RECLAMATION

Managing Water in the West

DRAFT Hood River Basin Study:

Groundwater Modeling and Analysis Technical Memorandum

U.S. Department of the Interior
Bureau of Reclamation
Pacific Northwest Region
Pacific Northwest Regional Office
Boise, Idaho

February 2014

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1.0 INTRODUCTION

The Bureau of Reclamation (Reclamation) and Hood River County have entered into an agreement to conduct a Basin Study in the Hood River basin (Figure 1). Reclamation and Hood River County are tasked with meeting the four objectives listed below during the Basin Study.

1. Define current and future basin water supply and demands, with consideration of potential climate change impacts.
2. Determine the potential impacts of climate change on the performance of current water delivery systems (e.g., infrastructure and operations).
3. Develop options to maintain viable water delivery systems for adequate water supplies in the future.
4. Conduct a tradeoff analysis of the options developed, summarize findings and make recommendations on preferred options.

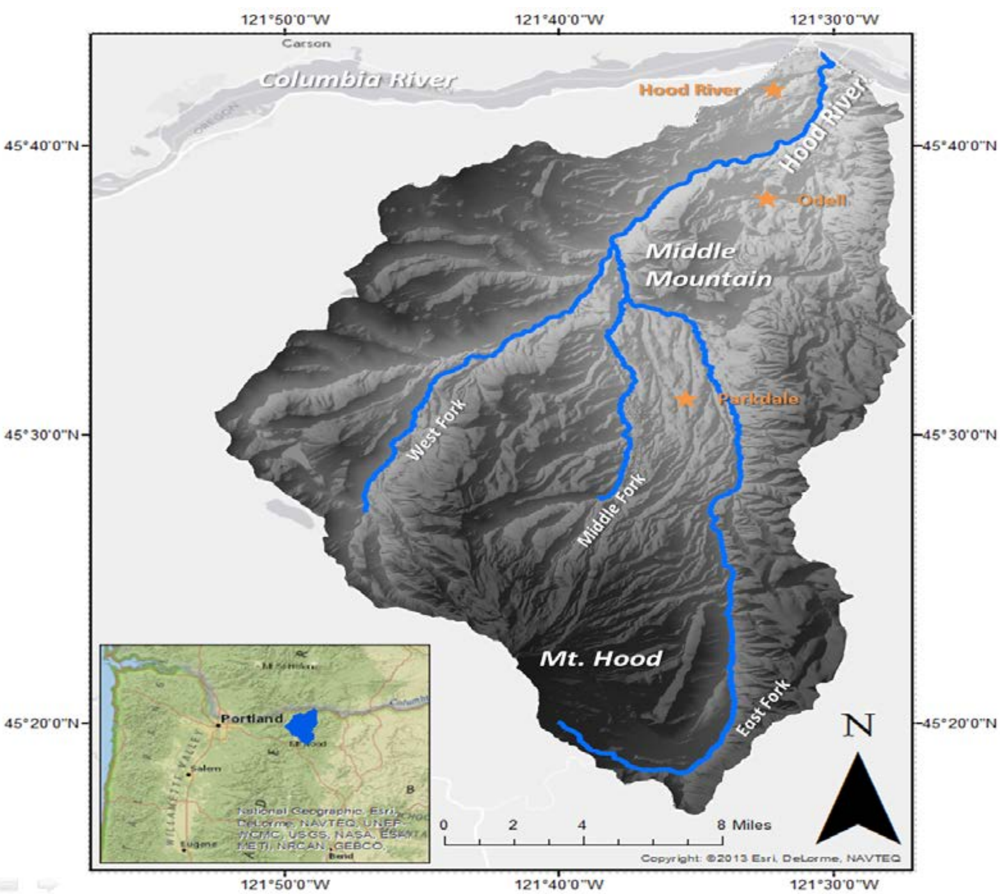

Figure 1. Shaded relief map of the Hood River Basin study area.

The Basin Study scope is limited to the appraisal level, which means that alternatives are evaluated using existing data and tools in an effort to determine alternatives that can be carried forward for further analysis.

Understanding the sources and rates of groundwater recharge and the geologic controls on its movement and discharge are vital to understanding the role that groundwater plays in the overall hydrology of the basin and groundwater contributions to streams and aquatic ecosystems. This information is also critical to understanding how much groundwater can be extracted through wells without causing adverse impact.

A groundwater model was developed by Reclamation as a means to gain insights into the groundwater hydrology in the Hood River Valley, test concepts, and better understand the hydrologic budget. The model was developed with input from geologists and hydrologists from the U.S. Geological Survey (USGS), Oregon Water Resources Department (OWRD), The Confederated Tribes of Warm Springs Reservation of Oregon (CTWSRO), Oregon Department of Geology and Mineral Industries (DOGAMI), and Hood River County (County).

Given the constraints of the Basin Study, this project was not able to address or investigate all of the issues related to groundwater hydrology in the Hood River Basin. Rather, the outcome of the project will serve as a starting point for future studies by evaluating the existing data; identifying data limitations and shortcomings; and providing a basic understanding of the hydrogeology through the water budget and model analyses.

1.1 Purpose and Scope

The purpose of this report is to document the design decisions that have been made regarding the groundwater modeling work that was accomplished in support of the Basin Study. This report describes the model development, calibration, and the scenarios that were evaluated with the model.

1.2 Groundwater Study

Groundwater in the Hood River basin was investigated as part of the Hood River Basin Study. Groundwater is a resource that has not been extensively developed in the basin; therefore, data critical to understanding the system are limited. This study focused on gaining a better understanding of the system through the compilation of existing data into a water budget and conceptual model of the system. A simple simulation model of the system was developed to provide insights regarding the following questions:

- How will new development impact groundwater conditions in the basin including discharge to streams?
- How will hydrologic changes due to climate change impact groundwater conditions?
- Is managed recharge a viable option for improving streamflow and temperature conditions?
- Can the basin aquifers be used for aquifer storage and recovery?

The alternatives that were chosen for modeling and evaluation during the Basin Study were predicated on the availability of the data needed to properly evaluate the alternative. The decision as to the alternatives that were evaluated was made by Reclamation with input from USGS, OWRD, DOGAMI, the County, and CTWSRO, and was limited based on available data. The simulation model of the basin is meant to serve as a mechanism to inform additional data needs, direct future investigations, and demonstrate basic hydrologic functioning of the basin. Its results are intended to be interpreted on a qualitative rather than on a quantitative basis; simulation outputs are more appropriate for providing insights into possible impacts of different alternatives rather than for providing absolute values.

2.0 GEOLOGY

2.1 General Understanding of Geology in Relation to Groundwater

This section presents a generalized description of the geology of the Hood River Valley and is based on the work by McClaughry and Wiley (2012) and McClaughry et al. (2012). The oldest geologic unit exposed in the study area is the Columbia River Basalt Group (CRBG), which consists of layers of basalt lava interbedded in places with sediment. Along the Columbia River, the upper part of the CRBG is interbedded with and overlain by the Troutdale Formation, a sedimentary unit deposited by the ancestral Columbia River and its tributaries. The younger Dalles Formation overlays and may interfinger with the Troutdale Formation, and is composed of volcanic-derived sedimentary deposits originating primarily from the Cascade Range. A series of Pliocene lavas, followed by late Pliocene and Quaternary lavas overlay The Dalles and Troutdale formations. These are overlain by younger deposits including surficial, semi-consolidated fluvial outwash and sands along the mainstem of the Hood River and lahar deposits from Mt. Hood. Missoula flood deposits occur in areas near the Columbia River Gorge and the lower valley. Figure 2 is a correlation chart that shows the general stratigraphy and stratigraphic nomenclature in the Hood River Valley (Tolan et al. 2002; McClaughry and Wiley 2012; McClaughry et al. 2012).

Wells in the Hood River Valley are drilled into the upper surficial sands and gravels and the Pliocene and Quaternary lavas and the CRBG, where it outcrops near Middle Mountain. Folds and faults add complexity to the system, and may locally form partial barriers to groundwater flow. Much of the Hood River Valley sits in a partial structural graben with thrust faults clearly defined to the east and less so to the west. Thrust faults in the area are known to often be hydraulic barriers to flow as is the case in the neighboring Mosier basin (Burns 2012; McClaughry et al. 2012).

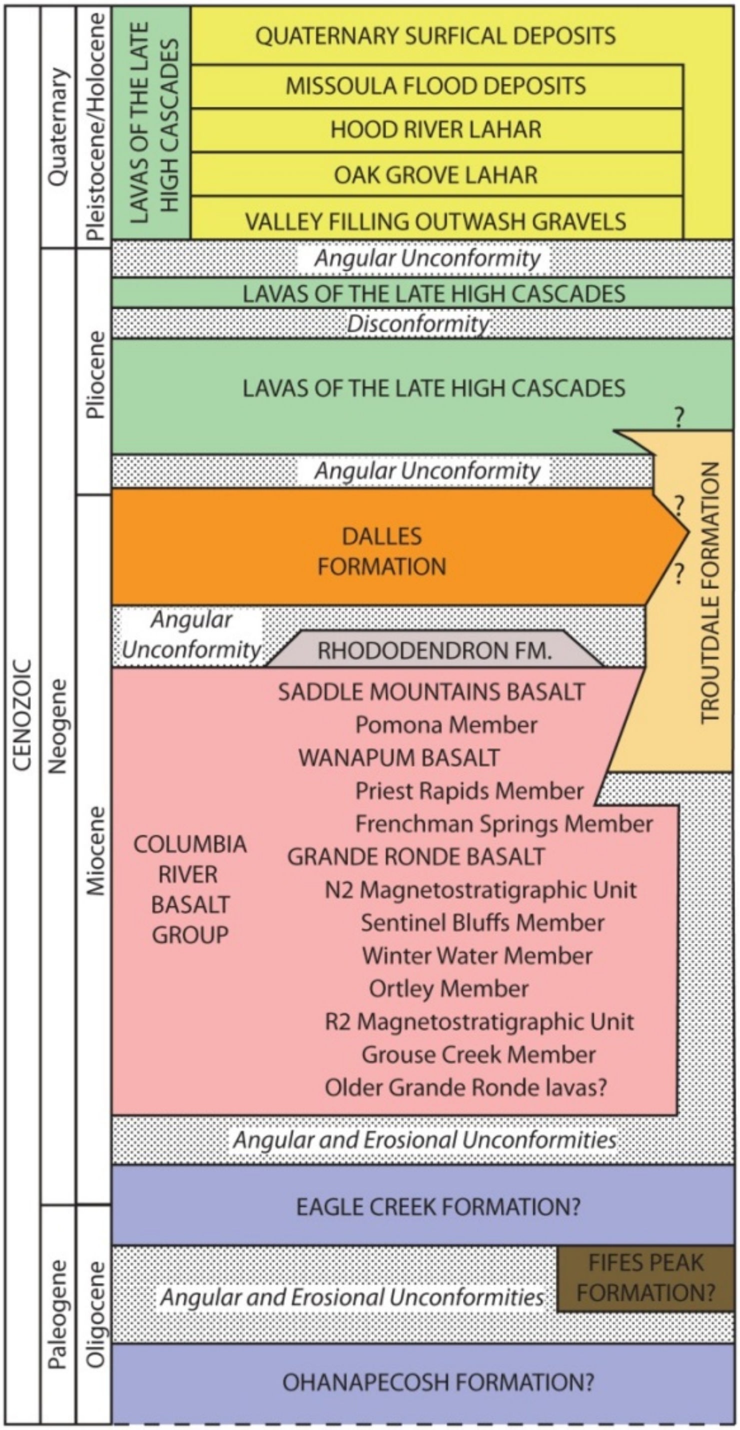

Figure 2. Generalized stratigraphy and nomenclature for the Hood River area (McClaughry and Wiley, 2012; Tolan et al. 2002).

3.0 HYDROGEOLOGIC SETTING

Knowledge of hydrogeology in the Hood River basin is rudimentary due to lack of data. Current knowledge of the hydrogeologic setting is primarily based on hydrologic principles, surficial geology, limited subsurface data from well logs, and the small but growing data set of periodic water-level measurements from wells. Well logs from drilling activities within the basin provide insight into the stratigraphy at individual locations; however, it is recognized that the material descriptions on driller's logs are of varying quality and generally not verified by independent means. Static water levels are, at best, measured quarterly by OWRD in 14 wells. A monitoring plan was recently developed by the County which resulted in projected quarterly water level measurements for an additional 16 wells.

Based on the limited amount of water level data, a general idea of the groundwater flow direction can be determined as shown by Figure 3. Groundwater flow generally mimics the topography and flows from south to north following the flow path of the Hood River. The groundwater system may be divided into two major basins by Middle Mountain, the upper basin to the south and the lower basin to the north. Middle Mountain is an uplifted section of the CRBG and seems to provide a limited hydrogeologic barrier to flow from the upper basin to the lower basin. Two wells drilled into Middle Mountain appear to have different head characteristics than wells nearby that are drilled into the upper andesite basalts and sediments. These two wells have higher water level elevations as compared to the wells in the proximity of Middle Mountain. It is likely that these two wells draw water from a perched aquifer.

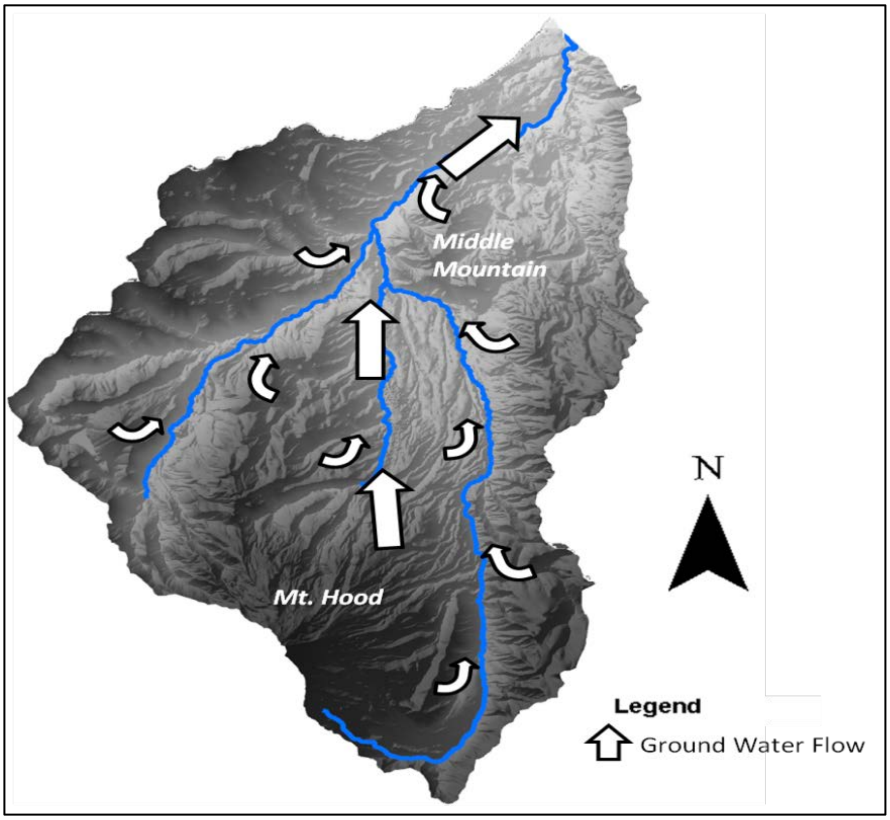

Figure 3. Estimated groundwater flow direction.

Little to no data exists regarding groundwater discharge to or recharge from the Hood River. Late-summer flow data from stream gages indicate that some amount of flow in the Hood River can be attributed to groundwater discharge. In addition, a number of springs discharge to the surface in many locations throughout the valley. Groundwater discharge to the Hood River is likely from a combination of the near-surface aquifer system and local recharge/discharge systems that are disconnected from the main aquifer (Grady 1983).

4.0 ESTIMATED WATER BUDGET

A water budget quantifies the inputs to and outputs from an aquifer system. The groundwater budget components in the Hood River basin are shown in Table 1.

Table 1. Inputs and outputs to the aquifer system in the Hood River Valley.

Inputs	Outputs
Recharge from Precipitation	Pumping Withdrawals
Stream Losses	Discharge to Streams
Boundary Inflow	Boundary Outflow
Canal Losses	Springs
On-farm Infiltration	

Available data; current knowledge and understanding; and initial estimates for each of the water budget items are described in the sections that follow. The sections also discuss the assumptions and rationale behind each estimated water budget item. The initial estimates and the reconciled water budget are shown in Table 2 and are also comparatively shown in Figure 4. Highlighted estimates in the table were made with limited or incomplete data and therefore have a higher degree of uncertainty. Values in Figure 4 are shown in relation to the aquifer; a positive value represents inflow and a negative value represents outflow.

Table 2. Estimated annual water budget table.

	Water Budget		
Aquifer Inflow	**Volume (acre-feet per year)**	**Aquifer Outflow**	**Volume (acre-feet per year)**
Precipitation Recharge	789,000	Pumping	12,000
Stream Losses	-	Discharge to Streams	290,000
Boundary Inflows	-	Boundary Outflows	482,000
Canal Losses	8,000	Springs	13,000
On-Farm Infiltration	-		
Sum	**797,000**	**Sum**	**797,000**

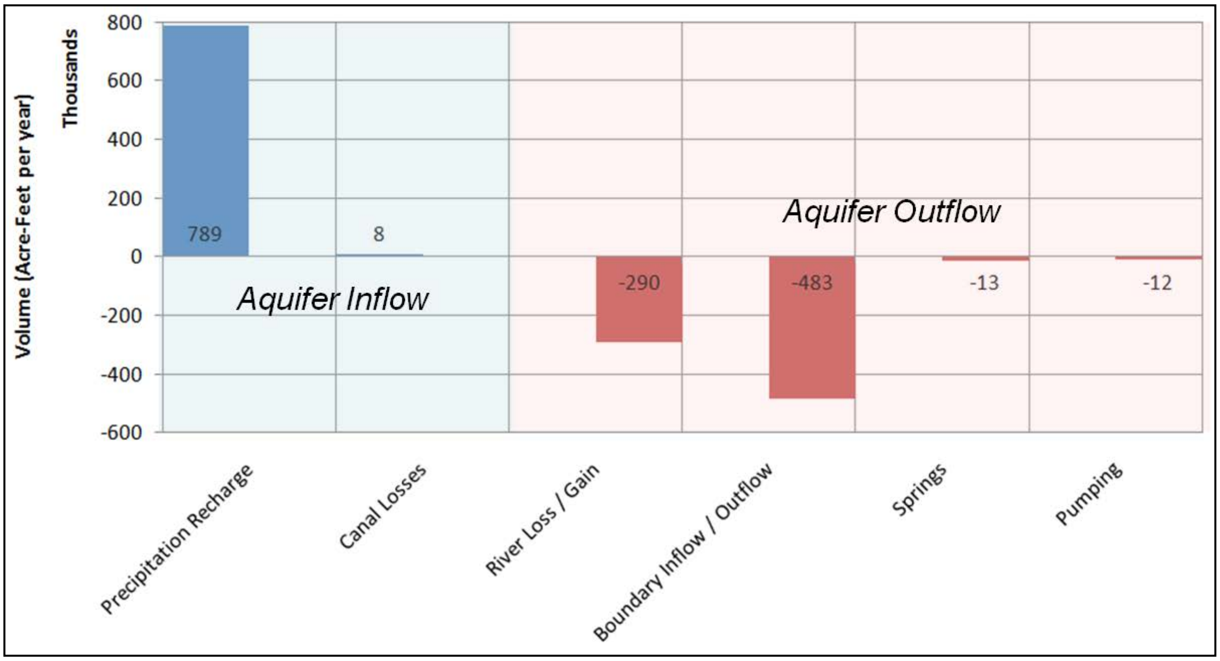

Figure 4. Estimated annual water budget chart.

4.1 Recharge from Precipitation

Based on earlier studies in the Hood River basin and nearby basins, precipitation is the largest contributor to recharge in the basin (Grady 1983; Burns et al. 2012). Comparing water levels in wells to precipitation illustrates the relation between precipitation and the groundwater system. Figure 5 shows the interquartile range of water level elevations for the long-term well, OWRD well HOOD372 (HOOD372), compared to average annual monthly precipitation for the Hood River Experiment Station located near the well. The interquartile range represents the 25th, 50th, and 75th percentiles of water level elevations for well HOOD372. Based on the observed groundwater hydrographs, it is evident that recharge increases immediately following the rainy season, which on average is from November to April, with peak water levels on average having a three-month lag in comparison with monthly peak precipitation.

