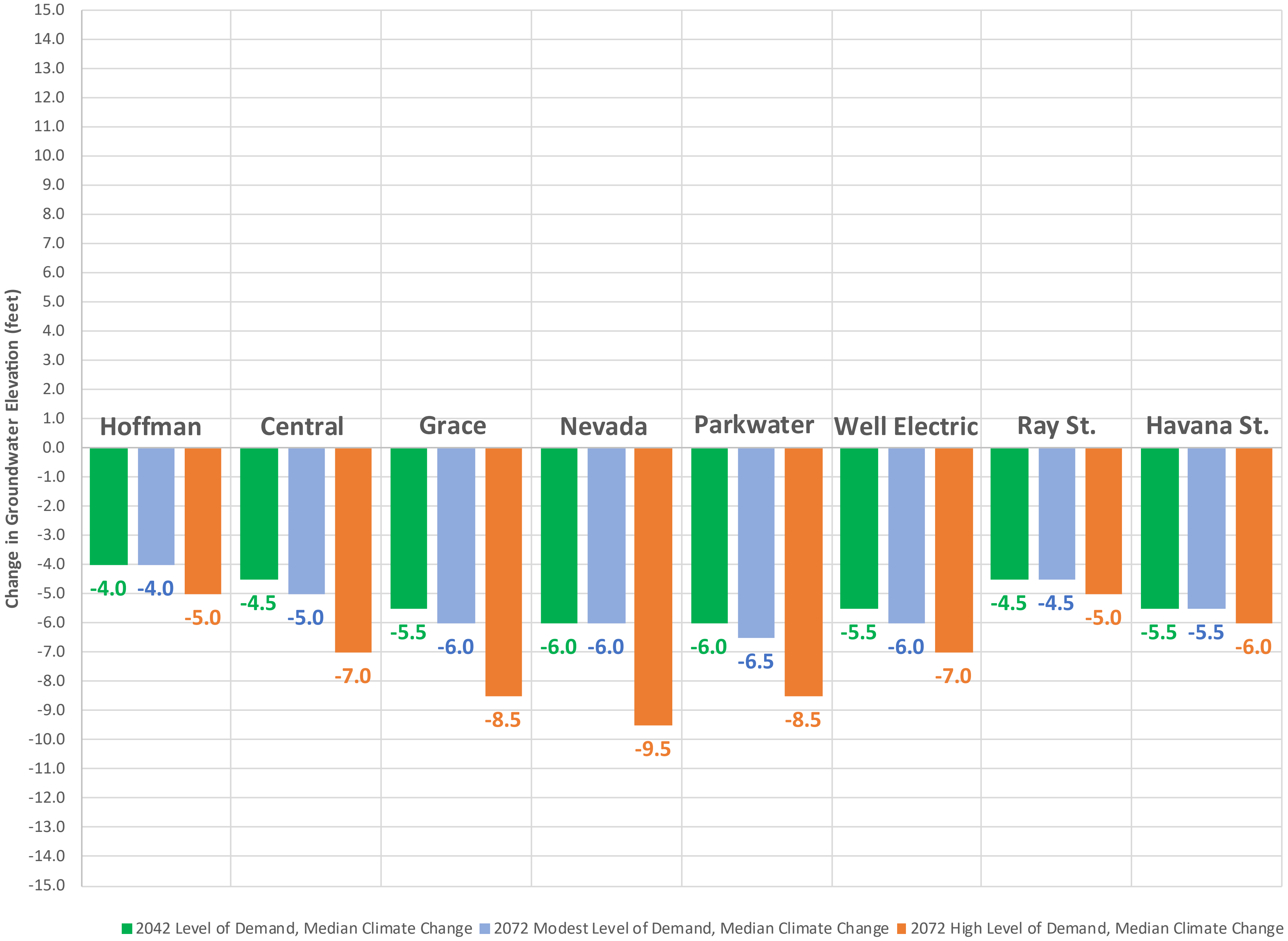

FIGURE 5

Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at City of Spokane Well Stations for the Median Projected Degree of RCP 8.5 Climate Change

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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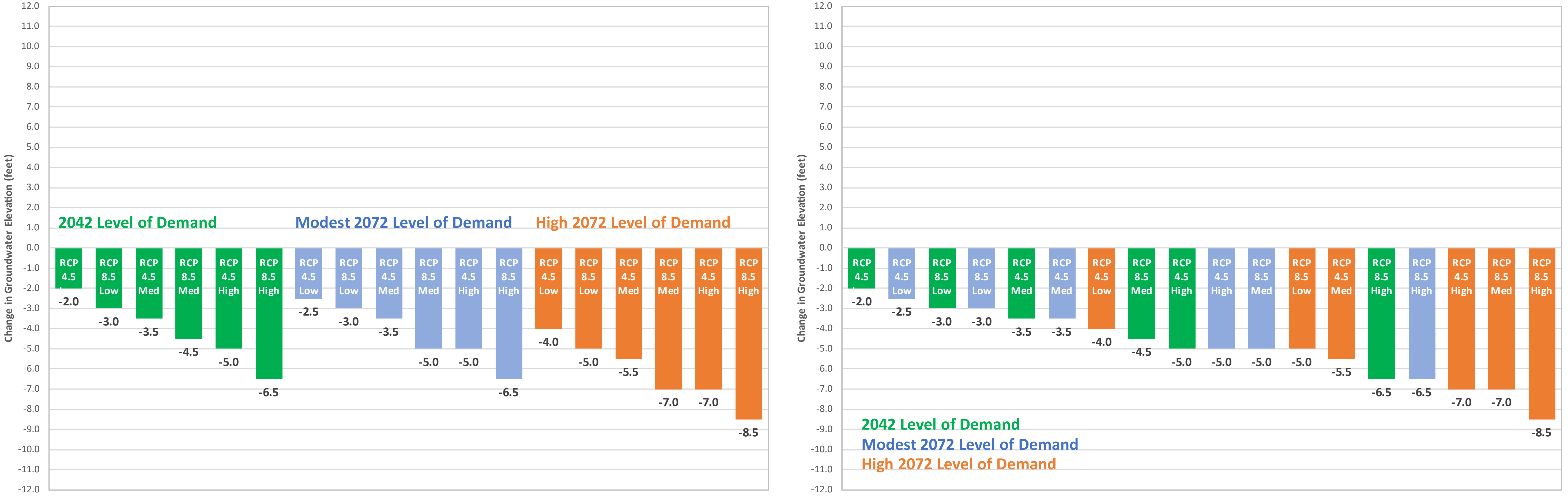

NOTES

On the vertical bars, the terms Low, Medium, and High refer to the degree of climate change influence on the aquifer system and the City's well stations in 2070-2099.

- The low degree of climate change involves the smallest projected reductions in May-October streamflows in the Spokane River combined with the smallest projected increases in winter-season tributary inflows.
- The high degree of climate change involves the largest projected reductions in May-October streamflows in the Spokane River combined with the largest projected increases in winter-season tributary inflows.
- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 6

Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Central Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.

NOTES

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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 7

Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Hoffman Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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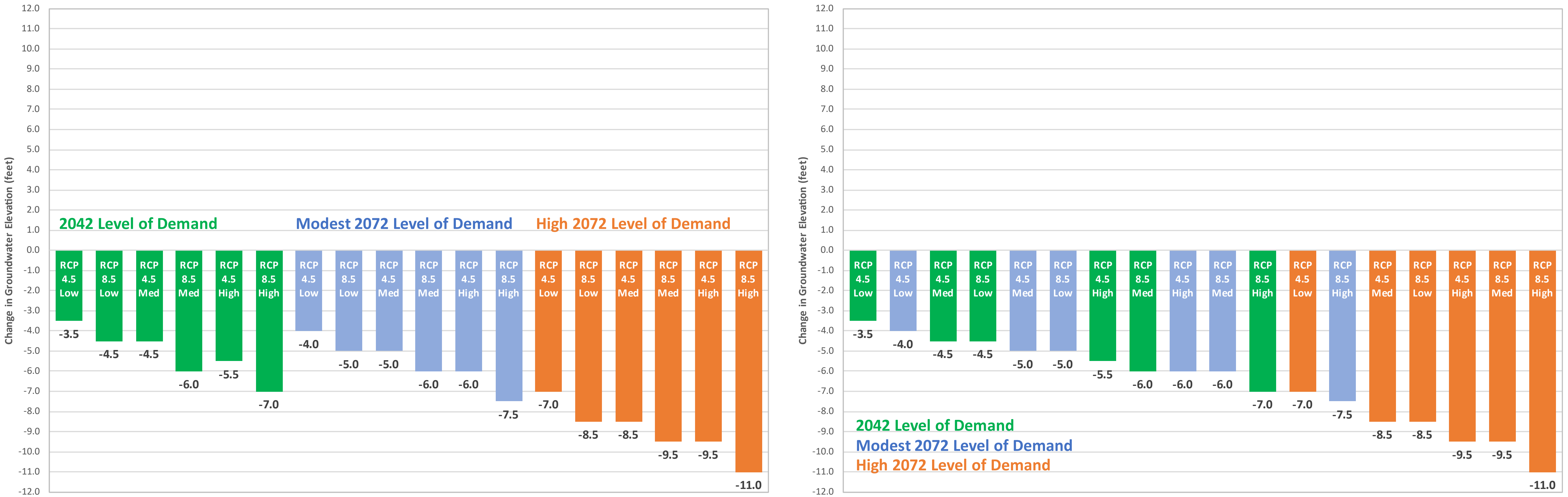
Water Solutions, Inc.



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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

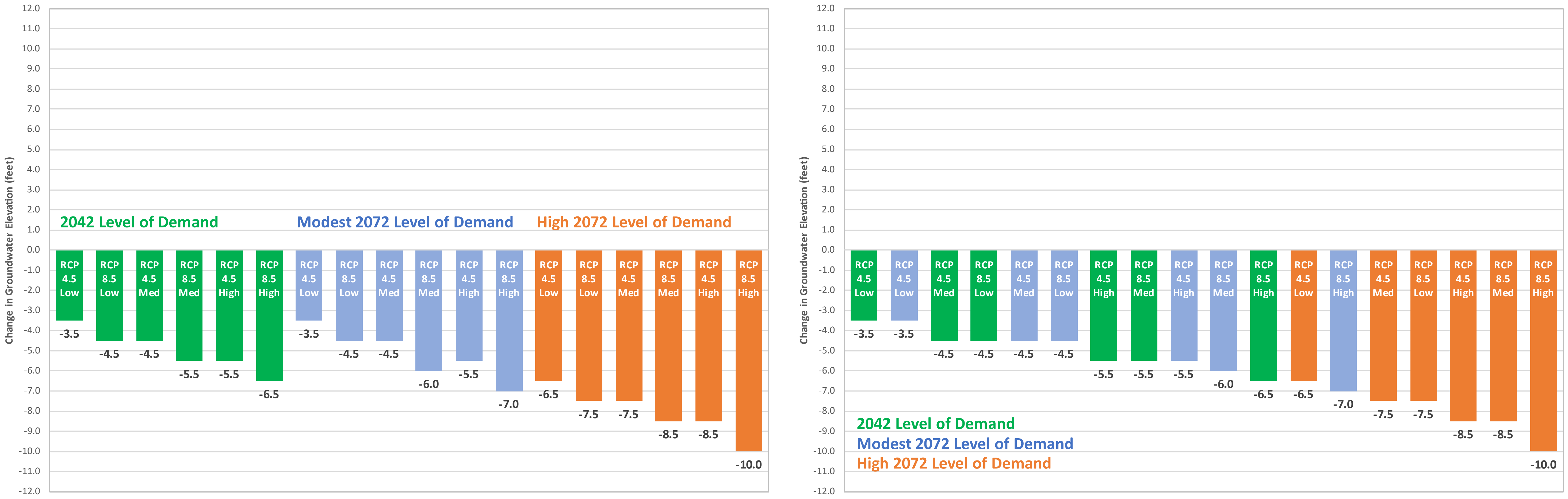
RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 8

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Nevada Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.



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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 9

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Grace Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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NOTES

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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 10

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Parkwater Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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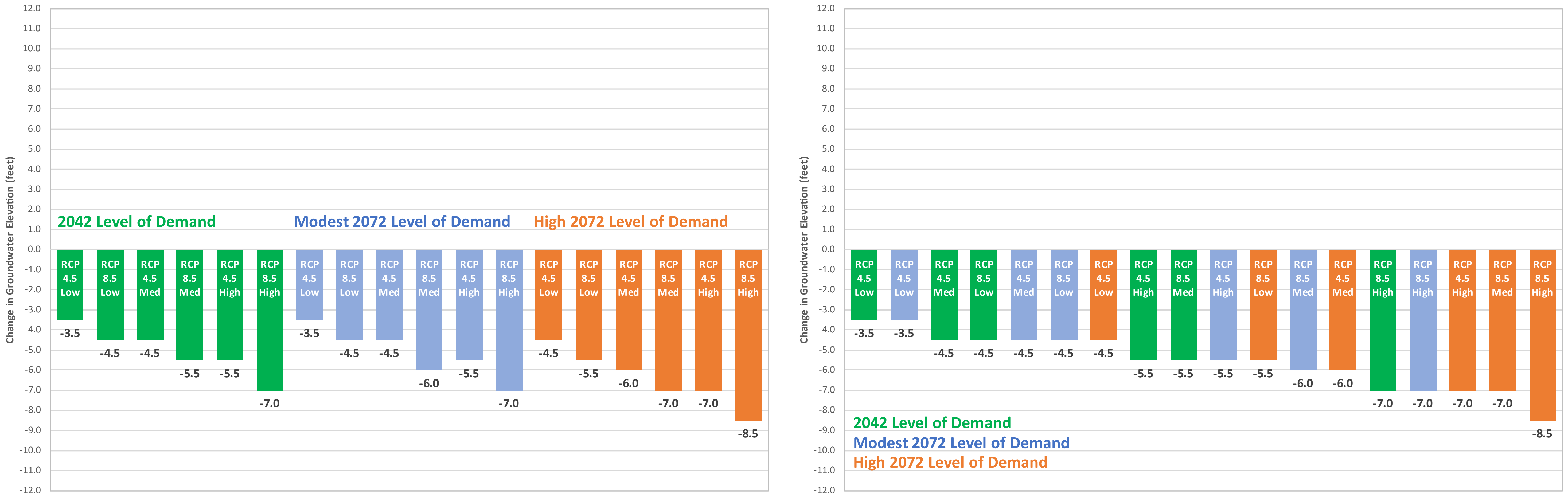

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- The high degree of climate change involves the largest projected reductions in May-October streamflows in the Spokane River combined with the largest projected increases in winter-season tributary inflows.
- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

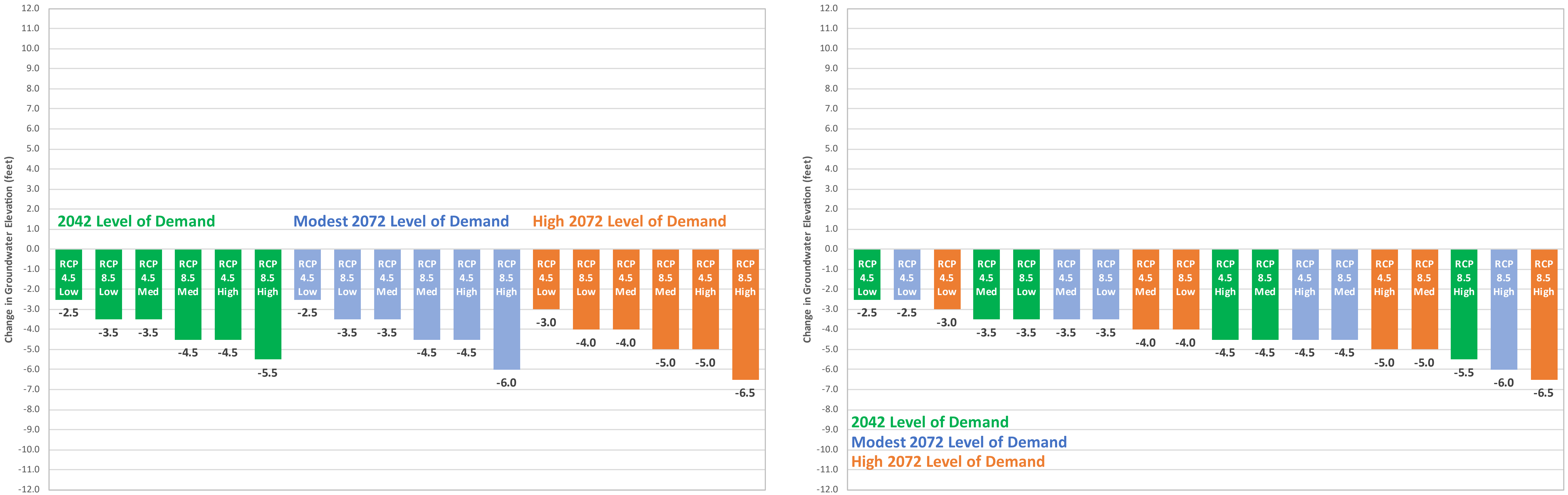
RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 11

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Well Electric Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.



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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 12

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Ray Street Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

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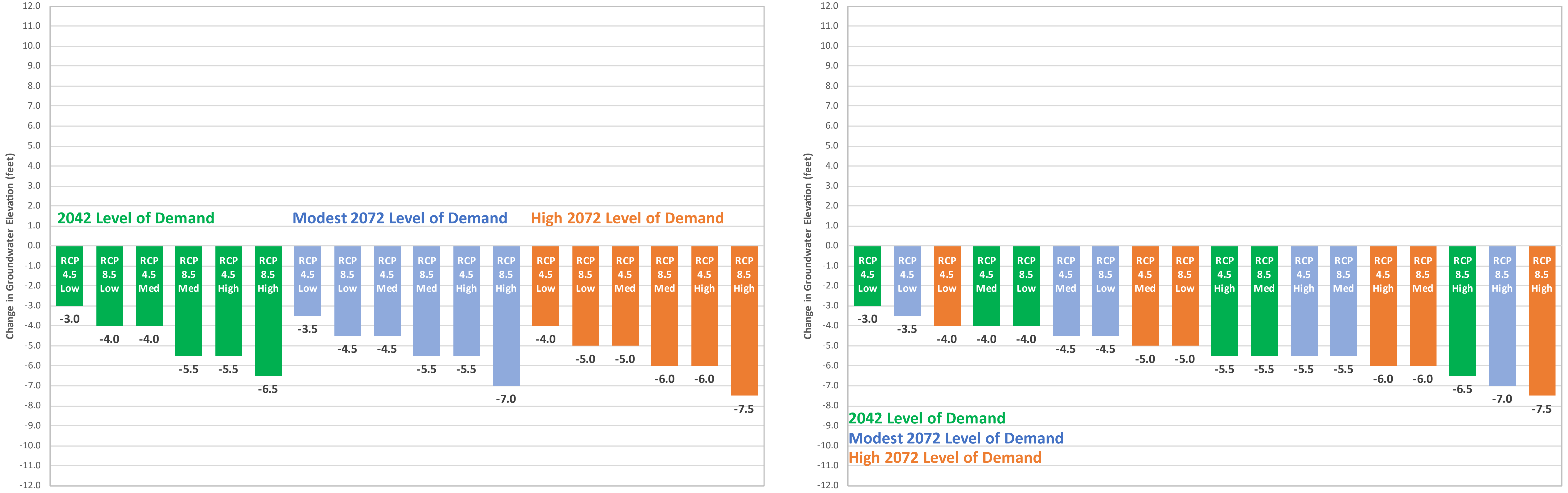
Water Solutions, Inc.



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- The median degree of climate change involves the median changes in Spokane River streamflows and tributary inflows.

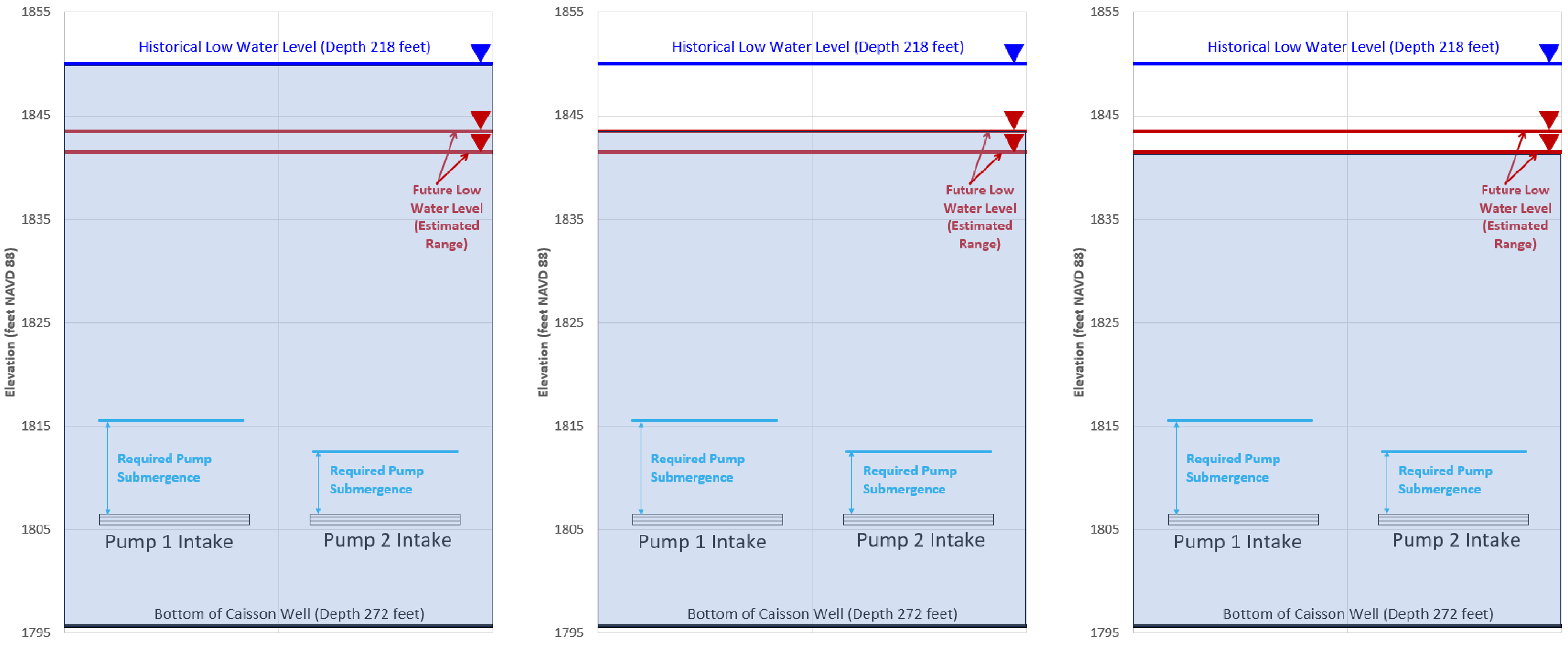
RCP = Representative Concentration Pathway for global greenhouse gas emissions.

