

Appendix &+. 'G]Yffa Jalley <ydrogeologic Gystem Aodel'UbX'K UhYf' 6 i X[YhF Ydcfh

Certification

This document was prepared in accordance with generally accepted professional hydrogeologic principles and practices. This document makes no other warranties, either expressed or implied as to the professional advice or data included in it. This document has not been prepared for use by parties or projects other than those named or described herein. It may not contain sufficient information for other parties or purposes.

DANIEL B. STEPHENS & ASSOCIATES, INC.



Douglas Tolley, PhD
Staff Hydrogeologist
gtolley@geo-logic.com
143E Spring Hill Drive
Grass Valley, CA 95945



Tony Morgan, PG, CHG
VP / Principal Hydrogeologist
tmorgan@geo-logic.com
3916 State Street, Garden Suite
Santa Barbara, CA 93105

Date signed: 1/17/2022



Table of Contents

1.0	Introduction and Purpose	1
2.0	Study Area	2
3.0	Modeling Approach and Framework	4
4.0	Upper Watershed Rainfall Runoff Model (PRMS)	8
4.1	PRMS Inputs	9
4.1.1	Climate	9
4.1.2	Landcover	12
4.1.3	Soils	12
4.1.4	Groundwater	19
4.2	PRMS Outputs	19
4.2.1	Streamflow	20
4.2.2	Mountain Front Recharge (MFR)	20
5.0	Soil-Water Budget Model (SWBM)	23
5.1	SWBM Inputs	23
5.1.1	Precipitation	23
5.1.2	Reference ET (ET_0)	23
5.1.3	Field Properties	24
5.1.4	Crop Coefficients	33
5.1.5	Surface Water Inflows	35
5.1.6	Specified Groundwater Pumping	36
5.2	SWBM Outputs	37
5.2.1	Evapotranspiration (ET)	38
5.2.2	Irrigation	38
5.2.3	Groundwater Pumping	38
5.2.4	Recharge	42
6.0	3D Geologic Model (Leapfrog Works)	44
6.1	3D Geologic Model Inputs	44
6.1.1	Faults	44
6.1.2	Wells	45
6.1.3	Bedrock Units and Contacts	45



6.1.4	Aquifer Units and Contacts.....	48
6.2	Outputs.....	50
6.2.1	Bedrock Surface.....	50
6.2.2	Sediment Volumes and Principal Aquifers.....	50
7.0	Groundwater-Surface-Water Model (MODFLOW)	53
7.1	MODFLOW Inputs	53
7.1.1	Hydraulic Properties	53
7.1.2	Groundwater Pumping.....	65
7.1.3	Evapotranspiration (ET).....	65
7.1.4	Mountain Front Recharge (MFR)	66
7.1.5	Surface Water.....	66
7.2	MODFLOW Outputs	69
7.2.1	Groundwater Elevations.....	69
7.2.2	Water Budgets.....	71
7.2.3	Streamflow	73
8.0	Sensitivity Analysis and Calibration.....	73
8.1	Methods.....	74
8.2	Observations	75
8.2.1	Streamflow	77
8.2.2	Groundwater Elevations.....	78
8.3	Results.....	78
8.3.1	Sensitivity Analysis	78
8.3.2	Calibration.....	80
9.0	Water Budgets.....	90
9.1	Historical Water Budgets.....	90
9.2	Current Water Budgets	97
9.3	Projected Future Water Budgets	100
10.0	Future Work.....	116
10.1	Collection of Additional Streamflow Data	116
10.2	Collection of Additional Lithology Data	117
10.3	More Frequent Collection of Pumping Volume Data.....	117
10.4	Subbasin Specific Calibration of PRMS.....	117
10.5	Testing Alternative Representations of Confining Layer(s).....	118



10.6	Testing Alternative Representations of Mountain Front Recharge	118
11.0	References.....	118

List of Tables

Table 4-1. Groundwater reservoir coefficients used in SVHSM.

Table 5-1. Landcover categories and associated properties.

Table 5-2. Landcover summary.

Table 5-3. Specified pumping volumes.

Table 6-1. SVHSM 3D geologic model lithology unit volumes.

Table 8-1. Summary of parameters evaluated in SWBM and MODFLOW submodels during sensitivity analysis.

Table 9-1. Historical (WY 2001-2015) surface water budget summary.

Table 9-2. Historical (WY 2001-2015) land surface water budget summary.

Table 9-3. Historical (WY 2001-2015) groundwater budget summary.

Table 9-4. Current (WY 2016-2020) surface water budget summary.

Table 9-5. Current (WY 2016-2020) land surface water budget summary.

Table 9-6. Current (WY 2016-2020) groundwater budget summary.

Table 9-7. Summary of future climate scenarios.

Table 9-8. Summary of projected surface water budgets.

Table 9-9. Summary of projected land surface water budgets.

Table 9-10. Summary of projected groundwater budgets.

List of Figures

Figure 1-1. Model Overview.

Figure 2-1. Study Area and Topography.

Figure 3-1. Hydrologic Subsystems.



Figure 3-2. Model Domains.

Figure 4-1. Precipitation Stations and PRISM Normals.

Figure 4-2. ET Coefficients.

Figure 4-3. PRMS land cover.

Figure 4-4. PRMS Reservoirs.

Figure 4-5. PRMS Water Holding Capacity.

Figure 4-6. PRMS Ksat.

Figure 4-7. PRMS slowcoef_lin.

Figure 4-8. PRMS slowcoef_sq.

Figure 4-9. PRMS Streamflow Locations.

Figure 4-10. MFR Zones.

Figure 5-1. SVHSM Reference ET.

Figure 5-2. SWBM Fields.

Figure 5-3. SWBM Landuse.

Figure 5-4. SWBM Irrigation Type.

Figure 5-5. SWBM Irrigation Water Source.

Figure 5-6. SWBM Surface Water Accounting Units.

Figure 5-7. SWBM Groundwater Irrigation Wells and Fields.

Figure 5-8. SWBM Water Holding Capacity.

Figure 5-9. SWBM Kc Values.

Figure 5-10. Upper Watershed Inflows.

Figure 5-11. SWBM Average Annual ET.

Figure 5-12. SWBM Average SW Irrigation.

Figure 5-13. SWBM Average SW Irrigation.

Figure 5-14. SWBM Average GW Recharge.

Figure 6-1. 3D Geologic Model Faults.

Figure 6-2. 3D Geology Model Wells.

Figure 6-3. Bedrock Contacts.



Figure 6-4. SVHSM 3D Geology Bedrock with Wells.

Figure 6-5. 3D Geologic Model Cross Sections.

Figure 7-1. MODFLOW Discretization.

Figure 7-2. Hydraulic Property Zones.

Figure 7-3. MODFLOW MFR.

Figure 7-4. MODFLOW Surface Water Network.

Figure 7-5. Streambed Hydraulic Conductivity.

Figure 7-6. Water Budget Zones.

Figure 8-1. Observation Locations.

Figure 8-2. Streamflow Observations.

Figure 8-3. Composite Scaled Sensitivity.

Figure 8-4. PRMS Calibration Results.

Figure 8-5. Simulated vs Observed Groundwater Heads.

Figure 8-6. Groundwater Head Residuals.

Figure 8-7. Average Head Residuals.

Figure 8-8. Minimum Head Residuals.

Figure 8-9. Maximum Head Residuals.

Figure 8-10. Selected Groundwater Hydrographs.

Figure 8-11. Observed and Simulated Streamflow.

Figure 9-1. Annual Surface Water Budget.

Figure 9-2. Annual Land Surface Water Budget.

Figure 9-3. Annual Groundwater Budget.

Figure 9-4. MODFLOW Budget Zones.

Figure 9-5. Eastside - Westside Annual Net Recharge.

Figure 9-6. Eastside - Westside Annual Pumping.

Figure 9-7. Eastside Upper-Lower Annual Net Recharge.

Figure 9-8. Eastside Upper-Lower Pumping.

Figure 9-9. Cumulative Future Climate Input Comparison.



Figure 9-10. Average Monthly Change in Climate Inputs.

Figure 9-11. Observed and Simulated Groundwater Pumping.

Figure 9-12. Estimated Future Groundwater Pumping.

Figure 9-13. Estimated Future Streamflow Inputs.

Figure 9-14. Future Climate Surface Water Budgets.

Figure 9-15. Future Climate Land Surface Water Budgets.

Figure 9-16. Future Climate Groundwater Budgets.

Figure 9-17. Future Climate Cumulative Groundwater Storage Change.

Figure 9-18. Eastside-Westside projected future cumulative storage.

Figure 9-19. Eastside Upper-Lower projected future cumulative storage.

List of Appendices

Appendix A. PRMS Water Budgets

Appendix B. SWBM Water Budgets

Appendix C. MODFLOW Water Budgets



List of Acronyms

AF - Acre Feet

AFY - Acre Feet Per Year

CASGEM - California Statewide Groundwater Elevation Monitoring

CFS - Cubic Feet Per Second

CGS - California Geological Survey

CIMIS - California Irrigation Management Information System

DBS&A - Daniel B. Stephens & Associates, Inc.

DMS - Database Management System

DWR - Department Of Water Resources

ET - Evapotranspiration

GIS - Geographic Information System

GPM - Gallons Per Minute

GSA - Groundwater Sustainability Agency

GSP - Groundwater Sustainability Plan

HCM - Hydrogeologic Conceptual Model

HRU - Hydrologic Response Unit

LWA - Larry Walker Associates

MAF - Million Acre Feet

MFFR - Middle Fork Feather River

PRMS - Precipitation-Runoff Modeling System

SFR - Streamflow Routing Package

SGMA - Sustainable Groundwater Management Act

SSURGO - Soil Survey Geographic Database

SVGMD - Sierra Valley Groundwater Management District

SVHSM - Sierra Valley Hydrogeologic System Model

SWBM - Soil-Water Budget Model

SWP - State Water Project



TAF - Thousand Acre feet

USGS - United States Geological Survey

1.0 Introduction and Purpose

Daniel B. Stephens & Associates, Inc. (DBS&A) was contracted by Larry Walker Associates (LWA) under LWA Project No. 649.01 to develop an integrated hydrologic model of the Sierra Valley and database management system (DMS) to assist with Groundwater Sustainability Plan (GSP) development and implementation. This report provides a description and evaluation of the Sierra Valley Hydrogeologic System Model (SVHSM). Documentation of the DMS is included in a separate document that will be included as an appendix of the GSP; however, a link to the DMS web-interface is provided in this report.

The primary goal of SVHSM is to provide a scientifically based, objective tool that the Groundwater Sustainability Agency can use to better inform their management decisions. This is accomplished by linking three different hydrologic models that, combined, simulate the entire hydrologic flow system in the watershed (Figure 1-1). The integrated model provides detailed recent historical or projected future water budgets for the three main hydrologic subsystems: (1) land surface and soil zone, (2) surface water, and (3) groundwater. Water budgets are an accounting of all water that flows into or out of a defined project area, and provide information about changes in storage.

Sections 2 and 3 of this document summarize the basin setting and modeling approach.

Hydrologic flows in the Sierra Valley watershed are simulated using three coupled models along with a 3D geologic model that was used to define aquifer geometry and sediment distribution. These models are discussed in Sections 4-7. Sensitivity analysis and model calibration results are presented in Section 8. Historical and projected future water budgets for each hydrologic subsystem of the groundwater basin are provided in Section 9. Suggestions for future data collection and areas that additional calibration efforts should focus on are included in Section 10.