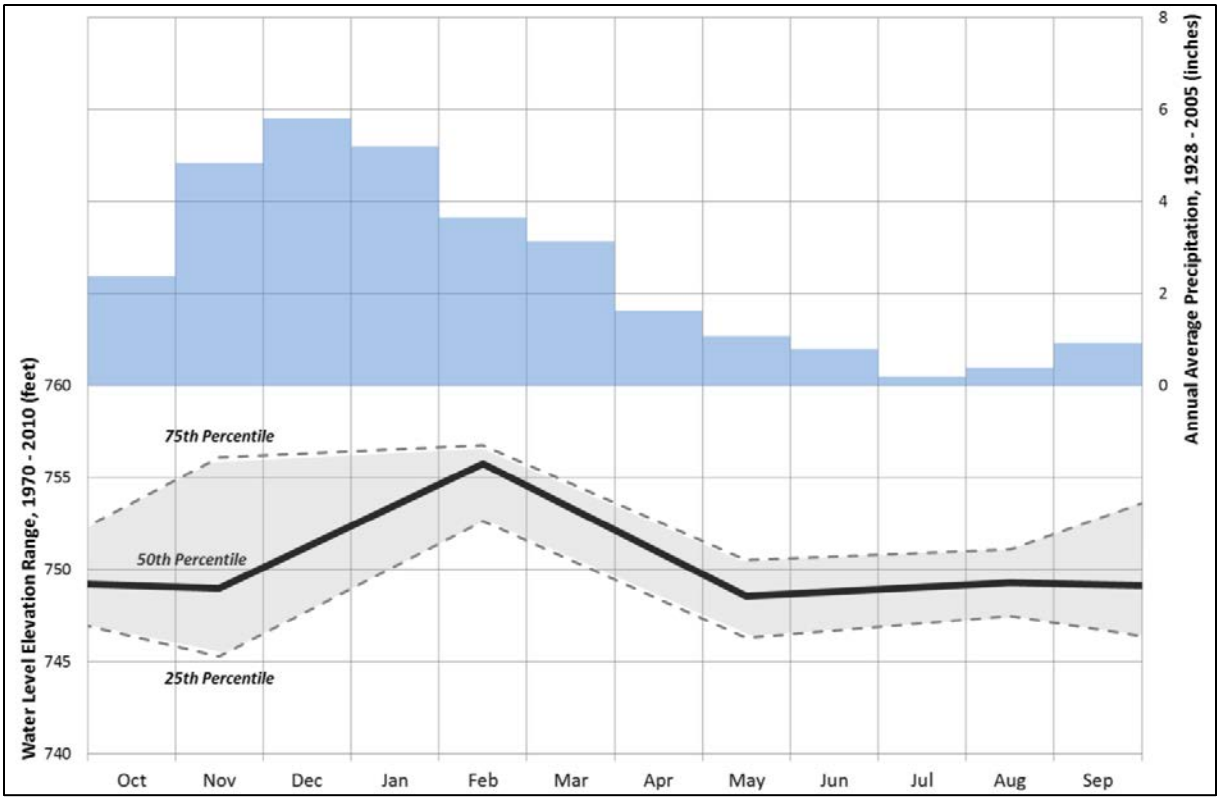

Figure 5. HOOD372 (Sec.4, T.2N R.10E) Water level elevation range and Hood River Experiment Station annual average precipitation.

Since precipitation is the largest contributor to recharge, it is important to accurately quantify its contribution. Available historical data reflects some orographic variability between observed precipitation measurements within the basin; this is supported by PRISM data as shown in Figure 6, which shows the spatial distribution of precipitation within the basin (PRISM 2013).

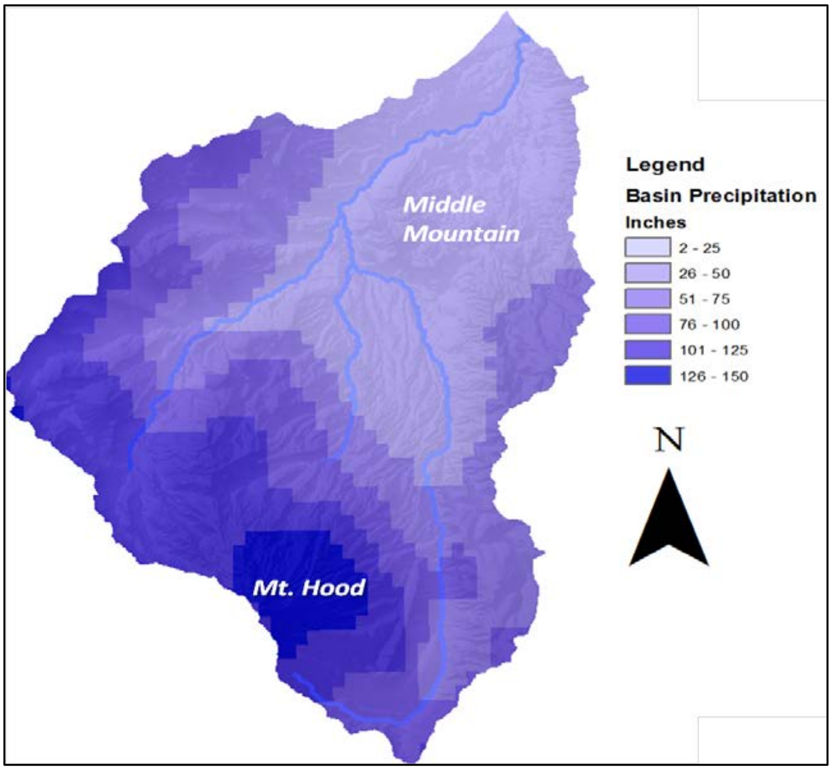

Figure 6. PRISM mean annual precipitation (1981-2010).[1]

Recharge from precipitation is dependent on many physical parameters including soil type, geologic conditions, slope of the landscape, and vegetation cover. In addition, the volume, duration, intensity, and form (snow or rain) of precipitation all play an important role in the quantity of water that becomes recharge.

Previous studies in neighboring basins used modeling techniques to quantify groundwater recharge at the regional and basin scale. These techniques account for the physical parameters and processes that govern groundwater recharge and generally provide reasonable recharge estimates. However, such methods are beyond the scope of this appraisal level analysis.

As an alternative to a recharge model, recharge was estimated using a regression equation formulated by Bauer and Vaccaro (1990), hereafter called the Vacarro equation, which represents the relationship between measured annual precipitation and modeled annual recharge using the Deep Percolation Model (DPM) in the Columbia River Basin. The deep percolation is a moisture and energy balance model that works on a daily time step, and that accounts for the movement of water from the precipitation phase to below the root zone

[1] Copyright © 2011, PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu. Map created January 28, 2013.

(Bauer and Vaccaro 1987). The regression equation was developed by fitting a polynomial curve between observed precipitation and DPM modeled recharge, and it has been applied with a modification to limit the maximum annual recharge, R, as a percentage of annual precipitation, P (Kahle et al. 2011) within the Columbia River Basin.

$$R = 0.00865P^2 + 0.1416P - 1.28$$

R: Annual Recharge (inches)
P: Annual Precipitation (inches)

In an effort to determine the applicability of the equation to the Hood River basin, the northwest area of the Deschutes River basin was evaluated. The area has an existing DPM (Gannett et al. 2001) and physical characteristics similar to the Hood River basin. Both the Vaccaro equation and the DPM were used to calculate recharge for the northwest area of the Deschutes River basin. Recharge calculated by the equation was limited to a maximum value equivalent to 70 percent of precipitation. Figure 7 shows a comparison of the output from each technique and a regression calculation that shows a reasonably close estimate for recharge with a correlation coefficient (R^2) of 0.93. A correlation coefficient of 1.0 indicates that the two datasets are perfectly correlated. From this analysis, it was determined that the equation developed for the Columbia River Basin would be applicable to the Hood River basin.

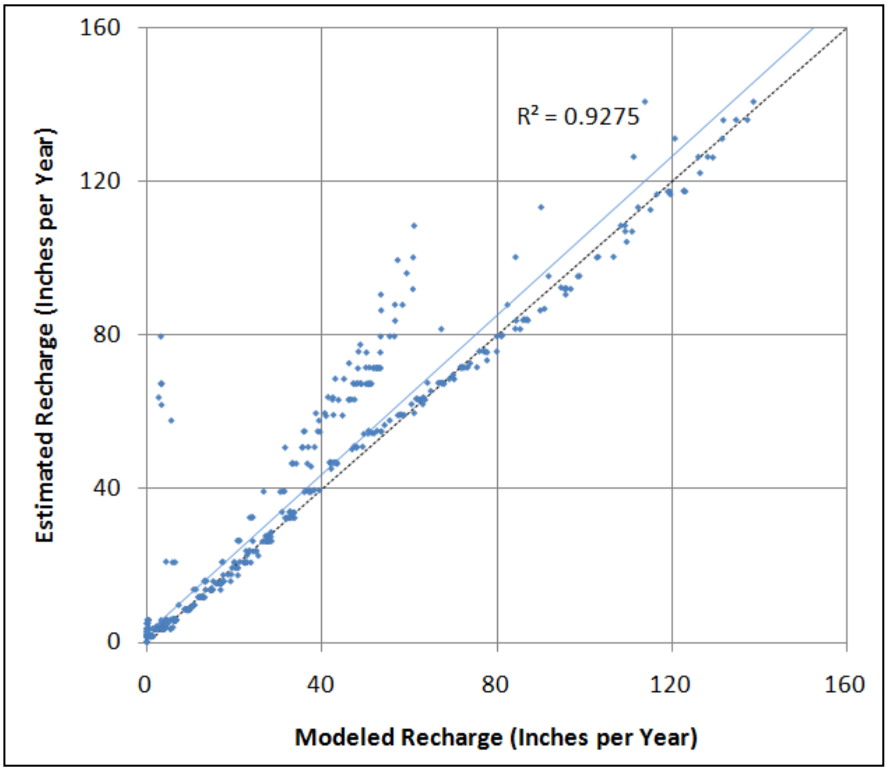

Figure 7. Deschutes basin modeled recharge via the DPM vs. estimated recharge via the Vaccaro regression equation.

Recharge for the Hood River basin was calculated using gridded PRISM data for annual average precipitation from 1981 through 2010 and the Vacarro equation. Calculated recharge was limited to a minimum value of zero, and a maximum value equal to 70 percent of precipitation. These same constants are used in the referenced study conducted by Kahle et al. (2011). This results in an average annual volumetric recharge of roughly 789,000 acre-feet per year. Figure 8 shows estimated recharge for the Hood River basin on both an annual and a quarterly basis. The first quarter which is also designated as the winter season, Q1, spans the months between January through March, the second quarter or the spring season, Q2, spans the months between April through June, and so on. The process used to estimate quarterly recharge given annual recharge is discussed in detail in Section 6.3.

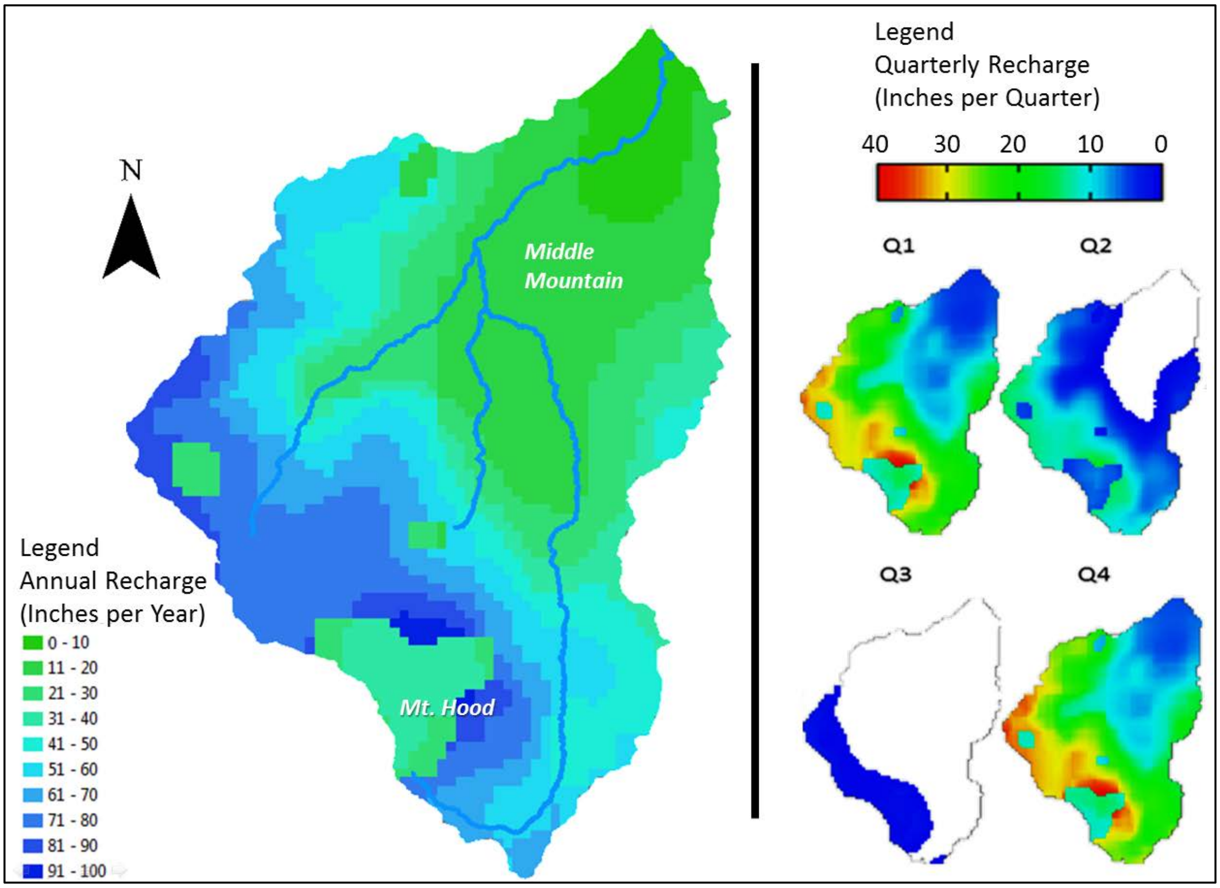

Figure 8. Estimated Recharge (Q1 = January - March, Q2 = April - June, Q3 = July - September, Q4 = October - December).

4.2 Canal Losses

Information on canal conveyance losses was from published reports from the irrigation districts in the valley. Farmers Irrigation District (FID) and Middle Fork Irrigation District (MFID) have fully piped distribution systems with very minimal, if not negligible, losses (FID 2011; MFID 2011). East Fork Irrigation District (EFID) reports a 20 percent canal loss rate on their main distribution canal (EFID 2011). Using the average flows on the East Fork Diversion Canal used by EFID, we can estimate an average annual loss of 7,530 acre-feet. Dee Irrigation District reports an estimate of 726 acre-feet total conveyance loss during the peak months of June, July, August, and September.

4.3 On-Farm Infiltration

The same reports (FID 2011; MFID 2011; EFID 2011) that outlined canal losses also provided information regarding on-farm application practices. FID, MFID, and EFID irrigators use sprinklers and micro-sprinklers to apply water to irrigated farmland. For the purposes of this study, on-farm infiltration resulting from sprinkler application is assumed to be negligible and as such, its contribution to groundwater recharge is zero.

4.4 Pumping Withdrawals

There are no measurements of pumping rates or pumped volumes within the Basin Study area. Water well reports (well logs) filed with OWRD include a defined well use type (e.g., domestic, irrigation, community); however, the well logs do not include a pumped rate or volume for the well. Water rights include an estimate of pumped rate or volume, but they are not directly associated with a well. Given this limited and somewhat disjointed set of data, current pumping rates and volumes for individual wells were estimated using average maximum pumping rates allowed by the water right type and the well use type associated with each well. Table 3 shows the breakdown of wells with filed water well reports through OWRD along with their filed well use type. Table 4 shows details about the groundwater water right types on file with OWRD.

Table 3. Well Use reported on OWRD water well reports.

Well Use	Count
Domestic	370
Irrigation	21
Community	5
Livestock	0
Industrial	15
Injection	0
Thermal	2
Dewatering	4
Piezometer	0
Other	2
Undefined	243
Abandoned	461
Total	**1123**

Table 4. Water uses and rates listed on OWRD groundwater right files.

Water Right Use	No. of Rights	Water Right Rate (cfs)		
		Minimum	Maximum	Average
Agricultural Uses	4	0.04	0.33	0.26
Air Conditioning or Heating	1	-	-	0.22
Commercial Uses	3	0.22	0.78	0.41
Fish Culture	6	0.13	1	0.65
Frost Protection	1	-	-	0.4
Group Domestic	1	-	-	0.12
Industrial/Manufacturing Uses	1	-	-	0.27
Irrigation	15	0.1	1.38	0.5
Supplemental Irrigation	10	0.08	0.78	0.28
Pollution Abatement	2	0.33	0.33	0.33
Quasi-Municipal Uses	1	-	-	0.11
Temperature Control	5	0.33	0.4	0.35

Table 3 and Table 4 demonstrate that well use information from well logs and use types in water rights files do not match nor do they have a one-to-one relationship. To calculate the pumped volumes for the water budget, known water rights were assigned to the nearest well given the water right's mapped place-of-use while the remaining wells have pumping flow rates estimated based on the procedure outlined in the next paragraph.

Well 438 is a community well with no identified water right attached to it and therefore falls into the category of "Group Domestic" as indicated in Table 4. The estimation of flow in Well 438 is used as an example of how pumping rates were estimated for the water right uses listed in Table 4. The "Group Domestic" category flow rate of 0.12 cfs was assigned to Well 438, and since it was a domestic well, it was assumed to pump year-round from January 1 through December 31. Individual domestic pumping rates without a water right were estimated based on the local average household size (2.5 persons) and a regional average per person water use (90 gallons per person per day). Abandoned and leftover undefined wells were ignored in the water budget. Although it is likely that a sizable portion of undefined wells are actually individual domestic wells, the relatively small estimated flow rates for these wells should not significantly impact the outcome of the estimation process as a whole.

Steady-state and transient pumping rates are equal for all of the well use categories except for the irrigation wells. Irrigation wells are deemed inactive in the fall and winter and only withdraw groundwater in the spring and summer while all the other wells are deemed to be active year-round. Care was exercised in ensuring that annual volumes for irrigation wells between the steady-state and transient models are equal.

The steady-state average flow rates for each well use category shown in Table 5 were calculated using the methods described above. Some wells were combined in the model due to their proximity to other wells. Despite the large number of domestic wells in the area, the largest share of groundwater withdrawals are used for irrigation, fish, and industrial purposes as listed in the OWRD water rights database.

Table 5. Basin pumping wells.

Well Use	Well Count	% Total Count	Total Pumping (cfs)	% Total Pumping
Community	1	0.43%	0.12	0.51%
Domestic	176	75.86%	0.05	0.21%
Fish	5	2.16%	4.25	18.15%
Industrial	7	3.02%	2.45	10.46%
Irrigation	18	7.76%	15.85	67.68%
Thermal	2	0.86%	0.70	2.99%
Unidentified	23	9.91%	0.00	0.00%

4.5 River Gains and Losses

There are no observed data or studies that specify locations of where, and quantities of how much, the aquifer loses water to the river (river gains) or is being recharged by the river (river losses) for the Hood River. In the Hood River basin, measured river gains contain both groundwater and runoff from glacier melt originating from Mt. Hood. Because of this, large uncertainties are associated with estimating the groundwater component of streamflows (baseflows) since it is estimated that a portion of summer flows are due to glacial melt (Nolin et al. 2010).

An initial approximation of baseflows was derived from unregulated streamflow measurements. Figure 9 shows the average unregulated monthly streamflows which were calculated by adding recorded diversions by local irrigation data back to historical streamflow measurements (Christensen 2013). The minimum flow typically occurs in October when median streamflow at the Tucker Bridge gage is roughly 400 cfs. Although a small portion of the October flow may be attributed to glacier melt, it is reasonable to assume that the majority of flow in October can be attributed to groundwater since October ambient temperatures in the higher elevations are not conducive for snow and glacial melt. Assuming the 400 cfs minimum flow is attributed only to groundwater and that 400 cfs is a reasonable estimate for the baseflow throughout a year, an annual estimate of 290,000 acre-feet per year can be calculated.

Since baseflows likely increase as a response to seasonal fluctuations in precipitation, the estimated volume of river gains can be considered a lower bound to the actual baseflow above the Tucker Bridge gage. An upper bound for baseflow can also be estimated by using the natural streamflow data. The natural streamflow is the sum of river and stream gains, natural runoff, and glacial melt; it is unlikely that river gains alone will exceed this amount on an average annual basis. Using the median natural streamflow, an upper bound of 750 cfs on an average annual basis is estimated.