FIGURE 13

Model-Estimated Changes in Summer-Low Groundwater Elevations in 2070–2099 at the Havana Street Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.



LEGEND

▬ Historical Low Water Level

▬ Future Low

▬ Bottom of Caisson Well

■ Water Column

FIGURE 14

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Central Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.

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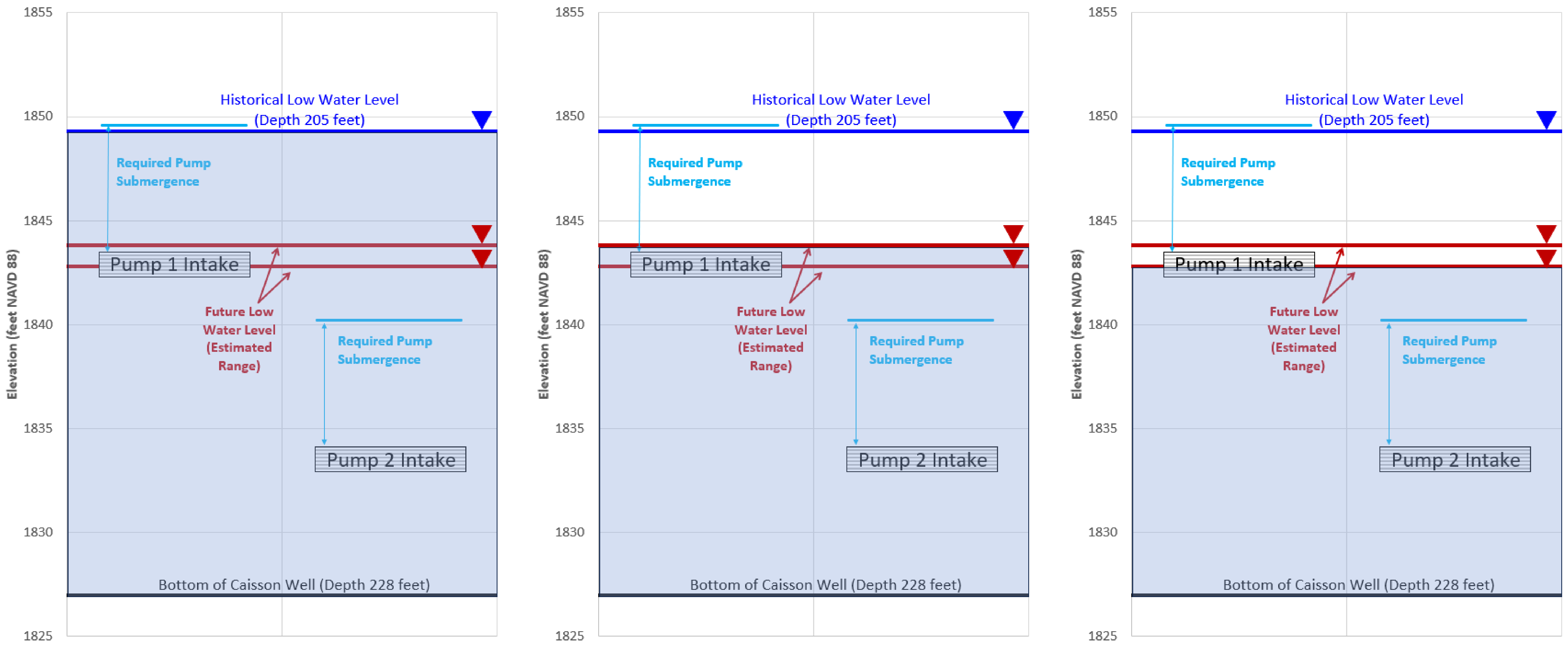


LEGEND

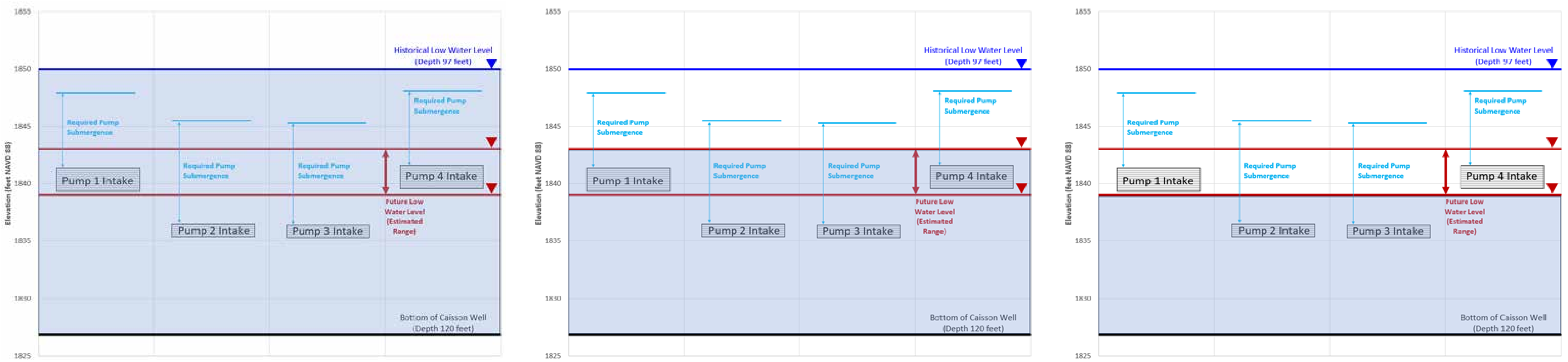
- ▬ Historical Low Water Level
- ▬ Future Low
- ▬ Bottom of Caisson Well
- ▭ Water Column

FIGURE 15

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Hoffman Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System

GSI
Water Solutions, Inc.



LEGEND

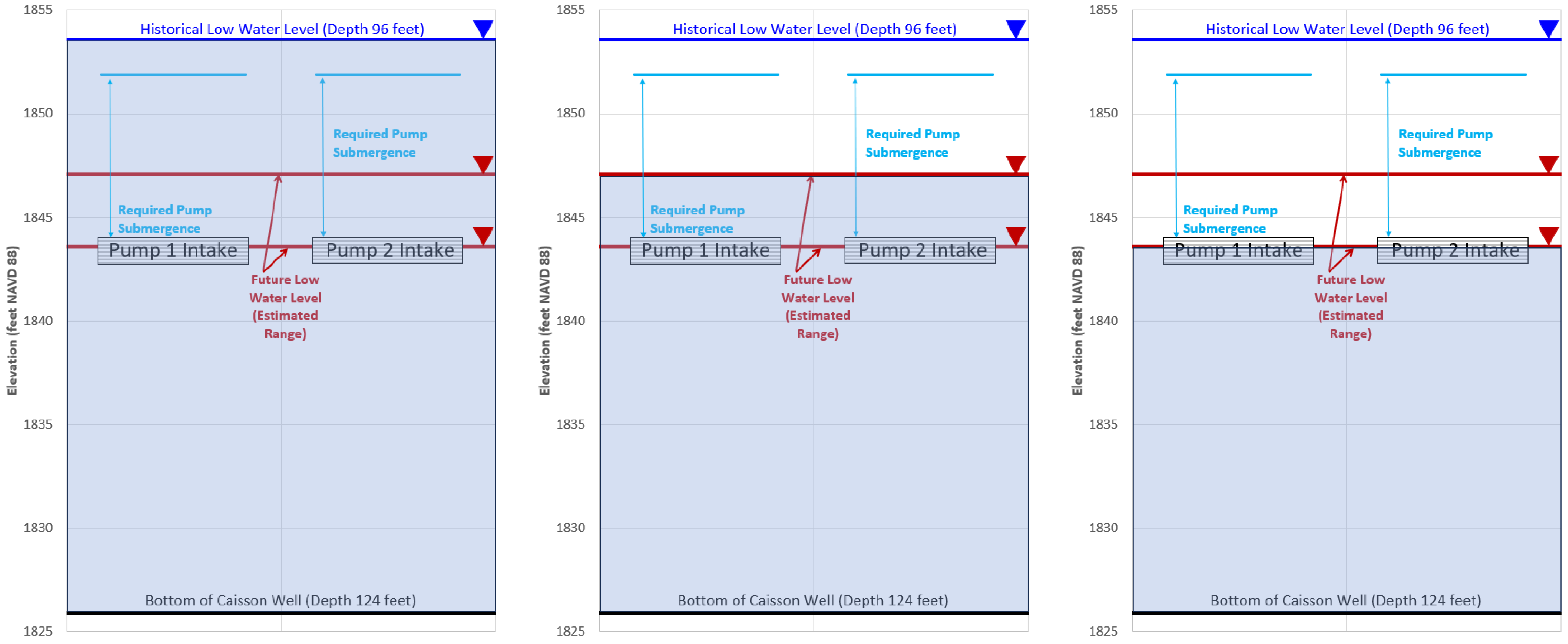
- Historical Low Water Level
- Future Low
- Bottom of Caisson Well
- ▨ Water Column

FIGURE 16

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Nevada Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.



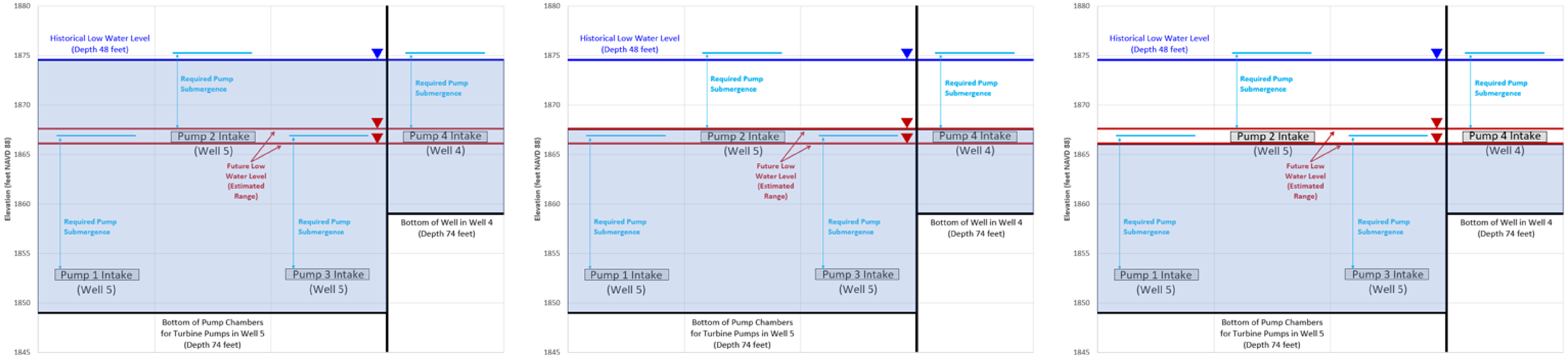
LEGEND

- Historical Low Water Level
- Future Low
- Bottom of Caisson Well
- Water Column

FIGURE 17

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Grace Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System



LEGEND

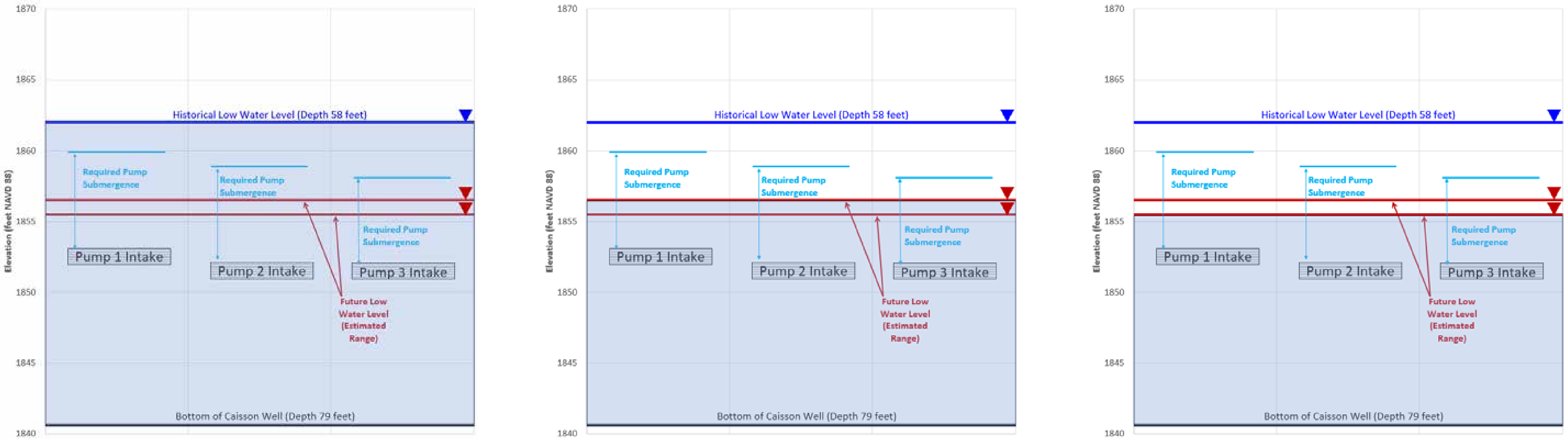
- 🟦 Historical Low Water Level
- 🟥 Future Low
- ⬛ Bottom of Caisson Well
- ▨ Water Column

FIGURE 18

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Well Electric Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in
City of Spokane Well Stations Arising from Increased Water Demands and
Climate Change Influences on the Regional Aquifer System

GSI
Water Solutions, Inc.



LEGEND

▬ Historical Low Water Level

▬ Future Low

▬ Bottom of Caisson Well

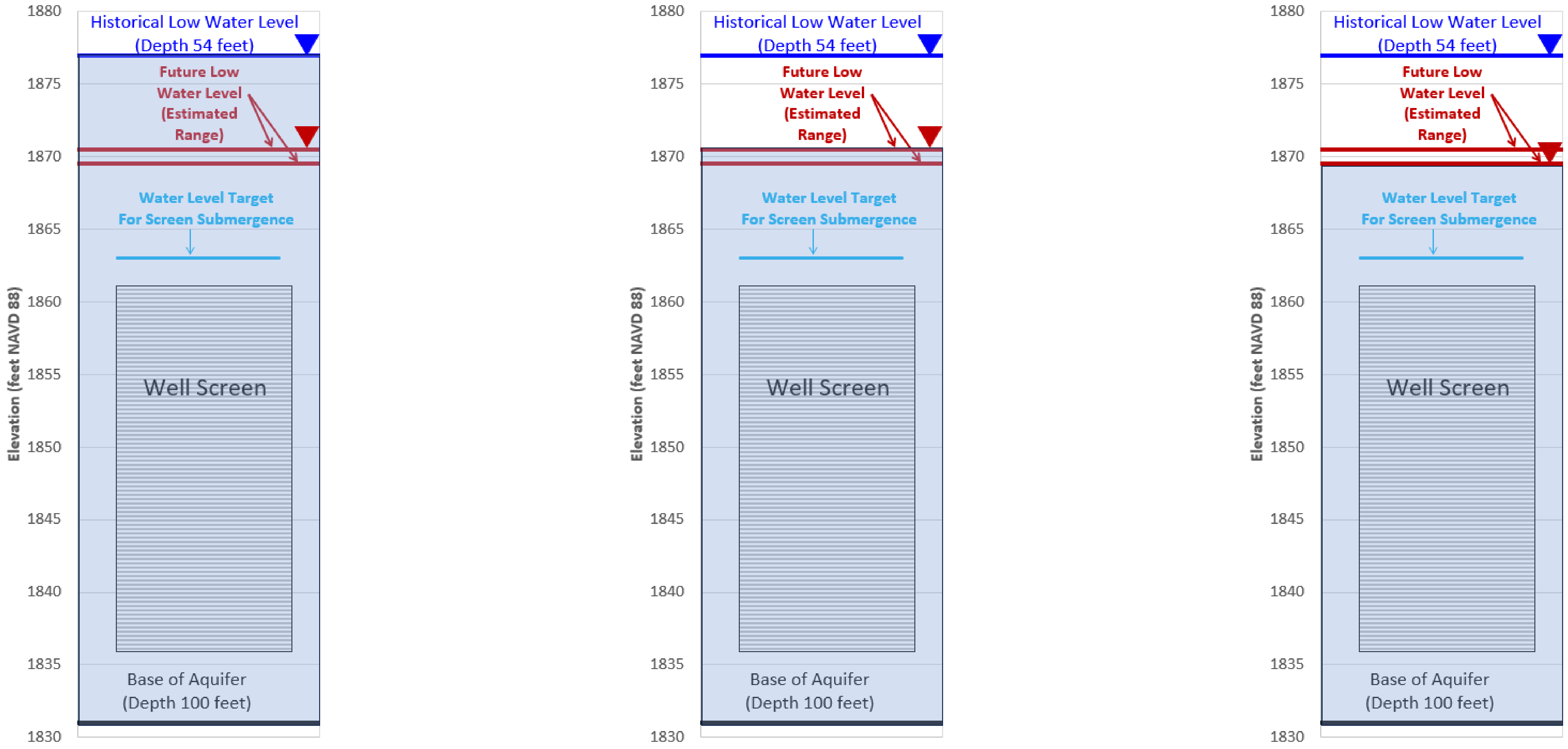
▨ Water Column

FIGURE 19

Comparison of Historical and Projected Groundwater Levels with Well Depths, Pump Depths, and Pump Submergence Requirements for the Ray Street Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI
Water Solutions, Inc.



LEGEND

— Historical Low Water Level

— Future Low

— Bottom of Caisson Well

▨ Water Column

FIGURE 20

Comparison of Historical and Projected Groundwater Levels with Well Depths and Well Screen Submergence Requirements for the Havana Street Well Station

Groundwater Modeling Study of Potential Changes to Water Levels in City of Spokane Well Stations Arising from Increased Water Demands and Climate Change Influences on the Regional Aquifer System

GSI Water Solutions, Inc.

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Attachment A

Development of Monthly Distributions for Groundwater Pumping at City of Spokane Well Stations Under Future Water Demand Scenarios

GSI
Water Solutions, Inc.

TECHNICAL MEMORANDUM

Attachment A: Development of Monthly Distributions for Groundwater Pumping at City of Spokane Well Stations Under Future Water Demand Scenarios

To:	Marcia Davis, City of Spokane Integrated Capital Management Department
From:	John Porcello, LHG, GSI Water Solutions, Inc. Dan Kegley, GSI Water Solutions, Inc.
CC:	Anne Lynch, GHD, Inc.
Date:	May 16, 2024

Introduction

This memorandum describes the methodology that was used by GSI Water Solutions, Inc. (GSI), to translate average-day demand (ADD) and maximum-day demand (MDD) projections of future City of Spokane (City) water demands into monthly distributions of groundwater pumping system-wide and at each of the City's well stations. The monthly distributions described in this technical memorandum were used in groundwater modeling analyses of potential demand-driven and climate-driven changes in groundwater levels at each of the City's well stations.

Summary of Available Demand Projections

Three demand scenarios were used for the groundwater modeling analyses. The three scenarios consisted of a 20-year demand projection by HDR (2022) that GSI adjusted for climate change influences, and two 50-year demand projections by HDR) (2023) that GSI also adjusted for climate-change influences. Table A-1 shows the system-wide ADD and MDD values for recent historical usage (the average of demands from 2015 through 2020), each of HDR's three future demand scenarios, and the three climate-adjusted scenarios that were simulated in the groundwater flow model for this study.

Table A-1. Water Demand Values for Recent Historical Usage and Future Demand Scenarios

Demand Scenario	ADD	MDD
Recent Historical Usage (Average for 2015 through 2020)	63.56	141.30
20-Year Projection (HDR, 2022), No Climate Change	73.90	173.41
20-Year Projection with 2070–2099 Climate Change (GSI)	91.47	186.42
50-Year Projection: Scenario 4 (HDR's Moderate Scenario) ▪ Demographics: Baseline ▪ Conservation: Standard ▪ Climate Change: Limited	78.28	208.30
50-Year Projection: Scenario 4 (GSI's Moderate Scenario) ▪ Demographics: Baseline ▪ Conservation: Standard ▪ Climate Change: Aggressive (RCP 8.5, 2070–2099)	95.32	217.40
50-Year Projection: Scenario 3 (HDR's Aggressive Scenario) ▪ Demographics: High Growth/High Commercial ▪ Conservation: No Change from Current Conditions ▪ Climate Change: Limited	104.91	251.27
50-Year Projection: Scenario 3 (GSI's Aggressive Scenario) ▪ Demographics: High Growth/High Commercial ▪ Conservation: No Change from Current Conditions ▪ Climate Change: Aggressive (RCP 8.5, 2070–2099)	127.06	259.75

Notes

All values are in units of millions of gallons per day (mgd). See HDR (2023) for the 50-year demand projections.
ADD = average-day demand
GSI = GSI Water Solutions, Inc.
MDD = maximum-day demand
RCP = Representative Concentration Pathway for future global greenhouse gas emissions

Process for Calculating Monthly Pumping Rates for Each City Well Station

For each of the three future water demand scenarios, the process for calculating monthly pumping at each of the City's well stations required consideration of four factors:

- **Published Demand Projections:** The analysis used the published ADD and MDD values for each specific demand scenario.
- **Climate Influences on Demands:** Factors were used to scale up the amount of water demand arising from future changes in temperatures and future changes in the length of the growing season, both of which will affect outdoor irrigation water demands.
- **Distribution of Pumping Between City Well Stations:** The historical percentage usage of each City well station in a given month was evaluated during all 12 months of the calendar year under recent historical demands and system operations and was extrapolated to future conditions.
- **Water Rights:** Pumping rates and volumes were checked against instantaneous pumping rates and annual production volumes specified in the City's water rights.