The model presented and discussed in this report is separate from that developed for the Sierra Valley by researchers at UC Davis (Dib and others, 2016). Efforts were made to acquire the input files for this model to assess if they could be updated to meet

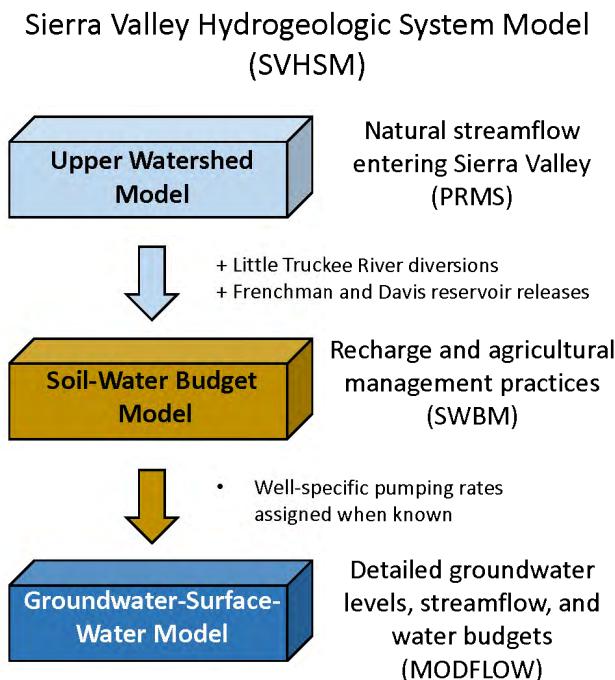


Figure 1-1. Schematic overview of the Sierra Valley Hydrogeologic System Model



GSP needs or be used to reduce effort in development of a new model. Unfortunately, the model files could not be obtained. If they become available in the future, they can be evaluated and incorporated into SVHSM as applicable.

2.0 Study Area

Sierra Valley is a large sub-alpine valley located in the eastern Sierra Nevada Mountains in the northern portion of the Sierra Nevada geomorphic province of California, and drains nearly 374,000 acres (Figure 2-1). The groundwater basin is about 125,900 acres and consists of the Sierra Valley (5-012.01) and Chilcoot (5-012.02) subbasins. The valley is surrounded by steep mountains and alluvial fans with various slope gradients.

Climate in the Sierra Valley watershed is strongly correlated with elevation, with higher elevations being cooler and generally receiving the greatest amount of precipitation. The watershed experiences more precipitation in the west due to the “rain shadow effect” caused by the Sierra Nevada Mountains. The combination of topography and the “rain shadow effect” results in highly variable precipitation in the watershed.

The majority of the Sierra Valley basin is private land, while the surrounding watershed is primarily national forest. On the valley floor, alfalfa grown for hay is the dominant irrigated crop. Braided streams and agricultural irrigation support wetland and riparian communities. The western valley supports approximately a 20,000-acre wetlands complex and 30,000-acre meadow complex, both the largest in the Sierra Nevada (NRCS, 2016).

Soils within the Sierra Valley Watershed vary considerably in productivity, depth, and use based on parent material, topography, and precipitation. Surface soil types within the groundwater basin are dominated by sands, clays, and silts. Silty sands make up the largest fraction of surficial soils in the groundwater basin, accounting for about 41% of the surface area. Finer-grained soil textures, such as silts and clays, make up approximately 37% of the surface area and are generally located adjacent to stream channels and wetland regions. The rest of the basin has either not been classified or is composed of relatively small fractions of mixed soils.

The groundwater basin is part of a series of downdropped fault blocks, or grabens, surrounded by uplifted mountains, or horsts. The valley floor consists of an irregular surface of basement rock, formed by steeply dipping northwest and northeast-trending vertical, normal, and strike-slip faults. Throughout its geologic history, the fault trough floor gradually subsided, while being occupied by one or several lakes (Durrell, 1986). Lacustrine (lake), fluvial, and alluvial deposits were formed as sediments eroded from the surrounding uplands and volcanic tuffs (ash deposits) and filled the space created by the fault trough floor as it continued to subside. Sierra Valley geologic units can be divided into three groups: (1) basement complex metamorphic and granitic rocks, (2) Tertiary volcanics, and (3) Quaternary sedimentary deposits of clay, silt, sand, and gravel.



Sierra Valley and the surrounding uplands support the MFFR headwaters and provide water to Lake Oroville as part of the California State Water Project (SWP). Many named and unnamed streams enter the Sierra Valley basin creating a large braided stream network on the valley floor. These stream flows are fed seasonally by rainfall, snowmelt, and groundwater discharge. The western portion of the valley receives greater precipitation and has more surface water than the eastern valley. Appropriate and riparian water rights holders divert most of eastern stream flow during summer, such that the downstream stretches usually dry out completely before confluence with the western channels (Vestra, 2005; Bohm, 2016). Releases from Frenchman Lake and imported water from the Little Truckee River Diversion support valley irrigation during the growing season (DWR, 1983). Many of these tributaries drain the valley as they connect to the headwaters of MFFR through a water gap in the northwestern corner of the Sierra Valley watershed.

Inflows to the Sierra Valley groundwater system are primarily sourced from infiltration of surface water in the alluvial fans at the periphery of the valley from adjacent uplands and flow from the fractured bedrock in contact with the shallow and deep aquifers (Bohm, 2016). A small amount of recharge is likely derived from direct precipitation on fan surfaces, deep percolation from irrigated agricultural fields, seepage from losing reaches of tributaries, and irrigation ditches in the valley. Recharge areas tend to be high elevation areas with underlying soils and geologic formations containing sufficient hydraulic conductivity and the right combination of climate.

Most natural groundwater discharge occurs on the valley floor in the form of evapotranspiration (ET), direct surface evaporation, outflowing reaches of streams, natural springs, seeps, and wetlands. Approximately 70 to 80% of the watershed's total water budget is lost to evapotranspiration (Vestra, 2005). Springs and wetlands are found around the edges of the valley floor and are generally more abundant in the southwestern portions of the valley, where the uplands receive significantly more precipitation. Some exist along the northern valley perimeter, likely fed by the relatively large upland recharge areas that exist north of the valley (Bohm, 2016). Flowing artesian wells are present in many parts of the valley and discharge confined ground water at varying rates; flow during the winter and spring is usually greater than the summer and fall flows.

From 1999 to 2017 annual average groundwater pumping was about 8,500 acre-feet (Bachand, 2020). Approximately 90% of this pumping was from agricultural wells, with annual volumes substantially influenced by precipitation and snow pack. Average annual municipal pumping for residential water supply in Sierra Brooks, Calpine, and Loyalton was about 665 acre-feet (SVGMD, 2019). Domestic pumping in the Sierra Valley is unmetered and mostly occurs along the margin of the valley, with many domestic wells completed in bedrock outside of the groundwater basin boundary.

3.0 Modeling Approach and Framework

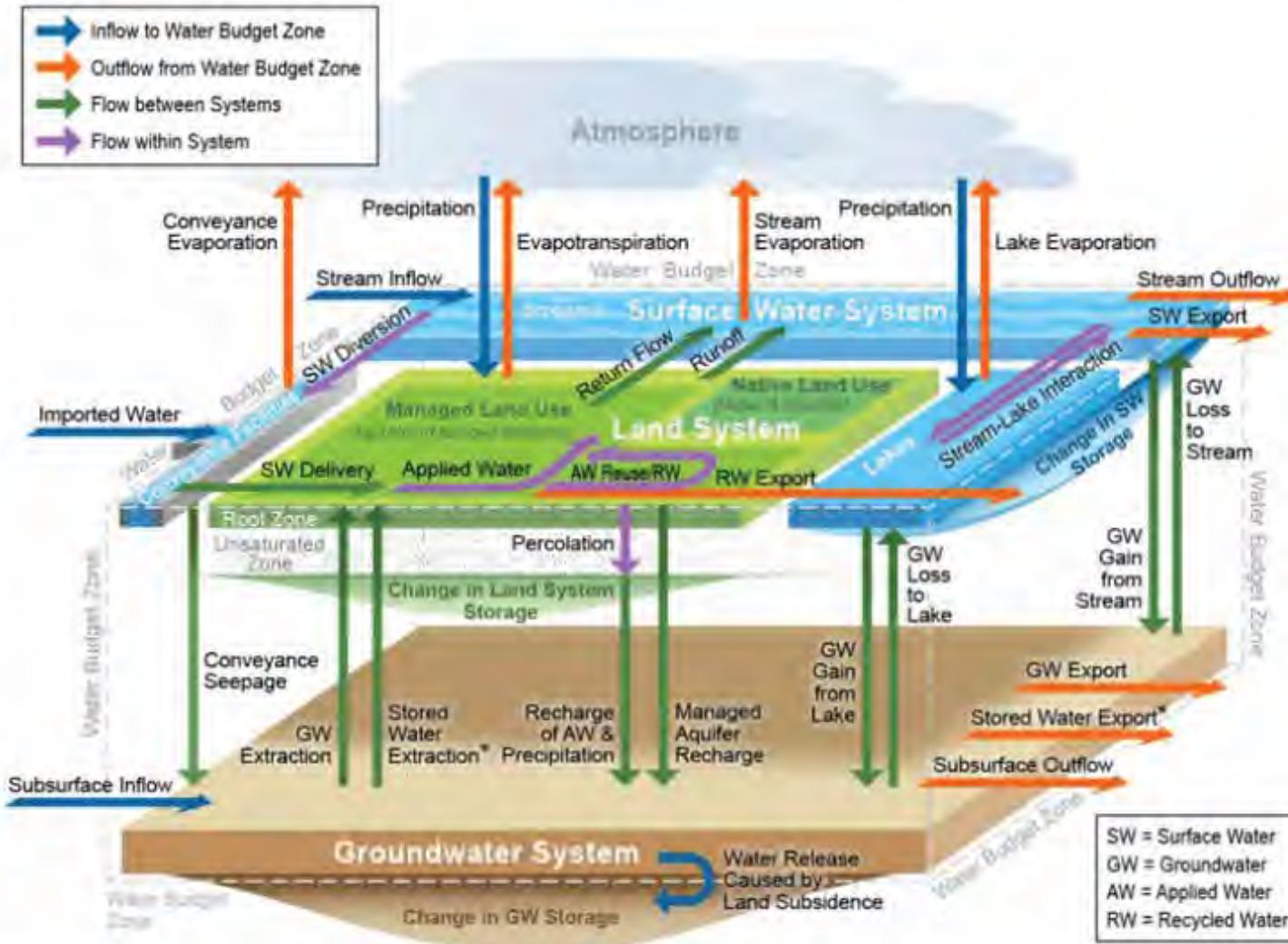
The Sierra Valley hydrogeologic system has been conceptualized into two primary geographic areas consisting of the Bulletin 118 groundwater basin boundary (DWR, 2018) and the upper



watershed, defined as the contributing area to the Sierra Valley that is outside of the groundwater basin boundary. The hydrogeologic system in each of these two areas was subdivided into three broad categories: (1) land surface and unsaturated soil zone, (2) surface water, and (3) groundwater (Figure 3-1). This was done because flow processes that operate within each hydrologic subsystem have varying characteristic response times and spatial scales. For example, surface water flow is typically limited spatially to channels, but has short response times on the order of hours to days. In contrast, groundwater flow occurs within the entire aquifer volume and has much longer responses times on the order of days to months. Therefore, different specially tailored computer programs are required to simulate the multiple hydrogeologic processes operating within the watershed. Presentation of water budgets by hydrologic subsystem is also the method preferred by the California Department of Water Resources (DWR) (see Figure 1-1 in *Handbook for Water Budget Development: With or Without Models*).