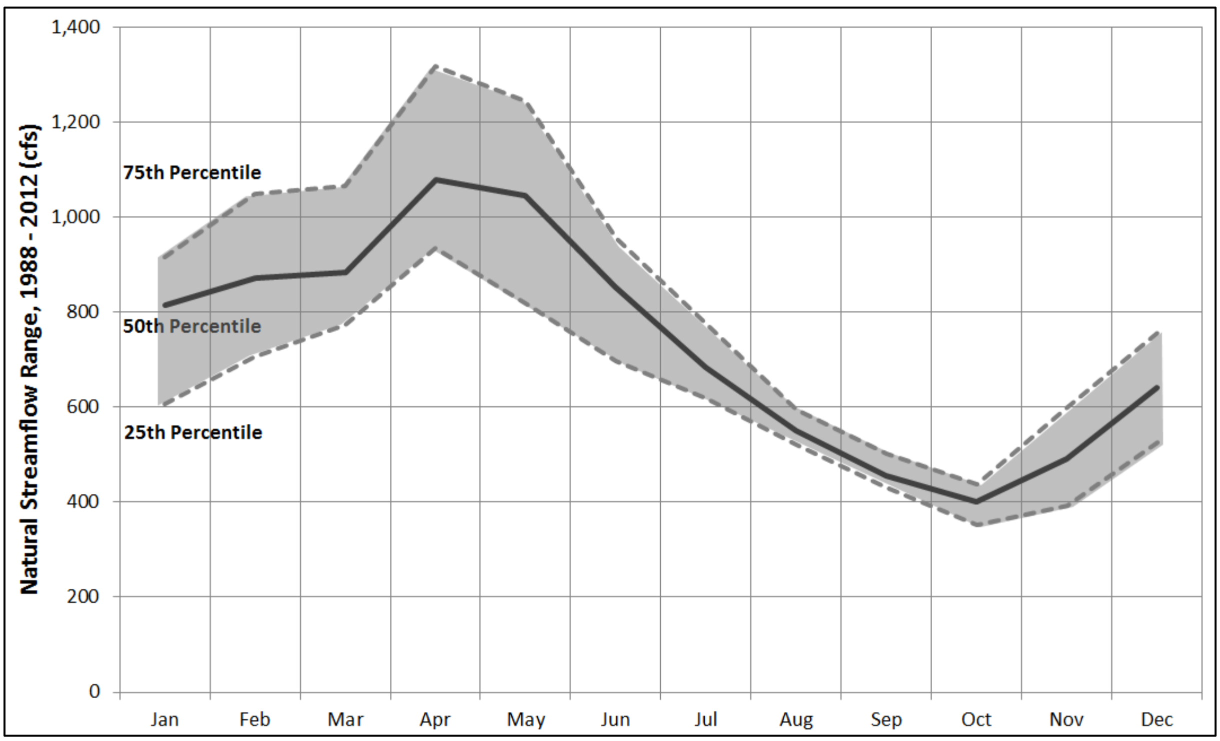

Figure 9. Mean monthly flow of Hood River at Tucker Bridge natural flow inter-quartile range (Christensen 2013).

River and stream losses to the aquifer are assumed to be negligible since they are mostly underlain by the CRBG (McClaughry et al. 2012). This assumption is adapted from a study in the neighboring Mosier Creek basin where it is assumed that rivers and streams underlain by the CRBG have negligible aquifer losses as compared to gains (Burns et al. 2012).

4.6 Springs

There are a large number of springs in the Hood River basin. Although the locations of some springs are known, many have unmeasured discharge. Water use reports for gaged springs show that the irrigation districts only report their water use from the spring and not necessarily the total spring discharge. Anecdotal evidence suggests that the reported spring water use represents only about 20 percent of the total spring discharge at each source (Christensen 2012).

An annual average diversion from springs of roughly 2,300 acre-feet was calculated by using reported water use data and irrigation district reports. Adjusting this estimate by assuming that it only accounts for 20 percent of total spring discharge results in a total reported spring discharge of 11,500 acre-feet per year. It is important to recognize that this estimate only serves as a lower bound for the basin's total spring discharge since there are other springs within the basin with no reported data in terms of water use.

4.7 Boundary Flows

Based on geologic information and general knowledge of the basin, the south, east, and west boundaries are assumed to be no-flow boundaries. The eastern boundary is considered a no-flow boundary because of the thrust faults that occur in the area. A portion of the northern boundary is assumed to be a flow boundary due to its proximity to the Columbia River and its relatively low elevation. The southwestern boundary and southern boundaries are considered no-flow boundaries based on topography.

Water likely leaves the basin via the north boundary at the Columbia River. The boundary outflows can be estimated using the previously estimated water budget components. By reconciling the water budget, a boundary outflow of 458,000 acre-feet per year is estimated. This estimate is considered to be an upper bound to boundary outflows since it is highly likely that spring discharge and river gains are underestimated. Figure 10 shows the assumed boundary conditions in the basin.

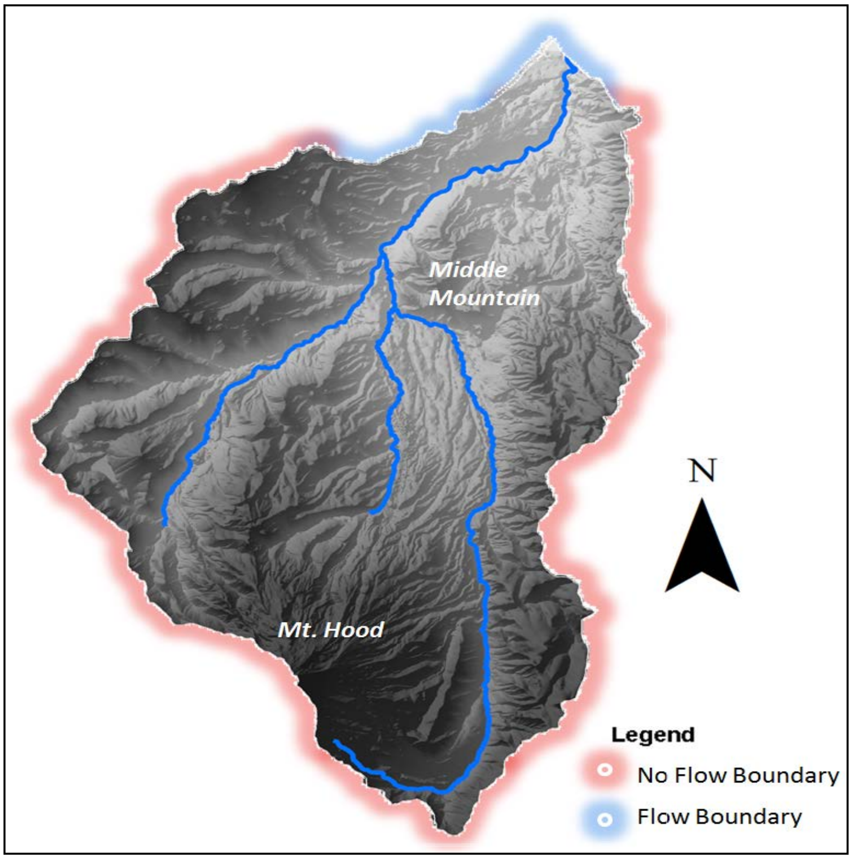

Figure 10. Assumed boundary conditions.

5.0 OBSERVATION DATA

Head data from observation wells and static water level measurements from previous reports and available well logs were used to calibrate the groundwater model. They were also used to develop the best possible understanding of the system prior to developing the model.

Out of all the wells identified in the area, there were only 14 wells with quarterly water level elevation measurements. One well has measurements starting in 1968, with the remainder having consistent quarterly measurements only since 2009. There are seven wells in the upper basin and seven in the lower basin. Water level data for these wells were referenced against LiDAR elevations and mean sea level as shown in Figure 11 and Figure 12. Average screened depths and the material that each well is screened in is shown in Table 6.

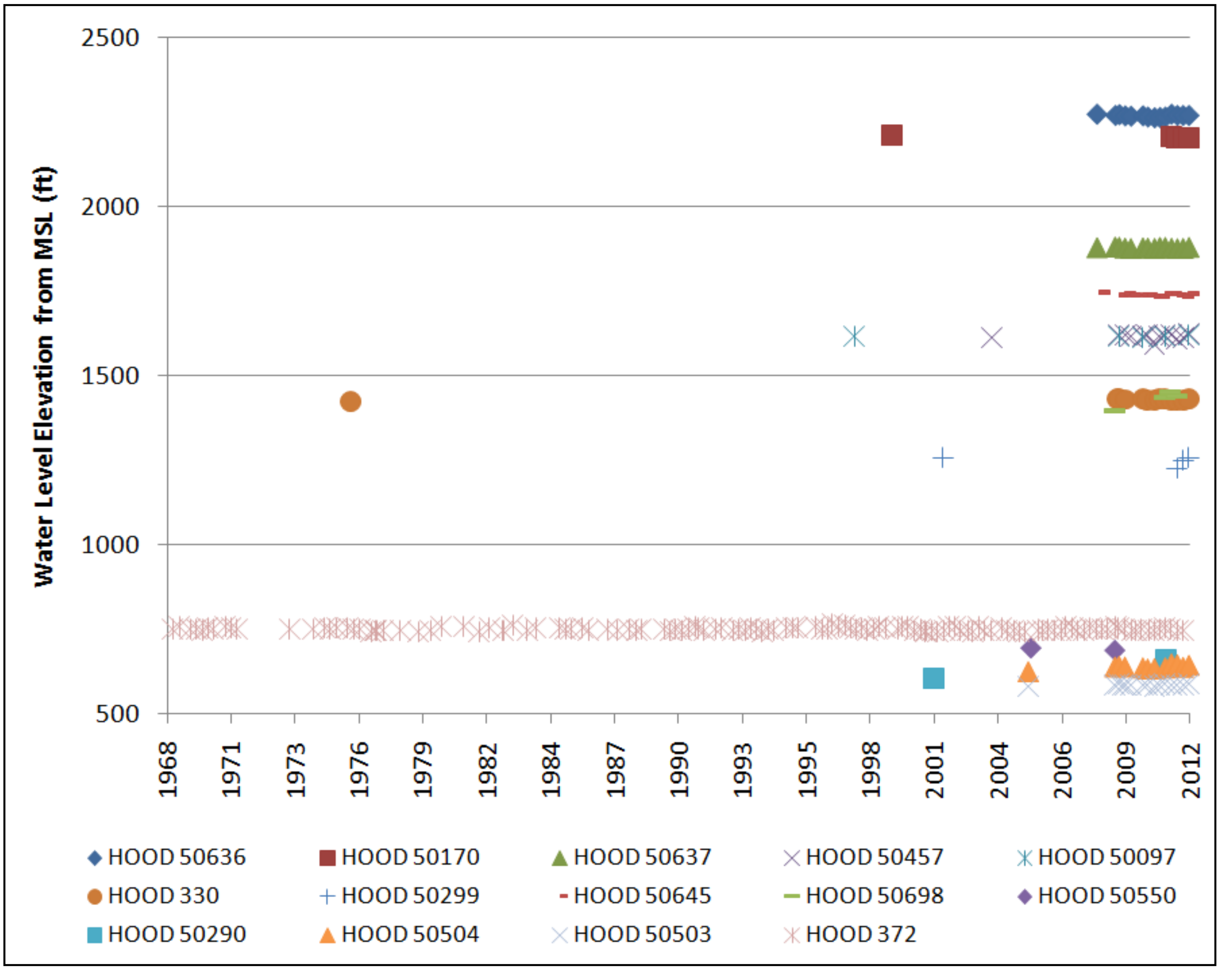

Figure 11. Measured well water level elevations: long-term trends.

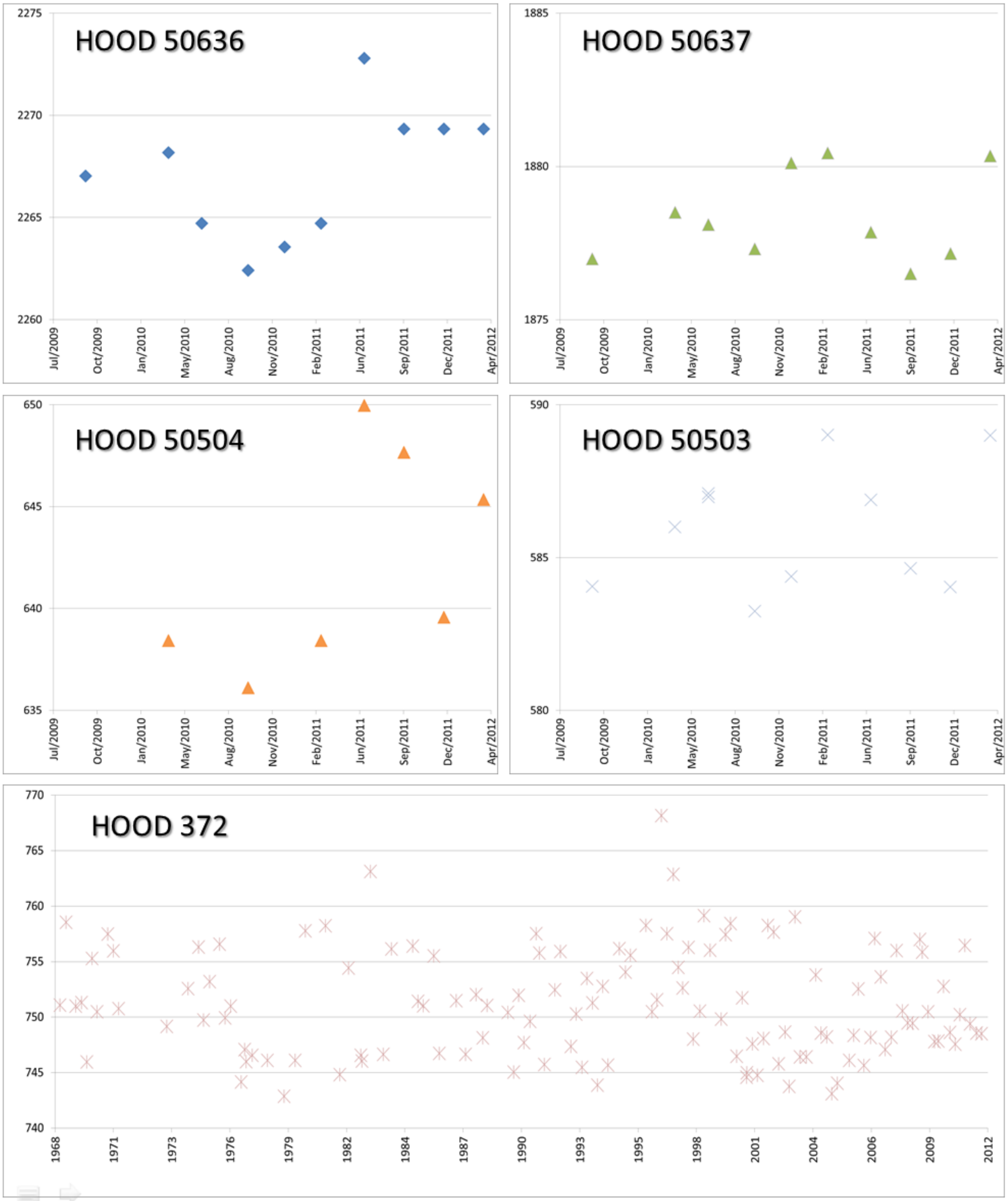

Figure 12. Measured well water level elevations: seasonal fluctuations.

Table 6. Measured well screen data.

OWRD Well Number	Location		Screened Material and Average Screened Depth (feet)	
	Upper Valley	Lower Valley	Basalt/Andesite	Conglomerate
HOOD 50550		x	225	-
HOOD 50698		x	200	-
HOOD 372		x	-	50
HOOD 50645		x	200	-
HOOD 50299		x	400	-
HOOD 50290		x	380	-
HOOD 50503		x	200	-
HOOD 50504		x	300	-
HOOD 330	x		-	60
HOOD 50170	x		110	-
HOOD 50097	x		100	-
HOOD 50637	x		210	-
HOOD 50636	x		400	-
HOOD 50457	x		230	-
		Well Count	12	2

Streamflow data is extremely limited with only three long-term streamflow gages within the Hood River area. Two gages, one near Tucker Bridge and the other on the West Fork, are directly on the river while the other is on the main diversion canal for EFID. Daily streamflow data has been measured consistently for these three gages since 1965. These data were not used to directly calibrate the model since irrigation and storage operations along with glacial melt affect the measurements. The estimates of total stream gains shown in Section 4.5 were instead used to check against the model calculated values.

6.0 MODEL DESIGN

In an effort to answer the questions posed in Section 1.2, a numeric model of the aquifer system underlying the Hood River Valley was developed. The small amount of available data and rudimentary understanding of the hydrogeological setting limit the complexity that can be simulated and require that the model be relatively simple. Because of this, the model results should be considered qualitative and not quantitative. The following sections describe the model design based on the available data and limited scope of this study.

6.1 Modeling Software

The numerical model of the Hood River aquifer system was developed using the USGS MODFLOW-2000 modeling code (Harbaugh et al. 2000), a three-dimensional, finite-difference modeling system that simulates flow through porous media. MODFLOW has been used for over 30 years to answer questions related to groundwater flow and changes to groundwater flow systems.

6.2 Spatial and Temporal Extent and Discretization

The modeled area includes the aquifer system beneath the Hood River Valley and is bound by the surface drainage boundary as shown by Figure 1. A grid resolution of 0.5-by-0.5-kilometer squares was used for the model. A single layer was used to represent the groundwater flow system. The model extent, grid cells, and its boundary definitions are shown in Figure 13. Each boundary definition is explained in depth in section 6.3.

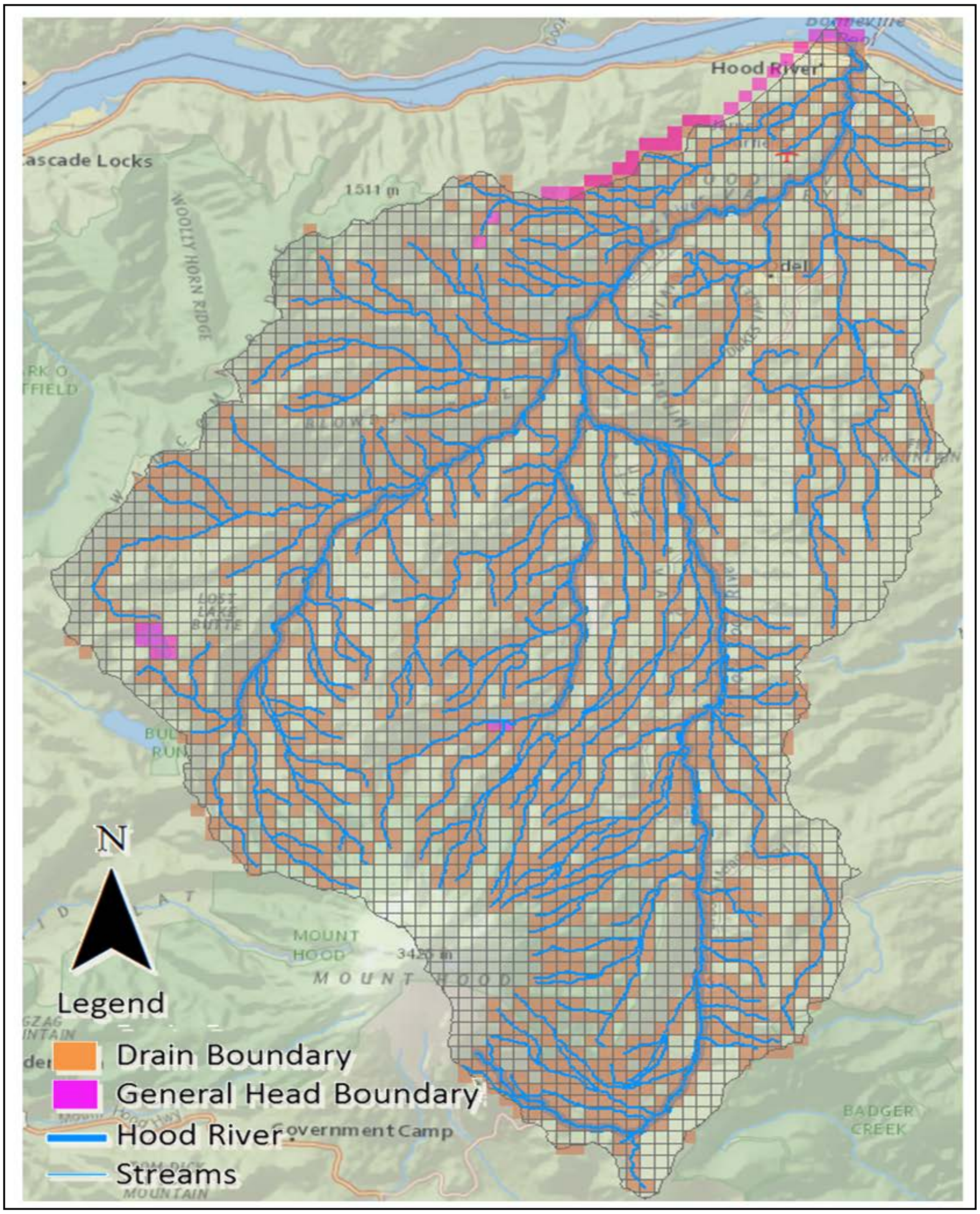

Figure 13. Model grid and boundary definitions.