The second and third factors listed above are discussed below.

Climate Influences on Demands

Table A-2 shows details regarding the changes in the growing season and the changes in the number of days above certain temperature and heat-index thresholds that are projected to occur by the year 2070 under the RCP 4.5 and RCP 8.5 greenhouse gas (GHG) emissions scenarios.[1] GSI obtained these data using the "Future Climate Scenarios" tool on the Climate Toolbox website[2]. The values in Table A-2 represent the mean of the 20 climate models for which data are available in the Climate Toolbox.[3] The growing-season and heat-index projections have been compiled and programmed into the Climate Toolbox by researchers at the University of California Merced using procedures described by Abatzoglou and Brown (2012) and are available at an approximately 2.5-mile by 2.5-mile resolution. The data presented in this table are for Spokane, Washington at latitude 47.6588 degrees North (°N) and 117.4260 degrees West (°W).

Table A-2. Growing Season and Temperature Projections for Spokane, Washington

	Date of Last Spring Freeze	Date of First Fall Freeze	Length of Growing Season (Days)	No. of Days Above 86°F	No. of Days with Heat Index Above 90°F	No. of Days with Heat Index Above 100°F	No. of Days with Heat Index Above 105°F
RCP 4.5							
Historical (1950–2005)	Apr. 25	Oct. 9	166.65	37	11	0.2	0
2070–2099	Mar. 9	Oct. 10	215.44	68.34	37.2	6.1	1.3
Change (No. of Days)	**-47**	**1**	**48.8**	**31.3**	**26.2**	**5.9**	**1.3**
RCP 8.5							
Historical (1950–2005)	Apr. 25	Oct. 9	166.65	37	11	0.2	0
2070–2099	Feb. 15	Oct. 26	252.29	91.21	61.4	22.7	10.1
Change (No. of Days)	**-69**	**17**	**85.6**	**54.2**	**50.4**	**22.5**	**10.1**

Notes

°F = degrees Fahrenheit

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

As shown in Table A-2, compared with present conditions the date of the last spring freeze is projected to occur 1.5 to 2 months sooner, and the growing season is projected to be approximately 1.5 months to nearly 3 months longer in duration. The number of days with a heat index above 90°F is projected to be 26 to 50 days more than at present. These changes mean that irrigation water demands will begin in March rather than

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[1] RCP 4.5 and RCP 8.5 each describe a specific "Representative Concentration Pathway" (RCP) for future GHG emissions. Under RCP 4.5, GHG emissions stabilize by the year 2050 and then decline steadily; this can be thought of as a somewhat optimistic scenario for future GHG emissions. Under RCP 8.5, GHG emissions do not decline and continue at their historical rates, resulting in continued accumulation of GHGs in the atmosphere; this can be thought of as a "business as usual" scenario for future GHG emissions.

[2] The Climate Toolbox website is accessible at https://climatetoolbox.org/.

[3] The 20 climate models used in the Climate Toolbox are locally downscaled versions of 20 global climate models that are made available to the research community by the World Climate Research Programme through its Coupled Model Intercomparison Project (CMIP). The version of the models used in the Climate Toolbox are from a Phase 5 update of the climate models, which was released in 2013 and is commonly referred to as CMIP5.

currently beginning in April or May, and these demands will continue through at least October and likely into early or even mid-November. Accordingly, GSI estimates that the changes in total water demands for any given month will follow the pattern presented in Table A-3. The monthly pattern in climate-driven increases also raises peak-month (July and August) demands by 5.0 to 7.5 percent based on the observation that the projected number of days with a heat index above 90°F is likely to be at least three times greater than historical conditions under RCP 4.5 and 5 to 6 times greater under RCP 8.5.

Table A-3. Estimated Effect of 2070–2099 Climate Change on Monthly Water Demands in Spokane

Month	RCP 4.5	RCP 8.5
January	Unchanged	Unchanged
February	Unchanged	2.5% Below Historical Feb–March Average
March	Same as Historical April	2.5% Above Historical April
April	Same as Historical May	5.0% Above Historical May
May	2.5% Above Historical June	5.0% Above Historical June
June	2.5% Above Historical July	5.0% Above Historical July
July	5.0% Above Historical July	7.5% Above Historical July
August	5.0% Above Historical August	7.5% Above Historical August
September	5.0% Above Historical Sept	7.5% Above Historical Aug-Sept Avg.
October	5.0% Above Historical Sept-Oct Avg.	7.5% Above Historical Sept-Oct Avg.
November	2.5% Above Historical Oct-Nov Avg.	3.5% Above Historical Oct-Nov Avg.
December	Unchanged	Unchanged
Annual	16.5% Above Historical Annual Avg.	23.8% Above Historical Annual Avg.

Note

RCP = Representative Concentration Pathway for future global greenhouse gas emissions

Distribution of Pumping Between City Well Stations

The translation of ADD and MDD values into monthly demands system-wide and the allocation of pumping between wells was based on an assumption that the future monthly and seasonal operations of each City well station would be similar to recent historical operations. Table A-4 shows the percentage of total water supply that on average was provided from each City well station each month, during the period of calendar years 2015 through 2020. On a percentage basis, the Well Electric and Parkwater well stations have provided almost all water supply during the winter months. Beginning in April, the remaining City well stations have provided a gradually increasing percentage of the City's water supply until reaching maximum production (on a percentage basis) during July and August. By October, the Well Electric and Parkwater well stations return to providing 85 percent or more of the City's water supply.

Table A-4. Monthly Contribution of Each City Well Station to Total Water Supply (Historical Average, 2015-2020)

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana Street	Ray Street
Jan	36.35%	63.13%	0.06%	0.11%	0.12%	0.05%	0.09%	0.09%
Feb	25.46%	64.78%	0.09%	6.41%	0%	2.29%	0.48%	0.48%
Mar	28.31%	62.99%	0.10%	7.39%	0.17%	0.77%	0.14%	0.14%
Apr	13.85%	65.01%	0.81%	12.51%	0.53%	4.98%	1.15%	1.15%
May	14.81%	51.35%	4.11%	11.75%	2.26%	9.24%	3.24%	3.24%
Jun	24.65%	38.80%	7.43%	9.81%	1.23%	9.08%	4.50%	4.50%
Jul	21.28%	28.80%	14.26%	10.36%	3.06%	9.34%	6.44%	6.44%
Aug	15.57%	25.16%	23.07%	10.54%	3.88%	9.43%	6.18%	6.18%
Sept	19.67%	33.38%	19.11%	7.27%	2.97%	9.48%	4.06%	4.06%
Oct	30.53%	57.30%	3.00%	1.37%	0.68%	6.18%	0.46%	0.46%
Nov	34.21%	64.52%	0.10%	0.34%	0%	0.76%	0.04%	0.04%
Dec	36.04%	62.84%	0.34%	0.54%	0.01%	0.11%	0.06%	0.06%
Annual	22.57%	43.77%	9.74%	8.03%	1.91%	6.98%	3.50%	3.50%

Note
The Havana Street Well Station is under construction and is expected to come online in 2024. This table shows how the actual historical percentage at the Ray Street Well Station is assumed to be distributed equally between Ray Street and Havana Street in the future.

Monthly Pumping Rates System-Wide and By Well Station

The climate scenarios presented in Table A-1 and Table A-3 were coupled together to develop the system-wide pumping profile shown in Table A-5 for each month of the year under each of the three demand scenarios. For comparison purposes, Table A-5 also shows the recent historical average production, based on actual recorded water uses during the 6-year period of 2015 through 2020. Month-by-month values of average daily production for each City well station and each scenario are presented in units of millions of gallons per day (mgd) in Tables A-6 through A-15:

- **Pumping under historical conditions** which is the historical average for calendar years 2015 through 2020 (Table A-6)
- **Pumping under the 20-year demand projection** under no climate change (Table A-7), RCP 4.5 climate change (Table A-8), and RCP 8.5 climate change (Table A-9)
- **Pumping under the 50-year modest demand projection** under no climate change (Table A-10), RCP 4.5 climate change (Table A-11), and RCP 8.5 climate change (Table A-12)
- **Pumping under the 50-year aggressive demand projection** under no climate change (Table A-13), RCP 4.5 climate change (Table A-14), and RCP 8.5 climate change (Table A-15)

Table A-5. Monthly System-Wide Demand for Recent Historical Average Conditions and Three Future Demand Scenarios

	Current Average Use (2015–2020)	20-Year Projection			50-Year Modest Projection (Scenario 4)			50-Year Aggressive Projection (Scenario 3)		
Month	No Climate Change	No Climate Change	RCP 4.5 Climate Change	RCP 8.5 Climate Change	No Climate Change	RCP 4.5 Climate Change	RCP 8.5 Climate Change	No Climate Change	RCP 4.5 Climate Change	RCP 8.5 Climate Change
Jan	34.74	40.40	40.40	40.40	42.10	42.10	42.10	56.12	56.12	56.12
Feb	34.76	40.41	40.41	42.15	42.11	42.11	43.92	56.14	56.14	58.55
Mar	35.77	41.59	48.33	49.54	43.34	50.37	51.63	57.78	67.14	68.82
Apr	42.95	49.94	88.05	92.45	52.05	91.75	96.34	69.38	122.31	128.42
May	73.28	85.21	114.35	117.14	88.79	119.17	122.07	118.36	158.85	162.73
Jun	99.15	115.28	133.62	152.70	120.14	139.24	159.13	160.14	185.61	212.12
Jul	121.04	140.74	147.78	151.30	146.66	154.00	157.66	195.51	205.28	210.17
Aug	120.27	139.84	146.83	150.33	145.73	153.01	156.66	194.26	203.97	208.83
Sept	85.58	99.51	104.49	131.16	103.70	108.89	136.68	138.24	145.15	182.20
Oct	44.91	52.22	77.98	79.83	54.42	81.26	83.19	72.55	108.32	110.90
Nov	33.60	39.07	47.68	48.14	40.71	49.69	50.17	54.27	66.23	66.88
Dec	34.07	39.61	39.61	39.61	41.28	41.28	41.28	55.02	55.02	55.02
ADD	**63.56**	**73.90**	**86.08**	**91.47**	**77.01**	**89.71**	**95.32**	**102.66**	**119.58**	**127.06**
MDD	**141.30** (in 2022)	**173.41**	**182.08**	**186.42**	**202.23**	**212.34**	**217.40**	**241.63**	**253.71**	**259.75**

Notes
All values are in units of millions of gallons per day (mgd).
ADD = average-day demand MDD = maximum-day demand

Table A-6. Average Daily Production from Each City Well Station (2015–2020 Average Actual Historical Usage)

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	12.63	21.93	0.02	0.04	0.04	0.02	0	0.06	**34.74**
Feb	8.85	22.51	0.03	2.23	0	0.80	0	0.34	**34.76**
Mar	10.13	22.53	0.03	2.64	0.06	0.28	0	0.10	**35.77**
Apr	5.95	27.93	0.35	5.37	0.23	2.14	0	0.99	**42.96**
May	10.85	37.63	3.01	8.61	1.66	6.77	0	4.75	**73.28**
Jun	24.44	38.47	7.36	9.73	1.22	9.00	0	8.93	**99.15**
Jul	25.76	34.86	17.26	12.55	3.71	11.31	0	15.59	**121.04**
Aug	18.72	30.26	27.74	12.68	4.67	11.34	0	14.86	**120.27**
Sept	16.84	28.57	16.35	6.22	2.54	8.11	0	6.95	**85.58**
Oct	13.71	25.74	1.35	0.62	0.31	2.78	0	0.41	**44.92**
Nov	11.49	21.68	0.04	0.11	0	0.25	0	0.02	**33.59**
Dec	12.28	21.41	0.12	0.18	<0.01	0.04	0	0.04	**34.07**
Average	**14.34**	**27.82**	**6.19**	**5.10**	**1.21**	**4.43**	**0**	**4.46**	**63.56**

Note
All values are in units of millions of gallons per day (mgd).

Table A-7. Average Daily Production from Each City Well Station for the 20-Year Demand Projection with No Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	14.68	25.50	0.03	0.04	0.05	0.02	0.04	0.04	**40.40**
Feb	10.29	26.18	0.04	2.59	0	0.93	0.19	0.19	**40.41**
Mar	11.77	26.20	0.04	3.07	0.07	0.32	0.06	0.06	**41.59**
Apr	6.92	32.47	0.40	6.25	0.26	2.49	0.58	0.58	**49.95**
May	12.62	43.75	3.50	10.01	1.93	7.87	2.76	2.76	**85.20**
Jun	28.42	44.73	8.56	11.31	1.41	10.46	5.19	5.19	**115.27**
Jul	29.96	40.54	20.07	14.59	4.31	13.15	9.07	9.07	**140.76**
Aug	21.77	35.18	32.26	14.75	5.43	13.19	8.64	8.64	**139.86**
Sept	19.58	33.22	19.01	7.24	2.96	9.43	4.04	4.04	**99.52**
Oct	15.95	29.93	1.57	0.72	0.36	3.23	0.24	0.24	**52.24**
Nov	13.36	25.21	0.04	0.13	0	0.30	0.01	0.01	**39.06**
Dec	14.27	24.89	0.13	0.21	<0.01	0.04	0.02	0.02	**39.58**
Average	**16.68**	**32.35**	**7.20**	**5.93**	**1.41**	**5.15**	**2.59**	**2.59**	**73.90**

Note
All values are in units of millions of gallons per day (mgd).

Table A-8. Average Daily Production from Each City Well Station for the 20-Year Demand Projection with RCP 4.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	14.68	25.50	0.03	0.04	0.05	0.02	0.04	0.04	**40.40**
Feb	10.29	26.18	0.04	2.59	0	0.93	0.19	0.19	**40.41**
Mar	13.68	30.44	0.05	3.57	0.08	0.37	0.07	0.07	**48.33**
Apr	12.20	57.24	0.71	11.01	0.46	4.39	1.02	1.02	**88.05**
May	16.93	58.72	4.70	13.44	2.58	10.56	3.71	3.71	**114.35**
Jun	32.94	51.84	9.92	13.11	1.64	12.13	6.02	6.02	**133.62**
Jul	31.45	42.57	21.07	15.32	4.53	13.80	9.52	9.52	**147.78**
Aug	22.86	36.94	33.87	15.48	5.70	13.85	9.07	9.07	**146.84**
Sept	20.55	34.88	19.96	7.60	3.11	9.90	4.24	4.24	**104.48**
Oct	23.81	44.68	2.34	1.07	0.53	4.82	0.36	0.36	**77.97**
Nov	16.31	30.76	0.05	0.16	0	0.36	0.02	0.02	**47.68**
Dec	14.27	24.89	0.13	0.21	<0.01	0.04	0.02	0.02	**39.58**
Average	**19.22**	**38.77**	**7.80**	**6.99**	**1.57**	**5.96**	**2.88**	**2.88**	**86.08**

Note
All values are in units of millions of gallons per day (mgd).

Table A-9. Average Daily Production from Each City Well Station for the 20-Year Demand Projection with RCP 8.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	14.68	25.50	0.03	0.04	0.05	0.02	0.04	0.04	**40.40**
Feb	10.73	27.30	0.04	2.70	0	0.97	0.20	0.20	**42.14**
Mar	14.03	31.21	0.05	3.66	0.08	0.38	0.07	0.07	**49.55**
Apr	12.81	60.10	0.75	11.57	0.49	4.61	1.07	1.07	**92.47**
May	17.35	60.15	4.82	13.77	2.65	10.82	3.80	3.80	**117.16**
Jun	37.64	59.25	11.34	14.98	1.87	13.86	6.88	6.88	**152.70**
Jul	32.20	43.58	21.57	15.68	4.64	14.13	9.75	9.75	**151.30**
Aug	23.40	37.82	34.68	15.85	5.83	14.18	9.29	9.29	**150.34**
Sept	25.80	43.78	25.06	9.54	3.90	12.43	5.33	5.33	**131.17**
Oct	24.38	45.75	2.40	1.10	0.55	4.94	0.37	0.37	**79.86**
Nov	16.47	31.06	0.05	0.16	0	0.36	0.02	0.02	**48.14**
Dec	14.27	24.89	0.13	0.21	<0.01	0.04	0.02	0.02	**39.58**
Average	**20.36**	**40.89**	**8.47**	**7.46**	**1.69**	**6.42**	**3.09**	**3.09**	**91.47**

Note
All values are in units of millions of gallons per day (mgd).

Table A-10. Average Daily Production from Each City Well Station for the 50-Year Moderate Demand Projection with No Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	15.30	26.58	0.03	0.04	0.05	0.02	0.04	0.04	**42.10**
Feb	10.72	27.28	0.04	2.70	0	0.97	0.20	0.20	**42.11**
Mar	12.27	27.30	0.04	3.20	0.07	0.34	0.06	0.06	**43.34**
Apr	7.21	33.84	0.42	6.51	0.27	2.59	0.60	0.60	**52.04**
May	13.15	45.60	3.65	10.43	2.01	8.20	2.88	2.88	**88.80**
Jun	29.61	46.61	8.92	11.79	1.47	10.90	5.41	5.41	**120.12**
Jul	31.22	42.25	20.91	15.20	4.50	13.70	9.45	9.45	**146.68**
Aug	22.68	36.66	33.62	15.37	5.66	13.75	9.00	9.00	**145.74**
Sept	20.40	34.62	19.81	7.54	3.08	9.83	4.21	4.21	**103.70**
Oct	16.62	31.19	1.63	0.75	0.37	3.37	0.25	0.25	**54.43**
Nov	13.93	26.27	0.04	0.14	0	0.31	0.01	0.01	**40.71**
Dec	14.87	25.94	0.14	0.22	<0.01	0.05	0.03	0.03	**41.28**
Average	**17.38**	**33.71**	**7.50**	**6.18**	**1.47**	**5.36**	**2.70**	**2.70**	**77.01**

Note
All values are in units of millions of gallons per day (mgd).

Table A-11. Average Daily Production from Each City Well Station for the 50-Year Moderate Demand Projection with RCP 4.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	15.30	26.58	0.03	0.04	0.05	0.02	0.04	0.04	**42.10**
Feb	10.72	27.28	0.04	2.70	0	0.97	0.20	0.20	**42.11**
Mar	14.26	31.73	0.05	3.72	0.08	0.39	0.07	0.07	**50.37**
Apr	12.71	59.65	0.74	11.48	0.48	4.57	1.06	1.06	**91.75**
May	17.64	61.19	4.90	14.00	2.69	11.01	3.86	3.86	**119.15**
Jun	34.32	54.02	10.34	13.66	1.71	12.64	6.27	6.27	**139.23**
Jul	32.78	44.36	21.96	15.96	4.72	14.39	9.92	9.92	**154.01**
Aug	23.82	38.49	35.30	16.13	5.94	14.43	9.45	9.45	**153.01**
Sept	21.42	36.35	20.80	7.92	3.24	10.32	4.42	4.42	**108.89**
Oct	24.81	46.56	2.44	1.12	0.56	5.03	0.37	0.37	**81.26**
Nov	17.00	32.06	0.05	0.17	0	0.38	0.02	0.02	**49.70**
Dec	14.87	25.94	0.14	0.22	<0.01	0.05	0.03	0.03	**41.28**
Average	**20.03**	**40.40**	**8.13**	**7.29**	**1.64**	**6.22**	**3.00**	**3.00**	**89.71**

Note
All values are in units of millions of gallons per day (mgd).

Table A-12. Average Daily Production from Each City Well Station for the 50-Year Moderate Demand Projection with RCP 8.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	15.30	26.58	0.03	0.04	0.05	0.02	0.04	0.04	**42.10**
Feb	11.18	28.45	0.04	2.82	0	1.01	0.21	0.21	**43.92**
Mar	14.62	32.52	0.05	3.82	0.09	0.40	0.07	0.07	**51.64**
Apr	13.34	62.63	0.78	12.05	0.51	4.80	1.11	1.11	**96.33**
May	18.08	62.68	5.02	14.35	2.76	11.27	3.96	3.96	**122.08**
Jun	39.23	61.74	11.82	15.61	1.95	14.44	7.17	7.17	**159.13**
Jul	33.56	45.41	22.48	16.34	4.83	14.73	10.16	10.16	**157.67**
Aug	24.38	39.41	36.14	16.52	6.08	14.78	9.68	9.68	**156.67**
Sept	26.89	45.62	26.11	9.94	4.06	12.95	5.55	5.55	**136.67**
Oct	25.40	47.67	2.50	1.14	0.57	5.15	0.38	0.38	**83.19**
Nov	17.16	32.37	0.05	0.17	0	0.38	0.02	0.02	**50.17**
Dec	14.87	25.94	0.14	0.22	<0.01	0.05	0.03	0.03	**41.28**
Average	**21.22**	**42.61**	**8.82**	**7.77**	**1.76**	**6.69**	**3.22**	**3.22**	**95.32**

Note
All values are in units of millions of gallons per day (mgd).