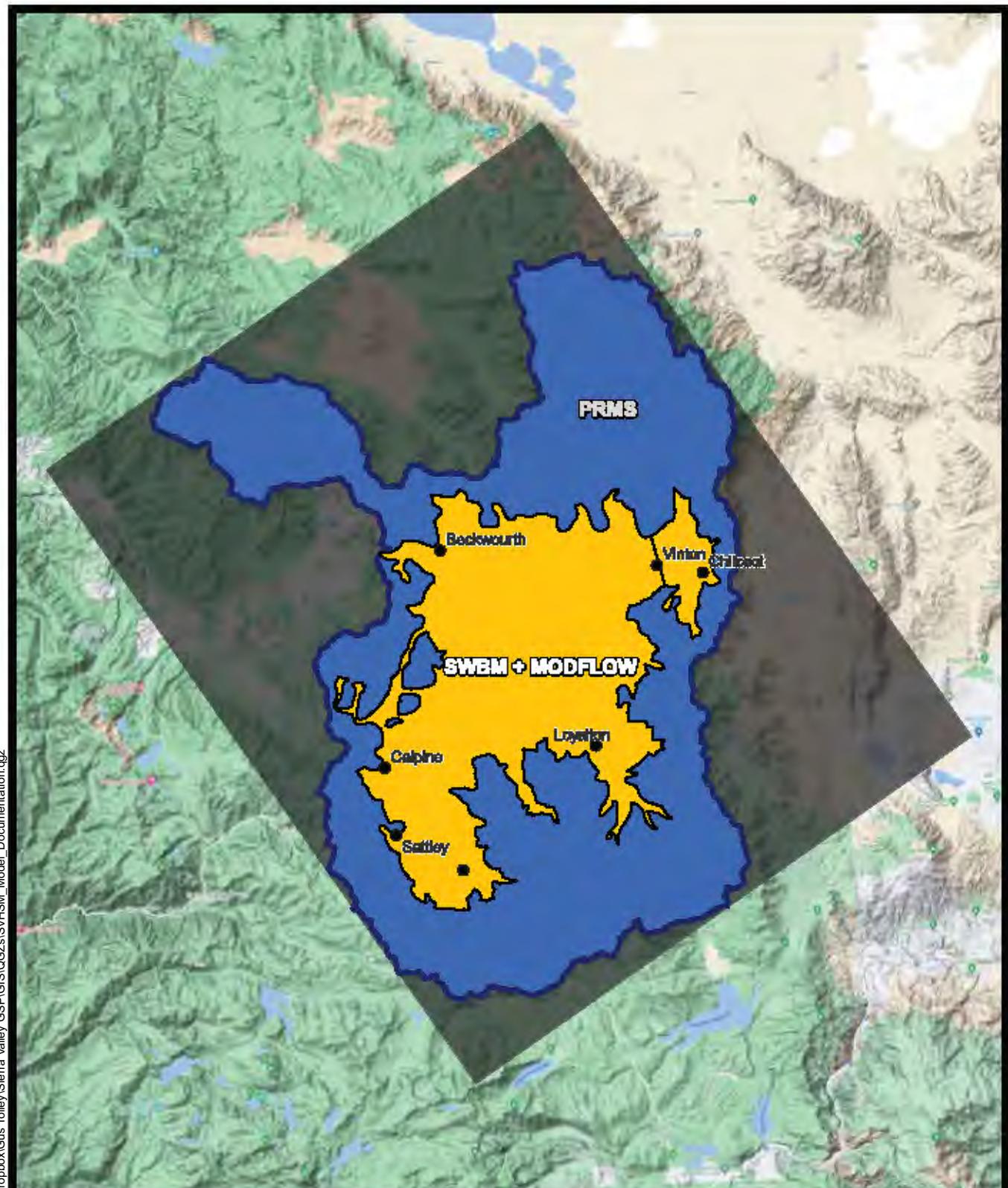
Three computer programs are used to represent the flow of water in the Sierra Valley watershed (Figure 3-2). The upper watershed is simulated using the Precipitation Runoff Modeling System (PRMS) (Markstrom and others, 2015) developed by the U.S. Geological Survey (USGS), and is used to represent all three hydrologic subsystems outside of the groundwater basin boundary. The primary outputs of PRMS are estimates of streamflow entering the groundwater basin from the upper watershed since observed flow data are either sparse or nonexistent. The PRMS model also provides an upper limit of potential inflows to the groundwater basin from mountain front recharge processes (see Section 7.1.4). For more details on PRMS, see Section 4. The groundwater basin is simulated using two numerical models and one geologic model. Land surface processes within the groundwater basin boundary, including agricultural management practices, are simulated using the Soil Water Budget Model (SWBM) (Foglia and others, 2013; Tolley and others, 2019). Precipitation, reference ET (ET_0), and streamflow are used as inputs, with actual ET (ET_a), runoff (RO), surface water irrigation (IRR_{sw}), groundwater irrigation (IRR_{gw}), and recharge (RCH) calculated on a daily time step based on properties assigned to each field. Water demand in SWBM is estimated using the crop coefficient method (Allen and others, 1998). Pumping rates can be specified for any well such that simulated pumping rates match observed pumping rates. For more details on the SWBM, see Section 5.

Well logs, seismic study data, geologic maps, and geologic interpretations were used to develop a 3D geologic model of the Sierra Valley aquifer system using the software Leapfrog Works. The results from this model were then mapped onto the MODFLOW grid in order to distribute physical aquifer properties (hydraulic conductivity, storage coefficients, etc.) within the model domain. As more subsurface data are collected in the future, they can be incorporated into the geologic model, which can then be used to update the distribution of aquifer properties. This could improve representation of groundwater and surface water flows by the model, as there are some portions of the basin where subsurface knowledge is limited or completely lacking. For more details on the 3D geologic model, see Section 6.



Notes:

1. Figure 1-1 in DWR Handbook for Water Budget Development



C:\Users\500\Sierra Valley GSP Dropbox\Gus Tolley\Sierra Valley GSP\GIS\QGZs\SVHSM_Model_Documentation.qgz

Explanation

- PRMS
- SWBM + MODFLOW
- Inactive

City or Town

0 2.5 5 mi



Notes:
1. SWBM = Soil-Water Budget Model



SVHSM Documentation
Model Domains



Recharge and groundwater pumping estimated by the SWBM, along with surface water inflows from PRMS (adjusted for irrigation diversions), estimated mountain front recharge (MFR), and subsurface parameter distribution obtained from the 3D geologic model, are used to drive the groundwater-surface water submodel (MODFLOW). Results include detailed water level elevations and flows within the groundwater basin, which are simulated using monthly stress periods with a daily time step. Boundary conditions (recharge, pumping, etc.) within a stress period are constant, but heads (water level elevations) and fluxes (water flows) can change within a stress period. Daily time steps are used in order to better represent surface water flow in the model. For more details on the groundwater-surface water model, see Section 7.

The combination of these numerical models ultimately produces monthly and annual water budgets for each hydrologic subsystem within the Sierra Valley watershed. Depending on the boundary conditions imposed on the model, these water budgets can represent historical and current conditions or projected future water budgets that incorporate anticipated climate change (see Section 9).

4.0 Upper Watershed Rainfall Runoff Model (PRMS)

PRMS was used to evaluate surface water runoff and general hydrologic processes for the upper Sierra Valley watershed (Figure 3-2). PRMS is a deterministic, physically based modeling system. Components of the hydrologic cycle (ET, infiltration, etc.) are simulated using physical laws or established empirical relationships based on measurable watershed characteristics. SVHSM uses a distributed parameterization of PRMS, where physical properties are assigned to specified hydrologic response units (HRUs). In SVHSM, each model cell is designated as an individual HRU so the terms are equivalent.

The PRMS model domain is 599 rows and 484 columns rotated by 35 degrees counter-clockwise around 727096.781207E, 4368418.236840N (NAD 83 UTM Zone 10 N). The grid rotation was to align the principal axes in the groundwater model with the Loyalton and Grizzly Valley faults. The ability to convert the PRMS and MODFLOW models into a single GSFLOW (Markstrom and others, 2008) model in the future was desired, so the PRMS grid was also rotated for consistency. Horizontal discretization is 100 m in both the x and y direction, with a total of 152,841 active model cells. The simulation period is from October 1, 1989 through September 30, 2020 using a daily time step.

Due to the quantity of required inputs and possible outputs, a complete description of inputs to and outputs from the PRMS model used in SVHSM is beyond the scope of this documentation. The most relevant model inputs and outputs are described below. Model inputs files were generated using a series of Python/ArcPy (ArcGIS) scripts developed by the USGS and Desert Research Institute known as GSFlow ArcPy (Gardner and others, 2018). All model files are publicly available at the SVGMD website (<https://www.sierravalleygmd.org/>).



4.1 PRMS Inputs

Inputs to PRMS can be either temporal, semi-temporal, or spatial. Temporal inputs are specified on a daily basis, and include precipitation and temperature data. Semi-temporal inputs are specified for each calendar month, but the value for a given month is constant for the entire simulation period. For example, the temperature lapse rate for January is the same value every year, but can differ from the February temperature lapse rate. Spatial inputs are constant throughout the model run but can vary by location. These typically represent physical properties of the watershed (slope, roughness, etc.). Spatial inputs can be specified for each model cell, or a single value that applies to all model cells can be used.

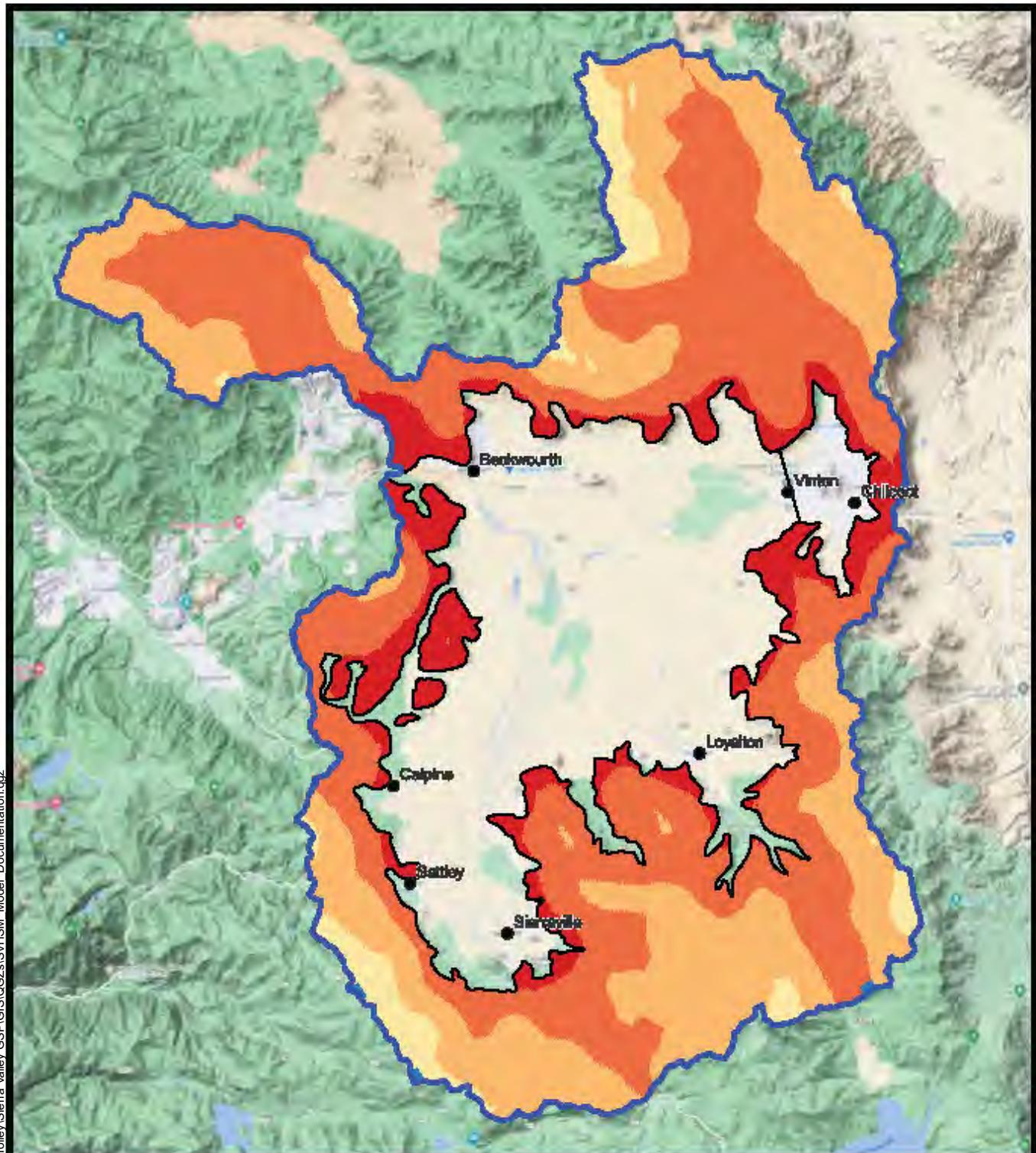
Formatted PRMS input files were largely generated using GSFlow ArcPy, a collection of Python/ArcPy (ArcGIS) scripts (<https://github.com/gsflow/gsflow-arcpy>). Selected inputs were then modified manually based on parameter values from the nearby Sagehen Creek model (available as an example in the PRMS software download) or via manual calibration.