Well log analysis on the screened depths and material for all active non-domestic wells is shown in Table 7. Most of the groundwater withdrawals appear to come from basaltic or andesitic lava flows. In referencing Figure 2, these strata correlate to the Quaternary or Pliocene lavas shown on Figure 2.

Table 7. Basin pumping well screen data.

Well Number	Well Use	Average Screened Depth (feet)	Screened Material
289	Fish	304	basalt
50096	Fish	177	basalt
50097	Fish	100	basalt
50456	Fish	300	cinders
50457	Fish	320	andesite
402	Industrial	175	basalt
404	Industrial	135	basalt
436	Industrial	152	rock
50179	Industrial	220	basalt
50547	Industrial	690	basalt
50548	Industrial	520	basalt
50550	Industrial	225	cinders
364	Irrigation	434	basalt
411	Irrigation	204	rock
417	Irrigation	206	rock
437	Irrigation	125	conglomerate
582	Irrigation	200	conglomerate
50017	Irrigation	757	rock
50018	Irrigation	920	basalt
50019	Irrigation	278	rock
50062	Irrigation	16	sand
50182	Irrigation	380	basalt
50290	Irrigation	395	basalt
50299	Irrigation	722	rock
50300	Irrigation	247	basalt
50503	Irrigation	280	cinders
50504	Irrigation	355	cinders
50507	Irrigation	435	basalt
50646	Irrigation	40	basalt
50698	Irrigation	490	basalt

The model is defined with a single layer that represents the materials that for the most part overlay the CRBG: the Troutdale Formation, the Dalles Formation, the Pliocene and Quaternary lavas, and the overlying surficial materials. The CRBG is included to the extent that it outcrops on the surface, such as at Middle Mountain and along the Columbia River Gorge. A constant depth of 800 meters (2,600 feet) from the surface was used as a representation of the single layer model. A depth of 800 meters was used based on a previous study in the nearby Deschutes basin which suggests that convective heat transport and groundwater flow is greatly diminished at depths greater than 800 meters (Ingebritsen et al. 1992). Figure 14 shows vertical slices of the model which are representative of the entire model domain.

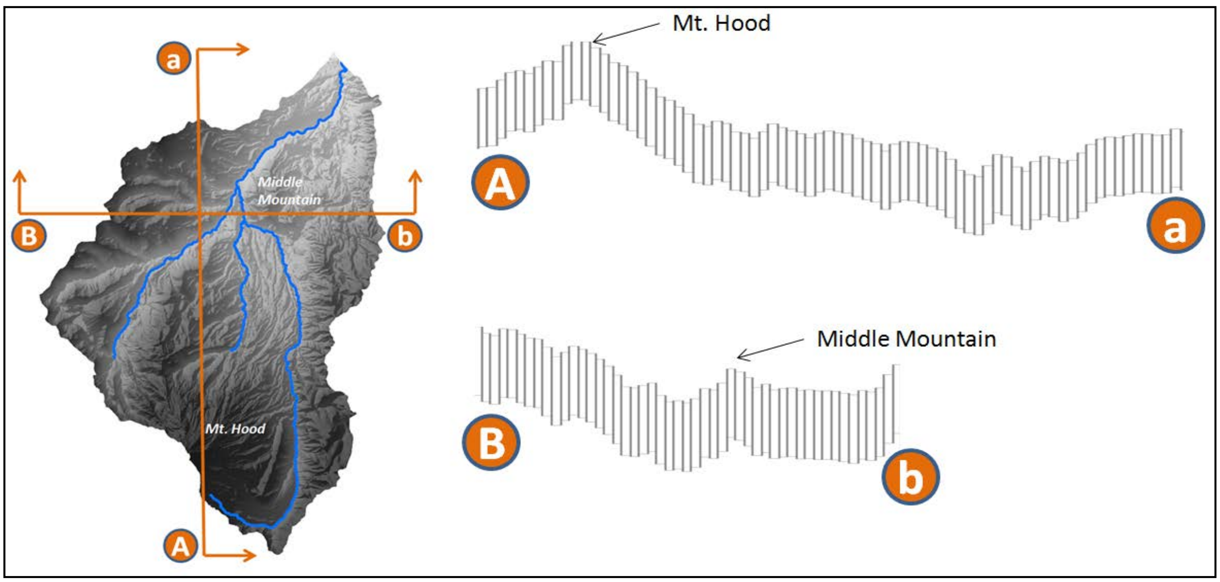

Figure 14. Model cross section samples.

The steady-state model was built to simulate long-term average conditions while the transient model was built to simulate a 15-year time span with quarterly stress periods representing average quarterly conditions. The transient model was calibrated only for the last 5 years of simulation with the first 10 years acting as a "spin-up" period for the model.

6.3 Boundary Conditions

The boundary conditions reflect known or assumed geologic conditions and inflow/outflow boundary locations. The northern boundary represents the aquifer outflow to the Columbia River using the Constant Head Boundary package. The eastern boundary is a no-flow boundary that follows the thrust faults which are assumed to be a hydraulic barrier to flow. The southern boundary follows the drainage boundary to the top of Mount Hood and is assumed to be a no-flow boundary. The western boundary is also represented as a no-flow boundary, as it is believed to contain thrust faults that provide a hydraulic barrier to flow.

The Hood River is represented with the Drain package in accordance with the assumptions made in Section 4.5 (i.e., Hood River only gains water from the aquifer). LiDAR data and the average historical river stage were used to determine the elevation of each drain. The Drain package is also used in areas where there are springs, streams, and irrigation drainage features. Locations of intermittent streams were obtained from the National Hydrography dataset and imported into the model. Pumping wells were represented using the well package, with flow rates that were determined in the water budget. The General Head Boundary (GHB) package was used to define the major lakes and reservoirs within the basin. Heads at these boundaries were estimated by using average annual water level elevations. The GHB package was also used for the northern boundary where the basin connects to the Columbia River. The head at this boundary was estimated using the average annual water level elevation of the Columbia River. Initial heads for the model domain were estimated from the reported static water levels in the basin well logs; a two-dimensional surface was developed from the well data using a geographic information system and this surface was used for starting heads in the model.

The Recharge package is used to apply recharge to the model using the spatially varying rates determined in the water budget. The Vaccaro equation that was used to estimate recharge takes annual precipitation and calculates an annual recharge value. The equation assumes that recharge only occurs after a minimum amount, roughly 6.5 inches, of annual precipitation has occurred. The transient flow model used quarterly stress periods, so the annual recharge value was divided into quarterly values using the percentage of historical quarterly precipitation average between 1980 through 2010 as modeled by PRISM. This approach does not take snow storage and snow melt into account as a means of further adjusting the way in which precipitation is transformed into recharge. Recharge timing often does not parallel precipitation timing and Figure 5 suggests that this is also the case for the Hood River basin. Figure 5 suggests that there might be a 2-month lag between precipitation and recharge as shown by the lag between the timing of the average annual peak precipitation and the annual water level elevation in the long-term observation well. This lag is not accounted for in the quarterly recharge partitioning. Only four unique recharge distributions were used for the calibration of the transient model, one for each quarter repeated annually as shown by Figure 8. The quarterly recharge distributions are assumed to represent a seasonal average for the years 1980 through 2010.

Because they are based on a 30-year average precipitation value, the generated recharge estimates does not capture year-to-year variations in actual recharge. Figure 15 shows the difference between the 30 year average values and the continuous time series for a single PRISM cell in the upper valley of the Hood River basin based on actual seasonal precipitation values. As an example, the top left plot in Figure 15 shows the PRISM January-through-March precipitation time series from 1980 to 2010 along with the PRISM generated precipitation average for the same period (solid lines). The same plot also shows the calculated and partitioned recharge using both the precipitation time series and the precipitation average (dashed lines). Figure 15 illustrates how the recharge used in the model is not accounting for year-to-year differences and fluctuations in precipitation. The greatest mean absolute error (MAE) occurs during Q3 with a relative difference of 58 percent between the 30-year average value and the time series calculated recharge. The large relative MAE in Q3 is not expected to significantly impact recharge calculations because of the relatively small precipitation during this quarter. Estimation impacts are expected to mostly be seen during Q1, Q2, and Q4 with a relative MAE of between 30 to 40 percent.

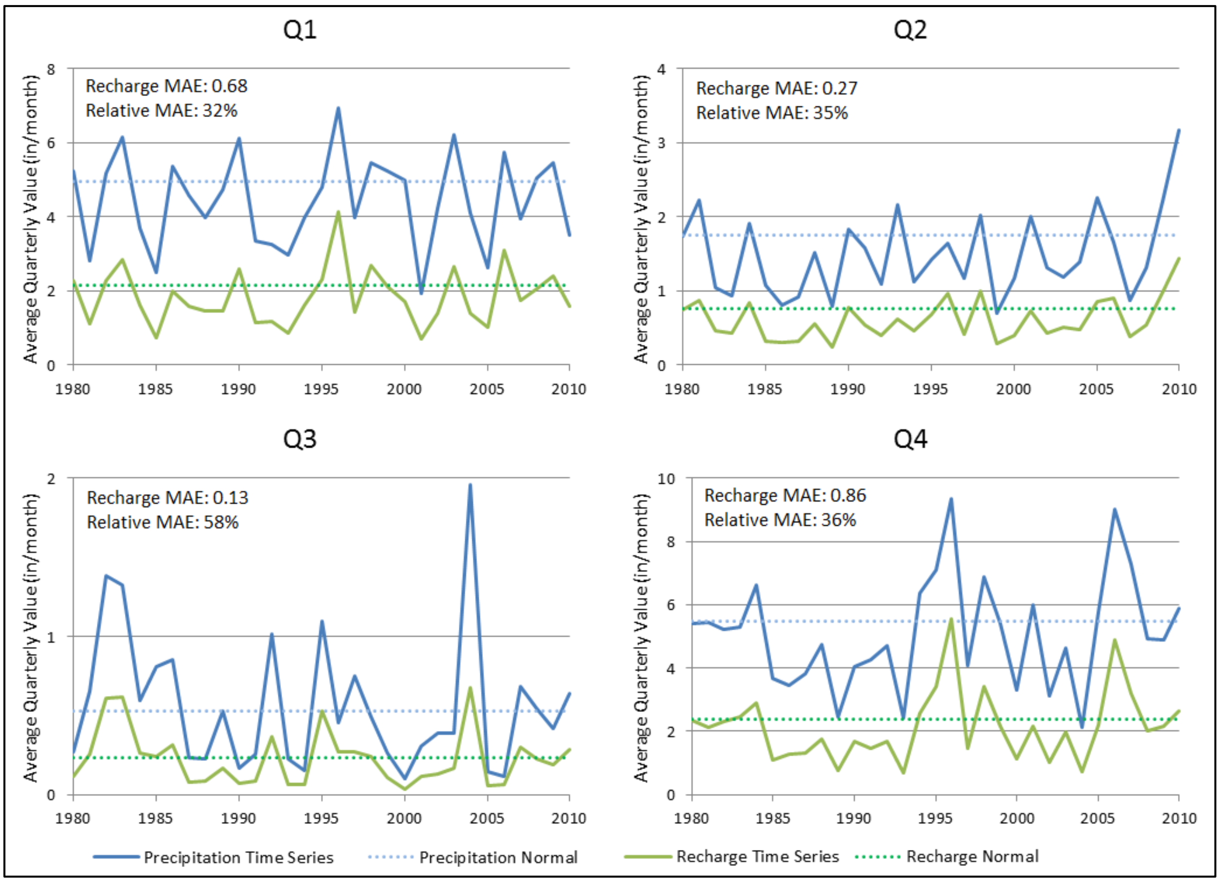

Figure 15. Time series vs. 30-year average precipitation and recharge, Long: -121.626, Lat: 45.559 (Q1 = January - March, Q2 = April - June, Q3 = July - September, Q4 = October - December).

6.4 Calibration

PEST (Doherty 2005), a parameter estimation tool, was used to calibrate the model by adjusting hydraulic conductivity, drain conductance values for the rivers and streams, and conductance values for the general and constant head boundaries for the steady-state model. In addition, storage coefficient values were adjusted for the transient model.

The steady-state model was calibrated to the observed groundwater levels described in Section 5.0, and modeled stream flux values were compared to the estimated lower bound for the Hood River streamflow at the Tucker Bridge gage from the water budget. The transient model was calibrated to seasonal averaged groundwater levels also described in Section 5.0. Pilot points were used to calibrate hydraulic conductivity and storage parameters. Pilot points allow the parameters to vary spatially allowing for the variability of the parameters to be determined by the calibration process.

Two wells drilled in the Middle Mountain area were excluded from the calibration when it was suspected that they tap a local perched aquifer. Calibration attempts using PEST with these two wells resulted in a poor fit for the head and flux targets, along with unrealistic parameter estimates for hydraulic conductivity and drain conductance values. PEST calibrations which exclude these two wells result in an excellent fit to head and flux targets, along with realistic parameter estimates.

PEST was also used to provide statistical information on the quality of model fit. A comparison of modeled and observed heads and the error residuals for the steady-state and transient models are shown in Figure 16. These plots show the model's success in simulating water levels in the basin. The modeled and observed heads for both the steady-state and transient models produce a correlation coefficient of 0.99 which indicates a high degree of correlation between the observed and modeled head values. The steady-state model has a negative bias with a mean of -12.60 which means that the model is overestimating water level elevations by12.60 feet on average. The transient model has a positive bias with a mean of 8.46 which means that the model is underestimating water levels by 8.46 feet on average. Root-mean-square error divided by the total change in head values is 0.011 for the steady-state model and 0.006 for the transient model; a value of no more than 0.100 is considered to be indicative of a well calibrated groundwater model.

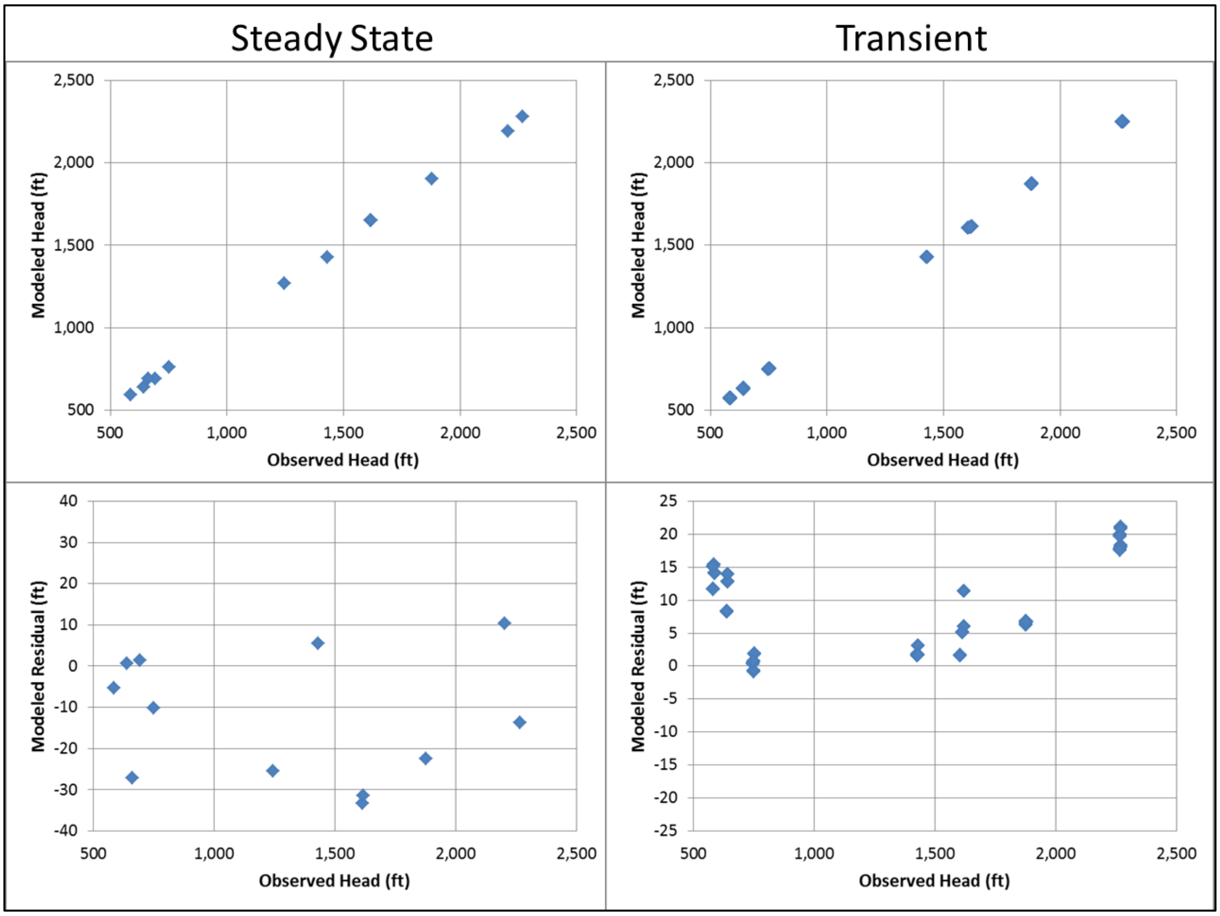

Figure 16. Steady-state and transient model calibration plots.

Steady-state modeled flux for drains above the Tucker Bridge gage is equal to 913 cfs. This overestimates the expected value based on the estimated groundwater-contributed baseflows from the groundwater budget. The upper bound for this flux was estimated to be roughly 750 cfs based on calculated natural flows at the Tucker Bridge gage. Transient modeled quarterly flux for drains above the Tucker Bridge gage is shown in Figure 17. Although the transient model captures the seasonality of the estimated groundwater gains, it overestimates those magnitudes especially during the summer and the fall since the modeled gains go above the assumed upper bound which is the average natural streamflow.

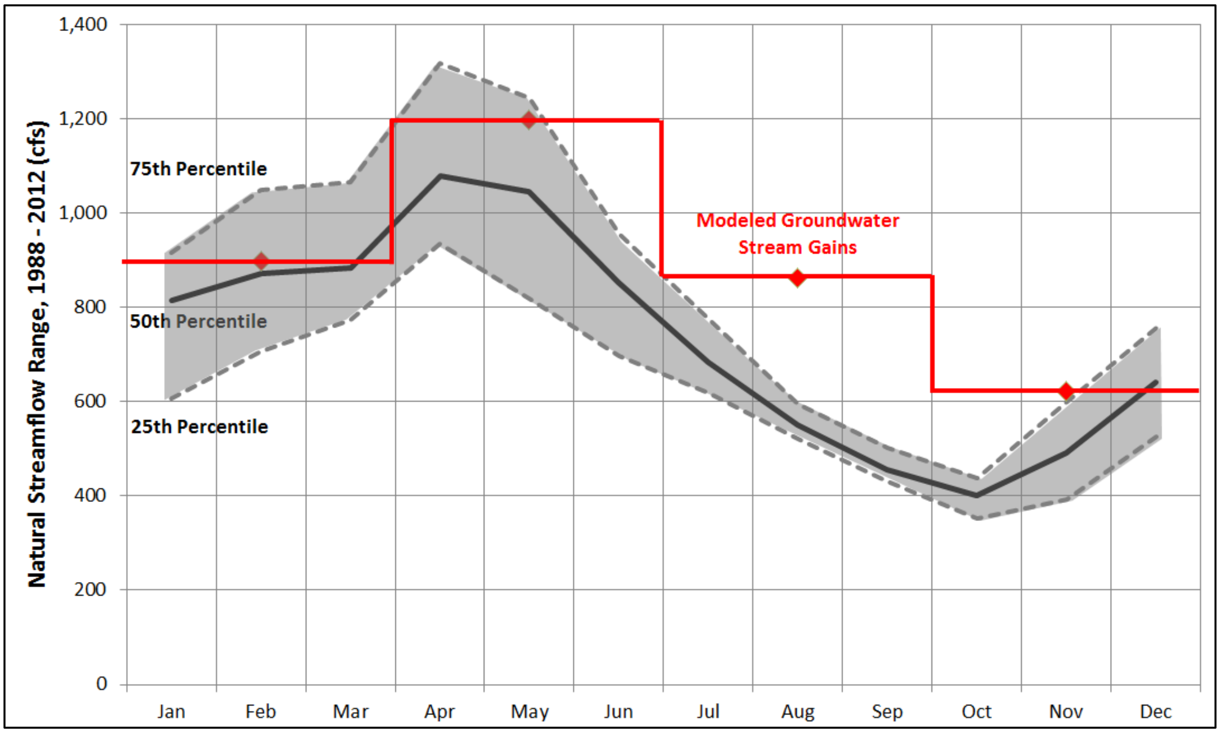

Figure 17. Historical natural streamflow range at Tucker Bridge vs. simulated baseflows above Tucker Bridge.