Table A-13. Average Daily Production from Each City Well Station for the 50-Year Aggressive Demand Projection with No Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	20.40	35.43	0.04	0.06	0.07	0.03	0.05	0.05	**56.13**
Feb	14.29	36.37	0.05	3.60	0	1.29	0.27	0.27	**56.14**
Mar	16.36	36.39	0.06	4.27	0.10	0.45	0.08	0.08	**57.79**
Apr	9.61	45.11	0.56	8.68	0.37	3.46	0.80	0.80	**69.39**
May	17.53	60.78	4.87	13.91	2.67	10.93	3.84	3.84	**118.37**
Jun	39.48	62.13	11.90	15.71	1.96	14.54	7.21	7.21	**160.14**
Jul	41.61	56.31	27.87	20.26	5.99	18.26	12.59	12.59	**195.48**
Aug	30.24	48.87	44.81	20.48	7.54	18.32	12.00	12.00	**194.26**
Sept	27.19	46.14	26.41	10.05	4.11	13.10	5.61	5.61	**138.22**
Oct	22.15	41.57	2.18	1.00	0.50	4.49	0.33	0.33	**72.55**
Nov	18.56	35.02	0.06	0.18	0	0.41	0.02	0.02	**54.27**
Dec	19.83	34.58	0.19	0.30	<0.01	0.06	0.03	0.03	**55.02**
Average	**23.17**	**44.94**	**10.00**	**8.24**	**1.96**	**7.15**	**3.60**	**3.60**	**102.66**

Note
All values are in units of millions of gallons per day (mgd).

Table A-14. Average Daily Production from Each City Well Station for the 50-Year Aggressive Demand Projection with RCP 4.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	20.40	35.43	0.04	0.06	0.07	0.03	0.05	0.05	**56.13**
Feb	14.29	36.37	0.05	3.60	0	1.29	0.27	0.27	**56.14**
Mar	19.01	42.29	0.06	4.96	0.11	0.52	0.09	0.09	**67.13**
Apr	16.94	79.52	0.99	15.30	0.64	6.09	1.41	1.41	**122.30**
May	23.52	81.57	6.53	18.67	3.59	14.67	5.15	5.15	**158.85**
Jun	45.75	72.01	13.79	18.21	2.28	16.85	8.36	8.36	**185.61**
Jul	43.69	59.13	29.27	21.28	6.29	19.18	13.22	13.22	**205.28**
Aug	31.75	51.31	47.05	21.51	7.92	19.24	12.60	12.60	**203.98**
Sept	28.55	48.45	27.73	10.55	4.32	13.75	5.89	5.89	**145.13**
Oct	33.08	62.07	3.25	1.49	0.74	6.70	0.50	0.50	**108.33**
Nov	22.66	42.73	0.07	0.22	0	0.50	0.02	0.02	**66.22**
Dec	19.83	34.58	0.19	0.30	<0.01	0.06	0.03	0.03	**55.02**
Average	**26.70**	**53.86**	**10.84**	**9.71**	**2.18**	**8.29**	**4.00**	**4.00**	**119.58**

Note
All values are in units of millions of gallons per day (mgd).

Table A-15. Average Daily Production from Each City Well Station for the 50-Year Aggressive Demand Projection with RCP 8.5 Climate Change

Month	Well Electric	Parkwater	Nevada	Grace	Hoffman	Central	Havana	Ray	Total
Jan	20.40	35.43	0.04	0.06	0.07	0.03	0.05	0.05	**56.13**
Feb	14.91	37.93	0.05	3.76	0	1.34	0.28	0.28	**58.55**
Mar	19.48	43.35	0.07	5.09	0.12	0.53	0.09	0.09	**68.82**
Apr	17.79	83.49	1.04	16.07	0.68	6.40	1.48	1.48	**128.43**
May	24.09	83.56	6.69	19.12	3.68	15.03	5.28	5.28	**162.73**
Jun	52.29	82.30	15.76	20.81	2.60	19.25	9.55	9.55	**212.11**
Jul	44.73	60.54	29.96	21.78	6.44	19.63	13.54	13.54	**210.16**
Aug	32.50	52.54	48.17	22.02	8.10	19.70	12.90	12.90	**208.83**
Sept	35.84	60.82	34.81	13.25	5.42	17.26	7.40	7.40	**182.20**
Oct	33.86	63.55	3.33	1.52	0.76	6.86	0.51	0.51	**110.90**
Nov	22.88	43.15	0.07	0.23	0	0.51	0.02	0.02	**66.88**
Dec	19.83	34.58	0.19	0.30	<0.01	0.06	0.03	0.03	**55.02**
Average	**28.28**	**56.81**	**11.76**	**10.36**	**2.34**	**8.92**	**4.29**	**4.29**	**127.06**

Note
All values are in units of millions of gallons per day (mgd).

References

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Attachment B

Development of Climate-Change Factors for the City of Spokane Climate-Change Study

GSI
Water Solutions, Inc.

TECHNICAL MEMORANDUM

Attachment B:
Development of Climate-Change Factors for the City of Spokane Climate-Change Study

To:	Marcia Davis, City of Spokane Integrated Capital Management Department
From:	John Porcello, LHG, GSI Water Solutions, Inc. Dan Kegley, GSI Water Solutions, Inc.
CC:	Anne Lynch, GHD, Inc.
Attachments	Tables B-1 and B-2 Figures B-1 through B-3
Date:	May 16, 2024

Introduction

This memorandum describes the methodology that was used by GSI Water Solutions, Inc. (GSI), to obtain, process, and simulate climate-change influences on future municipal water demands and the natural hydrologic processes occurring in the Spokane River and the Spokane Valley-Rathdrum Prairie (SVRP) Aquifer. The climate-change projections described in this technical memorandum were used in groundwater modeling analyses of potential demand-driven and climate-driven changes in groundwater levels at each municipal water supply well station owned and operated by the City of Spokane (City).

The groundwater model simulated multiple scenarios of climate-driven changes in (1) future surface water flows at the headwaters of the Spokane River at Post Falls, Idaho, (2) inflows (runoff) from tributaries adjoining the SVRP Aquifer, and (3) changes in groundwater pumping arising from increased irrigation demands caused by a longer growing season and hotter temperatures. The climate projections were obtained from an online data portal called The Climate Toolbox, which is accessible at https://climatetoolbox.org/. The Climate Toolbox provides climate-change projections for two future global greenhouse gas (GHG) emissions pathways, which are called Representative Concentration Pathway (RCP) 4.5 and RCP 8.5. Projections are available for a range of future climates under each GHG emissions pathway and for multiple time frames (including the 3-decade periods of 2010–2039, 2040–2069, and 2070–2099). For streamflows and runoff, the projections on The Climate Toolbox website are projections from 10 individual spatially downscaled global climate models,[1] as well as a projection that is the average condition simulated by the full suite of global climate models. For growing season and temperature projections, 20 global climate models are available, as well as the average of the 20 models. The projections available on The Climate Toolbox website were

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[1] These 10 global climate models are listed in the downloaded runoff data sets as the bcc-csm1-1m, CanESM2, CCSM4, CNRM-CM5, CSIRO-Mk3-6-0, HadGEM2-CC365, HadGEM2-ES365, IPSL-CM5A-MR, MICOR5, and NorESM1-M models. The output from these large-scale global climate-models has been downscaled to a 1/16th-degree grid resolution for publication on the Climate Toolbox website.

processed and downscaled by the National Atmospheric and Oceanic Administration's Climate Impacts Research Consortium at Oregon State University (Mote et al., 2014) and made available to the public on The Climate Toolbox website by Hegewisch and Abatzoglou (2022).

GSI downloaded climate projections for each of these three hydrologic variables (Spokane River flows, runoff from adjoining tributaries, and growing season length and temperatures) in October 2022 and focused on the period 2070–2099 for this study, because the City designs its capital improvements to water infrastructure to last for 50 years or longer. Following are discussions of the projections for Spokane River flows and runoff from adjoining tributaries. See Attachment A to the main GSI climate change study report for details regarding the growing season.

Projections of Spokane River Flows at Post Falls, Idaho

Historical and future streamflow projections are available for two gages on the Spokane River: at Coeur d'Alene, Idaho (representing inflow to Coeur d'Alene Lake) and at Post Falls, Idaho (representing outflow from Coeur d'Alene Lake that provides inflow into the first portion of the river to enter the SVRP Aquifer area). The projections were developed by Mote et al. (2014) using a streamflow routing model developed by Lohmann et al (1996). GSI downloaded streamflow projections for the Spokane River at Post Falls to provide direct input to the groundwater flow model where the river first crosses over the SVRP Aquifer.[2]

These streamflow projections are available from the "Future Streamflows" tool in the "Water" application menu on The Climate Toolbox website. The Climate Toolbox contains two sets of streamflow projections: bias-corrected and non-bias-corrected. The non-bias-corrected data route gridded data from hydrologic rainfall-runoff models into stream channels, with less regard for historical streamflow observations than are applied to the bias-corrected data sets. Therefore, GSI used the bias-corrected projections for the Spokane River at Post Falls in the groundwater model simulations.

Table B-1 and Figure B-1 show the projected changes in Spokane River flows at Post Falls on a monthly basis. The highest percentage increases in flow (compared with historical average conditions for the period 1950–2005) are projected to occur from December through March, potentially doubling (exceeding 100 percent increase) under the highest-flow scenarios but also being small changes under the lowest-flow scenarios. Percentage decreases dominate the period of April through November, with the greatest percentage decreases occurring during the transitional month of June (following the spring freshet) and also during the seasonal-low flow months of July through September.

Runoff Projections (Recharge from Tributary Valley Inflows)

Historical and future projections of total runoff by quarter were used to calculate monthly changes in inflows from tributaries that drain into the SVRP Aquifer at its margins. GSI used the 10-model-mean projected runoff values for Spokane County in 2070–2099 (as obtained from The Climate Toolbox) in the groundwater modeling analyses for the City's well stations.

The spatially downloaded data consisted of projected amounts of rainfall that become runoff, expressed in measurement units of depths in inches. For the 3-decade period 2070–2099, these runoff projections are available as 3-month averages for the time periods December through February, March through May, June through August, and September through November (Hegewisch and Abatzoglou, 2022). The data were obtained from the "Future Boxplots" tool in the "Water" application menu on The Climate Toolbox website. For a given 3-month period and a given GHG emission pathway, this tool provides the runoff depths as the

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[2] The Climate Toolbox refers to this location as Spokane River at Post Falls, Washington. This is in contrast with stream gaging measurements, which are collected at a dedicated stream gaging station identified by the U.S. Geological Survey (USGS) as Spokane River at Post Falls, Idaho (USGS gage number 12419000).

minimum, 5th percentile, median (50th percentile), 95th percentile, and maximum values simulated by the 10 global climate models as a group, As shown in Table B-2, GSI converted these quarterly runoff depths into (1) percentage changes by month and (2) monthly multipliers that GSI applied to historical long-term average tributary inflows already programmed into a steady-state version of the groundwater flow model.

For both RCP 4.5 and RCP 8.5, the runoff depths for each quarter are shown in Figure B-2, and the percentage changes in runoff are shown in Figure B-3. The figures show that 2070–2099 runoff is expected to be greater than historical runoff during the fall and winter seasons and lower than historical runoff during the spring and summer seasons. During the latter part of the 21st century, runoff during the December–February quarter is projected to be (approximately) 20 to 30 percent higher under RCP 4.5 and 25 to 35 percent higher under RCP 8.5. Spring runoff during the latter part of the 21st century is projected to be (approximately) 1 to 12 percent lower under RCP 4.5 and 3 to 15 percent lower under RCP 8.5.

Degrees of Climate Change

For modeling and presentation purposes, the future projections of Spokane River streamflows and runoff entering the aquifer from tributary valleys were combined in a specific manner as to create analyses that reflect differing degrees of climate change influences on the regional aquifer system during the latter part of the 21st century (the years 2070 through 2099). Specifically:

- **Spokane River Streamflows.** Changes in Spokane River streamflows during the late spring through early fall seasons were used to define the degree of climate change, given that the concerns about future water levels at City wells are focused on the summer season. Each climate-change model projects that for the months of May through October, the 2070–2099 streamflows will be lower than historical average flows. The least degree of reduction in May through October streamflows is classified in the model as a “low” degree of climate change, while the greatest degree of reduction is classified as a “high” degree of climate change. The median projected streamflows in all months comprise the “median” degree of climate change.
    - Because of the significant influence of snowpack in the Spokane River’s watershed, the months of November through April are simulated with the highest projected streamflows for the “low” degree of climate change and the lowest projected streamflows for the “high” degree of climate change.
- **Recharge from Tributary Valley Inflows.** The late fall and winter seasons were used for classifying the degree of climate change related to recharge from tributary valley inflows. Each climate-change model projects that for the months of September through February, the 2070–2099 runoff from tributary valleys will be higher than historical average runoff, because of rising temperatures and the subsequent increase in the influence of rainfall rather than snowmelt on the magnitudes and timing of runoff from tributary valleys. The smallest increase in September through February tributary inflows is classified in the model as a “low” degree of climate change, while the greatest increase in September through February tributary inflows is classified as a “high” degree of climate change. The median projected tributary inflows in all months comprise the “median” degree of climate change.
    - The months of March through August are projected to have reduced tributary inflows because of rising temperatures and evaporative demands. Accordingly, these months are simulated with smaller reductions in tributary inflows for the “low” degree of climate change and larger reductions in tributary inflows for the “high” degree of climate change.

In summary:

- The low degree of climate change involves the smallest reductions in projected dry-season Spokane River streamflows, the highest projected wet-season streamflows in the Spokane River, the smallest projected increases in September through February tributary inflows, and the smallest projected reductions in March through August tributary inflows.

- The median degree of climate change involves the median projected changes in Spokane River streamflows and tributary inflows in all months.
- The high degree of climate change involves the largest reductions in projected dry-season Spokane River streamflows, the lowest projected wet-season streamflows in the Spokane River, the largest projected increases in September through February tributary inflows, and the largest projected reductions in March through August tributary inflows.

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Tables

Table B-1. Spokane River Streamflows at Post Falls, Idaho

		RCP 4.5					
	Historical	2070-2099 Streamflow			2070-2099 % Change in Streamflow		
Month	Streamflow	Low Streamflow	Average Streamflow	High Streamflow	Low Streamflow	Average Streamflow	High Streamflow
Jan	5,236	4,869	6,884	8,690	-7.02%	31.47%	65.96%
Feb	7,463	7,819	12,274	16,039	4.77%	64.46%	114.91%
Mar	8,941	9,166	11,558	14,068	2.52%	29.26%	57.34%
Apr	15,394	11,086	14,714	17,831	-27.99%	-4.42%	15.83%
May	17,408	7,236	10,278	13,064	-58.43%	-40.96%	-24.95%
Jun	9,118	1,675	2,436	3,484	-81.63%	-73.29%	-61.79%
Jul	2,381	595	741	971	-75.03%	-68.88%	-59.21%
Aug	877	195	297	388	-77.81%	-66.10%	-55.70%
Sep	798	236	318	411	-70.43%	-60.10%	-48.53%
Oct	1,368	632	740	886	-53.80%	-45.94%	-35.23%
Nov	2,903	1,999	2,824	3,642	-31.15%	-2.72%	25.47%
Dec	4,646	4,869	6,414	9,570	4.81%	38.05%	105.99%
Annual Average	6,361	4,173	5,744	7,361	-34.40%	-9.70%	15.72%

		RCP 8.5					
	Historical	2070-2099 Streamflow			2070-2099 % Change in Streamflow		
Month	Streamflow	Low Streamflow	Average Streamflow	High Streamflow	Low Streamflow	Average Streamflow	High Streamflow
Jan	5,236	6,530	7,874	8,731	24.72%	50.38%	66.76%
Feb	7,463	12,044	14,007	17,239	61.39%	87.69%	130.99%
Mar	8,941	8,290	11,640	15,357	-7.28%	30.19%	71.76%
Apr	15,394	7,742	12,974	17,121	-49.71%	-15.72%	11.22%
May	17,408	3,152	6,420	9,846	-81.89%	-63.12%	-43.44%
Jun	9,118	931	1,410	2,181	-89.78%	-84.54%	-76.08%
Jul	2,381	396	543	754	-83.39%	-77.21%	-68.35%
Aug	877	132	207	348	-84.89%	-76.39%	-60.30%
Sep	798	160	233	344	-79.99%	-70.85%	-56.90%
Oct	1,368	494	600	793	-63.92%	-56.13%	-42.01%
Nov	2,903	1,953	2,529	3,600	-32.72%	-12.87%	24.00%
Dec	4,646	5,327	7,194	9,984	14.66%	54.84%	114.88%
Annual Average	6,361	3,876	5,412	7,124	-39.07%	-14.92%	11.99%

Note

The streamflow value for any given month is the average rate of flow, in cubic feet per second (cfs).

Table B-2. Translation of Runoff Depth Projections into Recharge Multipliers for Tributary Valley Inflows

Runoff Depths (inches) Downloaded from The Climate Toolbox

RCP 4.5

Quarter	2070-2099 Projected Depth of Runoff (inches)			
	Historical Avg.	Low	Median	High
Dec-Feb	1.779	2.126	2.205	2.281
Mar-May	2.213	1.950	2.074	2.185
Jun-Aug	1.360	1.230	1.271	1.315
Sept-Nov	1.471	1.627	1.708	1.803
Annual Average	1.706	1.733	1.815	1.896

RCP 8.5

Quarter	2070-2099 Projected Depth of Runoff (inches)			
	Historical Avg.	Low	Median	High
Dec-Feb	1.779	2.197	2.306	2.411
Mar-May	2.213	1.880	2.012	2.134
Jun-Aug	1.360	1.194	1.243	1.284
Sept-Nov	1.471	1.700	1.763	1.798
Annual Average	1.706	1.743	1.831	1.907

RCP 4.5

Quarter	2070-2099 Projected % Change in Runoff		
	Low	Median	High
Dec-Feb	19.51%	23.93%	28.22%
Mar-May	-11.89%	-6.27%	-1.25%
Jun-Aug	-9.56%	-6.53%	-3.32%
Sept-Nov	10.59%	16.14%	22.58%
Annual Average	1.61%	6.38%	11.16%

RCP 8.5

Quarter	2070-2099 Projected % Change in Runoff		
	Low	Median	High
Dec-Feb	23.49%	29.62%	35.53%
Mar-May	-15.05%	-9.05%	-3.57%
Jun-Aug	-12.20%	-8.60%	-5.62%
Sept-Nov	15.56%	19.83%	22.22%
Annual Average	2.17%	7.35%	11.78%

Calculated Recharge Multipliers

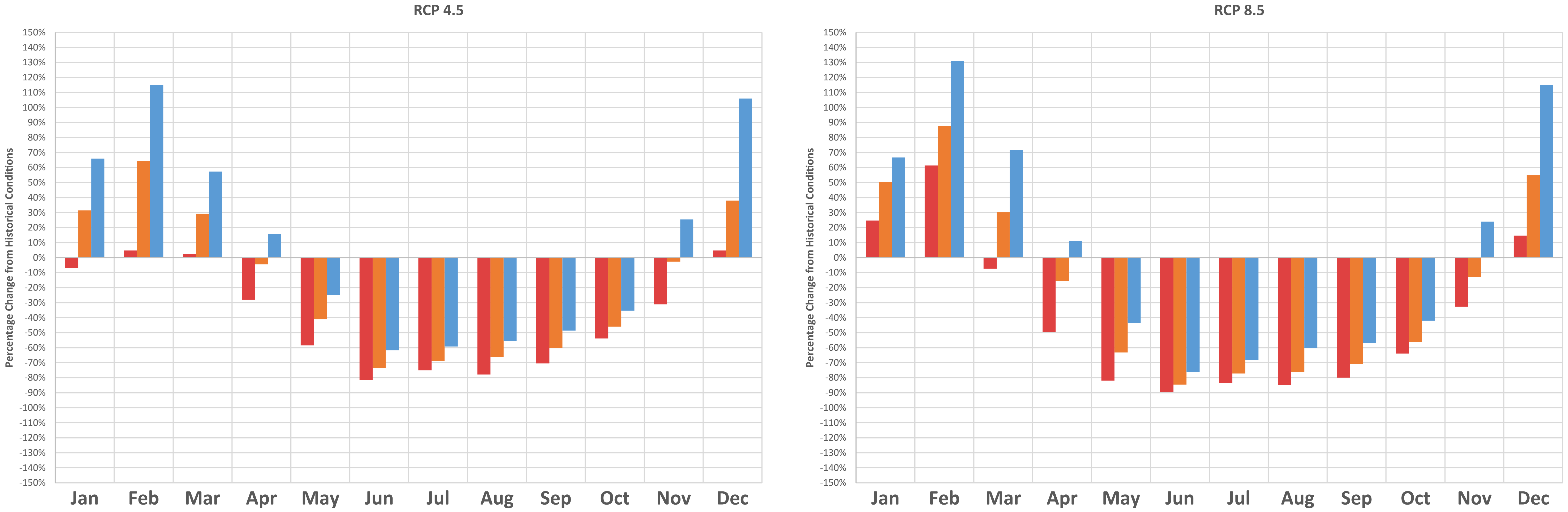
RCP 4.5

Month	Historical Multiplier	2070-2099 Projected % Change in Runoff			2070-2099 Multiplier		
		Low	Median	High	Low	Median	High
January	2.523	19.51%	23.93%	28.22%	3.015	3.127	3.235
February	1.676	19.51%	23.93%	28.22%	2.003	2.077	2.149
March	1.009	-11.89%	-6.27%	-1.25%	0.889	0.946	0.996
April	0.174	-11.89%	-6.27%	-1.25%	0.153	0.163	0.172
May	0.336	-11.89%	-6.27%	-1.25%	0.296	0.315	0.332
June	0.174	-9.56%	-6.53%	-3.32%	0.157	0.163	0.168
July	0.336	-9.56%	-6.53%	-3.32%	0.304	0.314	0.325
August	0	-9.56%	-6.53%	-3.32%	0	0	0
September	0	10.59%	16.14%	22.58%	0	0	0
October	0.841	10.59%	16.14%	22.58%	0.93	0.977	1.031
November	2.26	10.59%	16.14%	22.58%	2.499	2.625	2.77
December	2.691	19.51%	23.93%	28.22%	3.216	3.335	3.45

RCP 8.5

Month	Historical Multiplier	2070-2099 Projected % Change in Runoff			2070-2099 Multiplier		
		Low	Median	High	Low	Median	High
January	2.523	23.49%	29.62%	35.53%	3.116	3.27	3.419
February	1.676	23.49%	29.62%	35.53%	2.07	2.172	2.271
March	1.009	-15.05%	-9.05%	-3.57%	0.857	0.918	0.973
April	0.174	-15.05%	-9.05%	-3.57%	0.148	0.158	0.168
May	0.336	-15.05%	-9.05%	-3.57%	0.285	0.306	0.324
June	0.174	-12.20%	-8.60%	-5.62%	0.153	0.159	0.164
July	0.336	-12.20%	-8.60%	-5.62%	0.295	0.307	0.317
August	0	-12.20%	-8.60%	-5.62%	0	0	0
September	0	15.56%	19.83%	22.22%	0	0	0
October	0.841	15.56%	19.83%	22.22%	0.972	1.008	1.028
November	2.26	15.56%	19.83%	22.22%	2.612	2.708	2.762
December	2.691	23.49%	29.62%	35.53%	3.323	3.488	3.647

Figures



LEGEND

🟥 Low Streamlow

🟧 Average Streamflow

🟦 High Streamflow

FIGURE B-1

Projected Monthly Percentage Changes in 2070–2099
Spokane River Streamflows at Post Falls, Idaho

Development of Climate-Change Factors for the City of Spokane Climate Change Study

NOTE

RCP stands for Representative Concentration Pathway for future global greenhouse gas emissions.