4.1.1 Climate

Daily precipitation and temperature inputs from water year (WY) 1990-2020 were developed using data from the Sierraville ranger station (Figure 4-1). Days with missing data were filled in using nearby meteorological stations. Annual precipitation ranged from 10.4 to 52.8 inches per year (in/yr) (265.2 to 1,342.1 millimeters per year [mm/yr]) with an average of 23.4 in/yr (594.7 mm/yr). The PRMS module *precip_1sta* was used to distribute measured precipitation observed at the Sierraville ranger station (or inferred from other stations) across the model domain using parameters that account for elevation, spatial variation, and topography, among others. Precipitation in the model is partitioned between rain and snow, and is primarily a function of temperature. All precipitation is assumed to fall as snow below 38.3°F (3.5°C), and as rain above 59 to 68°F (15 to 20°C) depending on the calendar month. Between these temperatures, precipitation occurs as a mixture of rain and snow.

Maximum temperatures used for the model range from 90.3 to 100.3°F (32.4 to 38.0°F) and average about 95.1°F (35.1°C). Minimum temperatures at the station are about 1.1°F (-17.2°C) on average, and range from 8.6 to -17°F (-13.0 to -27.2°C). Temperatures were adjusted for elevation using a lapse rate that varied from about 15.4 to 23.2°F per mile (5.3 to 8.0°C per kilometer [km]) depending on the calendar month.

Potential ET in the PRMS submodel is calculated using the modified Jensen Haise formulation as a function of the air temperature, solar radiation, and two coefficients. Regional air temperature is represented by *jh_coef* and varies from 0.016 to 0.027 per °F depending on the calendar month. Local temperature effects on potential ET are represented by the parameter *jh_coef_hru* (Figure 4-2), with greater values indicating lower potential ET. Solar radiation data was distributed using the *ddsolrad* module, which estimates solar radiation using a modified degree-day method (Leavesley and others, 1983). This method was developed for the Rocky Mountain regions of the U.S., and is most applicable to areas where clear skies prevail on days without precipitation.



Explanation

jh_coef_hru (per degrees F)

< 20
20 - 21
21 - 22
22 - 23
23 - 24

24 - 25

25 - 26

> 26

City or Town

Groundwater Basin

Watershed Boundary

Notes:

1. Greater values indicate lower ET potential.



SVHSM Documentation
PRMS Potential ET Coeffiecents



4.1.2 Landcover

Landcover primarily affects if and to what degree canopy interception occurs, and can vary by season (winter and summer) and also by precipitation type (rain and snow). Five different classifications are available in PRMS and shown in Figure 4-3. These classifications are based on landcover data from the GAP/LANDFIRE database (USGS, 2016).

4.1.3 Soils

PRMS partitions the soil zone into three different zones (reservoirs) that represent different physical flow processes: 1) preferential-flow reservoir, 2) capillary reservoir, and 3) gravity reservoir (Figure 4-4). The preferential-flow reservoir accounts for rapid lateral interflow through large openings in the soil profile and is largely active only during rainfall events. The capillary reservoir represents soil-water content between the wilting point and field capacity thresholds. This water is immobile as it is held in place by capillary forces and can be considered to be the available water content for vegetation within the soil profile. The gravity reservoir accounts for slow, lateral interflow within the soil zone and drainage to the groundwater reservoir (not shown) represented in PRMS.

The type and distribution of soils are a significant control on most of the processes represented in PRMS, as they are used to define physical properties related to storage, infiltration, etc. Data from soil survey areas CA614, CA713, and CA719 in SSURGO (NRCS, 2020) were used to parameterize required soil inputs. Figure 4-5 shows the distribution of soil water holding capacity (field capacity) for the upper watershed. Some areas on the southern and western portions of the model domain tend to have greater soil storage capacity, but in general soil storage distribution in the upper watershed is heterogeneous. Saturated hydraulic conductivity of the soil (Figure 4-6) shows a stronger spatial correlation, with more conductive soils found in the northeast, southeast, and southwest portions of the upper watershed. Median values of hydraulic conductivity are found in the southern portion of the model domain, with the lowest hydraulic conductivities generally the north and east of the groundwater basin.

Two parameters that have a significant control over flow within the soil zone in PRMS are the parameters *slowcoef_lin* and *slow_coef_sq*, which are the linear and non-linear coefficients used to route gravity reservoir storage down slope for each HRU. Values of *slowcoef_lin* used in SVHSM ranged from about 0 to 0.005 fraction/day (Figure 4-7), and values of *slowcoef_sq* ranged from 0 to 0.63 (Figure 4-8). These are generally within the expected range provided in the PRMS user manual.