PEST calibrated parameters for hydraulic conductivities and storage coefficients were within the range of reasonable and documented values. Hydraulic conductivities ranged between 1 and 150 feet per day and are within the range of lateral hydraulic conductivity values for formations that overlay the CRB used in a USGS study within the neighboring Deschutes River basin (Gannett and Lite 2004). Calibrated storage coefficients were also within the range of those used in the Deschutes River basin with values between 10^{-3} and 10^{-6}. The distribution of hydraulic conductivity values also seem reasonable based on the existing knowledge of the local geology. Figure 18 show the distribution of hydraulic conductivity values within the basin.

The calibration process was also valuable in determining possible areas of improvement in terms of data collection. Throughout the calibration process, PEST showed that certain grid cells within the model domain were either hypersensitive or insensitive to incremental changes in its hydraulic conductivity parameter. Figure 18 shows the areas within the model domain that are insensitive to PEST calibration due to the absence of observed data and also possibly due to their distance from the existing observed data. The final sensitivity values as output by pest was analyzed and it was found that pilot points in certain areas were deemed to be insensitive during the PEST calibration process. The hydraulic conductivities and storage coefficients in this area more than likely require additional refinement.

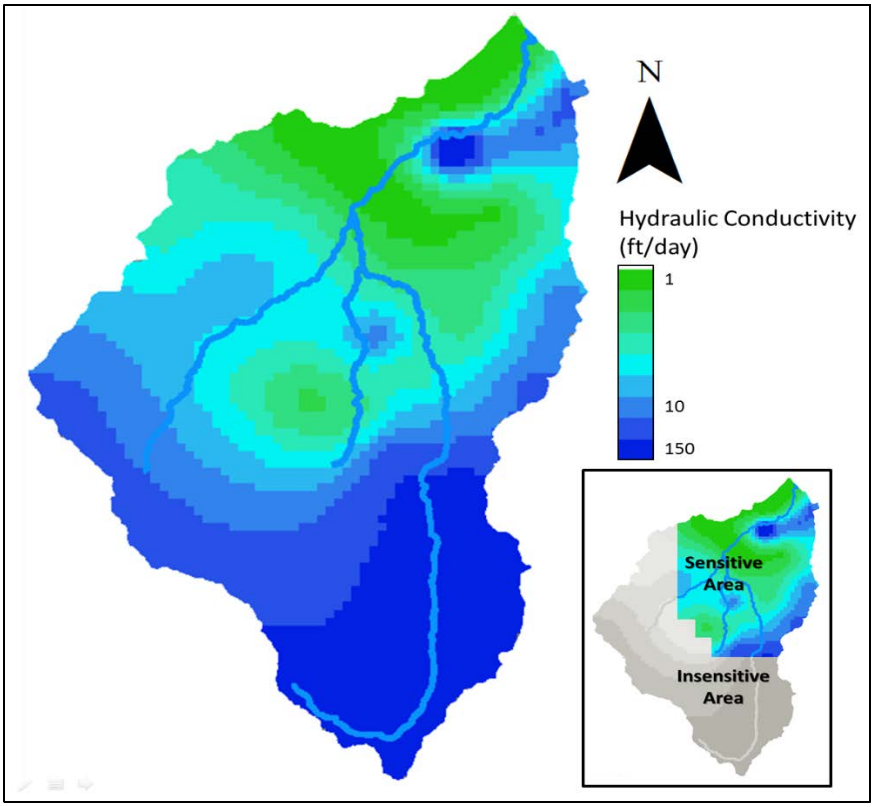

Figure 18. Calibrated hydraulic conductivity distribution.

6.5 Model Uncertainty

The model is successful in simulating groundwater levels and the seasonality of estimated stream gains. Although the model cannot simulate absolute heads and stream gains with a large degree of certainty, the model is useful in estimating relative changes in these same values given a particular groundwater management scenario.

Given the lack of data within the basin, multiple approximations and assumptions were made in constructing the model, and as such, the potential for uncertainty is inherent in the modeled results. Every "known" parameter within the model domain depends on the approximations and assumptions made during the water budget calculation, model construction, and calibration process. It is important to realize that this is only the first step towards a more comprehensive model and as data become available, the model should be modified and recalibrated accordingly. That said, the model is useful for identifying locations where additional data should be collected. It is also useful for identifying locations that may benefit from further investigation.

7.0 MODEL SCENARIOS

Model scenarios were developed to address the underlying groundwater management questions identified in Section 1.2 of this report. There are two underlying conditions for the developed scenarios. The current conditions simulates the present (1980 - 2009) conditions within the Hood River basin while the climate change condition simulates future conditions under a changed climate. Within each condition, there are defined scenarios that explore the groundwater management concerns within the basin.

The increased pumping scenario was formulated differently for each condition. It evaluates the basin's response to additional groundwater pumping demand due to a possible increase in irrigated acreage under the current conditions. It also evaluates the same due to a combined decrease in the availability of surface water supplies and an increase in crop water demand under climate change conditions.

The aquifer injection scenario evaluates the effectiveness of aquifer storage and recovery for irrigation season withdrawals and aquifer injection for streamflow augmentation under the current conditions. The modeled conditions and scenarios that were evaluated are enumerated below and shown a schematic in Figure 19.

1. Current Conditions
    a. Increased Pumping
    b. Aquifer Injection
2. Climate Change Conditions
    a. Increased Pumping
    b. Aquifer Injection

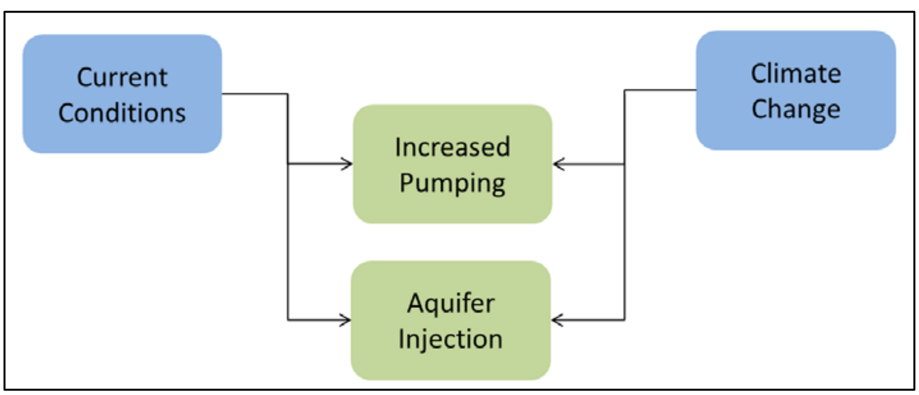

Figure 19. Model scenario schematic.

7.1 Conditions

7.1.1 Current Conditions

The current conditions scenario uses the original basin inputs developed in the steady-state and transient models. These inputs were formulated using average annual conditions from 1980 through 2010, and are assumed to be a reasonable representation of the current state of the aquifer water balance given the available information.

7.1.2 Climate Change Conditions

The climate change conditions adjust the original basin inputs developed in the steady-state and transient models to simulate the effects of climate change within the basin. Adjustments were made based on accepted statistical procedures (Reclamation 2008; Reclamation 2009; Reclamation 2010) using these procedural steps:

1. Select Global Climate Model (GCM) ensemble projections to best represent three possible climate change conditions from the current period (1980 through 2010) to the future period (2030 through 2060): a More Warming/Dryer (MW/D) condition, a Median (MED) condition, and a Less Warming /Wetter (LW/W) condition.

2. Apply the precipitation adjustment factors to quarterly recharge values that were used to calibrate the groundwater model.

3. Adjust the other model inputs to account for anthropogenic response to climate change.

The major elements of the climate change analysis are listed in the following sections.

7.1.2.1 Selection of Future Climate Projections

The 30-year annual average percent change in precipitation and absolute change in temperature are calculated for 112 GCMs based on a current period (1980 through 2010) and a future period (2030 through 2060). These values are plotted against each other in Figure 20.

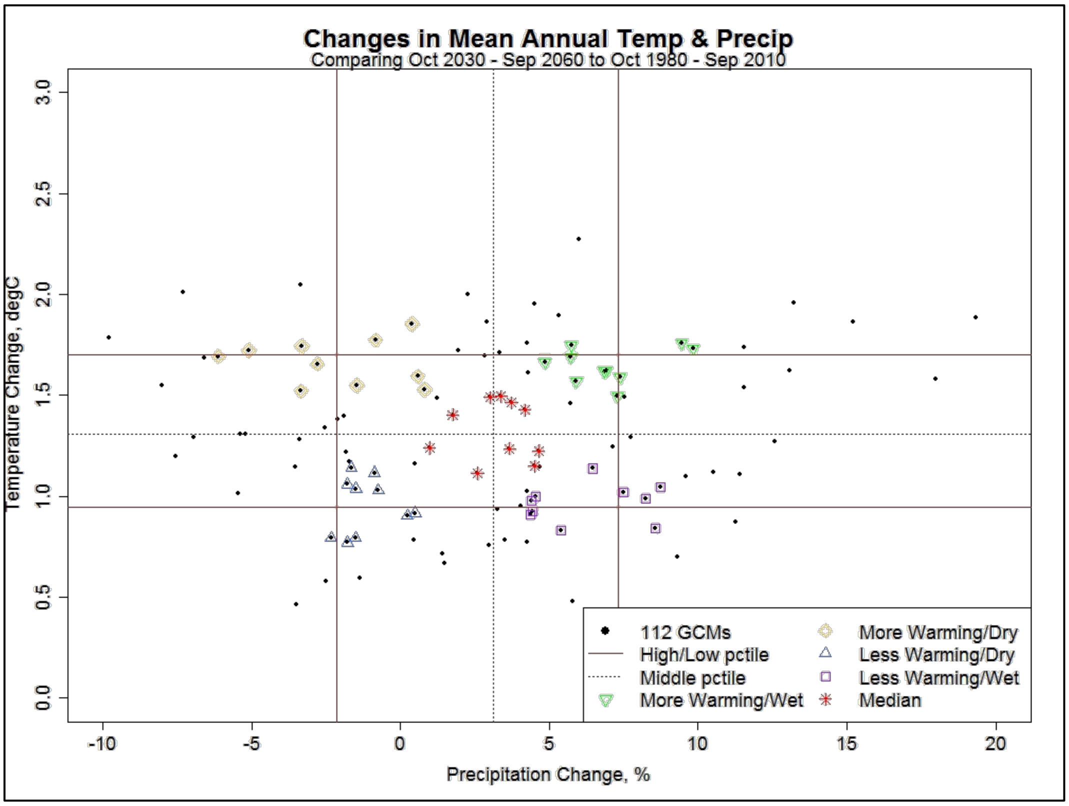

Figure 20. GCM ensemble selection.

For the Hood River basin, all projections indicated a potential increase in annual temperature compared to the current period that ranged from about 0.5 to 2.2 degree Celsius. The 20th, 50th, and 80th percentile temperature change values were approximately 0.9, 1.3, and 1.7 degrees C, respectively. The projections indicate a change in precipitation that ranges from -10 to 20 percent with the 20th, 50th, and 80th percentile values at -2, 3, and 7 percent, respectively. Each ensemble projection represents the 10 projections that are closest to the intersection of the indicated percentile of the change in temperature and precipitation. The 10 projections nearest the intersection of the 20th percentile for both temperature and precipitation represents the Less Warming/Drier (LW/D) ensemble projection (highlighted blue in Figure 20), the 10 projections nearest to the intersection of the 50th percentile represents the Median (MED) ensemble projection (highlighted red in Figure 20) , and the 10 projections nearest to the intersection of the 80th percentile represents the More Warming/Wetter (MW/W) ensemble projection (highlighted in green in Figure 20). The increase in precipitation generally occurs in the winter and spring months, with the summer and fall months indicating a general decrease in precipitation as shown by Figure 21.

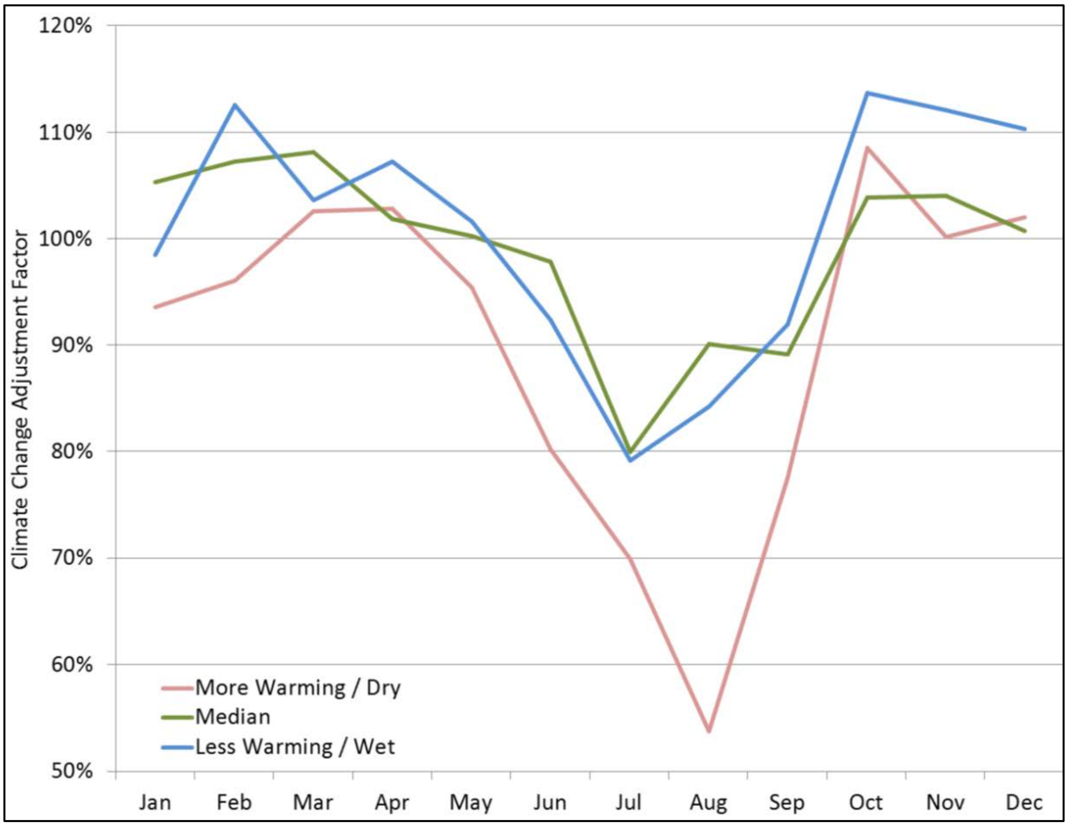

Figure 21. Monthly average precipitation adjustment factors.

7.1.2.2 Modification of Model Recharge to Reflect Future Climate Conditions

Recharge was developed for the Hood River basin MODFLOW model using the Vaccaro equation. The Vaccaro equation was developed using a linear regression of modeled and observed recharge in basins throughout the Columbia River Basin, of which the Hood River basin is a part. Because the Columbia River Basin covers a wide range of climate types, the use of the Vaccaro equation was assumed to be reasonable, even for the climate change representations.

The estimated quarterly recharge values were adjusted by precipitation adjustment factors that vary from quarter to quarter. In terms of the climate change signal, adjustment factors within the basin do not significantly vary spatially so an average adjustment factor was used over the entire basin.

The precipitation adjustment factors that were applied to the recharge values only account for the change in volume of precipitation. The factors did not account for the change in intensity, duration, or frequency of the precipitation events that may change the volume of water that becomes recharge. The monthly time-step of the bias-corrected GCM data that was used for this study does not allow for the level of detail required for this type of analysis. Without any information on climate-change-induced impacts to the intensity, duration, and frequency of precipitation events, possible outcomes can be assessed using a current understanding of rainfall-runoff-infiltration processes. Assuming historical durations will hold for the future conditions, then the increase in precipitation during Q4 and Q1 might likely cause an increase in runoff potential (duration stays the same, intensity increases). Assuming precipitation durations will decrease (more flashy, shorter duration precipitation events), then this might decrease recharge by a relatively greater amount during Q4 and Q1 since this would significantly increase runoff potential. If durations were to increase, then an increase in recharge would likely be seen since more water is made available to infiltrate through the soil by decreasing the occurrence of infiltration excess.

Although temperature changes have the ability to impact recharge, the temperature adjustment factors were not used to adjust the recharge values for this study. This decision may have the following effects on model output:

1. Changes in temperature have the potential to allow for more precipitation to fall as rain rather than snow. This allows more recharge to occur during low intensity precipitation events, but less recharge during high intensity events.

2. The recharge that occurs from snowmelt could also be reduced and/or shifted seasonally due to changes in the temperature regime.

3. The increase in temperature could likely cause the other hydrologic budget components (i.e., evaporation, transpiration, soil moisture capacity) to increase accordingly, causing less recharge throughout the range of possible precipitation intensities.

Because of these potential effects of temperature increase, it is possible that climate change impacts to recharge during the winter and spring months are incompletely estimated for this study. In addition, climate-change-induced shifts in the timing and seasonality of precipitation and recharge are not captured by the climate change adjustment factors since the adjustment factors only adjust historical magnitudes and not the occurrence and sequencing of precipitation events.

7.1.2.3 Climate-Change-Related Increases in Groundwater Demand

Aquifer responses to climate change may be caused by anthropogenic responses in addition to atmospheric and hydrologic changes. Currently, at least 90 percent of the irrigation water requirements are met by surface water. If a reduction in either the total or late irrigation season surface water supply occurs due to climate change, it is possible that irrigators will use additional groundwater to offset the decrease. In an effort to simulate the possible aquifer response to this change, the climate projections using the model will be run by (1) increasing current irrigation pumping to account for the increase in crop-water demand and (2) by adding new groundwater demand based on the decrease in irrigation season surface water supplies. This will give an indication of a wider range of possible impacts to the aquifer system under future climate conditions.

7.1.2.4 Climate-Related Model Scenarios and Analysis

The climate change scenario models are run for 45 years using the transient model. Separate models that append an additional 30 years to the current conditions baseline model were built to simulate each climate change condition.

For the increased pumping scenario, model outputs under different climate change conditions were compared to the current conditions baseline model and the change in 30-year quarterly average head and discharge to streams are reported. Each climate change model scenario was developed by applying precipitation adjustment factors to the baseline model and adjusting groundwater pumping based on the two possible scenarios described in the previous section.

For the aquifer injection scenario, model outputs for each climate change condition with the added injection well were compared to the same climate change condition without the injection well. On a relative change basis, comparing aquifer injection under each climate change condition to the current condition baseline model will not yield meaningful results. This is because changes in each climate change model's recharge would interfere with the artificial recharge imposed under an aquifer injection scenario.

7.2 Scenarios

7.2.1 Increased Pumping under Current Conditions

The increased pumping scenario was defined based on the groundwater demand that would result from irrigating the remainder of the irrigable acres within the Hood River basin irrigation district boundaries. A report authored by the Hood River Soil & Water Conservation District enumerates the amount of irrigable acreage and irrigated lands within each irrigation district's boundaries (Hood River County 1986). The increased pumping scenario relies on the addition of wells within each irrigation district based on the amount of irrigable land that is not being irrigated, an irrigation volume demand of 2 acre-feet per acre, and the assumption that each additional well can serve as much as 200 acres. This results in an average pumping demand of 1 cfs per well during the irrigation season. Table 8 shows the data that was used to determine the additional wells needed by this scenario.

Table 8. Determination of additional wells for the increased pumping scenario.