GSI Water Solutions, Inc.

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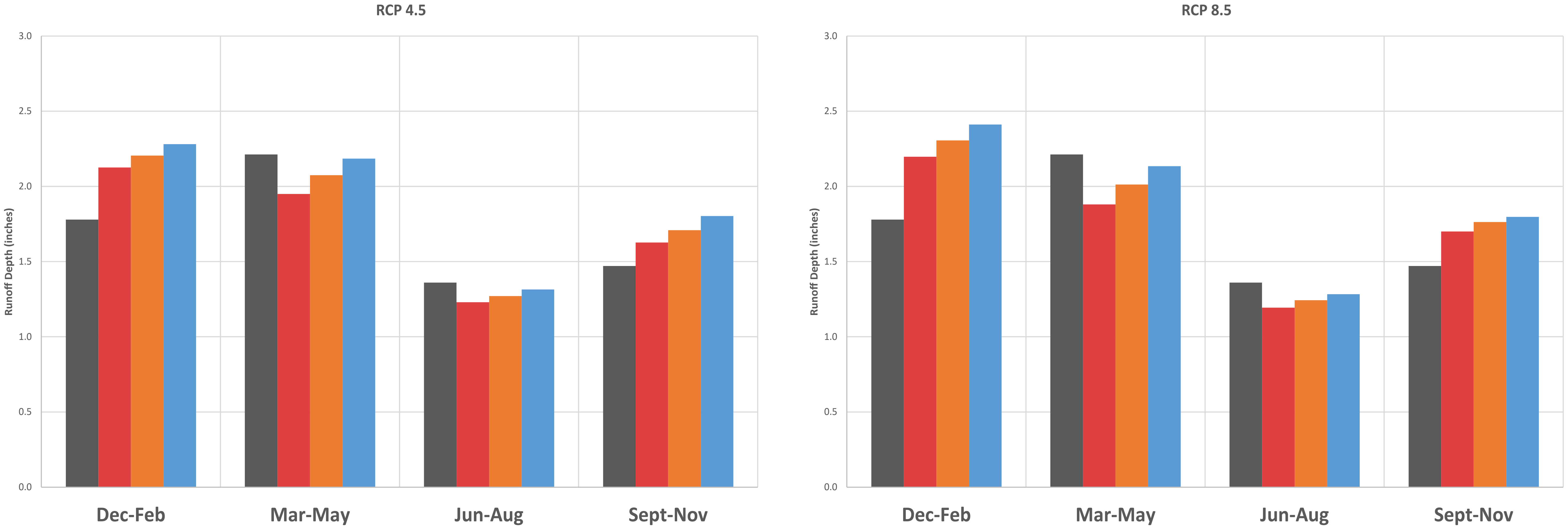


LEGEND

🟦 High 2070-2099 Recharge
🟧 Median 2070-2099 Recharge
🟥 Low 2070-2099 Recharge
⬛ Historical Average Recharge (1950-2005)

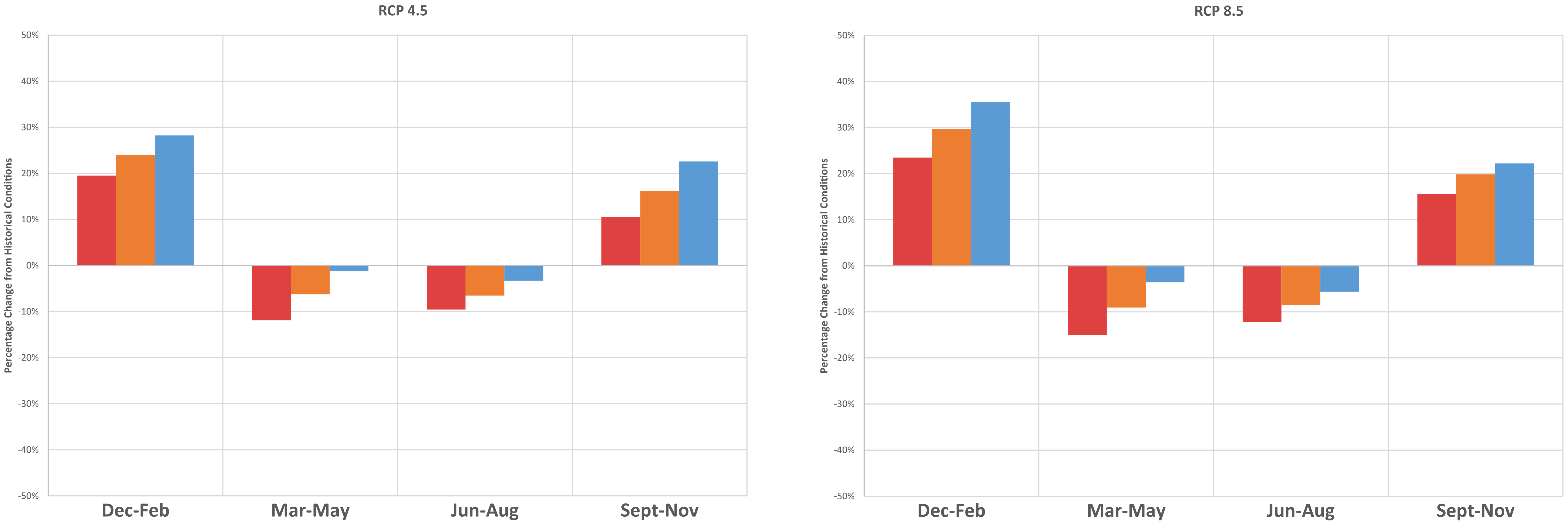
FIGURE B-2

Recharge from Tributary Inflows in 2070–2099 (Expressed as Runoff in Inches)

Development of Climate-Change Factors for the City of Spokane Climate Change Study

NOTE
RCP stands for Representative Concentration Pathway for future global greenhouse gas emissions.

GSI Water Solutions, Inc.



LEGEND

🟦 High 2070-2099 Recharge
🟧 Median 2070-2099 Recharge
🟥 Low 2070-2099 Recharge

FIGURE B-3

Projected Monthly Percentage Changes in 2070–2099 Recharge from Tributary Inflows

Development of Climate-Change Factors for the City of Spokane Climate Change Study

GSI
Water Solutions, Inc.

NOTE
RCP stands for Representative Concentration Pathway for future global greenhouse gas emissions.

Attachment C

Groundwater Flow Model Development for the City of Spokane

GSI
Water Solutions, Inc.

TECHNICAL MEMORANDUM

Attachment C:
Groundwater Flow Model Development for the City of Spokane

To: Marcia Davis, City of Spokane Integrated Capital Management Department

From: John Porcello, LHG, GSI Water Solutions, Inc.
Dan Kegley, GSI Water Solutions, Inc.

CC: Anne Lynch, GHD, Inc.

Attachment Figures C-1 through C-12

Date: May 16, 2024

Introduction

On behalf of the City of Spokane (City), GSI Water Solutions, Inc. (GSI), has developed an updated three-dimensional numerical groundwater flow model of the Spokane Valley-Rathdrum Prairie (SVRP) Aquifer to support the City's ongoing long-range groundwater supply source planning efforts, which are focused on capital improvements planning. This model builds upon prior groundwater models developed by the City (CH2M HILL, 1998; GSI, 2012) and by the U.S. Geological Survey (USGS) (Hsieh et al., 2007) and incorporates hydrogeologic data collected by the City in more recent years. Figure C-1 shows the locations of the City's well stations, each of which contain multiple caisson wells that are spaced closely together and can pump large quantities of groundwater with minimal drawdown because of the prolific water-yielding capabilities of the highly permeable SVRP Aquifer.

The City's updated groundwater flow model uses the USGS software MODFLOW-USG (Panday et al., 2013; Panday, 2023) and replaces a model that was first developed during the mid-1990s (CH2M HILL, 1998) using the European MicroFEM finite-element software (Hemker and de Boer, 2003 and 2017). The City's groundwater flow model simulates the occurrence and movement of groundwater flow in the SVRP Aquifer, which contains predominantly a thick sequence of highly permeable gravel, cobble, and sand deposits, but with sandier and siltier deposits in tributary drainages and in deep portions of the aquifer in a limited area along the Spokane River in the eastern portion of the City. The model simulates groundwater flow processes and groundwater budgets in the SVRP Aquifer, as well as the aquifer's connection to the Spokane River, the Little Spokane River, and lakes that adjoin the outer boundaries of the aquifer. The model uses multiple layers to provide a three-dimensional representation of groundwater movement horizontally within individual model layers and vertical movement between layers.

This technical memorandum describes the design and calibration of the City's new groundwater flow model and is organized into the following sections that discuss:

- Groundwater modeling software, including its benefits
- Design of the model grid, both horizontally and vertically (i.e., its three-dimensional layering)

- Boundary conditions and the groundwater system attributes they represent
- Assignment of values for the SVRP Aquifer's hydraulic properties (hydraulic conductivity, specific yield, and storage coefficient)
- Model calibration
- Model applicability for groundwater resource management
- Model limitations, and recommendations for model maintenance and improvements

Description and Benefits of the MODFLOW-USG Groundwater Modeling Software

MODFLOW-USG was selected as the software code for the development of the City's new model because it has particularly robust groundwater simulation capabilities, including detailed and flexible solvers; is well-supported by graphical user interfaces (GUIs) that help the modeler visualize and manage the modeling process; has the ability to communicate with other software packages such as geographic information systems (GIS) software; and has broad familiarity by—and support within—the groundwater modeling community. Although MicroFEM also had effective simulation capabilities, MODFLOW-USG offers the following benefits:

- It is part of the MODFLOW family of software tools, which are the most widely known models in the groundwater and hydrologic modeling community. These tools are widely used and are supported by multiple GUIs and visualization programs that facilitate the pre-processing, post-processing, information management, and visualization aspects of groundwater modeling efforts. The USGS provides ongoing support and continued development of the MODFLOW family of modeling codes, and training programs and conferences are widely available through the USGS and other public and private entities.
- MODFLOW-USG provides a variety of flexible gridding methods and grid types that allow a grid to have high spatial resolution where needed (such as the finite-element method built into MicroFEM), without adding more grid nodes/cells in places where higher resolution is unnecessary. These gridding methods also provide the capability to simulate the thinning and pinching out of model layers/geologic units in a more robust manner than is available with other software codes.
- MODFLOW-USG provides more detailed and sophisticated methods of representing stream/aquifer interactions than are available in MicroFEM, including in particular the ability to calculate flow rates and instream channel hydraulics during the groundwater solution process.
- MODFLOW-USG has a robust Connected Linear Network (CLN) package that greatly facilitates the process of simulating water levels in production wells. This package is similar to the Multi-Node Well (MNW2) package (Konikow et al., 2009) that is used for structured grids in software codes. However, the CLN package allows for specification of well efficiency values, whereas MNW2 makes use of empirical well-loss coefficients that are often unmeasured or harder to derive from commonly used aquifer test analysis methods than well efficiency estimates. MicroFEM simulates water levels only in the aquifer formation adjacent to a pumping well, which requires that calculations of water levels in a pumping well must be conducted as a manual post-processing calculation procedure outside of the model simulation environment.
- MODFLOW-USG provides the capability to simulate the movement and concentration of inorganic (geochemical) constituents and organic chemicals in groundwater, using the Block-Centered Transport process documented by Panday (2023).

Version 8 of Groundwater Vistas (GV) is the GUI that was used to develop the model and manage the modeling process (ESI, 2017). GV is a popular and widely used program for managing model simulations and has an enhanced level of support for MODFLOW-USG. GV supports the entire family of MODFLOW codes for groundwater flow, particle-tracking, and solute transport. GV also supports certain codes developed by parties other than the USGS, including (1) the mod-PATH3DU particle-tracking code (Muffels et al., 2018) developed specifically for MODFLOW-USG and (2) the PEST suite of utilities for model calibration (Doherty and Hunt, 2010; Doherty et al., 2010a and 2010b). The simulations developed to date with the new regional model (using GV Version 8) are expected to be readily usable in newer versions of GV, based on its long record of compatibility importing existing models into new updated versions of the GV software.

Grid Design

Horizontal Grid Design

The grid for the City's groundwater flow model consists of square cells having a 400-foot regular grid spacing regionally (in the parent grid), with imbedded grids that have refined (i.e., higher-resolution) spacing of 200 feet along the Spokane River and 50 feet at and around each of the City's well stations. Figure C-2 shows the active portion of the parent grid in the uppermost model layer (Layer 1), before refined grids were introduced along the Spokane River and at the City's well stations. The areal extent of the active grid covers the same geographic area as the original MicroFEM model, which conforms to the SVRP Aquifer boundary and covers both the Washington and Idaho portions of the aquifer. Figures C-3 and C-4 show the grid in and around the City after imbedding finer grids along the Spokane River and at the City's well stations. The model grid is georeferenced to the Washington State Plane, North American Datum of 1983 (NAD83) High Accuracy Reference Network (HARN) coordinate system.

Vertical Grid Design

The model uses eight layers to represent the full saturated thickness of the SVRP Aquifer. The vertical datum is the North American Vertical Datum of 1988 (NAVD 88).

The 2012 version of the City's MicroFEM model (GSI, 2012) used three layers to represent the significant spatial variability in the aquifer's thickness, and also to represent the partially penetrating nature of groundwater production wells throughout most of the SVRP Aquifer. Because few wells, if any, penetrate the full saturated thickness of the SVRP Aquifer, its thickness has been estimated primarily from regional- and subregional-scale geophysical surveys and hydrogeologic studies (see Hsieh et al., 2007; Kahle and Bartolino, 2007) and from exploratory drilling by the City at its Havana Street and Well Electric well stations (GSI et al., 2017 and 2019a).

Because of the aquifer's prolific ability to yield water, most production wells are shallow, pumping only from the upper 100 feet of the aquifer (as measured from the average water table depth). Accordingly, the layering scheme in the 2012 version of the MicroFEM model was as follows:

- Where the aquifer's saturated thickness exceeds 200 feet, model layers 1 and 2 (the upper two model layers) were each 100 feet thick, and model layer 3 (the deepest layer in the 2012 version of the model) simulated the remaining saturated thickness of the SVRP aquifer.
- Where the saturated thickness is greater than 100 feet, but does not exceed 200 feet, model layer 1 was 100 feet thick, model layer 2 simulated the remaining saturated thickness of the SVRP aquifer, and model layer 3 was inactive.
- Where the saturated thickness is 100 feet or less, model layer 1 simulated the full saturated thickness of the SVRP aquifer, and model layers 2 and 3 were inactive.

As discussed by GSI (2019a and 2019b), the MicroFEM model's layering was later further subdivided to support well condition assessments and capital improvement planning at three of the City's well stations (Hoffman, Ray Street, and Well Electric). This resulted in eight model layers, which are carried over to the City's new MODFLOW-USG groundwater flow model. This layering scheme is as follows:

- The upper two model layers (layers 1 and 2) are each 75 feet thick, and all existing pumping wells in the SVRP Aquifer are completed in one or both of these two layers.
- Model layers 3 through 7 simulate the underlying system in 50-foot-thick layers, from a depth of 150 feet to a depth of 400 feet. Model layer 8 simulates the remaining saturated thickness of the SVRP Aquifer wherever the base of the aquifer lies more than 400 feet below the water table.
- As with the three-layer model, at any given location in the eight-layer model where the saturated thickness is low enough that the aquifer does not penetrate into a particular model layer, that layer is inactive in the model at that location.

Currently, none of the City's well station facilities penetrate more than 75 feet below the water table. Therefore, all pumping by the City's existing production wells is simulated as occurring from the uppermost model layer (layer 1). Outside the City limits, production wells pump almost exclusively from model layer 1, though 17 wells pump from both model layers 1 and 2.[1]

Boundary Conditions

The new regional model uses no-flow boundary conditions to define inactive cells within the model grid. The model also uses the following MODFLOW-USG packages for boundary conditions that relate to specific hydrologic processes. These packages are the following:

- **The Streamflow-Routing (SFR7) package** uses head-dependent boundary conditions for computing groundwater/surface water exchanges in the Spokane River, specifying inflows to the river from the various outfalls for treated groundwater discharges, and routing streamflow from cell-to-cell for water-balance tracking purposes. Streambed elevations were derived from digital elevation models, and streambed hydraulic conductivity values were derived from the City's MicroFEM model (GSI, 2012) and checked against values used in the USGS-developed Bi-State groundwater flow model (Hsieh et al., 2007). Monthly variations in flow rates at the headwaters of the Spokane River (the outlet from Coeur d'Alene Lake, near Post Falls, Idaho) are historical average flow rates since 1979 and are summarized in Table C-1.[2] Table C-2 lists inflows to the Spokane River from water reclamation facilities and from one major tributary (Latah Creek) that were programmed into the SFR7 package and were assumed to be constant throughout the year.
- **The River (RIV) package** uses head-dependent boundary conditions for computing groundwater/surface water exchanges in the Little Spokane River. Unlike the SFR7 package, the RIV package does not specify inflows to the river or route and calculate streamflow rates. Head values for the RIV package were assigned using digital elevation models for each grid cell containing the Little Spokane River.
- **The Recharge (RCH) package** uses specified-flux boundary conditions to represent deep percolation of rainfall, river storm flows, and land-applied water. Values for long-term average annual recharge rates were imported directly from the MicroFEM model (GSI, 2012); these rates were developed by the USGS for the period of 1991 through 2005 (Bartolino, 2007; Hsieh et al., 2007). For the climate-change simulations, the average rate was then translated into monthly-variable rates in the updated groundwater flow model using multipliers that range between zero in the summer months to values (during December and January) as high as 2.5 to 2.7 times the annual average recharge rate (based on analyses for Spokane Airport published by the USGS; see Bartolino, 2007).
- **The Well (WEL) package** – The WEL package is primarily used as a specified-flux boundary condition to specify the rate of inflow into the SVRP Aquifer from the tributary valleys of contributing watersheds

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[1] These wells are the City of Millwood's New Park well; Consolidated Irrigation District's wellfields 4, 5, 6, 8, 9, 10, and 11; Model Irrigation District Well 6; Pasadena Park Irrigation District Well 2; the Riverside well; Spokane County Water District 3's Freeway&Vista well; and Vera Water and Power's wells 3, 9, 21, 22, and 33.

[2] These values were obtained in October 2022 from The Climate Toolbox website at https://climatetoolbox.org.

(including those draining from Fernan Lake and Hauser Lake in Idaho, and Newman and Liberty Lake in Washington). The WEL package also defines pumping rates for all groundwater supply wells. The same wells and pumping rates used in the City's MicroFEM model were used in the new MODFLOW-USG model; these rates are long-term average rates of groundwater pumping by municipal and private well owners, as derived from production records for 2012 and 2013 and from other data sources, as described by GSI (2012).

- **The Connected Linear Network (CLN) package** uses head-dependent boundary conditions to simulate flow exchanges between the aquifer matrix and the small number of groundwater production wells that span both of the upper two model layers.
- **The Time-Variant Specified-Head (CHD) package** uses specified-head boundary conditions to hold the groundwater elevation steady (at elevation 1,527 feet) where the SVRP Aquifer naturally discharges groundwater beneath Long Lake at the northwestern model boundary.
- **The General-Head Boundary (GHB) package** uses head-dependent boundary conditions to compute subsurface inflows into the SVRP Aquifer from four lakes in Idaho that bound the SVRP Aquifer along its outer margins. In this package, groundwater elevations on the GHB boundary are set at values reflective of groundwater elevations displayed in contour maps developed by the USGS (Kahle and Bartolino, 2007) and are held steady at all times during model simulations.[3]

Table C-1. Monthly Streamflow Rates for the Spokane River from Coeur d'Alene Lake (Historical Average for 1950–2005)

Month	Specified Flow Rate at Post Falls, Idaho (cfs)
January	5,236
February	7,463
March	8,941
April	15,394
May	17,408
June	9,118
July	2,381
August	877
September	798
October	1,368
November	2,903
December	4,646

Note

cfs = cubic feet per second

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[3] These head values (elevations in the NAVD 88 datum) are 2,050 ft at Lake Pend Oreille and Coeur d'Alene Lake; 2,120 ft at Hayden Lake; and 2,140 ft at Twin Lakes.

Table C-2. Specified Inflows into the Spokane River from Point Sources

Source of Inflow	Segment Number in SFR7 Package	Specified Flow Rate (mgd)	Specified Flow Rate (cfs)
Liberty Lake Sewer & Water District WRF	3	1.8	2.8
Kaiser Trentwood Outfall	7	2.4	3.7
Inland Empire Paper Outfall	10	5.7	8.8
Spokane County WRF	13	8.0	12.4
Latah Creek			
City of Spokane WRF	21	151.9	235.0

Notes

cfs = cubic feet per second mgd = millions of gallons per day WRF = water reclamation facility

Aquifer Hydraulic Properties

Following are discussions of the assignment of hydraulic conductivity, specific yield, and storage coefficient.