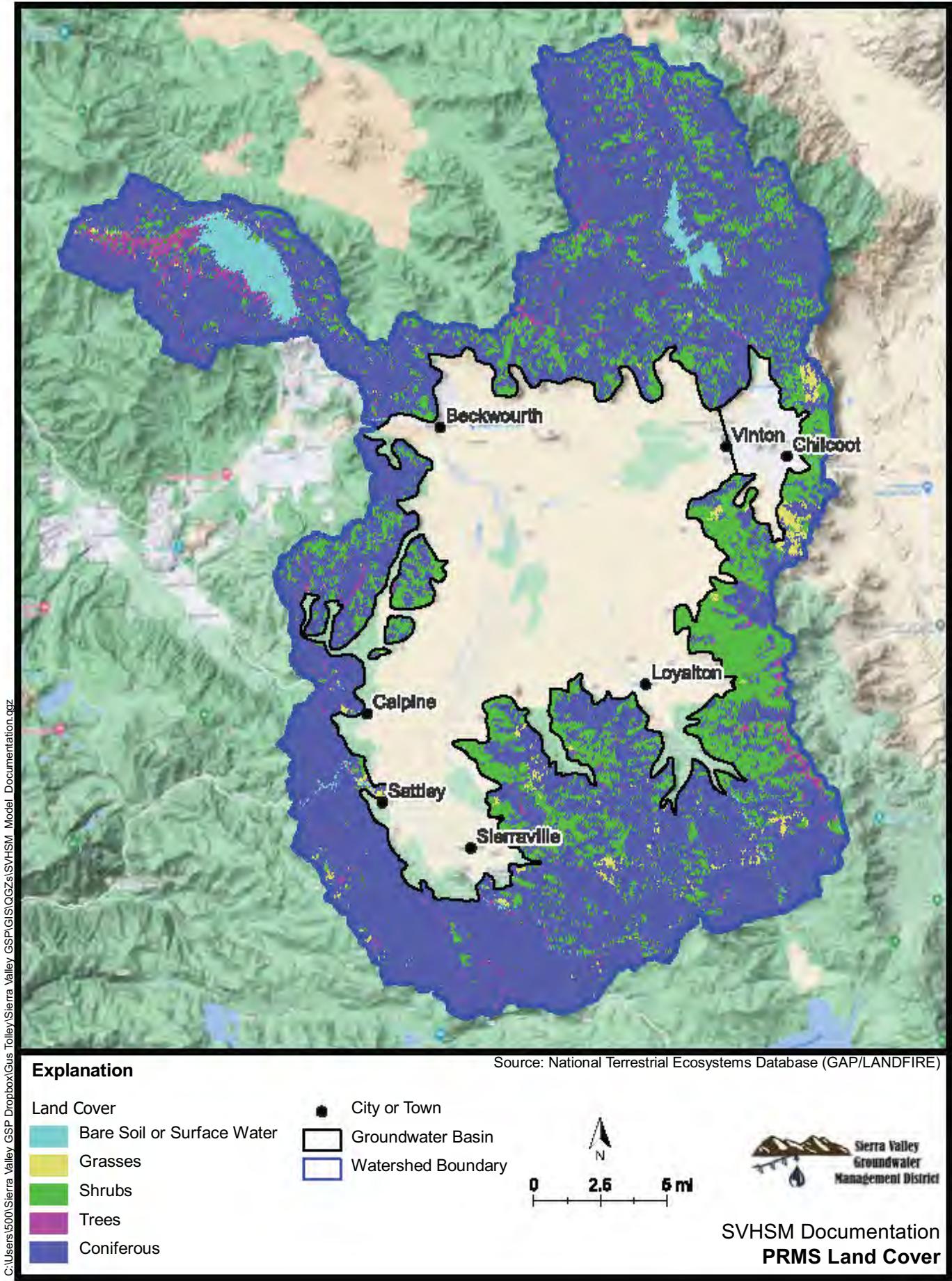


Figure 4-3

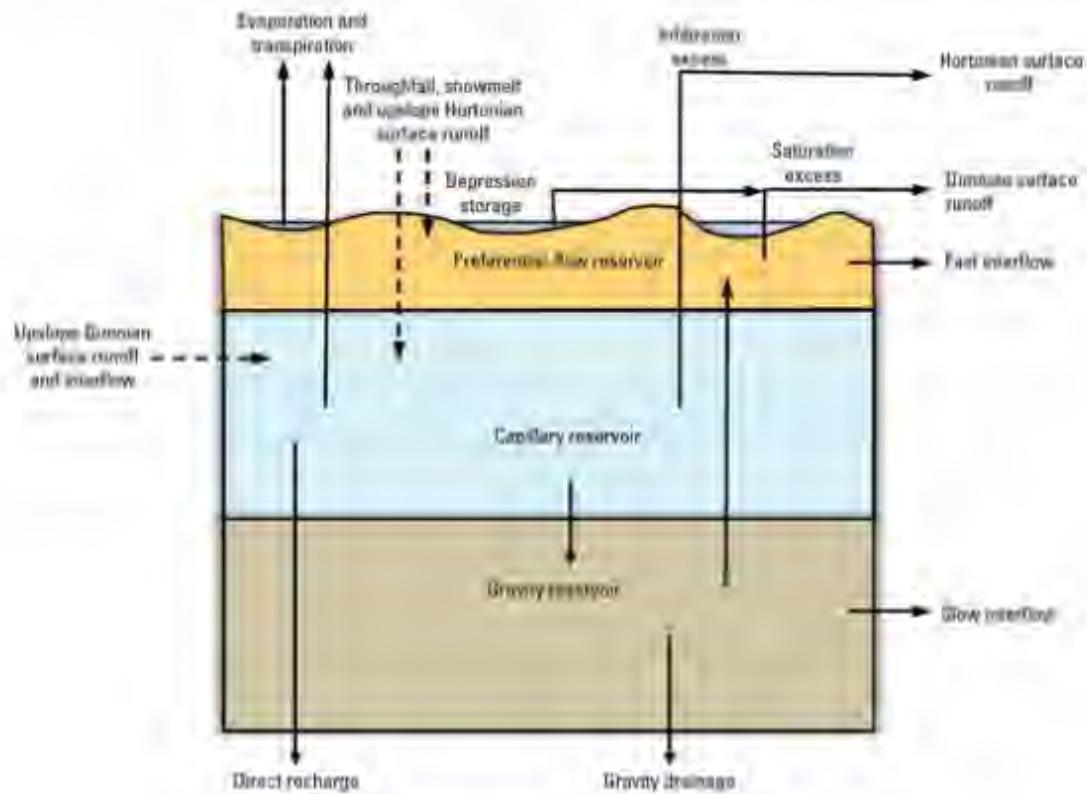
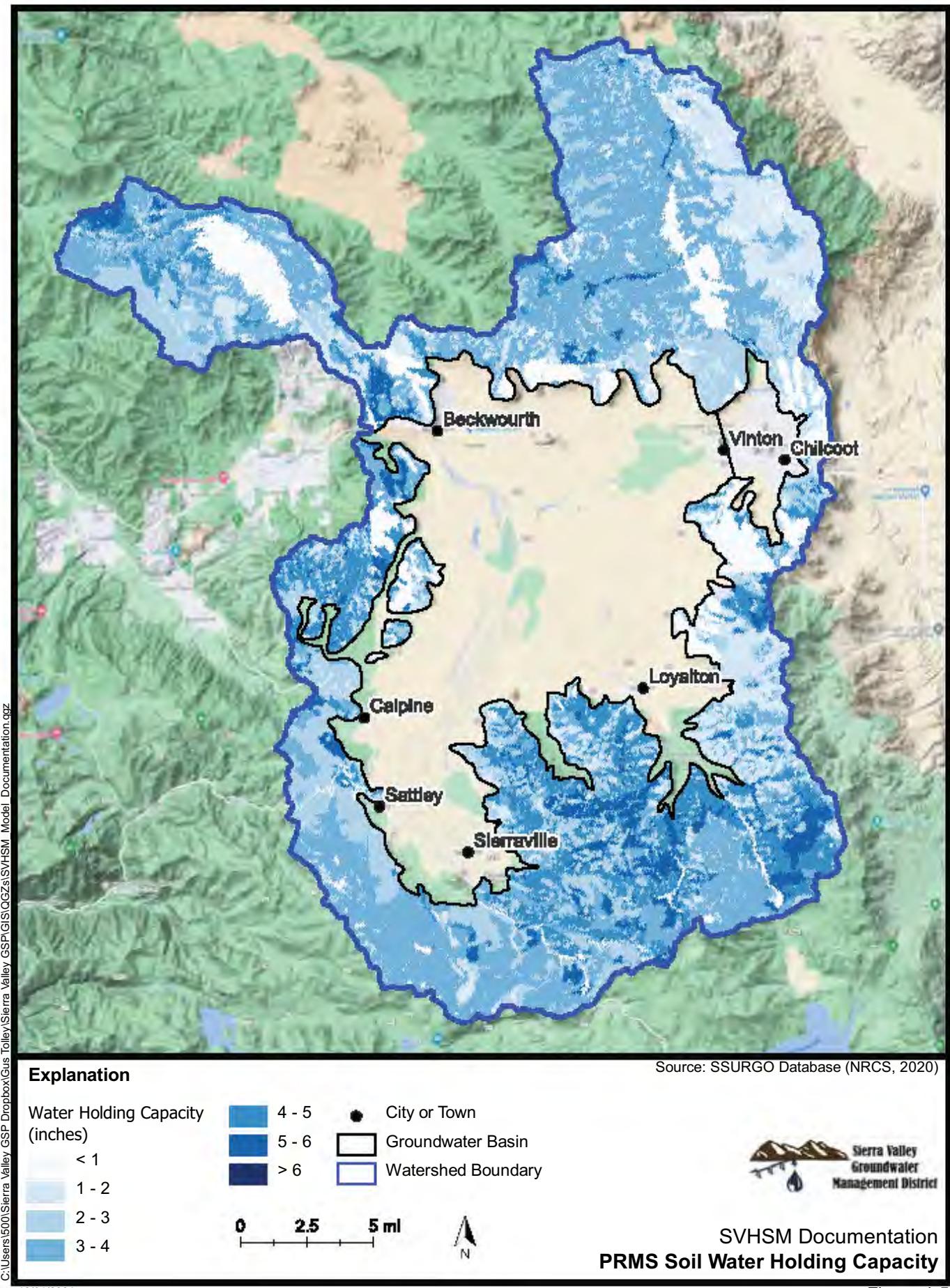
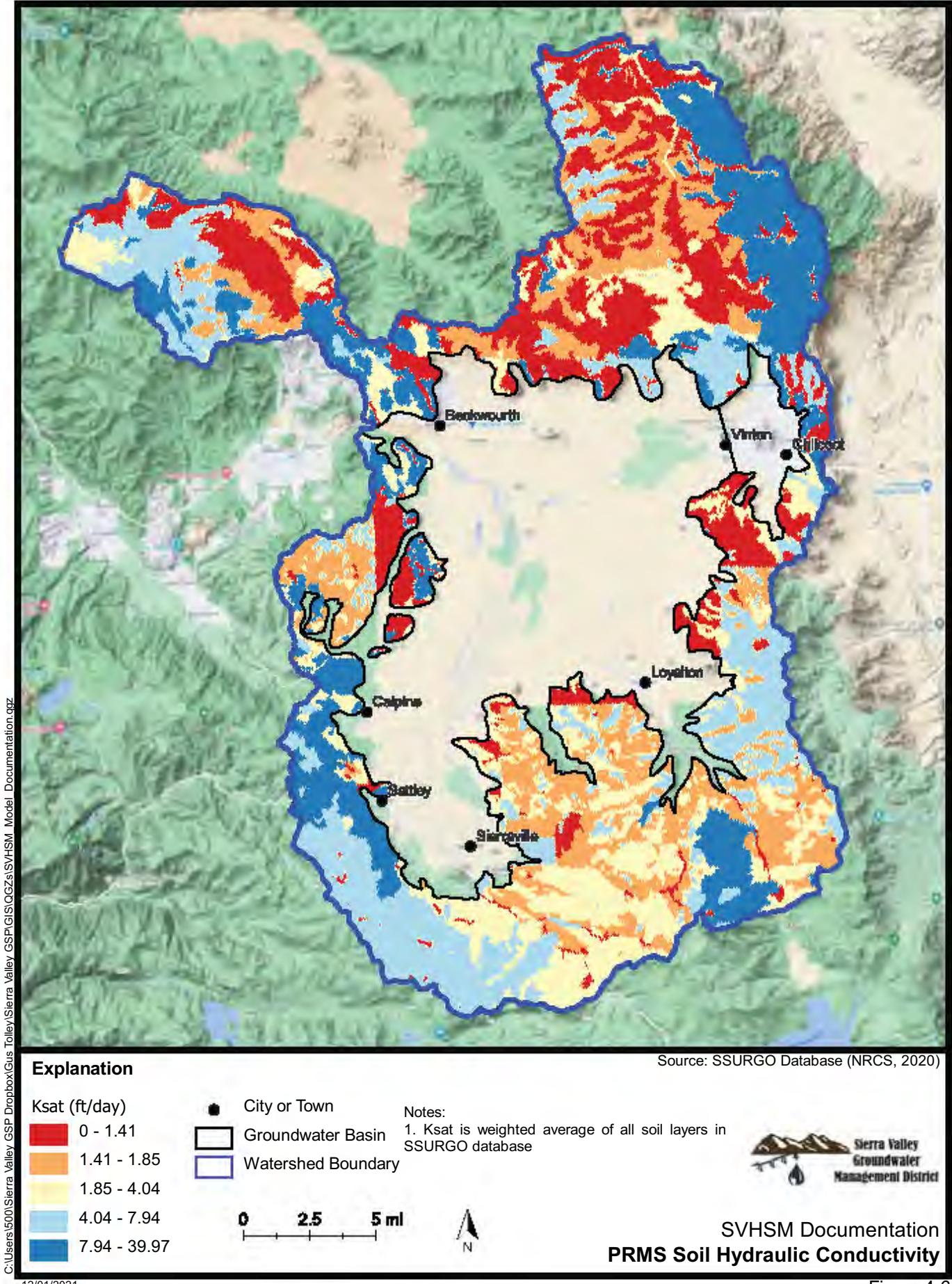
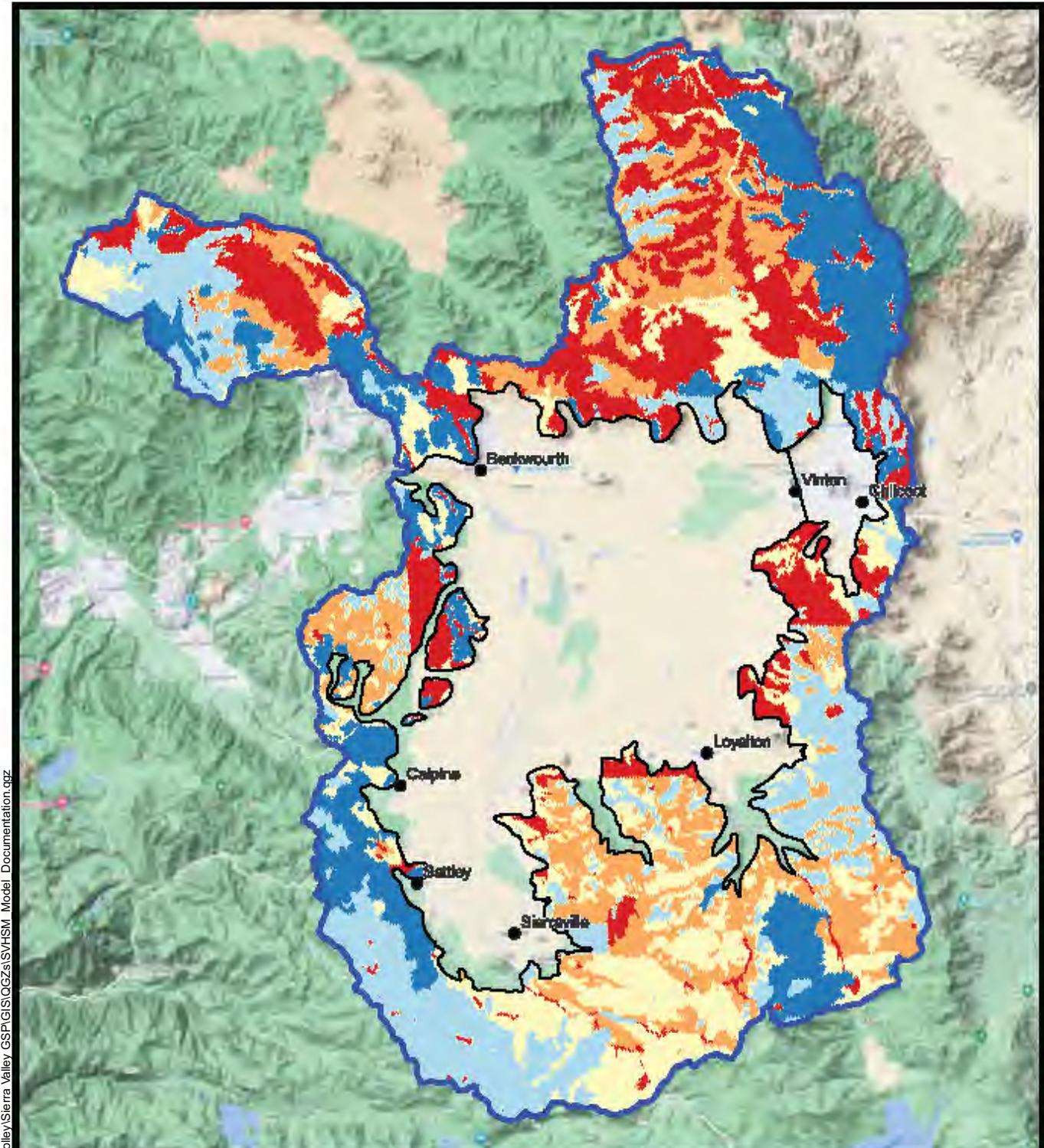