District	Irrigable Acres	Irrigated Acres	Available Acres	Additional Wells*
Dee ID	1,297	951	346	2
East Fork ID	10,400	8,525	1,875	10
Farmers ID	7,033	7,033	0	-
Middle Fork ID	8,000	6,373	1,627	9
Mount Hood ID	1,331	1,090	241	2

* Each additional well is assumed to serve as much as 200 acres and is assigned a volumetric demand of 2 acre-feet per acre

A rough analysis of mapped prime farmlands, irrigated lands, irrigation district boundaries, and existing groundwater wells was used to identify the locations where additional wells were added. The analysis involved using a geographic information system to find locations within each irrigation district where prime farmlands are currently not irrigated and do not have wells within the immediate vicinity. Sites of additional well locations were based on these criteria and they had roughly 200 acres of land available. Figure 22 shows each of these maps and the additional increased pumping wells that were added to the model. It is important to note that the selection of these well locations do not take into account any physical features, land ownership, or constructability factors that might serve to limit where wells might feasibly be located.

It is also important to note that the modeled impacts that result from this scenario are directly due to the methodology for adding wells described in the previous paragraph and that impacts would change depending on how and where additional wells are added to the model. The metrics used for reporting the impacts under this scenario were changes in water levels and groundwater-contributed stream gains.

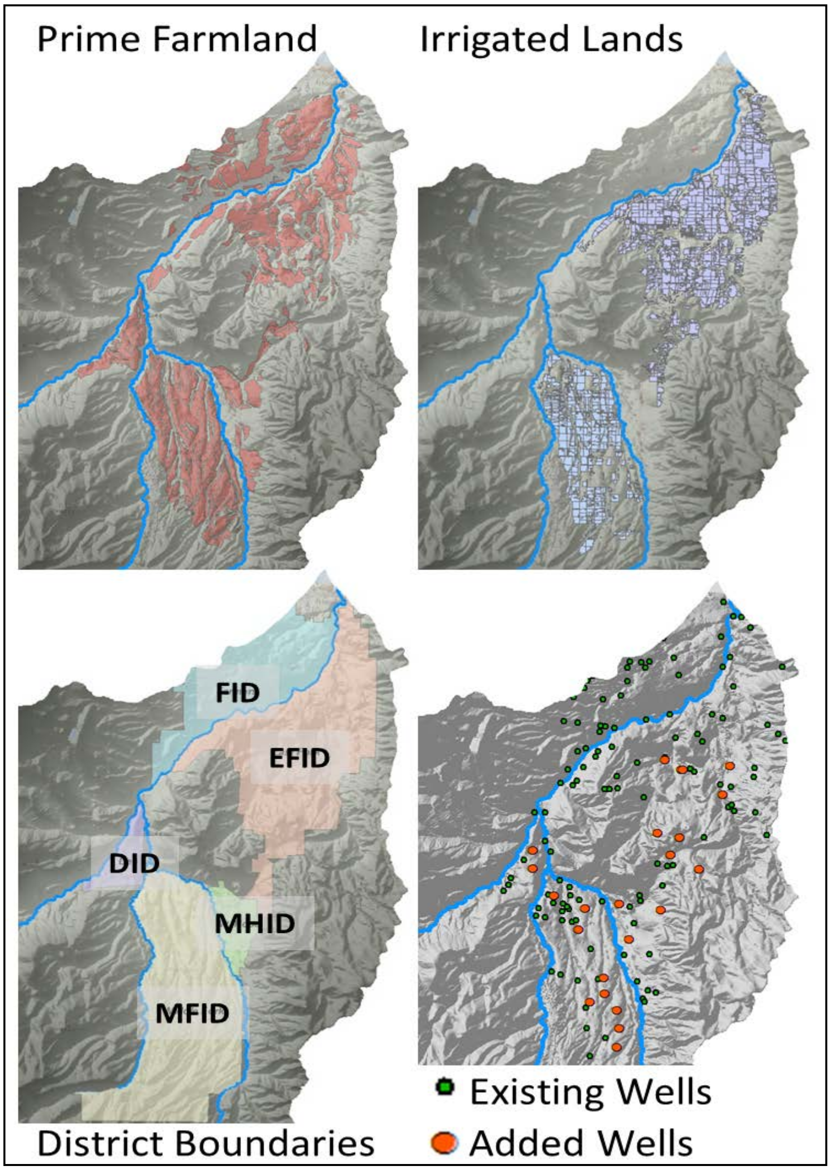

Figure 22. Spatial analysis of additional wells for the increased pumping scenario.

7.2.2 Increased Pumping under Climate Change Conditions

Increases in groundwater pumping due to climate change conditions were formulated differently than those under current conditions. Pumping rates under climate change conditions were adjusted based on outputs from the hydrologic modeling that was accomplished in support of the larger Hood River Basin Study. Hydrologic modeling was accomplished using a DHSVM model of the basin. Simulation, interpretation, and analysis of the hydrologic model and its results are in the hydrologic modeling technical report (Reclamation, in progress).

Increases in current pumping rates for irrigation demand due to climate change were calculated based on increases in the modeled potential evapotranspiration (PET) that were output by DHSVM. The increase in PET was used to adjust the modeled pumping rates via a direct percentage increase. As an example, in the LW/W climate change condition, the average increase for PET is equal to 2 percent during the irrigation season and as a result, modeled pumping rates were increased by 2 percent to reflect the additional water demand for crop irrigation. This approach assumes that planted crop mix does not change and that irrigators only increase pumping demand by the additional PET demand. Table 9 shows the modeled increase in PET as output by the hydrologic model for each climate change condition.

Table 9. Modeled potential evapotranspiration increase due to climate change.

Climate Change Condition	Period	Potential Evapotranspiration Increase	
		Percentage	Total Inches
Less Warming – Wet (LW/W)	January – March	3.5	0.20
	April – June	2.2	0.46
	July – September	1.8	0.66
	October – December	1.2	0.09
Median (MED)	January – March	4.7	0.27
	April – June	3.0	0.62
	July – September	2.1	0.72
	October – December	1.4	0.10
More Warming – Dry (MW/D)	January – March	5.2	0.29
	April – June	3.7	0.76
	July – September	3.0	1.09
	October – December	1.7	0.12

A new pumping demand was added to represent the water that will supplement decreases in the availability of surface water supplies, based on the DHSVM average modeled decrease in streamflows during the spring and summer seasons. The total decrease in streamflow for the Hood River was assessed at Tucker Bridge and a fraction of the total decrease during the irrigation season was divided equally among all the existing irrigation wells within the model. A value equal to 50 percent of the decrease in total streamflow at the Tucker Bridge gage was used for the new pumping demand in the model. Table 10 shows the average quarterly modeled streamflow change for the Hood River at Tucker Bridge for each climate condition. A positive value denotes a simulated increase in climate change projected streamflow while a negative value denotes a decrease. As an example, the flow rate increase in each of the 17 irrigation wells for the stress period spanning April through June (Q2) for the Median condition is 4 cfs (50% • [137 ÷ 17]).

Table 10. Modeled streamflow change due to climate change.

Climate Change Condition	Period	Streamflow Change (cfs), Future Climate – Current Climate
Less Warming – Wet (LW/W)	January – March	215
	April – June	-71
	July – September	-40
	October – December	103
Median (MED)	January – March	235
	April – June	-137
	July – September	-68
	October – December	43
More Warming – Dry (MW/D)	January – March	137
	April – June	-195
	July – September	-105
	October – December	28

Pumping increases due to increases in PET and decreases in streamflow were combined for each of the climate change model runs. Changes in water levels and groundwater-contributed stream gains were the metrics used for reporting the impacts under this scenario.

7.2.3 Aquifer Injection under Current and Climate Change Conditions

The aquifer storage and recovery scenario was evaluated by iteratively adding an injection well in selected model cells and comparing the model response with the baseline model. By using this approach, spatial locations and localized regions that are potential candidate sites for either aquifer storage or streamflow augmentation becomes more evident. This approach does not make inferences on the practicality and constructability of a well at iterated well locations, but rather is intended to be used to identify general locations where aquifer injection could prove to be beneficial. In contrast, evaluating specific cells or groups of cells on a location-by-location basis and evaluating hydrogeological conditions to account for both aquifer storage and streamflow augmentation would be more time consuming and is appropriate for a more in-depth study that focuses on this type of analysis.

Model cells or regions of the model were selected based on the location where there are already established wells and where there is more certainty with modeled results. The scenario injects a continuous 10 cfs flow rate for two consecutive seasons (fall and winter) and evaluates model response for the seasons and years that follow. The model response of particular interest occurs during the spring and summer that immediately follows injection since these are the periods when irrigation withdrawal and streamflow augmentation would be most needed. Figure 23 shows the region for which injection wells were iteratively added to each model cell under this scenario.

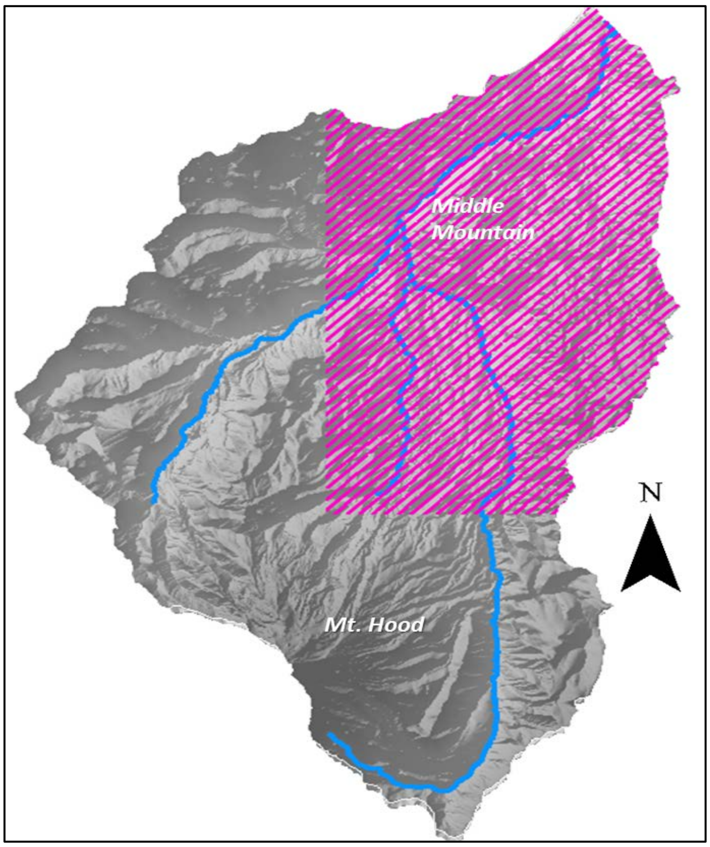

Figure 23. Model area used for aquifer injection.

Two metrics were defined to evaluate the effectiveness of each model cell for either storage or streamflow augmentation. The metric used for storage is the percentage of injected water retained within the model boundaries for all stress periods that follow injection. This metric compares the difference in the baseline water budget and the injection water budget for the entire model domain repeated for each model cell. In effect, the storage metric calculates how much of the injected water has left the model domain through any of the modeled boundary conditions. Conversely, this results in the injected water that remains within the model domain that is available for withdrawal. This metric is reported as a fraction of the injected volume.

The metric used for streamflow augmentation is the difference between the baseline and the simulated baseflows at the Tucker Bridge gage. The difference is determined by comparing the sum of the drain fluxes for the drain cells above the Tucker Bridge gage between the baseline and the injection model repeated for each injection cell (Figure 24). This metric is reported as a flow rate.

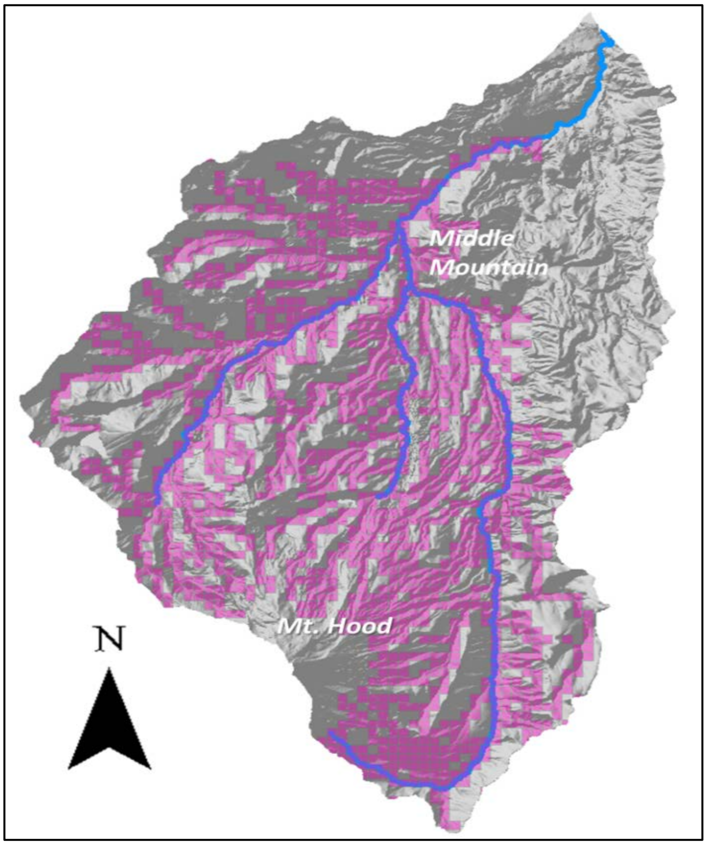

Figure 24. Drain cells used to evaluate relative change to Tucker Bridge gage streamflows.

8.0 Modeled Scenario Results

8.1 Modeled Baseline Water Levels

Modeled steady state water levels and average observed water levels are shown in Figure 25 and are measured relative to mean sea level. As mentioned in the calibration section of this report, the model is able to match the water level observations.

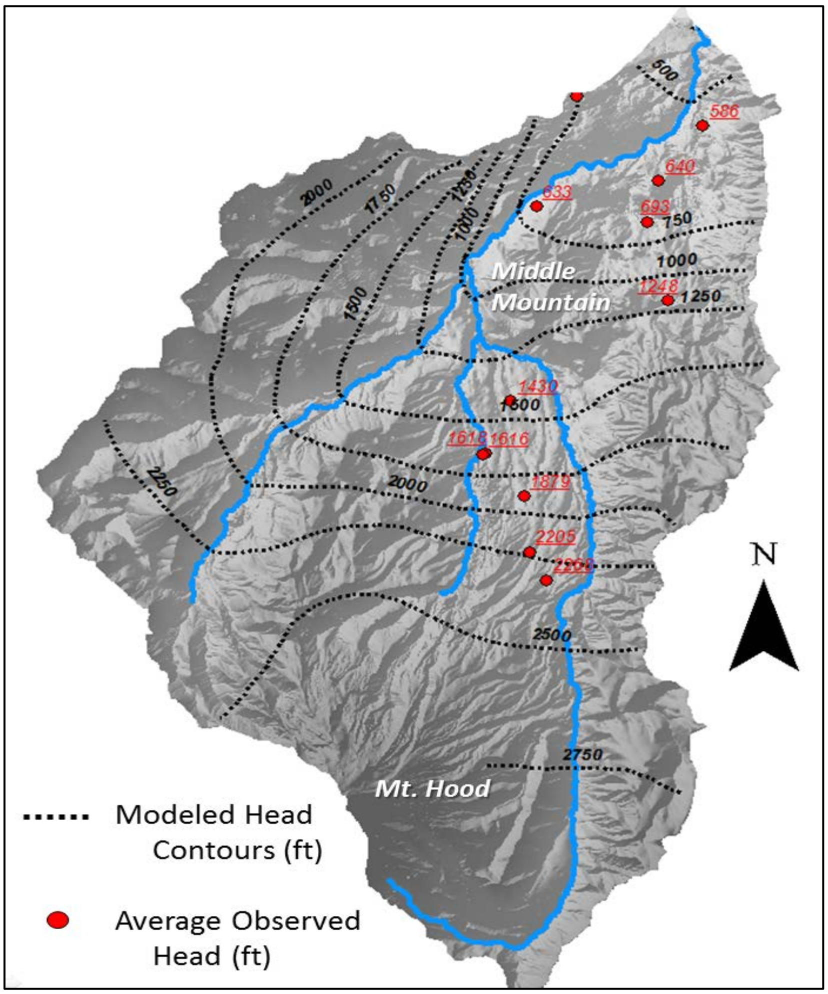

Figure 25. Modeled vs. observed groundwater levels.

8.2 Model Scenario Results

8.2.1 Current Condition: Increased Pumping

The additional wells mapped in Figure 22 result in a decrease in water levels as compared to the baseline current condition model run. The decrease in water level is shown spatially in Figure 26 and shows a maximum possible decline of several tens of feet within the EFID boundaries at the end of the fifth year of increased pumping. The location of the additional pumping wells that were added play a large part in the resulting modeled decrease. Different configurations of wells would result in different magnitudes and locations of groundwater level decrease. The decrease shown in Figure 26 is due to the well configuration outlined and discussed in section 7.2.1.

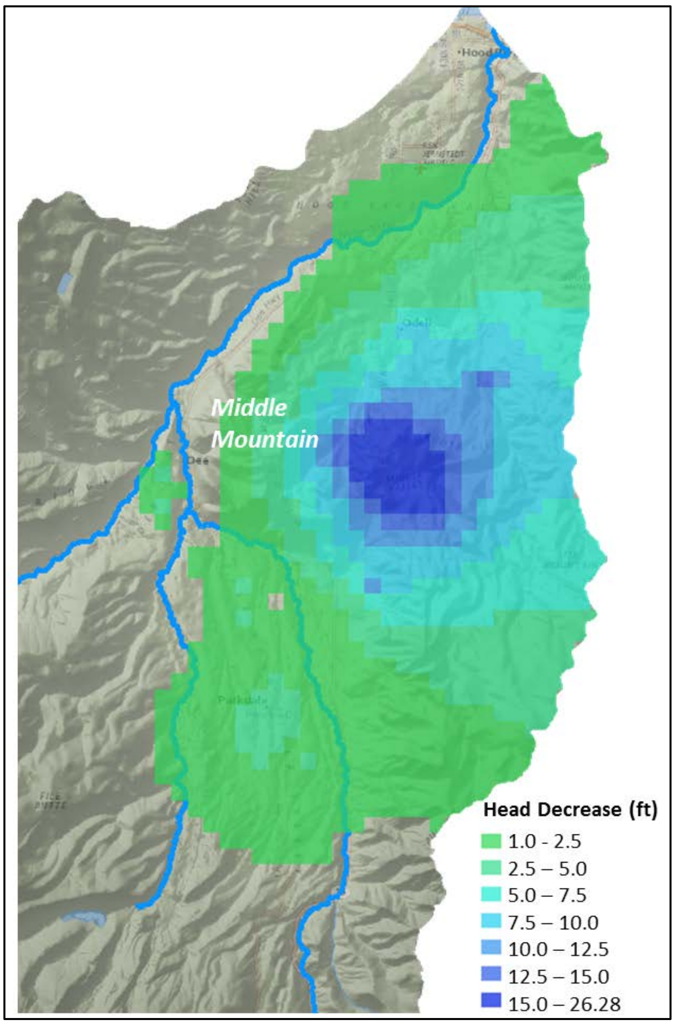

Figure 26. Water-level change due to the current conditions increased pumping scenario.

The average change in baseflow that the model simulates in this particular scenario is shown in Figure 27. The figure shows the pronounced effects of the increased pumping scenario to the April through September time frame when the increased pumping is active. From a volumetric standpoint, the additional demand imposed by the increased pumping scenario is 8,178 acre-feet per year while the annual average decrease in groundwater-contributed streamflow volume from the scenario is equal to 7,082 acre-feet per year. This suggests that roughly 80 to 90 percent of groundwater pumping is captured from the Hood River and its tributaries. The remainder of the impacts in terms of volume is seen at the Columbia River model boundary.

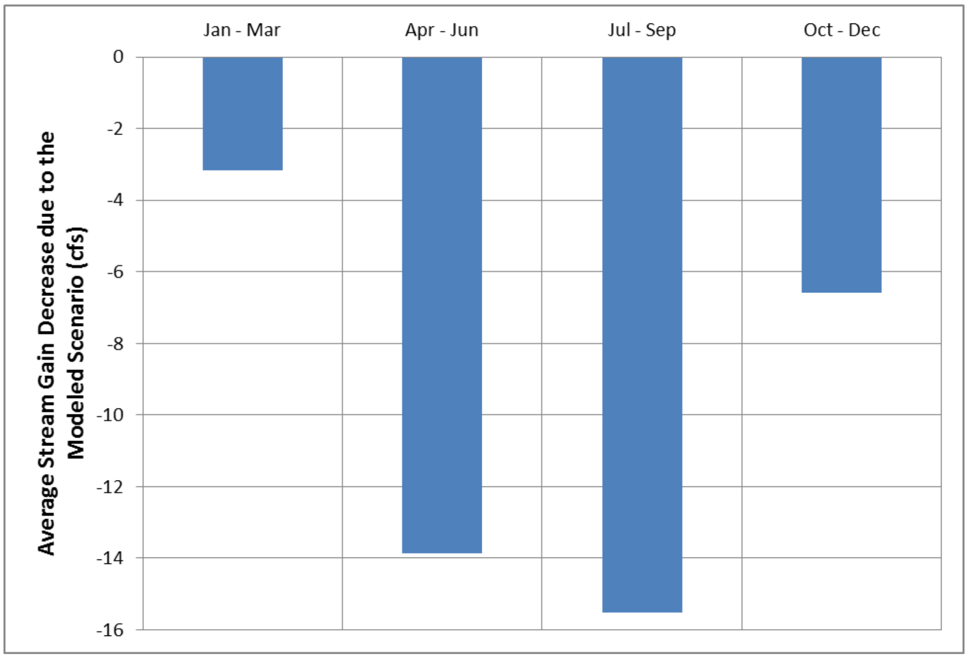

Figure 27. Groundwater-contributed streamflow change due to the current conditions increased pumping scenario.