Hydraulic Conductivity

Figures C-5 through C-11 show the spatial distribution of horizontal hydraulic conductivity in each model layer, as well as the geographic extent of the SVRP Aquifer in each model layer. In each layer, the horizontal hydraulic conductivity increases from the City upgradient to the state line and is highest along much of the Idaho portion of the aquifer situated between the state line and Lake Pend Oreille. Hydraulic conductivity values are notably lower at and downgradient of Coeur d'Alene Lake and in the western and northwestern edges of the SVRP Aquifer. In most areas, the horizontal hydraulic conductivity is uniform in each model layer. A notable exception is north of the City limits in Hillyard Trough, where a clay layer is known to bifurcate the SVRP Aquifer into an upper section and a lower section (CH2M HILL, 1998; Kahle and Bartolino, 2007). This clay layer is simulated as being present in model layer 2 (see Figure C-6), with a horizontal (and vertical) hydraulic conductivity value of 1×10^{-8} feet/day based on the USGS Bi-State model's calibration (Hsieh et al., 2007). Beneath this clay layer, the horizontal hydraulic conductivity is set at 200 feet/day in Hillyard Trough, based on the USGS Bi-State model. Along the Little Spokane River, the aquifer sediments in model layers 3 through 8 (beneath the clay layer) are assigned a horizontal hydraulic conductivity of 6,000 feet/day to allow groundwater in these deeper layers to discharge at the downgradient basin boundary at Long Lake.

In the Washington portion of the SVRP Aquifer, horizontal hydraulic conductivity values in the City's MicroFEM model (GSI, 2012) progressed in an upgradient direction from 1,000 feet/day in the northern and northwestern portions of the SVRP Aquifer to 7,000 feet/day at the Washington/Idaho state line. These values were based on limited testing conducted at City well stations during and before the 1990s. Hydrogeologic investigations at four City well stations between 2016 and 2019 included more sophisticated tests that identified much higher values for the hydraulic conductivity of the gravel deposits penetrated by the City's well stations. A 5-day controlled aquifer test from a test well at the Havana Street Well Station resulted in a hydraulic conductivity estimate of 15,000 feet/day (GSI et al., 2017). Performance testing at the Ray Street Well Station in Fall 2017 produced a similar estimate. Performance testing of two caisson wells at the City's Well Electric Well Station in Fall 2017 resulted in hydraulic conductivity estimates ranging between 12,500 and 31,000 feet/day, based on analytical and numerical modeling of the test results. These values are similar in their general order of magnitude to those used in the USGS Bi-State model (Hsieh et al., 2007), which ranged from 1,980 feet/day to 22,100 feet/day in much of the Washington portion of the SVRP Aquifer, and between 7,470 feet/day and 22,100 feet across the area extending from the state line downgradient to the northern City limits.

In the Idaho portion of the SVRP Aquifer, horizontal hydraulic conductivity values in the City's MicroFEM model (GSI, 2012) decreased in an upgradient direction from 9,100 feet/day near the state line, to 5,005 feet/day in central Rathdrum Prairie, 7,085 feet/day in the West (Main) Channel, and between 2,500 and 5,400 feet/day from there to Lake Pend Oreille. The effort to calibrate the City's new MODFLOW-USG model has resulted in hydraulic conductivity values that are higher and are largely the same magnitude as used in the USGS Bi-State model (Hsieh et al., 2007).

In areas where the horizontal hydraulic conductivity values exceed 200 feet/day, the vertical hydraulic conductivity is one-tenth of the horizontal hydraulic conductivity value. The ratio of 10:1 for horizontal-to-vertical hydraulic conductivity was used in the City's MicroFEM model and was found to not warrant adjustment during calibration of the City's new MODFLOW-USG model.

Specific Yield and Storage Coefficient

At the beginning of the model calibration process, the specific yield of the SVRP Aquifer's sediments is set at 0.35, based on the prevalence of gravels and cobbles with large pore spaces. This value is used to calculate groundwater levels in the uppermost saturated layer of the model (layer 1). In underlying layers, the model was assigned a storage coefficient of 0.0001 in each model layer at the beginning of the model calibration process. Both the specific yield and the storage coefficient are dimensionless coefficients (i.e., they have no unit of measurement) and were found to not warrant adjustment during model calibration.

Model Calibration

The calibration process consisted of constructing a 5-year simulation that varied natural recharge terms, groundwater pumping, and Spokane River flows on a monthly basis (using the same set of monthly variations from one year to the next). This simulation was used to conduct a general check of the model's ability to simulate conditions during the summer low-flow season, as described for regional groundwater levels by the USGS (Kahle and Bartolino, 2007) and as described for Spokane River gains and losses by the USGS (Kahle and Bartolino, 2007; Hsieh et al., 2007) and in unpublished data provided to the City from Spokane County during the City's development of its wellhead protection program.

Adjustments to horizontal hydraulic conductivity values in the SVRP Aquifer and streambed hydraulic conductivity values for the Spokane River were made to improve the initial model fit to these data sets. A summary of the calibration quality of the City's updated groundwater flow model is as follows:

- **Groundwater Elevations.** Figure C-12 compares the simulated seasonal-low groundwater levels against the September 2004 seasonal-low groundwater elevation contour map published by the USGS (Kahle and Bartolino, 2007). The shapes of the groundwater elevation contours are similar, and groundwater elevations are generally similar except for slight over-predictions of groundwater levels just east of the state line and extending upgradient roughly to a point halfway between the state line and Lake Pend Oreille. Groundwater elevations are generally well-matched near Coeur d'Alene and Hayden Lakes in Idaho and in the Washington portion of the SVRP Aquifer.
- **Spokane River Gains/Losses.** Table C-3 compares the simulated and field-measured estimates of the rates of Spokane River gains and losses for four major reaches of the river across the SVRP Aquifer. Values are shown in units of cubic feet per second (cfs). In general, the model provides a reasonable representation of gains and losses, despite the difficulty in interpretation that arises below Sullivan Road due to differences in the reaches used for reporting purposes and disagreements of some data sets about whether the river is gaining or losing in the reaches below Greene Street. Specific observations are:

- In the prominent upper losing reach of the river (extending from Post Falls to Sullivan Road), the calibrated model simulates a similar loss as the USGS Bi-State model and the Spokane County unpublished estimate, all of which show less loss than was estimated from field measurements by the USGS.
- From Sullivan Road to Green Street, the model simulates somewhat more gain than is estimated by the USGS and Spokane County, though the general order of magnitude is correct (i.e., in the hundreds of cfs, rather than tens or thousands of cfs).
- From Greene Street to Monroe Street, the model may be over-predicting the amount of gain occurring in this reach.
- From Monroe Street to Nine Mile Falls, the model simulates somewhat less gain in Spokane River flows than is estimated by the USGS, and does not simulate a losing condition as suggested by the unpublished data from Spokane County.

Table C-3. Model Calibration to Spokane River Gains/Losses During Low-Flow Month

Reach	Spokane County Unpublished Data for 1995	USGS Field Measurements for Sept. 2004	USGS Bi-State Model for Sept. 2004	Initial Version of New City Model	Calibrated Version of New City Model
Post Falls to Sullivan Road	-207 to -319	-606	-377	-409	-302
Sullivan Road to Greene St.	+416 to +537	+593	+623	+905	+760
Greene St. to Monroe St.	+63 to +122	-112		+278	+37
Monroe St. to Nine Mile Falls	-57 to -80	+268	+283	+103	+358

Notes

All values are in units of cubic feet per second.

USGS = U.S. Geological Survey

Model Applicability for Groundwater Resource Management

The City's new groundwater flow model (like previous models) has been created through a detailed process of planning, construction, and calibration, which has resulted in a model that is well-suited for a variety of applications related to wellfield evaluation and planning and aquifer resource management. The City's new MODFLOW-USG groundwater flow model is an improvement over the City's prior groundwater model because of the flexible gridding capabilities of the software, the more robust numerical solvers for computing groundwater elevations and groundwater budgets, and the more sophisticated method of simulating groundwater/surface water interactions.

Additionally, the City's new model incorporates the results of aquifer tests and single-well tests that were not available until recently—the data from which significantly improved the understanding of the general order of magnitude of hydraulic conductivity values in the SVRP Aquifer. Unlike previous models, which used either one or three layers to simulate the aquifer system, this model uses eight layers, which allows for greater vertical resolution in simulating the direction and magnitudes of vertical gradients in the aquifer at any given location, and for more accurately representing the exchanges between the shallowest portions of the aquifer system and the Spokane River. The model also provides good replication of the important attributes of the system, including groundwater elevations, groundwater flow directions, and the rates and locations of Spokane River gains and losses.

Model Limitations and Recommended Maintenance and Improvements

Despite its detail and the in-depth nature of the calibration and validation process, the City's new groundwater flow model is a simplification of a complex hydrogeologic system and has been designed with certain built-in assumptions. Like any model, it is not perfect and should be used with care. Predictive simulation results should be examined by qualified and experienced hydrogeologists and water resource managers. Future modeling analyses, interpretations, and conclusions should not be viewed as absolute results and could change as the model is refined in the future as new data becomes available.

Additionally, the City has developed this model with the intention of beginning a process to improve groundwater modeling tools and capabilities in the SVRP Aquifer. The City does not view this model as the final model of the aquifer system, but rather a first step in building an updated model across the region. This model development effort did not alter several hydrologic inputs to the model outside of the City—in particular, the spatial distribution and magnitude of areal recharge, which is controlled by precipitation, evaporation, septic system discharges, and deep percolation from irrigated agricultural areas and irrigated urban landscapes. Additionally, certain boundary conditions such as inflows from lakes and tributary valleys were retained from prior models (particularly the USGS Bi-State model) without evaluation of whether those boundary conditions should be modified to reflect current hydrologic conditions. Furthermore, detailed calibration to long-term groundwater-level data across the geographic extent of the aquifer has not been conducted since the USGS developed the Bi-State model during the mid-2000s.

Continued maintenance of the model is recommended, to ensure that it will continue to be useful for future groundwater resource planning and wellfield evaluation needs. Maintenance activities should be determined by the City and other local municipal groundwater users based on how they plan to use the model to support long-term programs (such as water supply planning, capital improvements planning, and groundwater resource protection) and to support near-term decision making on matters such as wellfield operations, site development impacts on groundwater, or other specific resource management topics. Maintenance activities could include one or more of the following activities:

- **Updating and checking calibration as new data becomes available.** This can be thought of as a "calibration check" process, for which the objective is to evaluate the model's ability to simulate new water use and hydrologic information that is collected as time progresses. Events that could warrant an extension of the calibration period include not only the continued collection of information at existing wells and existing monitoring locations in the aquifer and in the river systems, but also (1) the collection of data at new locations and (2) the occurrence of different groundwater conditions than those experienced in the past (e.g., if the onset of an extended drought were to cause decreased pumping at some wells, the need to increase pumping elsewhere, lower recharge to the aquifer, and accordant changes in observed groundwater levels). Additionally, whenever new production wells are installed, long-term water-level monitoring should commence in the well, and controlled pumping tests should be conducted to provide quantitative estimates of aquifer properties—particularly in areas where wells have not been recently constructed and tested. Incorporating new data sets into the model provides opportunities to incorporate refinements to the model-specified hydraulic parameters that are used in localized areas for the aquifer and/or the Spokane River.
- **Upgrades to model software.** New versions of the MODFLOW family of software tools periodically become available that add/improve existing MODFLOW packages and/or improve solver capabilities and reduce model run times. These updates can occur every few years. Additionally, updates to the GUI (GV) occur frequently, although major upgrades in its features occur only every few years. Updates to MODFLOW and

GV do not need to be conducted on a regular schedule for the model to remain functional and suitable for its desired uses. If municipal water providers elect to use the model in an updated version of MODFLOW or under a major update of GV, the model should be run with the new software to confirm that it converges and runs properly, and to check that simulation results are similar to those obtained from the earlier software.

- **Model-sharing and cooperative efforts with local stakeholders and other government agencies.** When a municipality or water provider has developed a detailed numerical groundwater model of a regional aquifer system, it is common to receive requests for the model from local landowners/stakeholders or other government agencies.

Keeping the model updated with recent software and a calibration that is not several years old is helpful for increasing the confidence of groundwater users and other stakeholders, and for providing the model's keepers with opportunities to ensure that the model is being used correctly. Accordingly, GSI and the City recommend that the City and other SVRP groundwater users work together to further update and improve the model in the coming years to support planning activities occurring at both local and regional scales.

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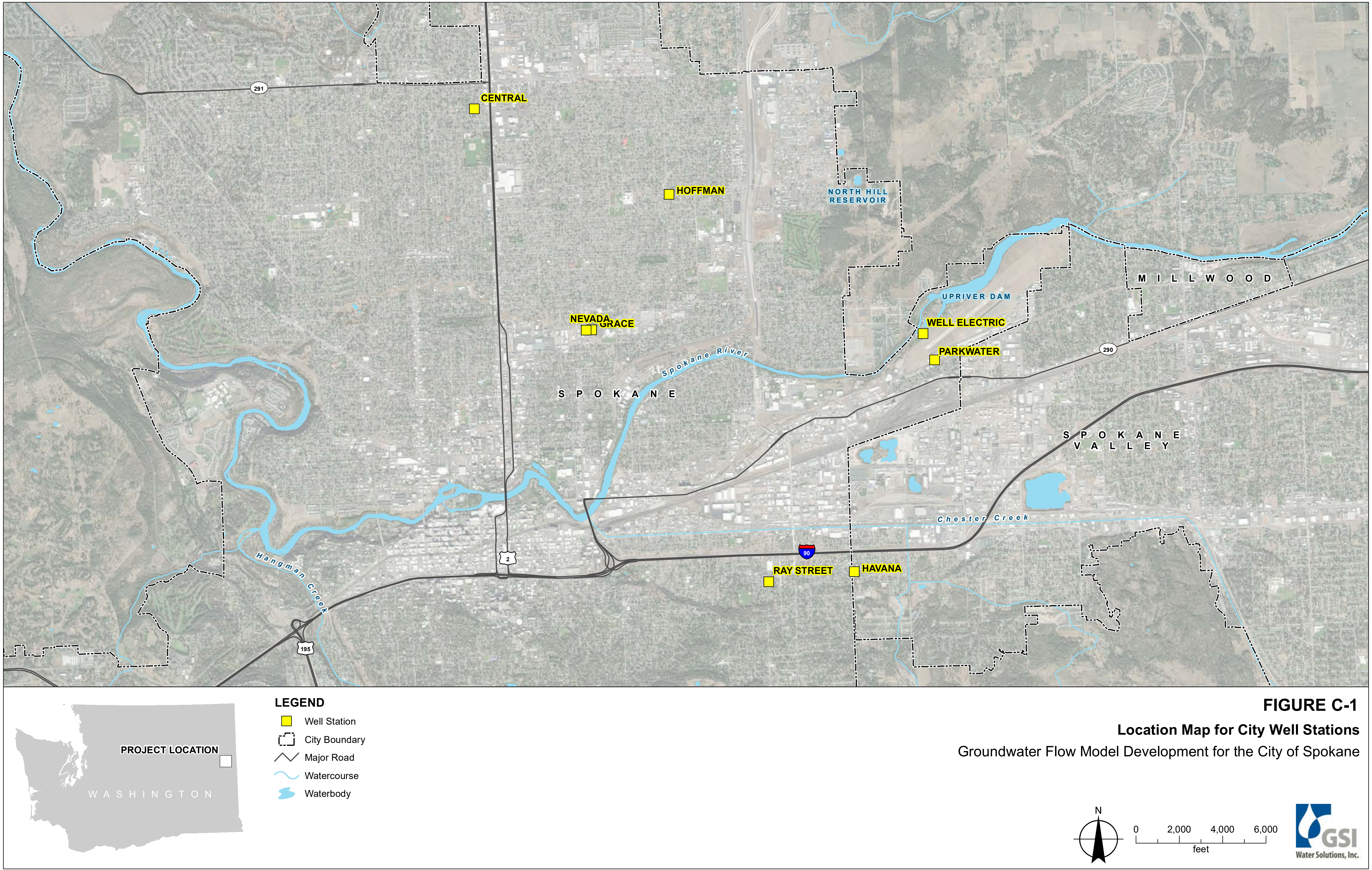
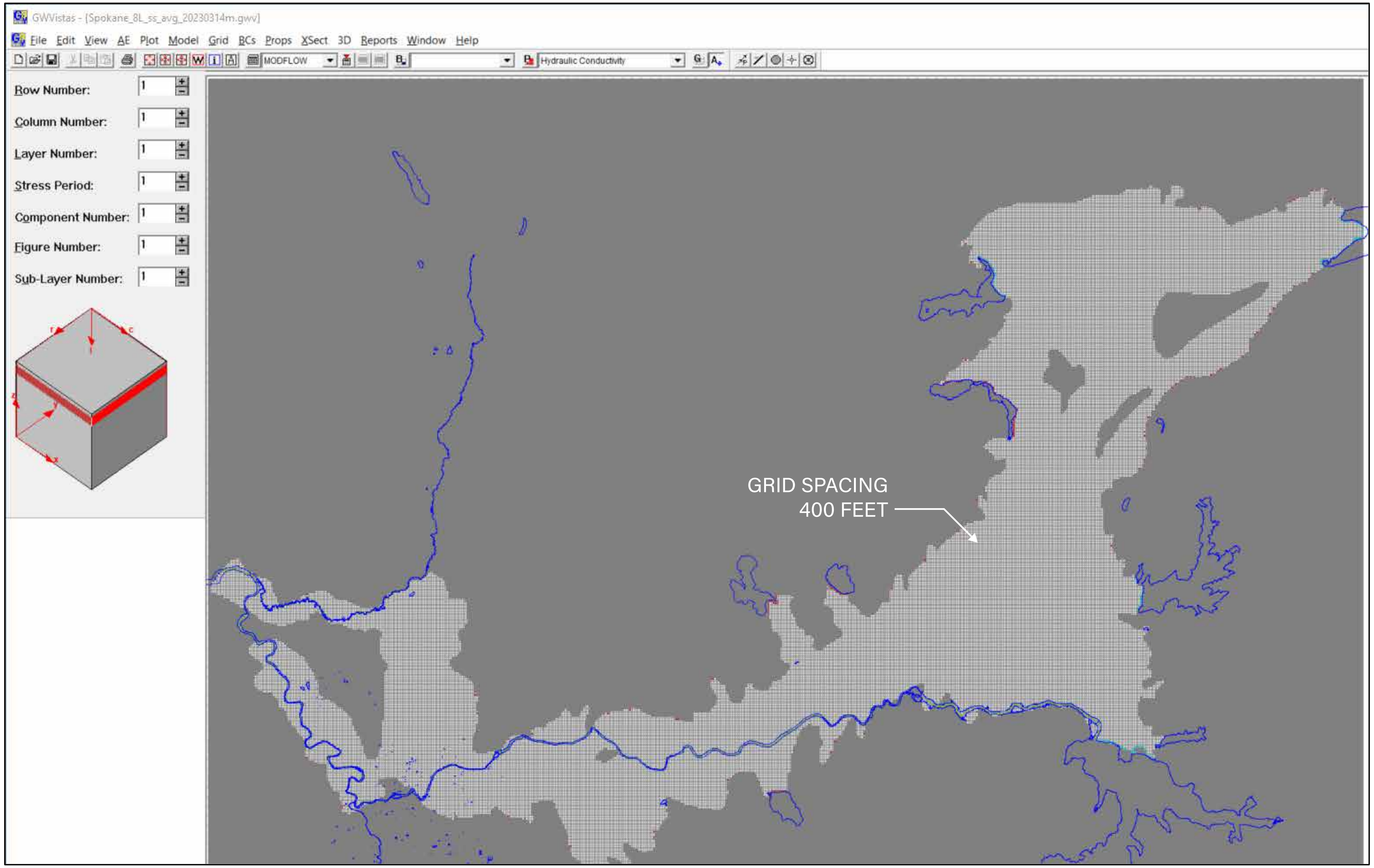


FIGURE C-1

Location Map for City Well Stations

Groundwater Flow Model Development for the City of Spokane



MODFLOW

Hydraulic Conductivity

Row Number: 1

Column Number: 1

Layer Number: 1

Stress Period: 1

Component Number: 1

Figure Number: 1

Sub-Layer Number: 1

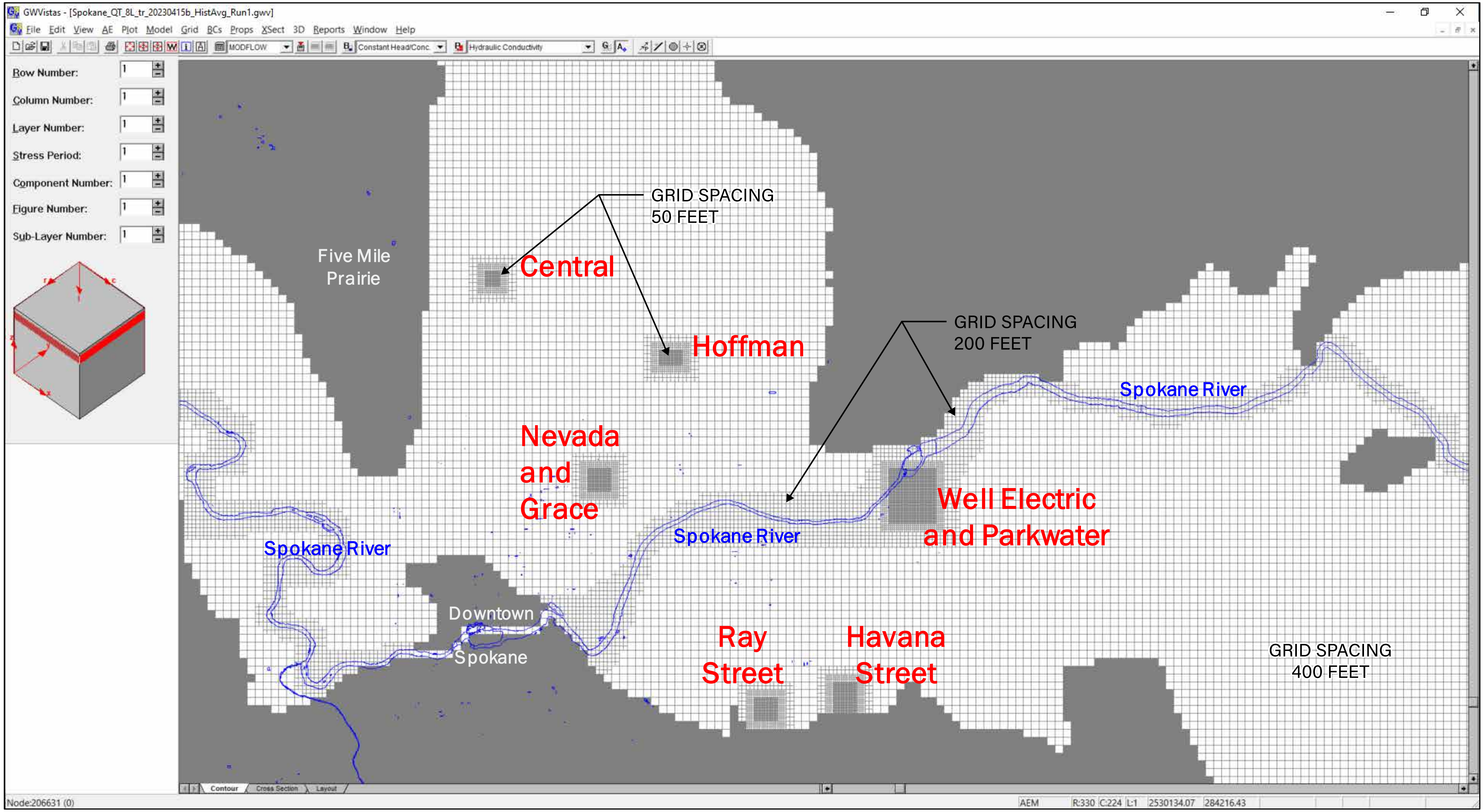
GRID SPACING
400 FEET

FIGURE C-2

Parent Model Grid for Entire SVRP Aquifer

Groundwater Flow Model Development for the City of Spokane

GSI
Water Solutions, Inc.