Figure 4-4. PRMS soil reservoirs







C:\Users\500\Sierra Valley GSP Dropbox\Gus Tolley\Sierra Valley GSP\GIS\GZs\SVHSM_Model Documentation.giz

Explanation

slowcoef_lin (fraction/day)
0 - 0.000067
0.000067 - 0.000124
0.000124 - 0.000234
0.000234 - 0.000625
0.000625 - 0.004927

- City or Town
- Groundwater Basin
- Watershed Boundary

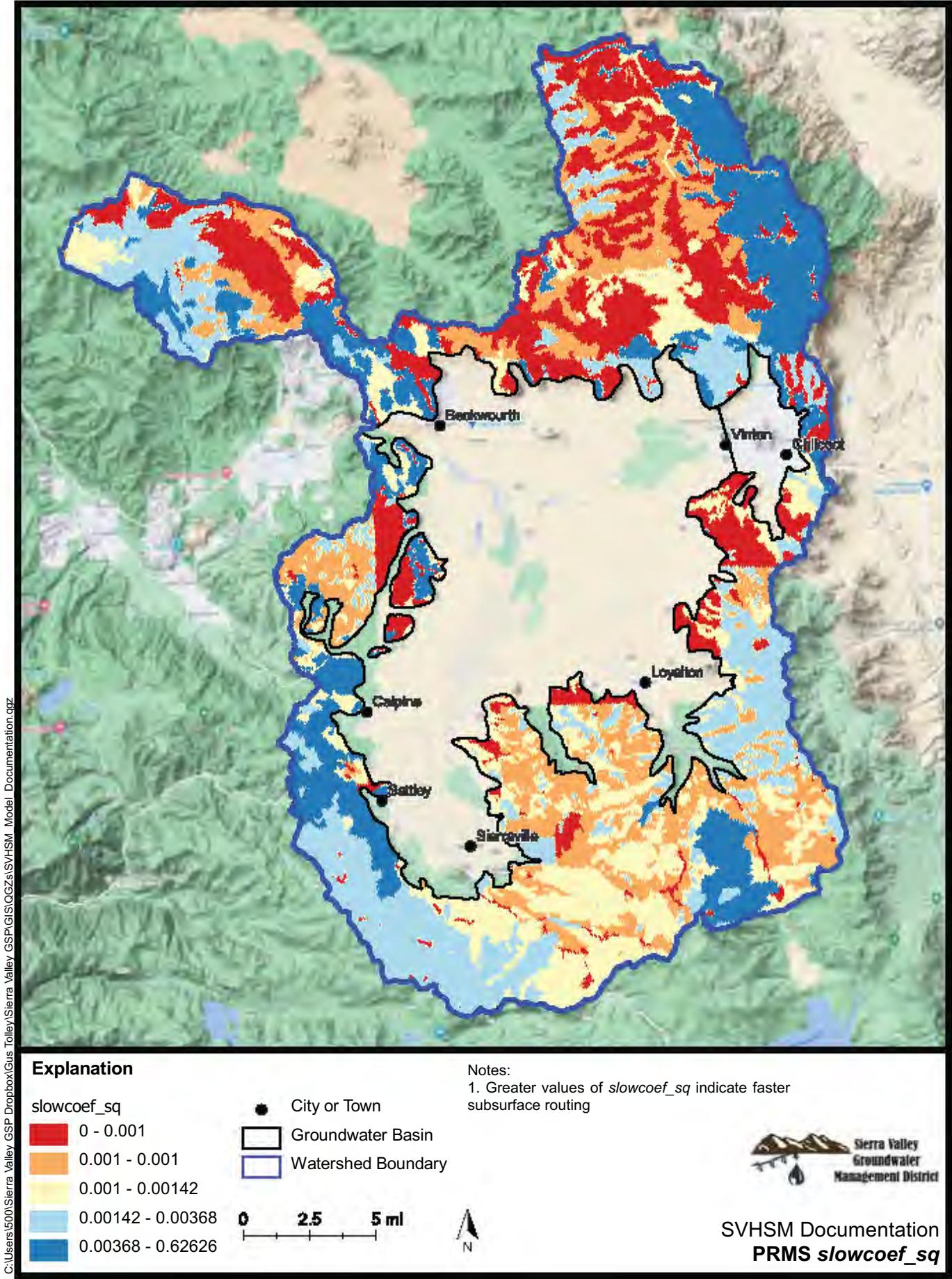
0 2.5 5 mi

Notes:

1. Greater values of *slowcoef_lin* indicate faster subsurface routing



SVHSM Documentation
PRMS *slowcoef_lin*



4.1.4 Groundwater

Parameterization of the groundwater reservoir in the PRMS submodel of SVHSM was generally accomplished by specifying a single value that applied to all HRUs. This method was chosen due to limited knowledge and data of the bedrock aquifer system in the upper portion of the watershed, as well as the inability to effectively explore spatial distributions of groundwater-related parameters during model calibration due to limited streamflow data. Key groundwater reservoir parameters used in SVHSM are provided in Table 4-1.

Table 4-1. Groundwater reservoir coefficients used in SVHSM.

Parameter	Description	SVHSM Value	Units	Typical Range
<i>gwflow_coef</i>	Coefficient for determining baseflow to streams.	0.08	fraction/day	0.001 - 0.5
<i>gwsink_coef</i>	Coefficient for determining losses from groundwater reservoir.	0.05	fraction/day	0.0 - 1.0
<i>gwstor_init</i>	Initial groundwater reservoir storage.	1.8	inches	0.0 - 10.0
<i>gwstor_min</i>	Minimum groundwater reservoir storage.	0.0	inches	0.0 - 1.0
<i>soil2gw_max</i>	Maximum amount of the capillary reservoir excess that is routed directly to the groundwater reservoir.	0.0	inches	0.0 - 5.0

4.2 PRMS Outputs

The two primary outputs desired from the PRMS submodel of SVHSM are (1) streamflow entering the groundwater basin and (2) spatially and temporally distributed groundwater recharge in the upper portion of the watershed. Additional outputs from PRMS are available, and can be evaluated in the future if a need arises. Tabulated water budgets from the PRMS submodel of SVHSM can be found in Appendix A.