8.2.2 Current Condition: Aquifer Injection

A comparison of the injection metric results for two cells is shown in Figure 28. The plots next to the map show the modeled metric value on the vertical axis and the modeled time represented by a MODFLOW stress period (SP) on the horizontal axis. Each SP represents an annual quarter with SP0 spanning the months from October through December, SP1 spanning January through March and so on. Aquifer injection occurs during the first fall and winter, SP0 and SP1 respectively, with a continuous injection rate of 10 cfs. In comparing the two cells shown in the figure, it is evident that the cell's spatial location has a direct effect on whether injection is conducive for aquifer storage and withdrawal, or for streamflow augmentation. In general, cells located near the river are more conducive for streamflow augmentation while cells that are farther away are better suited for aquifer storage and withdrawal. The red cell (red curve), located near the river, has most of the injected water returning to the river much earlier than the blue cell (blue curve) as shown on Figure 28 which shows the difference in modeled and baseline groundwater-contributed baseflows at Tucker Bridge. In contrast, the blue cell, located on Middle Mountain, may be better suited for aquifer storage and withdrawal as shown by the blue bars on Figure 28 which shows that the blue cell's injection location allows the aquifer to retain more of the injected volume as opposed to the red cell which quickly loses the injected water to the modeled boundary conditions.

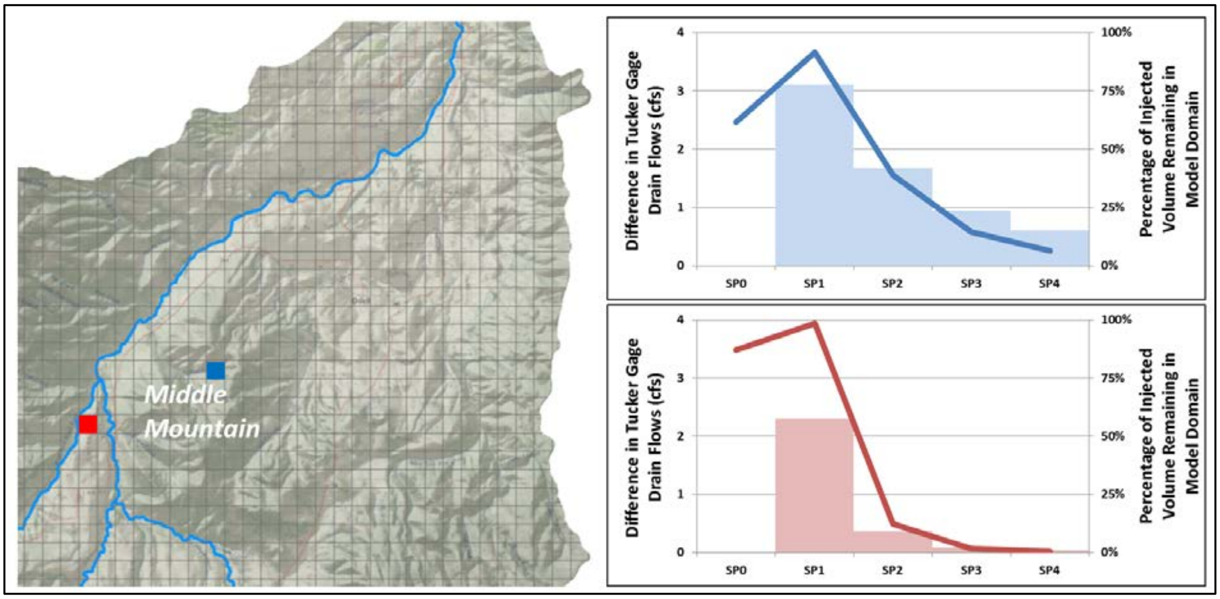

Figure 28. Cell-by-cell injection metric results comparison.

Figure 29 and Figure 30 show the geographic distribution of values shown in graphs on Figure 28 for the fall and winter when injection occurs, and the spring and summer that directly follow. Each cell is colored based on the modeled metric value at different stress periods for each cell. Of particular interest is the modeled result for the spring and summer since this is when benefits for irrigation withdrawals and streamflow augmentation are most needed.

8.2.2.1 Aquifer Storage and Recovery

Figure 29 is comprised of maps that show the remaining fraction of the injected water within the model domain which results from the cell-by-cell injection analysis. Cells located near the river are shown to be ineffective in terms of storage and withdrawal during the irrigation season with less than 10 percent of the injected volume remaining in aquifer storage during the spring and summer. A location where aquifer injection for aquifer storage and recovery might be feasible is the area directly southeast of Middle Mountain where roughly 40 to 50 percent of the injected volume is retained during the spring and summer. The area northeast of Middle Mountain is another location that shows potential for aquifer storage and recovery.

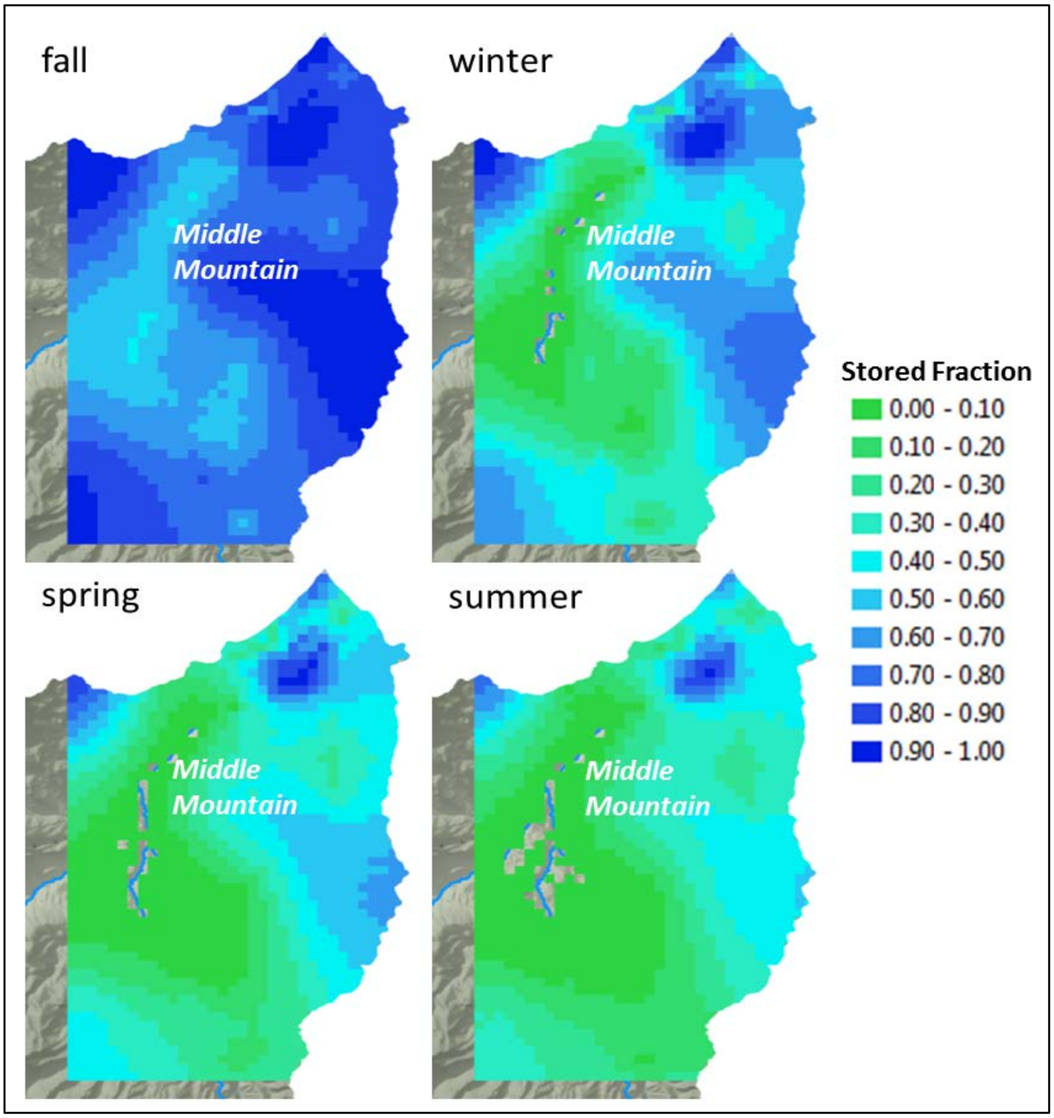

Figure 29. Cell-by-cell injection effects on aquifer storage volume, current conditions.

8.2.2.2 Streamflow Augmentation

Figure 30 shows the increase in baseflows at Tucker Bridge resulting from injection at individual model cells. A direct injection into the aquifer shows that the injected volume leaves the aquifer relatively quickly for cells near the river. These cells stop contributing to baseflows as early as the spring that directly follows aquifer injection.

None of the evaluated cells appear to be effective in augmenting baseflows at Tucker Bridge during the summer. Figure 30 shows that even among cells that are still contributing to a baseflows increase in the summer, the increase is relatively small at a maximum of 1 cfs out of the injected 10 cfs during the fall and winter. This results in a baseflow increase equivalent to a maximum of 10 percent of the injected flow rate.

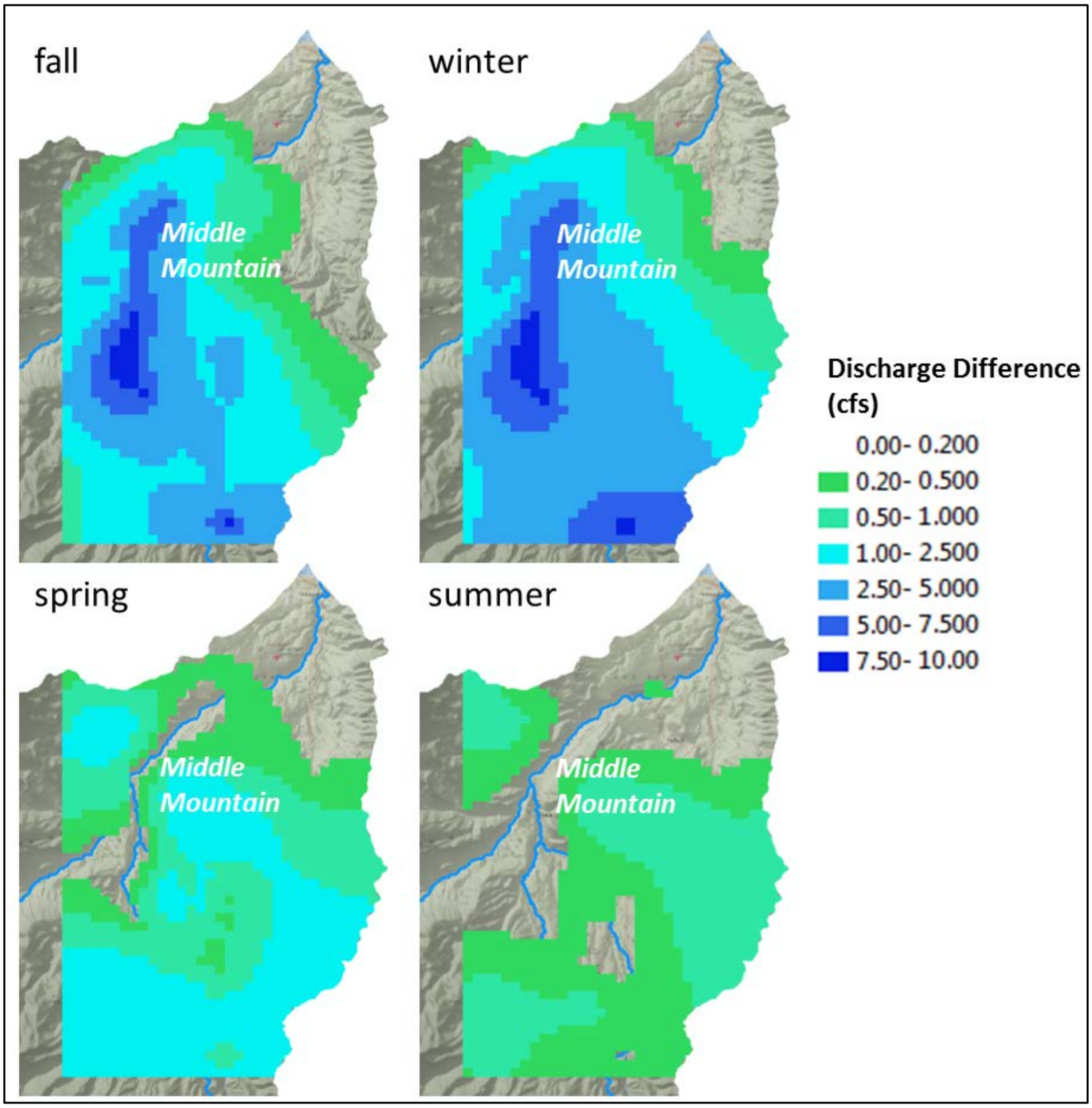

Figure 30. Cell-by-cell injection effects on Tucker Bridge streamflows, current condition.

8.2.3 Climate Change Condition: Increased Pumping

Changes in groundwater levels due to projected climate change conditions and estimated increases in groundwater use due to modeled irrigation and ET demand are shown in Figure 31. The water level differences represent the 30-year average for each climate condition per quarter at select locations in the Hood River basin. The MW/D climate conditions result in the greatest decrease while the LW/W climate conditions result in the least decrease with respect to modeled groundwater levels. Water level decreases are greatest near the northern part of the model domain due to estimated pumping increases and the clustering of irrigation wells in this region.

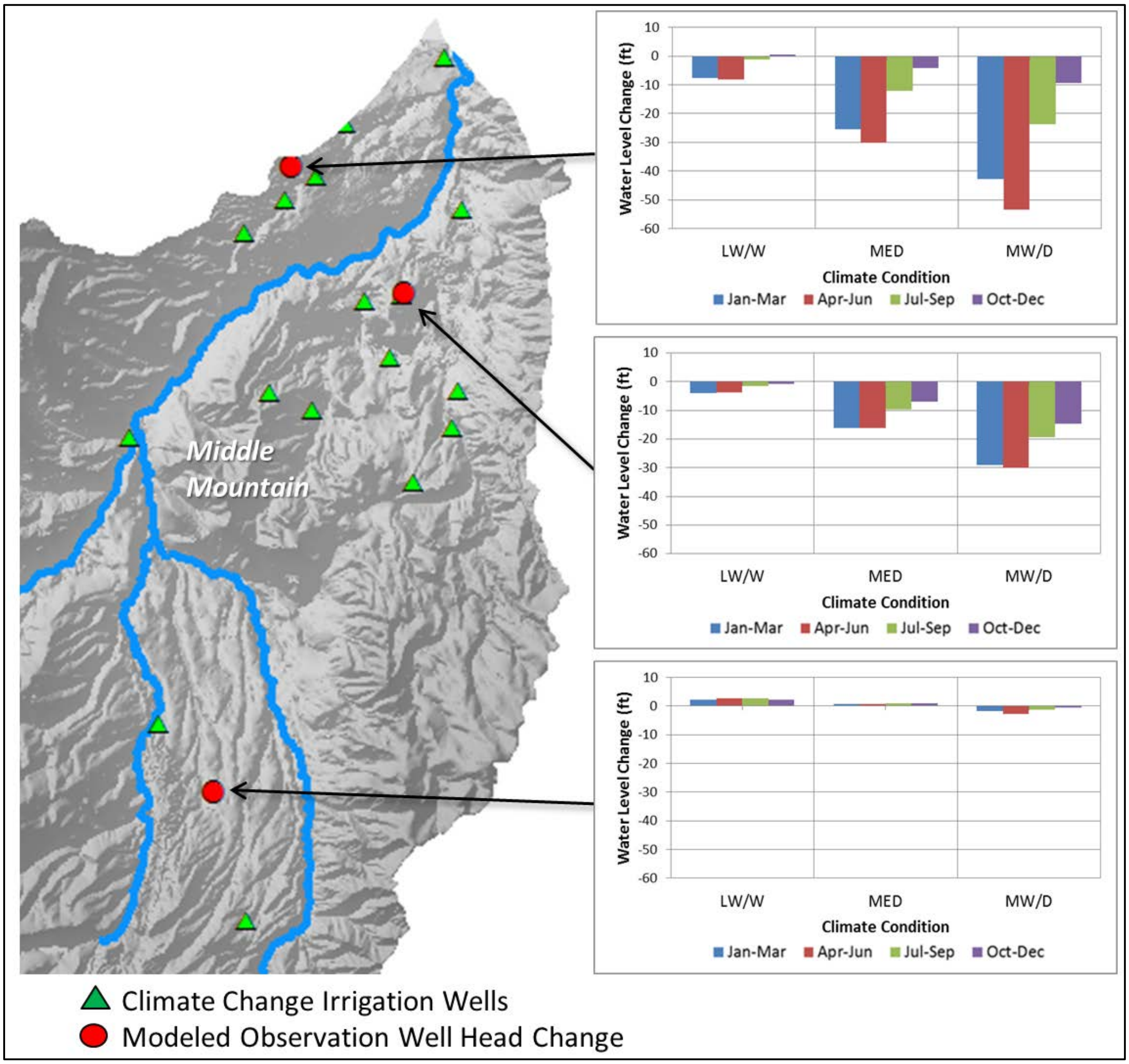

Figure 31. Climate change impacts on groundwater levels – modeled pumping increase.

For context on Figure 31, Figure 32 shows the basin-wide effect on groundwater levels due to changes in the recharge and pumping regimes for the MED climate condition after a typical summer. A positive value denotes an increase while a negative value signifies a decrease in groundwater levels. Groundwater levels generally increase in the upper elevations due to the modeled increase in precipitation and recharge during the fall and winter seasons. Decreases in water levels near the northern part of the model domain are primarily due to the modeled increase in groundwater demand and clustering of irrigation wells.

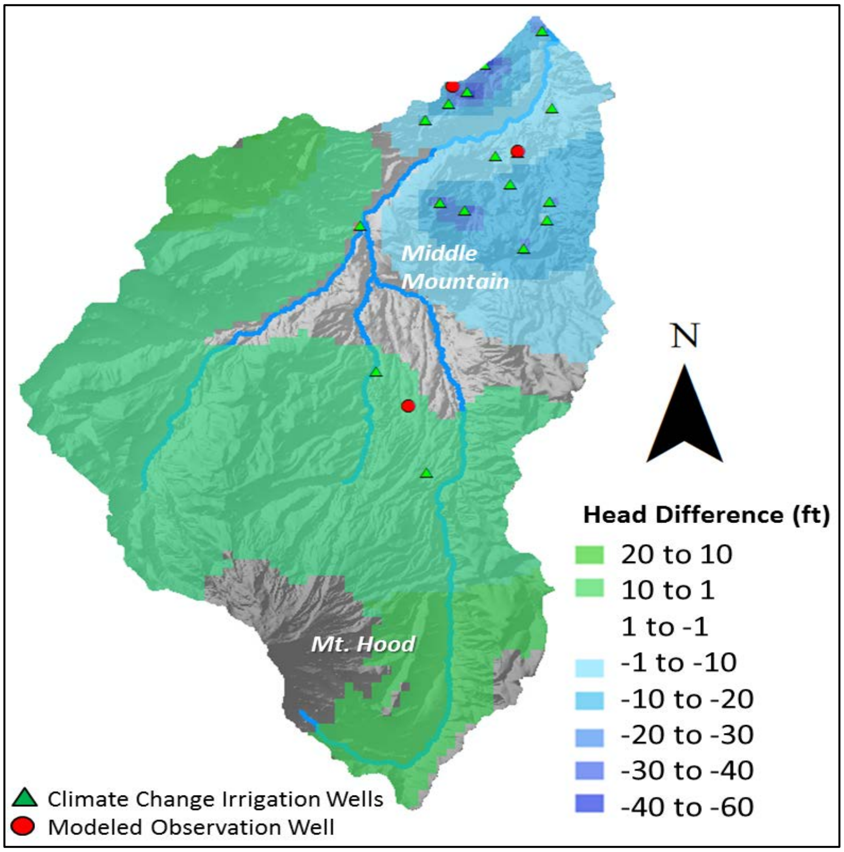

Figure 32. Climate change impacts on groundwater levels – modeled pumping increase (median climate change condition, stress period 180, Year 29, July - September).