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Row Number: 1

Column Number: 1

Layer Number: 1

Stress Period: 1

Component Number: 1

Figure Number: 1

Sub-Layer Number: 1

MODFLOW

Constant Head/Conc.

Hydraulic Conductivity

Node:206631 (0)

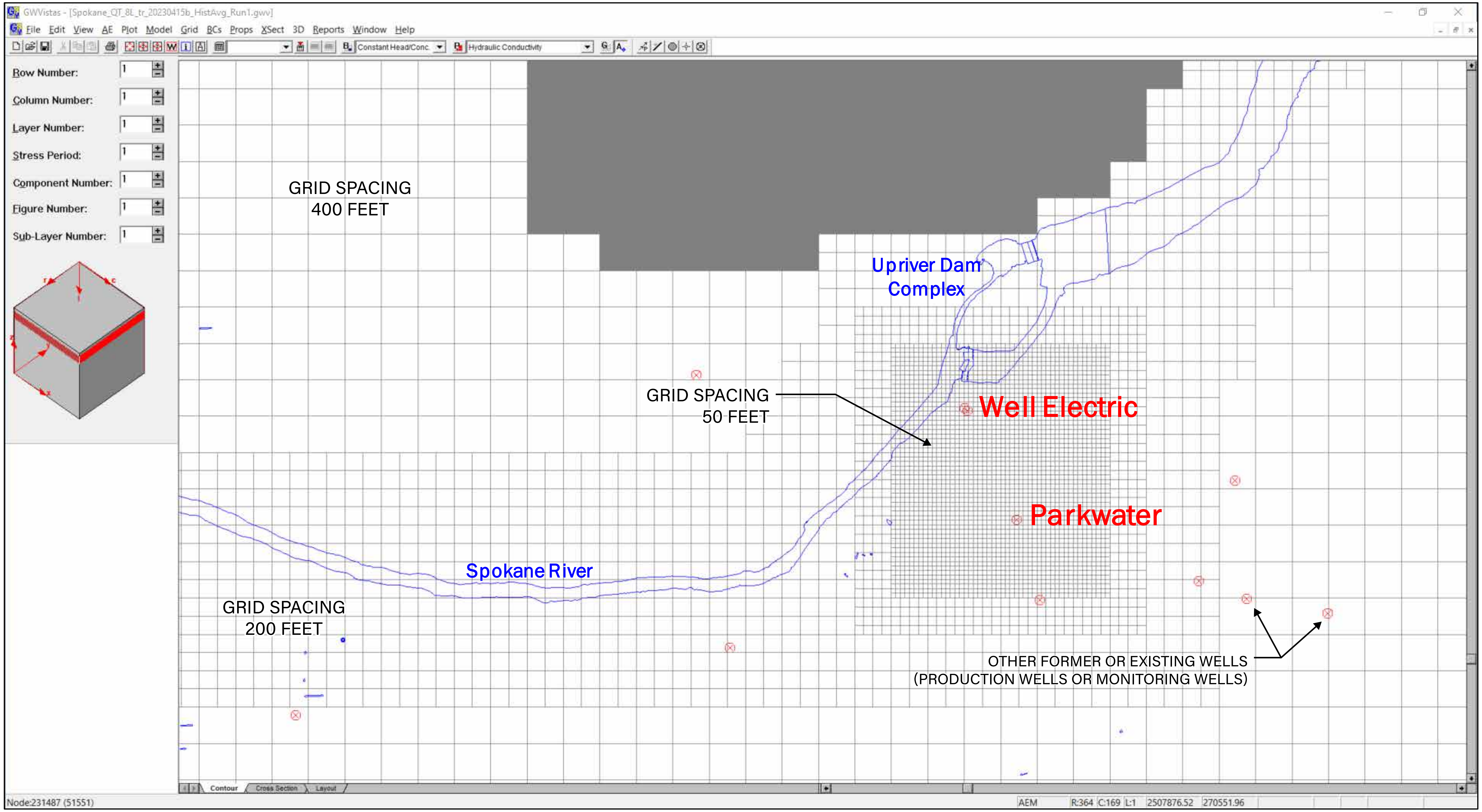
AEM R:330 C:224 L:1 2530134.07 284216.43

FIGURE C-3

**View of Irregular Grid Imbedded Inside the Parent Grid,
Along the Spokane River and Around City of Spokane Well Stations**

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.



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Row Number: 1

Column Number: 1

Layer Number: 1

Stress Period: 1

Component Number: 1

Figure Number: 1

Sub-Layer Number: 1

Node:231487 (51551)

AEM R:364 C:169 L:1 2507876.52 270551.96

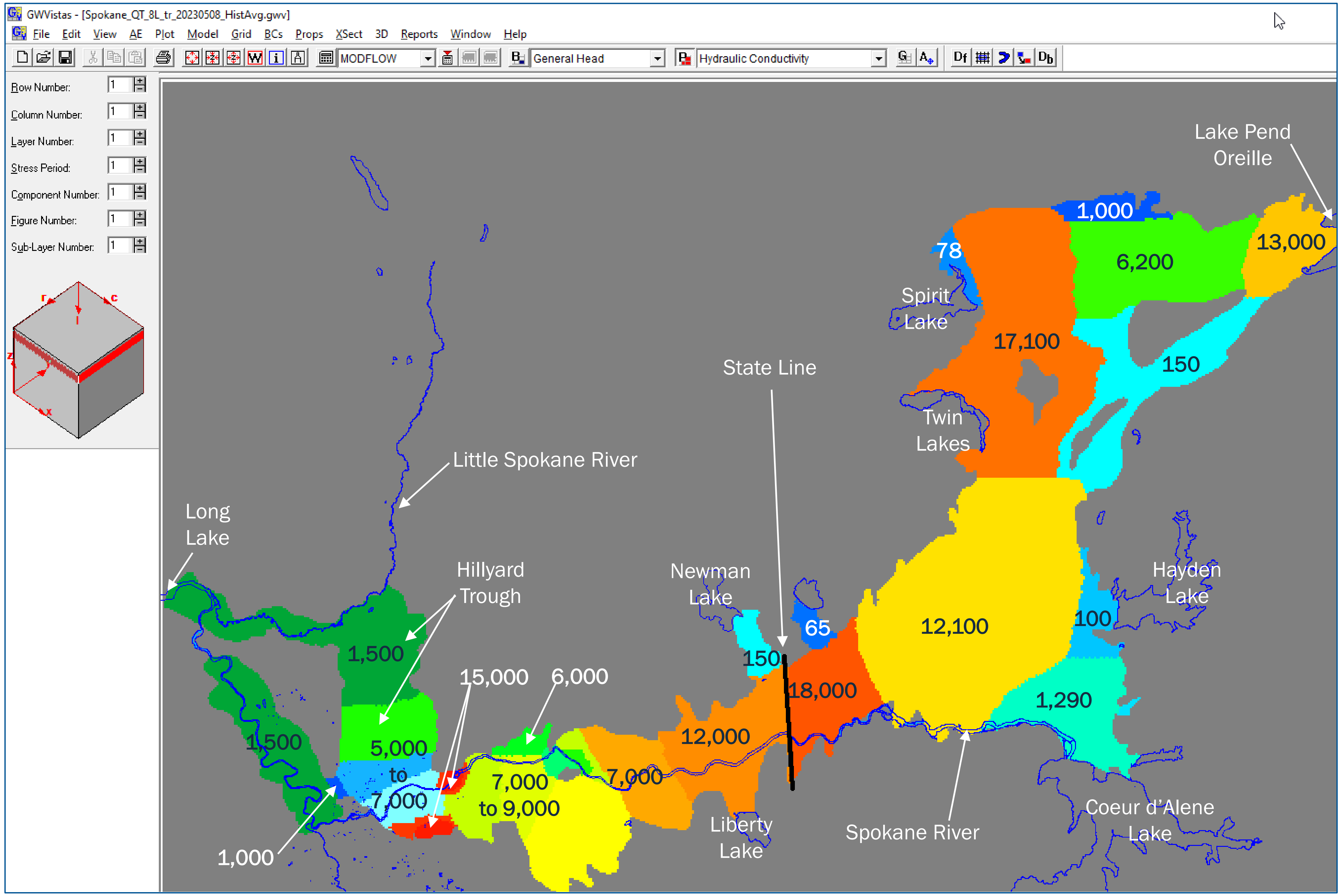
FIGURE C-4

View of Irregular Grid Along the Spokane River and at the Well Electric and Parkwater Well Stations

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.

Y:\0292_GHD\Source_Figures\004_Spokane_Link_Utilities\AttachmentC


GWVistas - [Spokane_QT_8L_tr_20230508_HistAvg.gwv]

MODFLOW

General Head

Hydraulic Conductivity

Row Number: 1

Column Number: 1

Layer Number: 1

Stress Period: 1

Component Number: 1

Figure Number: 1

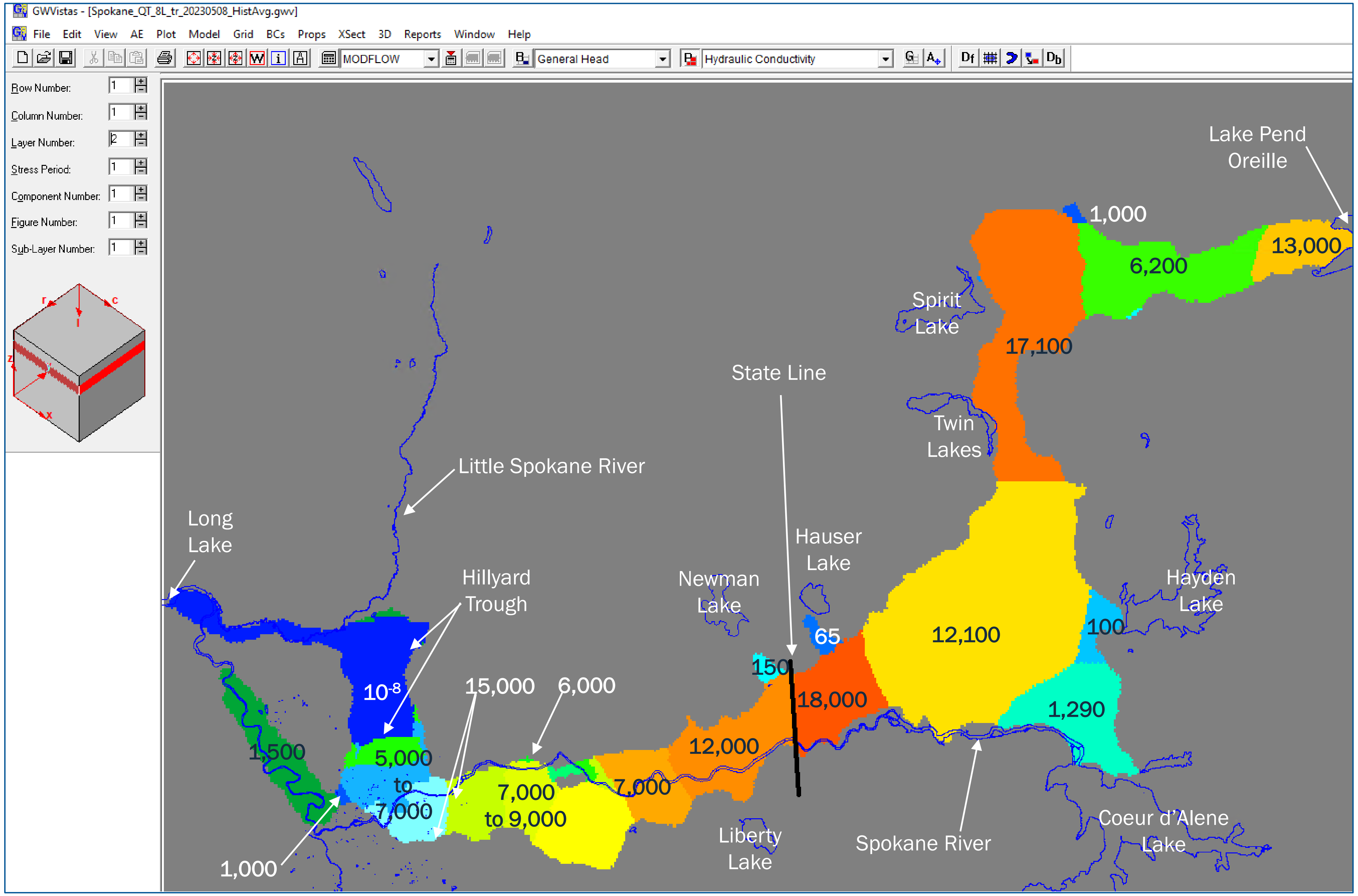
Sub-Layer Number: 1

FIGURE C-5

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 1

Groundwater Flow Model Development for the City of Spokane

GSI
Water Solutions, Inc.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Row Number: 1

Column Number: 1

Layer Number: 2

Stress Period: 1

Component Number: 1

Figure Number: 1

Sub-Layer Number: 1

MODFLOW

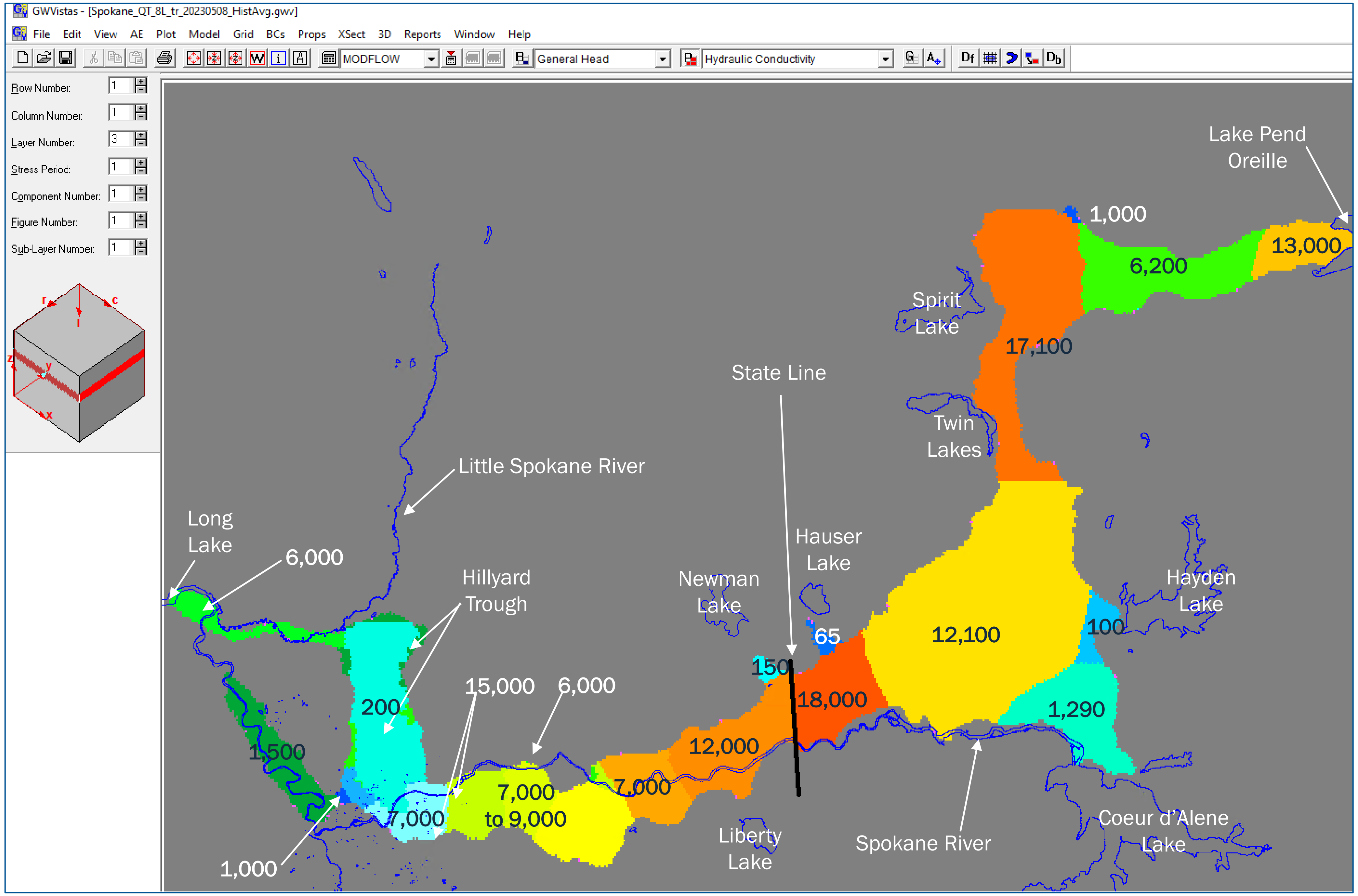
General Head

Hydraulic Conductivity

FIGURE C-6

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 2

Groundwater Flow Model Development for the City of Spokane



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Row Number: 1
Column Number: 1
Layer Number: 3
Stress Period: 1
Component Number: 1
Figure Number: 1
Sub-Layer Number: 1

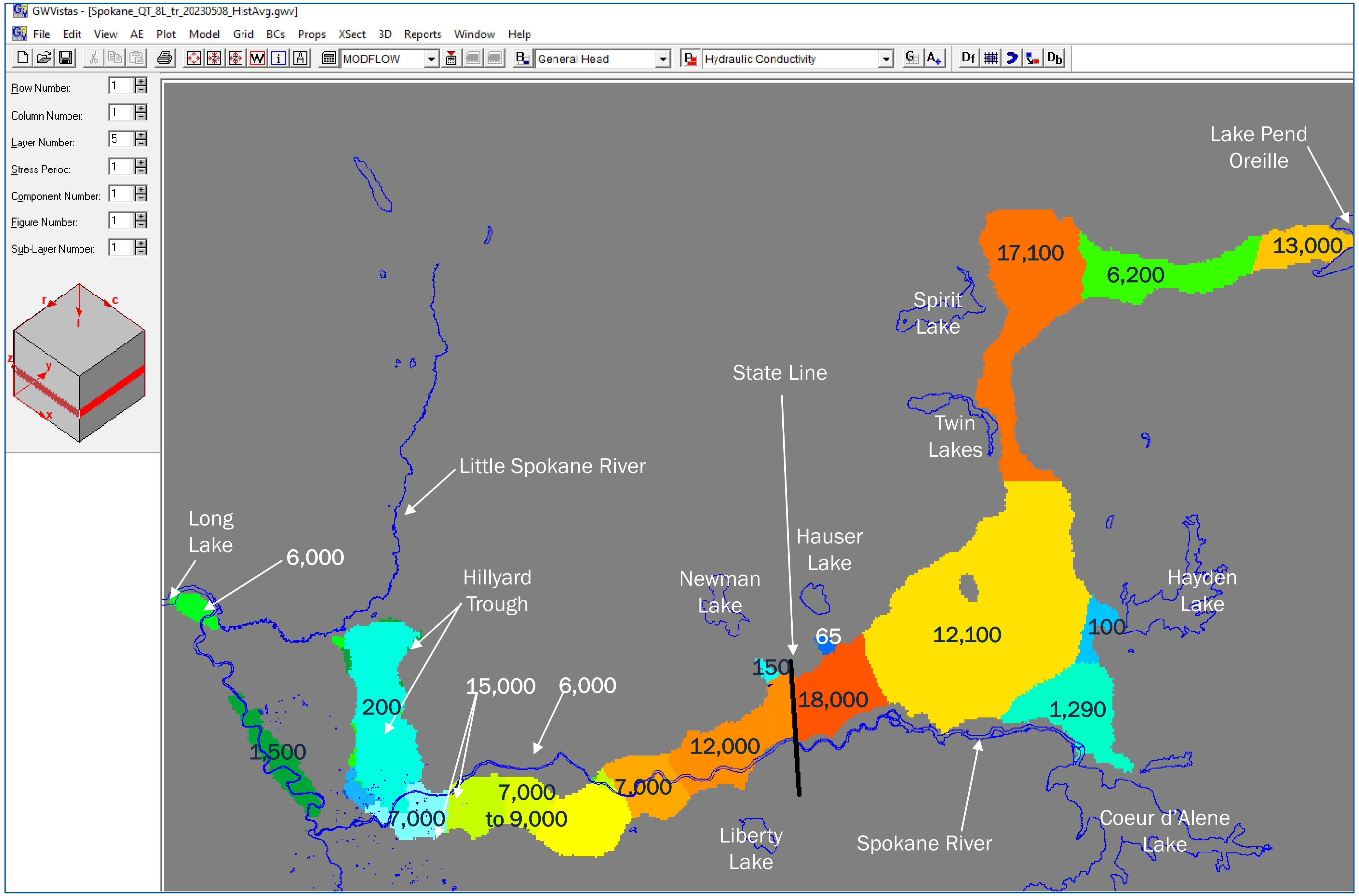
MODFLOW
General Head
Hydraulic Conductivity

FIGURE C-7

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layers 3 and 4

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.