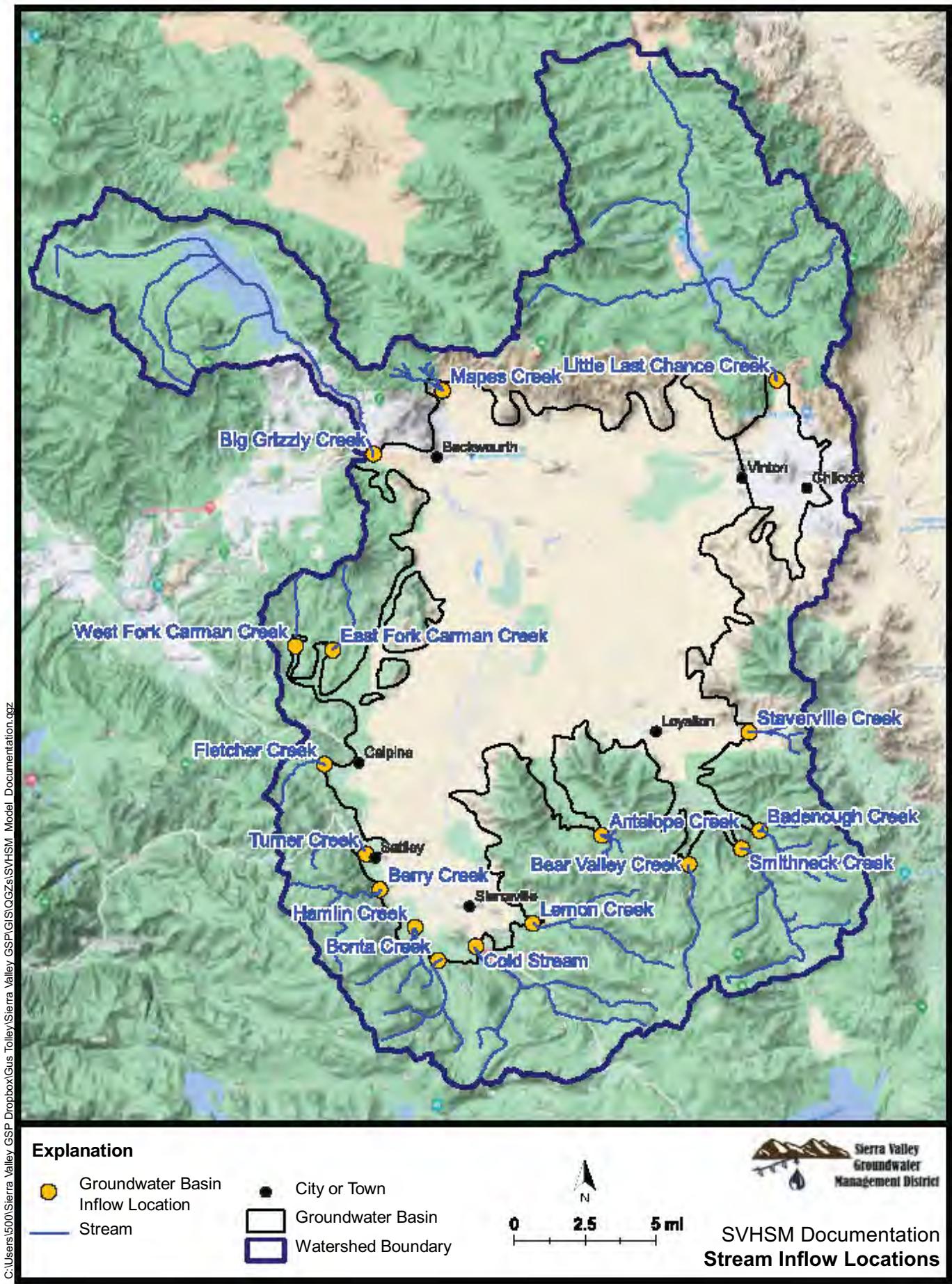
4.2.1 Streamflow

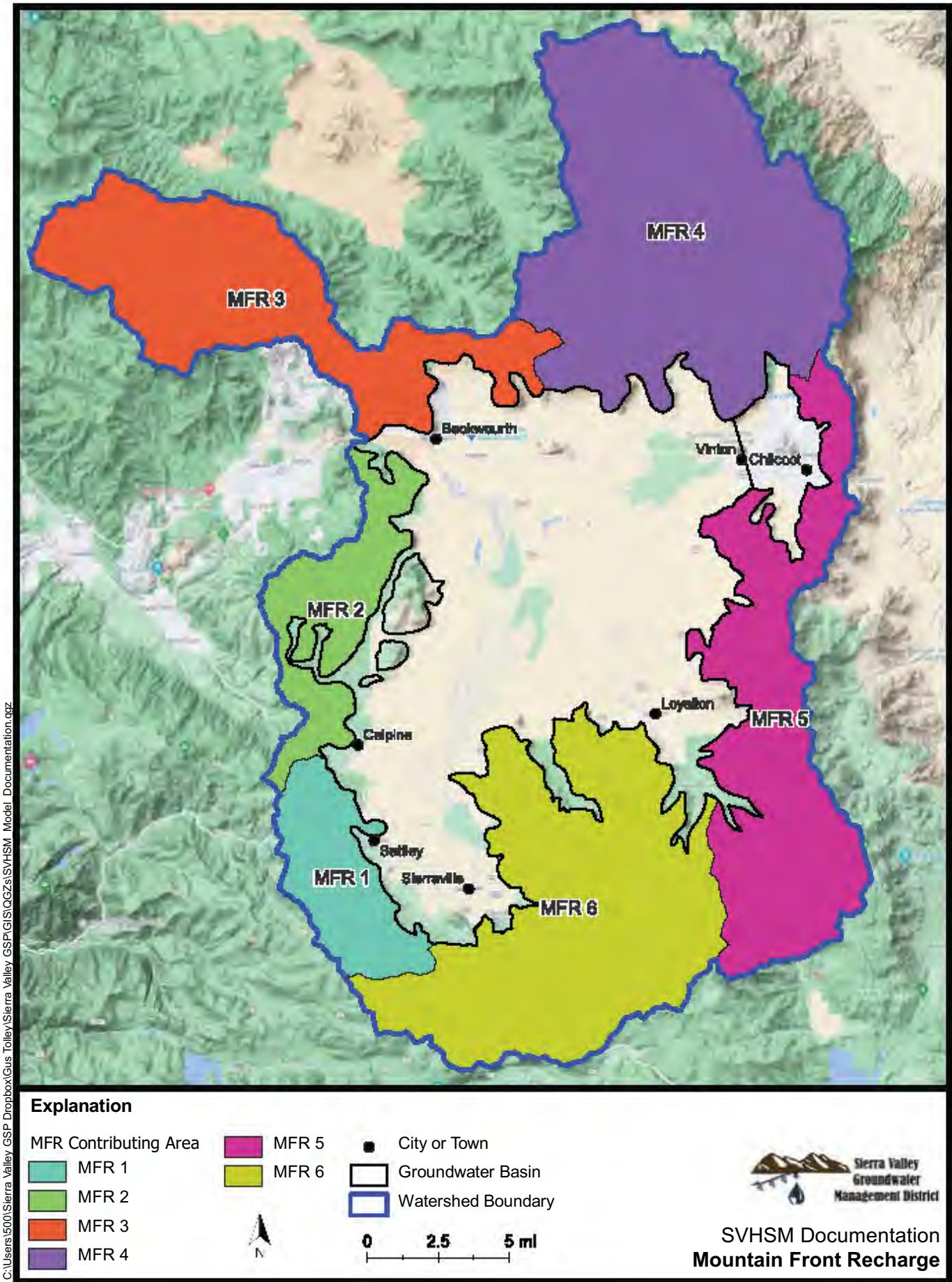
Surface water flow entering the groundwater basin from the upper portion of the watershed was simulated at 17 locations that represent the major streams in the basin (Figure 4-9). PRMS produces daily flow rates for the entire simulation period (WY 2000-2020) at each of these locations. Selected hydrographs are presented in Section 8.

4.2.2 Mountain Front Recharge (MFR)

MFR is the diffuse portion of recharge to a groundwater basin sourced from flow within adjacent mountain blocks with fractured bedrock (Wilson and Guan, 2004). Quantifying MFR is extremely difficult, as no current method for direct observation exists. Therefore, estimation is largely based on closure of basin water budgets and/or groundwater model calibration.

Spatially distributed groundwater recharge output from PRMS for the upper portion of the watershed was used to provide an estimate of MFR that enters the Sierra Valley groundwater basin. The upper watershed was split into six zones based on hydrogeologic understanding of the area and HUC-12 watershed boundaries (Figure 4-10). Estimated groundwater recharge in these areas is distributed across the interface between the basin sediments and surrounding bedrock (see Section 7.1.4 for more details).







5.0 Soil-Water Budget Model (SWBM)

A land use/crop-soil water budget model (“soil water budget model” or SWBM) developed by researchers at UC Davis was used to simulate agricultural practices in the valley to estimate hydrologic fluxes at the field scale (Foglia and others, 2013a; Foglia and others, 2013b). The model uses the crop coefficient method (Allen and others, 1998) combined with a tipping bucket approach to estimate the water budget for the valley floor. The primary goal of the SWBM is to estimate spatially distributed groundwater pumping and recharge, which are the two most significantly altered water budget components in an agricultural groundwater basin.

The SWBM was chosen to represent land surface hydrologic processes within the Sierra Valley groundwater basin because (1) it has been successfully applied to the Scott Valley (Tolley and others, 2019), which has a similar climate and crop distribution and (2) the project team was familiar with the source code and could provide customized features if needed. The SWBM is available at <https://github.com/gustolley/SWBM>.

5.1 SWBM Inputs

Inputs to the SWBM submodel include climate data (precipitation and reference ET), spatial data (physical properties for each field and landuse type), hydrologic data (surface water inflows to the groundwater basin), and operational data such as irrigation season dates and groundwater pumping volumes (when available). Specific types of spatial data, such as landuse and irrigation type, can change during the simulation to reflect crop rotations and changes in irrigation type.

Formatted input files for the SWBM were generated using a pre-processing script developed in R. This documents a large portion of the workflow for converting the conceptual model of the land surface system into a numerical simulation, and decreases the time required to update the model in the future.

5.1.1 Precipitation

Precipitation in the SWBM submodel of SVHSM is specified on a daily basis using the same dataset as the PRMS submodel and distributed across the valley using the PRISM 30-year normals (Figure 4-1). For days when precipitation was less than 20% of the reference ET (ET_0), precipitation was set to zero. This was done to exclude small, low intensity precipitation events that do not significantly contribute to the land surface water budget.

5.1.2 Reference ET (ET_0)

ET_0 data were sourced from the Buntingville (#57), Macdoel II (#236), and Sierra Valley Center (#264) stations of the California Irrigation Management Irrigation System (CIMIS) network (<https://cimis.water.ca.gov>). Data from the Sierra Valley Center station could not be used directly as it did not come online until late October 2020, but the approximately six months of data available during SVHSM development was used to evaluate the representativeness of the other two stations.

Comparison of available data for overlapping time periods at each station revealed that the Buntingville station generally overestimated ET_0 in Sierra Valley, and that the Macdoel II station data were generally more representative. Unfortunately, the Macdoel II station data are only available from April 2015 forward, while Buntingville station data are available for the entire model simulation period. Data from both stations were used to create an ET_0 dataset that spanned the entire model simulation period. Buntingville station data were used from October 1, 1999 through March 31, 2015, and Macdoel II station data were used from April 1, 2015 through September 30, 2015. Correction factors were developed for each calendar month using the ratio of the average ET_0 at the Macdoel II station to the ratio of the average ET_0 at the Buntingville station. These correction factors were applied to the Buntingville station data for each respective month to prevent overestimation of ET_0 used in the model. Daily values of reference ET are contained within the **ref_et.txt** input file

Annual reference ET for the simulation period ranged from 41.2 to 49.39 in/yr (104.7 to 125.4 mm/yr) with an average rate of 45.74 in/yr (116.2 mm/yr). December and July had the lowest and highest ET_0 rates on average, respectively (Figure 5-1).

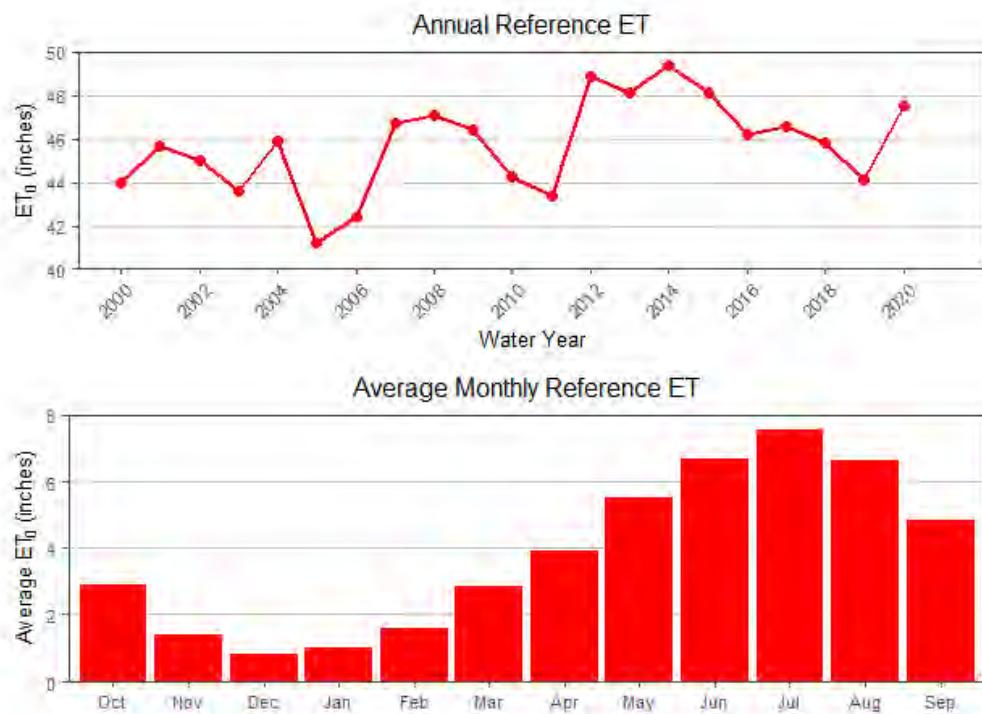


Figure 5-1. Annual total (top) and monthly average (bottom) reference ET rates used in SVHSM.

5.1.3 Field Properties

Fields are the fundamental spatial accounting unit in the SWBM, and are generally delineated using a combination of landuse surveys conducted by DWR and soil maps. The 2013 DWR landuse survey for Plumas and Sierra Counties was used as a base dataset for defining fields,