Impacts to baseflows as a result of climate change and the simulated increase in pumping due to streamflow decreases and PET increases are shown in Figure 33. Negative values in this figure shows that there is a large decrease in baseflows due to the increased pumping scenario under climate change conditions. The magnitude of the baseflows decrease is greatest for the dry condition (MW/D) and is the least for the wet condition (LW/W). This result is expected since the increased pumping due to climate change was defined as 50 percent of the DHSVM modeled streamflow decrease in addition to the PET increase.

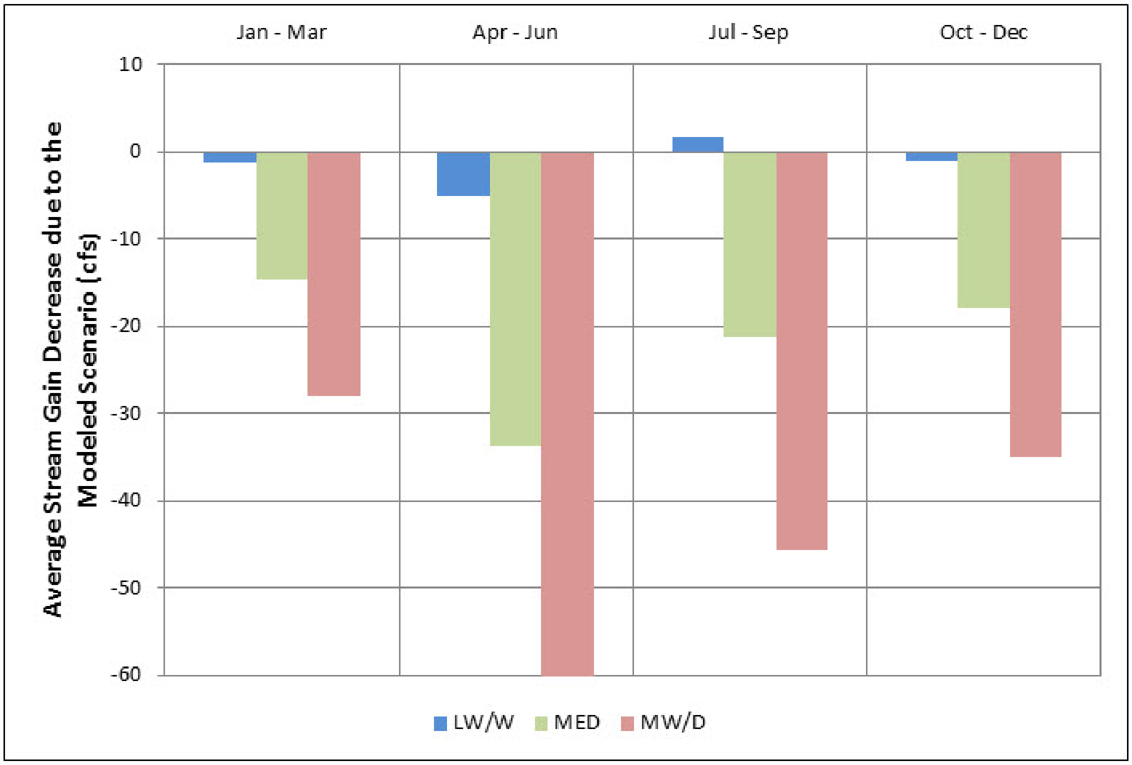

Figure 33. Groundwater-contributed streamflow change due to the climate change conditions, increased pumping scenario.

Without accounting for possible larger changes in demand for groundwater due to climate change, the results significantly vary from those shown in Figure 31. Simulations incorporating only the change in groundwater pumping due to increases in crop demand (base on PET changes), result in water level elevations that are nearly unchanged for the dry condition and increased for the median and wet conditions over the thirty year simulation period (Figure 34). These increases are mainly due to the increased groundwater recharge based on the assumed increase in precipitation under climate change conditions. Increases in precipitation are projected to occur during the winter and spring months, when most of the recharge occurs. Decreases in precipitation are projected only during the summer and fall months, when recharge is small or zero. As a result, decreases in precipitation that mainly occur during the spring and summer months have negligible impacts on recharge while increases in precipitation in the fall and winter; however small, have a noticeable impact on the same.

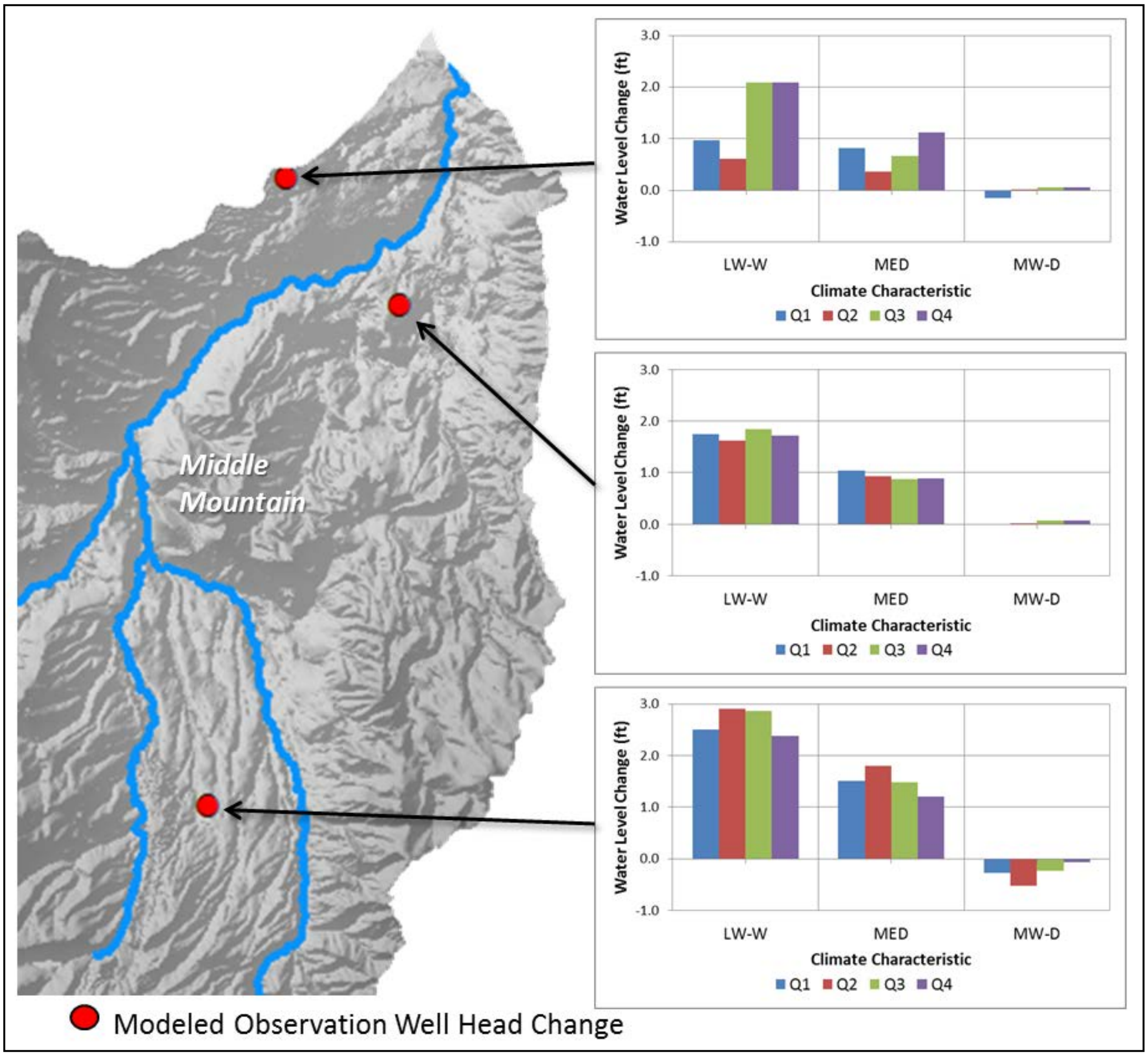

Figure 34. Climate change impacts on groundwater levels – no pumping change.

8.2.4 Climate Change Condition: Aquifer Injection

The aquifer injection scenario that was undertaken for the current conditions modeling was duplicated for the climate change conditions. An in-depth description of the modeling process is outlined in Section 8.2.2. The baseline scenario used for each climate change condition differs with respect to the climate change condition being simulated. As an example, the results for the MW/D aquifer injection model were generated by comparing the modeled results from the MW/D aquifer injection model against the MW/D model without aquifer injection. This was also done for the other two climate change condition aquifer injection scenario models. The baseline for the climate change condition aquifer injection models were so defined to isolate the effects of aquifer injection under climate change conditions.

8.2.4.1 Aquifer Storage and Recovery

The aquifer injection modeling for aquifer storage under climate change conditions resulted in very similar results as those under current conditions. This is not surprising given that the defined metric that quantifies benefits under the aquifer injection scenario relies on a relative change from a baseline condition. Figure 35 displays the benefit maps for the MED climate change condition that shows the remaining fraction of the injected water within the model domain which results from the cell-by-cell injection analysis.

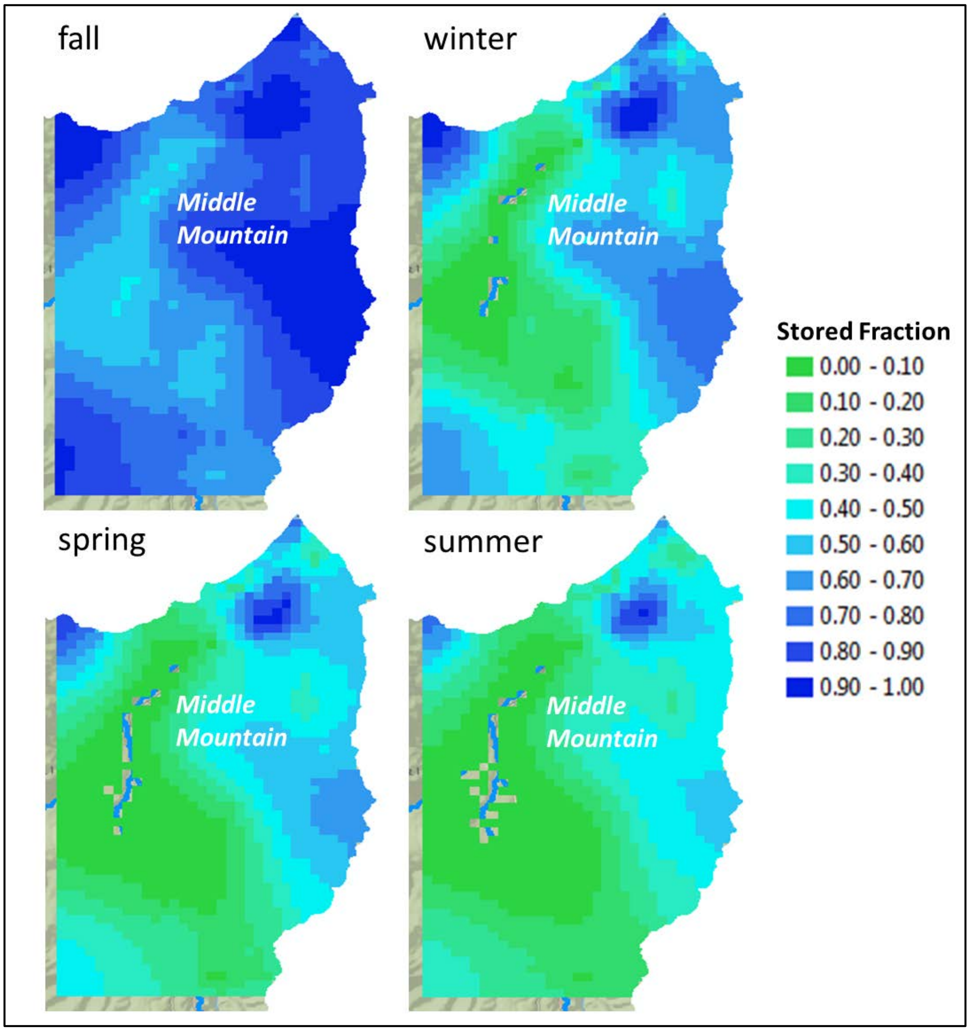

Figure 35. Cell-by-cell injection effects on aquifer storage volume, median climate change condition.

Results for all the climate change conditions models are very similar to those shown for the current conditions model in terms of where the likely benefits to aquifer storage are located. The climate change condition aquifer injection results, just like the current conditions aquifer injection model, identify the area southeast of Middle Mountain as an area with storage potential. This area retains between 40 and 50 percent of the injected volume in the summer.

8.2.4.2 Streamflow Augmentation

The aquifer injection modeling for streamflow augmentation under climate change conditions resulted in very similar results as those under current conditions for the same reasons mentioned in the previous section. Figure 36 shows the difference between modeled and baseline groundwater-contributed baseflows at Tucker Bridge which results from the cell-by-cell injection analysis. A direct injection into the aquifer shows that the injected volume leaves the aquifer relatively quickly for cells near the river. These cells stop contributing to groundwater-contributed baseflows as early as the spring that directly follows aquifer injection.

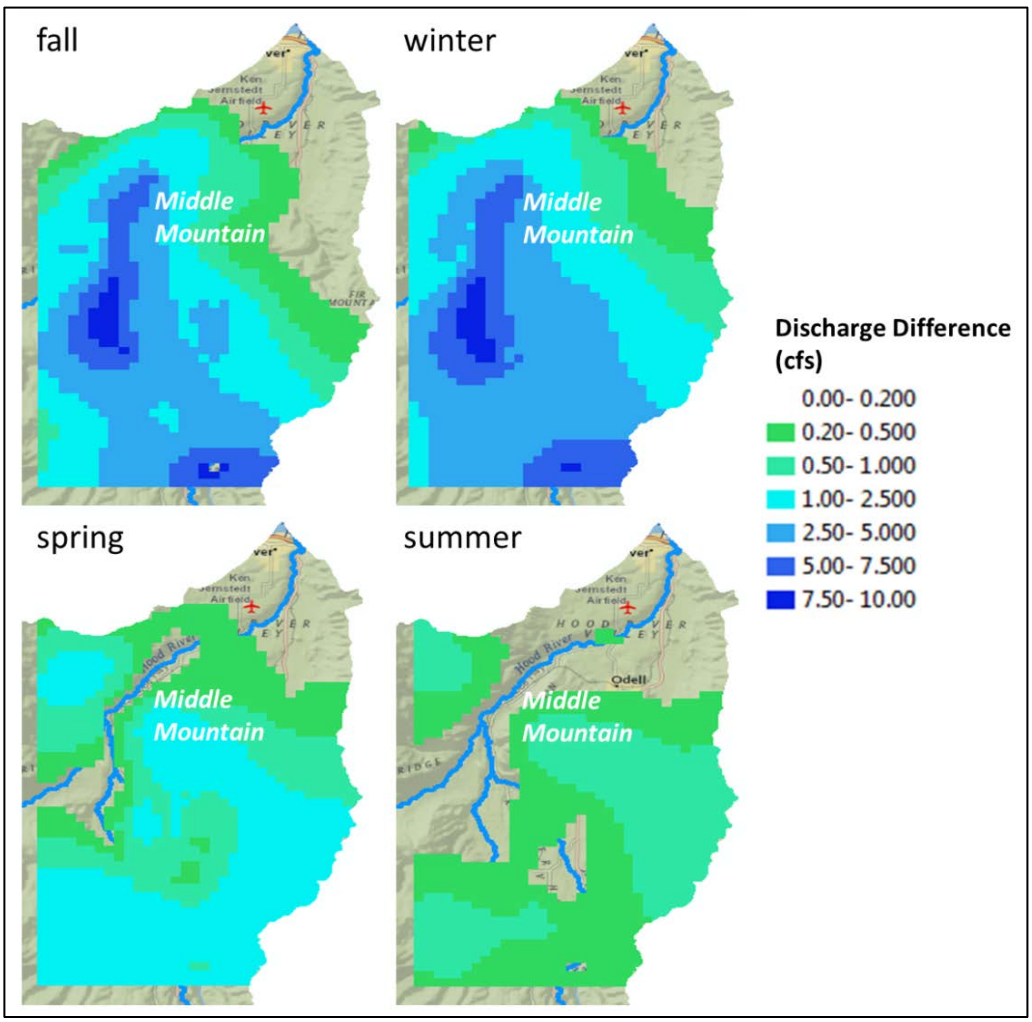

Figure 36. Cell-by-cell injection effects on Tucker Bridge streamflows, median climate change condition.

9.0 Model Scenario Conclusions and Recommendations

The scenario results outlined in this report are not intended to support new design and construction, but are intended as a mechanism to identify data needs, direct future investigations, and demonstrate basic hydrologic functioning of the basin. This information could be a starting point for more in-depth and focused studies. Results are intended to be interpreted on a qualitative rather than on a quantitative basis. The modeled values that are output by the model are more appropriate for providing insights into the possible impacts of different scenarios rather than for providing actionable absolute values. The recommendations that follow address the underlying groundwater management questions identified in Section 1.2 of this report and are based on the scenario results and the models that were used to generate these results. The definitions and simulation of specific scenarios for different groundwater management scenarios along with the definition of acceptable impacts are activities best suited for Hood River County planners and model end users.

How will new development impact groundwater conditions in the basin including discharge to streams?

The answer to this question would vary depending on the "new development" scenario that is being evaluated. The steady-state and transient models are able to simulate groundwater pumping impacts to groundwater levels and relative changes to baseflows.

The modeled increased pumping scenario under current climate conditions show groundwater level drawdowns of up to several feet in the DID, MFID, and MHID service areas as a direct result of allowing unirrigated lands to be primarily irrigated with groundwater. Drawdowns are relatively more substantial in the EFID service area with water level decreases of up to a few tens of feet given the modeled increase in pumping. Baseflows are decreased by 16 cfs on average in the summer due to the modeled scenario. The modeled scenario assumes that each of the 17 irrigation wells in the model withdraws an additional 1 cfs during the irrigation season.

How will hydrologic changes due to climate change impact groundwater conditions?

Climate change analysis shows a potential increase in precipitation and, possibly, aquifer recharge which would pose a direct impact to groundwater conditions within the basin. Increased recharge would result in an increase in groundwater levels and an increase in baseflows. Indirect impacts due to climate change could potentially result from increased air temperatures, increased crop water demand, and decreases in irrigation season streamflows. The indirect impacts were modeled as an increase in groundwater demand within the basin.

This approach does not analyze the recharge implications that a warming climate would have on snow hydrology.

Impacts due to climate change would vary depending which stresses described in the previous paragraph are included in the simulation. Simulations show average summer drawdowns in tens of feet in some areas under the MW/D worst case climate condition and increased pumping scenario.

Is managed recharge a viable option for improving streamflow conditions?

The transient model is able to simulate the relative change in baseflows and the results show that a direct injection to the aquifer can increase the groundwater contribution to summer streamflows.

The modeled results suggest that direct injection is minimally effective because a large portion of the direct injected volume returns to the stream during the same season as when injection occurs. Additional hydrogeologic data to further constrain the calibrated parameters in and around areas of interest for aquifer injection might help to quantify the viability of managed recharge. An option for further investigation would be the use of infiltration ponds which could impose a time-lag before water is seen in the aquifer. This activity would require a more in-depth site selection and investigation process to quantify the feasibility of the use of infiltration ponds.

Can the basin aquifers be used for aquifer storage and recovery?

The modeled results show that there are areas where direct injection to the aquifer could be beneficial for aquifer storage and recovery. The area south of Odell retains a large proportion of injected volume two seasons after injection and it also has the added benefit of improving summer streamflows. Further investigation is required to assess the feasibility of aquifer injection in this location.

The location is somewhat of a limiting factor as only the EFID and local municipalities would serve to directly benefit from injection at this location. A groundwater management scenario that could prove to be beneficial for the entire basin would be the exchange of EFID summer surface water flows for stored groundwater injected during the winter and spring at this location. Additional studies would be required to investigate the feasibility and reliability of any potential groundwater exchange program.

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