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Row Number: 1
Column Number: 1
Layer Number: 5
Stress Period: 1
Component Number: 1
Figure Number: 1
Sub-Layer Number: 1

MODFLOW
General Head
Hydraulic Conductivity

FIGURE C-8

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 5

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.

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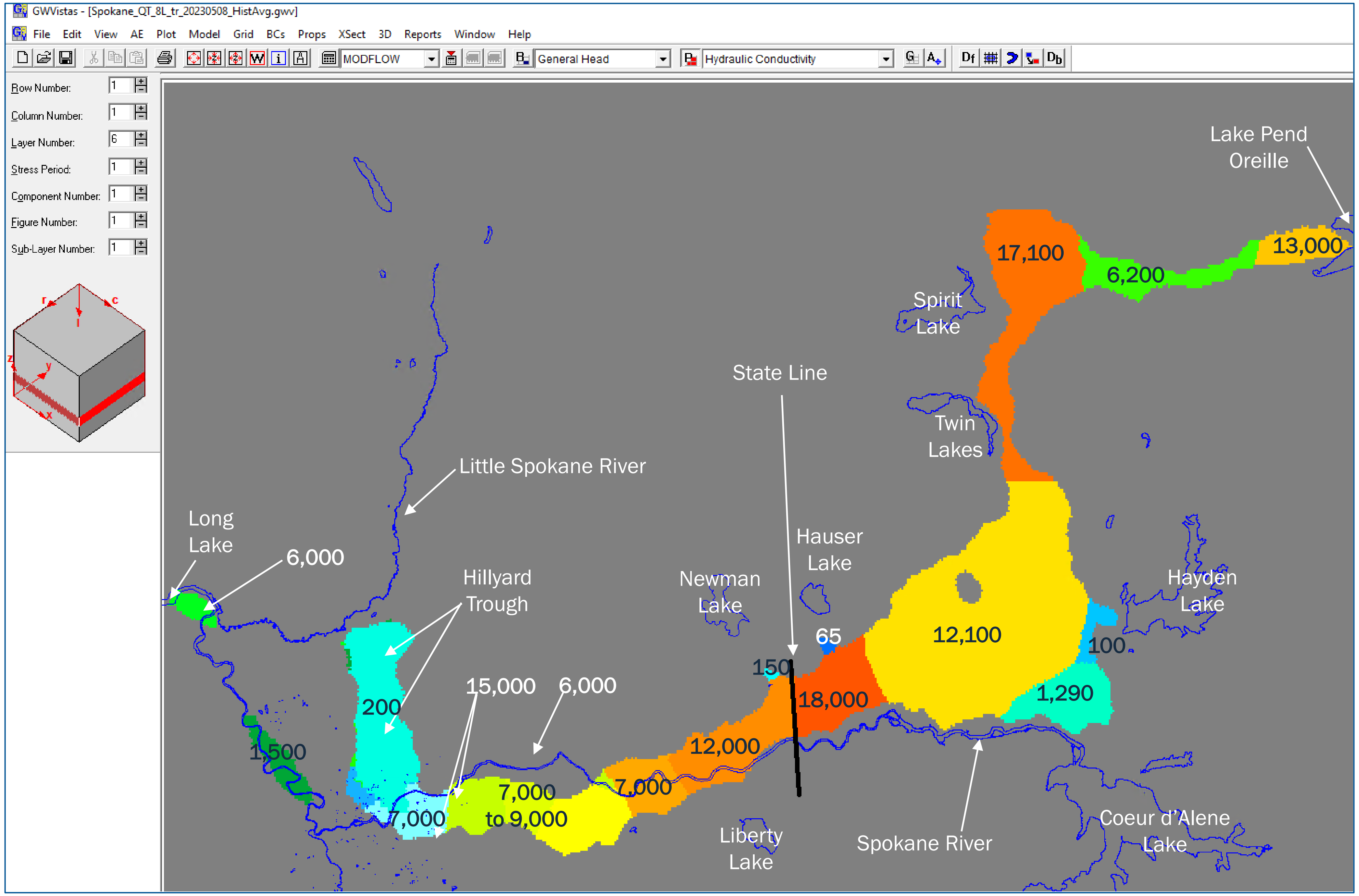

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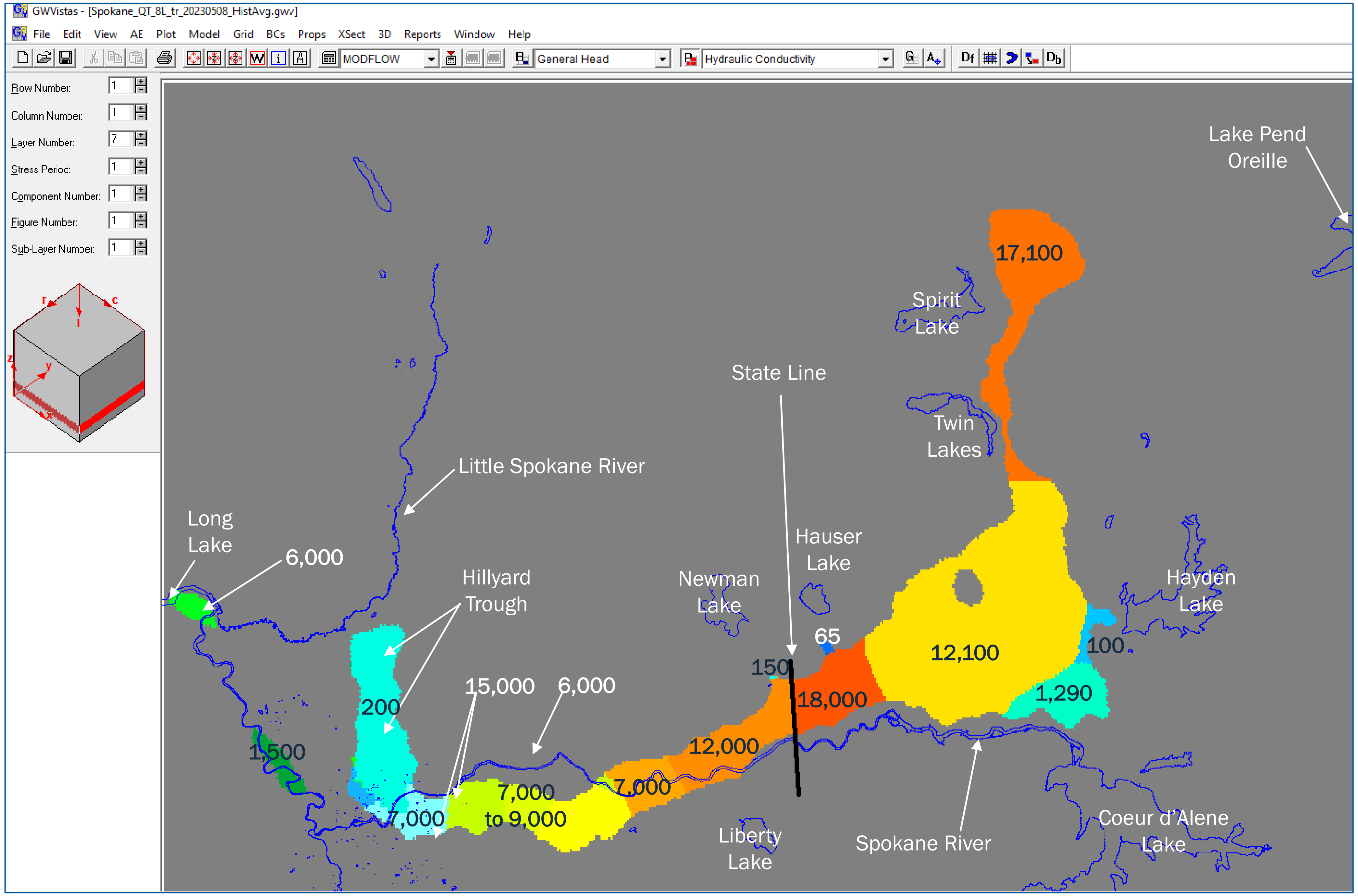
Row Number: 1
Column Number: 1
Layer Number: 6
Stress Period: 1
Component Number: 1
Figure Number: 1
Sub-Layer Number: 1

MODFLOW
General Head
Hydraulic Conductivity

FIGURE C-9

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 6

Groundwater Flow Model Development for the City of Spokane



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MODFLOW

General Head

Hydraulic Conductivity

Row Number: 1

Column Number: 1

Layer Number: 7

Stress Period: 1

Component Number: 1

Figure Number: 1

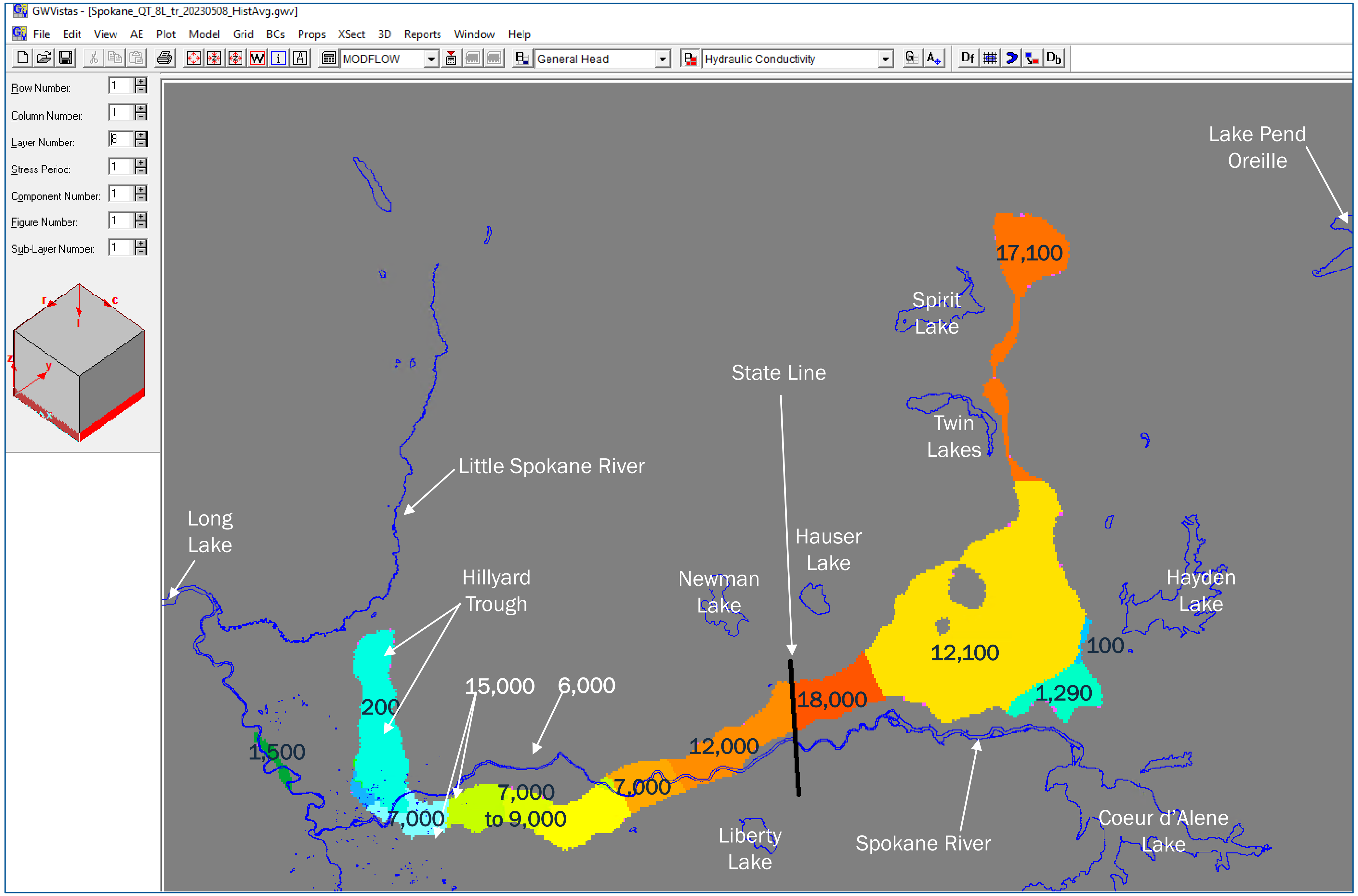
Sub-Layer Number: 1

FIGURE C-10

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 7

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.



Row Number: 1
Column Number: 1
Layer Number: 8
Stress Period: 1
Component Number: 1
Figure Number: 1
Sub-Layer Number: 1

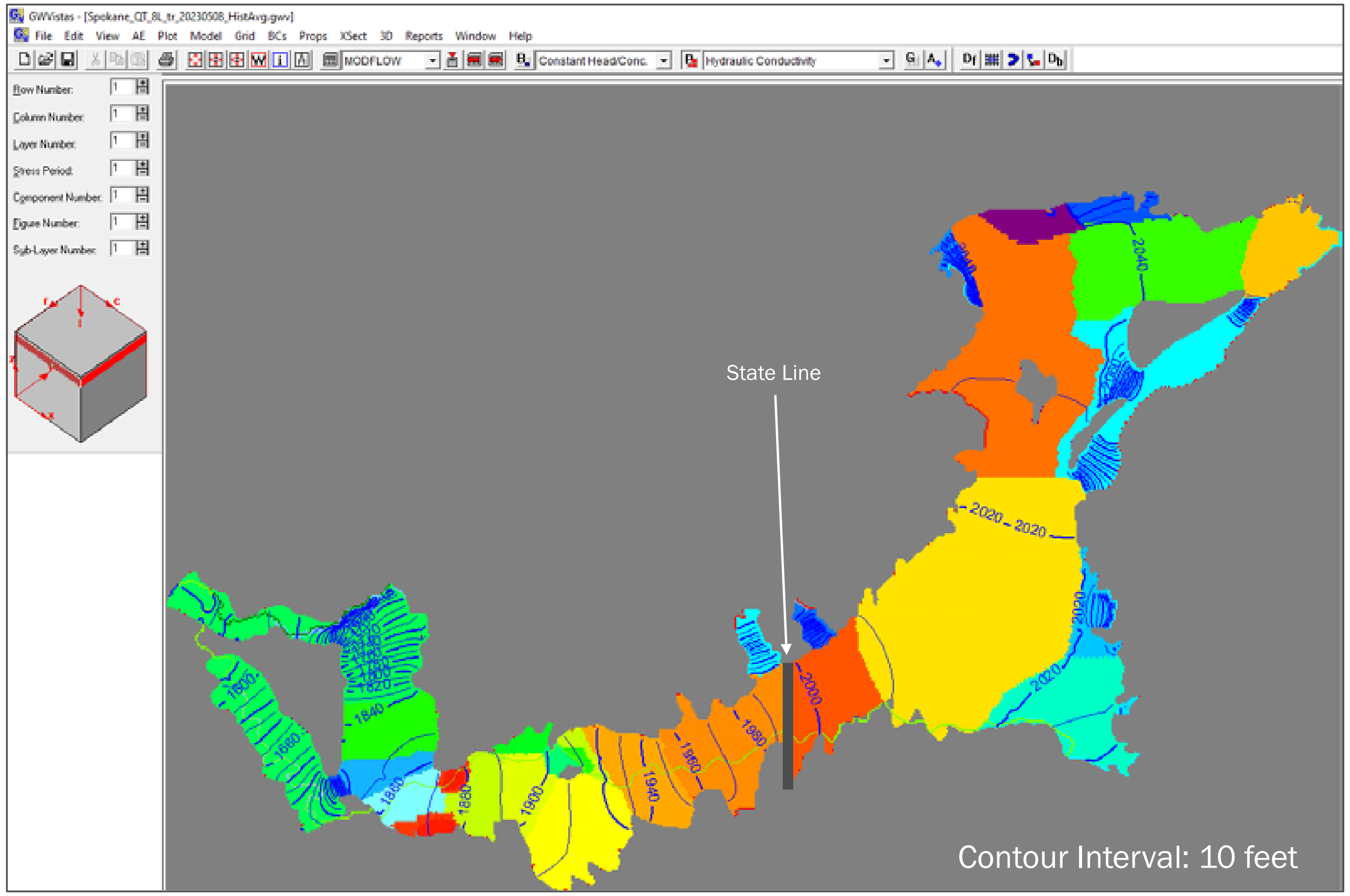
FIGURE C-11

Spatial Distribution of Horizontal Hydraulic Conductivity (feet/day) in Model Layer 8

Groundwater Flow Model Development for the City of Spokane

GSI Water Solutions, Inc.

Modeled Groundwater Elevations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MODFLOW

Constant Head/Conc.

Hydraulic Conductivity

Row Number: 1

Column Number: 1

Layer Number: 1

Stress Period: 1

Component Number: 1

Figure Number: 1

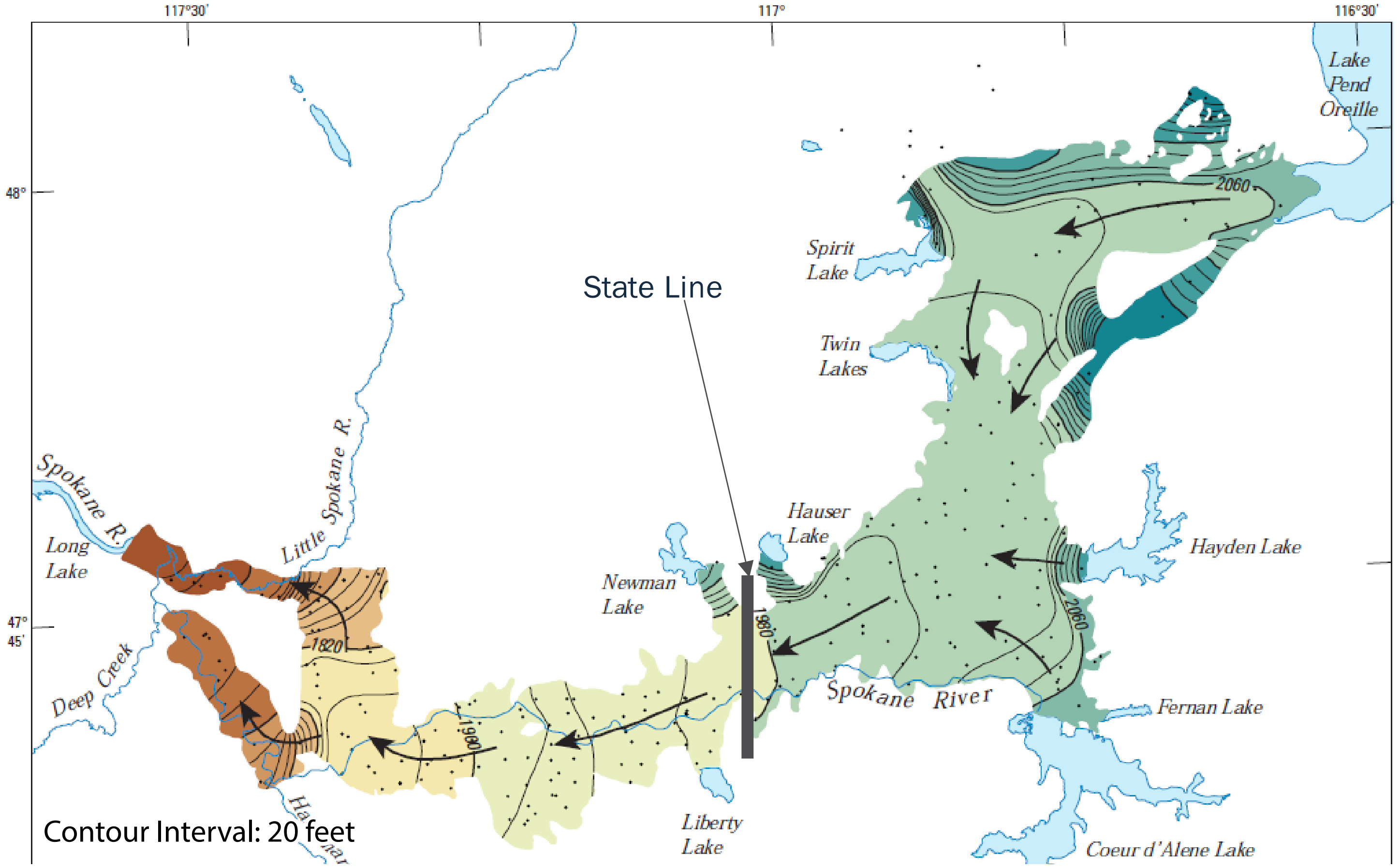
Sub-Layer Number: 1

State Line

Contour Interval: 10 feet

NOTE
Colors in the map of modeled groundwater elevations represent zones showing the differences in the spatial distribution of the aquifer's hydraulic conductivity.

Measured Groundwater Elevations (September 2004)


State Line

Contour Interval: 20 feet

NOTE
Colors in the map of measured groundwater elevations represent the spatial distribution of groundwater elevations (with the highest values in green and the lowest values in brown).

SOURCE
Kahle, S.C., and Bartolino, J.R., 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, 48 p., 2 pls.

FIGURE C-12

Modeled and Measured Groundwater Elevation Contours for Seasonal-Low Conditions

Groundwater Flow Model Development for the City of Spokane

GSI
Water Solutions, Inc.