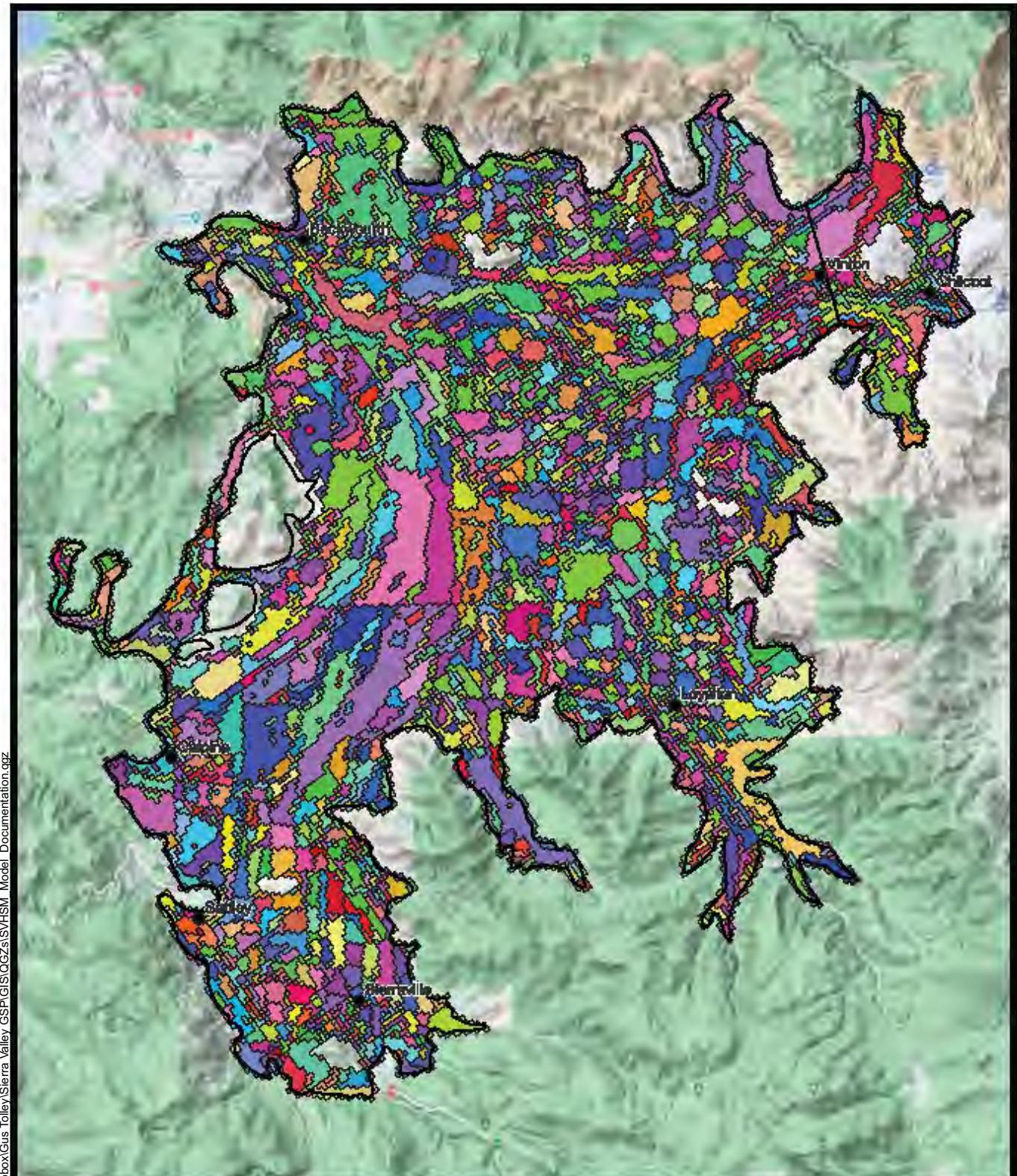


and was supplemented with additional crop mapping efforts and local knowledge provided by growers and residents. This effort resulted in a total of 2953 fields being defined in SVHSM (Figure 5-2). Landuse is assigned to each field on a monthly basis and controls if, when, and how much irrigation water is applied. Nine landcover types are simulated in SVHSM (Table 5-1), and are specified on a monthly basis to account for agricultural management practices such as crop rotation and fallowing. The landcover types were chosen based on the DWR land use datasets and input from local growers and stakeholders. Landcover distribution at the beginning of the model simulation is shown in Figure 5-3 and summarized in Table 5-2. Alfalfa is assumed to rotate with grain on an eight year cycle (seven years of alfalfa, one year of grain).

Irrigation methods used in the valley include flood, wheel line sprinklers, and center pivot sprinklers (Figure 5-4). Irrigation efficiency, also known as the water application efficiency, is the ratio of the water used by a crop to the water applied. Irrigation efficiency values less than one indicate that more water is applied than is utilized by the crop. This may occur for a variety of reasons including (but not limited to) non-uniform water application, minor topographical variations across a field, and heterogeneous soils. Effective irrigation efficiency values greater than one indicate some portion of water demand is being met by depletion of soil moisture storage over the growing season. Effective irrigation efficiency values greater than 1 have been observed in the Scott Valley (Tolley and others, 2019) which has a similar crop types and management as the Sierra Valley. The combination of high water demand crops (i.e., alfalfa and pasture) and management practices that limit when water can be applied (i.e., surface-water availability, irrigation type, and cutting schedules) create conditions where crop water demand is greater than applied water deficit irrigation). Effective irrigation efficiencies in SVHSM were applied to fields according to irrigation type (Table 5-1).

Applied irrigation water in Sierra Valley can be sourced from surface water, groundwater, or a combination of the two (Figure 5-5). Fields are assigned to a surface water accounting unit based on geographic location (Figure 5-6). Surface water inflows to the groundwater basin are assigned to one of these accounting units, which determines surface-water availability for a field. Irrigation with surface water only occurs during the specified irrigation season (Table 5-1) when maximum allowable depletion has been exceeded and surface water is available. If no surface water is available then the only source of water is that remaining in the soil profile. Fields with a mixed water source preferentially use surface water when it is available, otherwise irrigation water is sourced from groundwater.

Groundwater pumping occurs on irrigated fields with a mixed or groundwater source. Figure 5-7 shows the location of fields where groundwater irrigation is applied along with the location of irrigation wells used in the model. Applied groundwater irrigation for each field is assigned to a well. No publicly available dataset exists that identifies which fields are irrigated with known wells, so wells were initially assigned to fields based on proximity, and then refined with the help of growers. Groundwater pumping occurs when maximum allowable depletion for a field is exceeded during the specified irrigation season.



Explanation

- SWBM Field
- Groundwater Basin
- City or Town

Notes:

1. SWBM fields shown are mapped to MODFLOW grid.

Source: modified from 2013 DWR land use survey

0 2 4 mi



SVHSM Documentation
SWBM Fields

Table 5-3. Landcover categories and associated properties.

Landcover	Maximum Allowable Depletion ¹	Irrigation Season Dates	Effective Root Depth (ft) ²	Effective Irrigation Efficiency ³			Kc Factor
				Flood	Wheel Line	Center Pivot	
Alfalfa (Irrigated)	45%	3/25 - 9/31	19.68	0.7	1.25	1.35	0.96
Grain (Irrigated)	45%	3/16 - 7/10	6.56	0.7	1.25	1.35	0.96
Pasture (Irrigated)	55%	4/15 - 10/15	6.56	0.7	1	1.15	0.96
Native Vegetation	-	-	9.84	-	-	-	-
Urban/Barren	-	-	0	-	-	-	-
Water/Ponds	-	-	6.56	-	-	-	-
Alfalfa (Non-Irrigated)	-	-	19.68	-	-	-	-
Grain (Non-Irrigated)	-	-	6.56	-	-	-	-
Pasture (Non-Irrigated)	-	-	6.56	-	-	-	-

1. Maximum percentage of soil moisture depletion before irrigation is triggered.

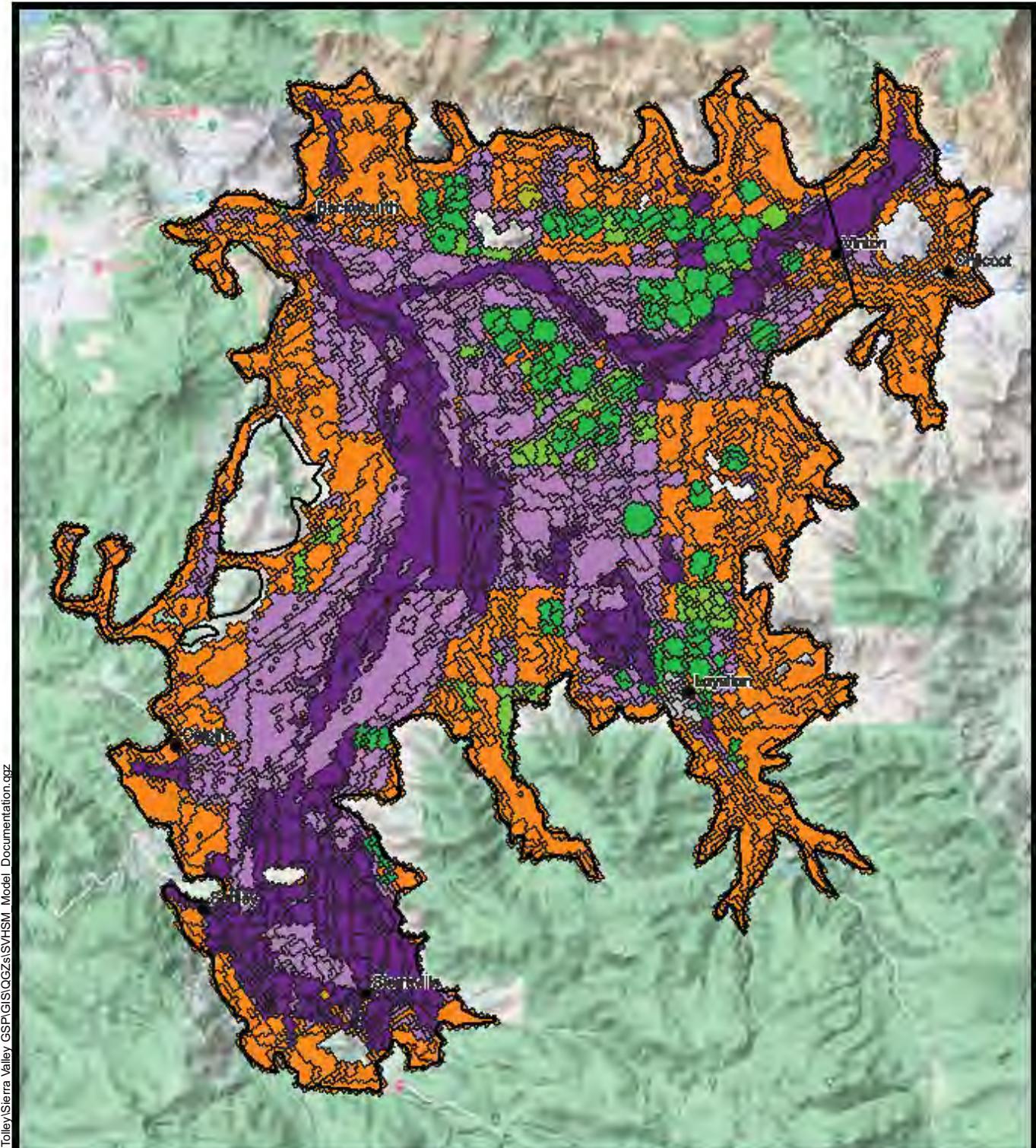
2. Total depth that plants are able to source water from. Can be greater than plant rooting depth due to capillary wicking.

3. Values greater than 1 indicate deficit irrigation with crop water demand satisfied in part by gradual soil moisture depletion over the growing season.

4. Scaling factor for crop coefficient. Allows for uniform adjustment Kc timeseries.

Table 5-4. Landcover summary.

Landcover	Irrigation Type	Area (acres)	Area (%)
Native Vegetation	Non-Irrigated	49,826	41.6%
Pasture	Non-Irrigated	33,464	27.9%
Pasture	Flood	24,550	20.5%
Alfalfa/Grain	Center Pivot	6,122	5.1%
Alfalfa/Grain	Non-Irrigated	3,818	3.2%
Alfalfa/Grain	Wheel Line	1,123	0.9%
Barren	Non-Irrigated	685	0.6%
Pasture	Center Pivot	124	0.1%
Water	Non-Irrigated	79	0.1%
Pasture	Wheel Line	64	0.1%
Alfalfa/Grain	Flood	39	0.0%
Native Vegetation	Wheel Line	8	0.0%
TOTAL		119,902	100.0%



Explanation

SWBM Landcover

- Water/Ponds
- Alfalfa (Irrigated)
- Alfalfa (Non-Irrigated)
- Grain (Irrigated)
- Grain (Non-Irrigated)
- Pasture (Irrigated)
- Pasture (Non-Irrigated)
- Native Vegetation
- Urban/Barren

- Water/Ponds
- Alfalfa (Irrigated)
- Alfalfa (Non-Irrigated)
- Grain (Irrigated)
- Grain (Non-Irrigated)
- Pasture (Irrigated)
- Pasture (Non-Irrigated)
- Native Vegetation
- Urban/Barren

- Groundwater Basin
- City or Town

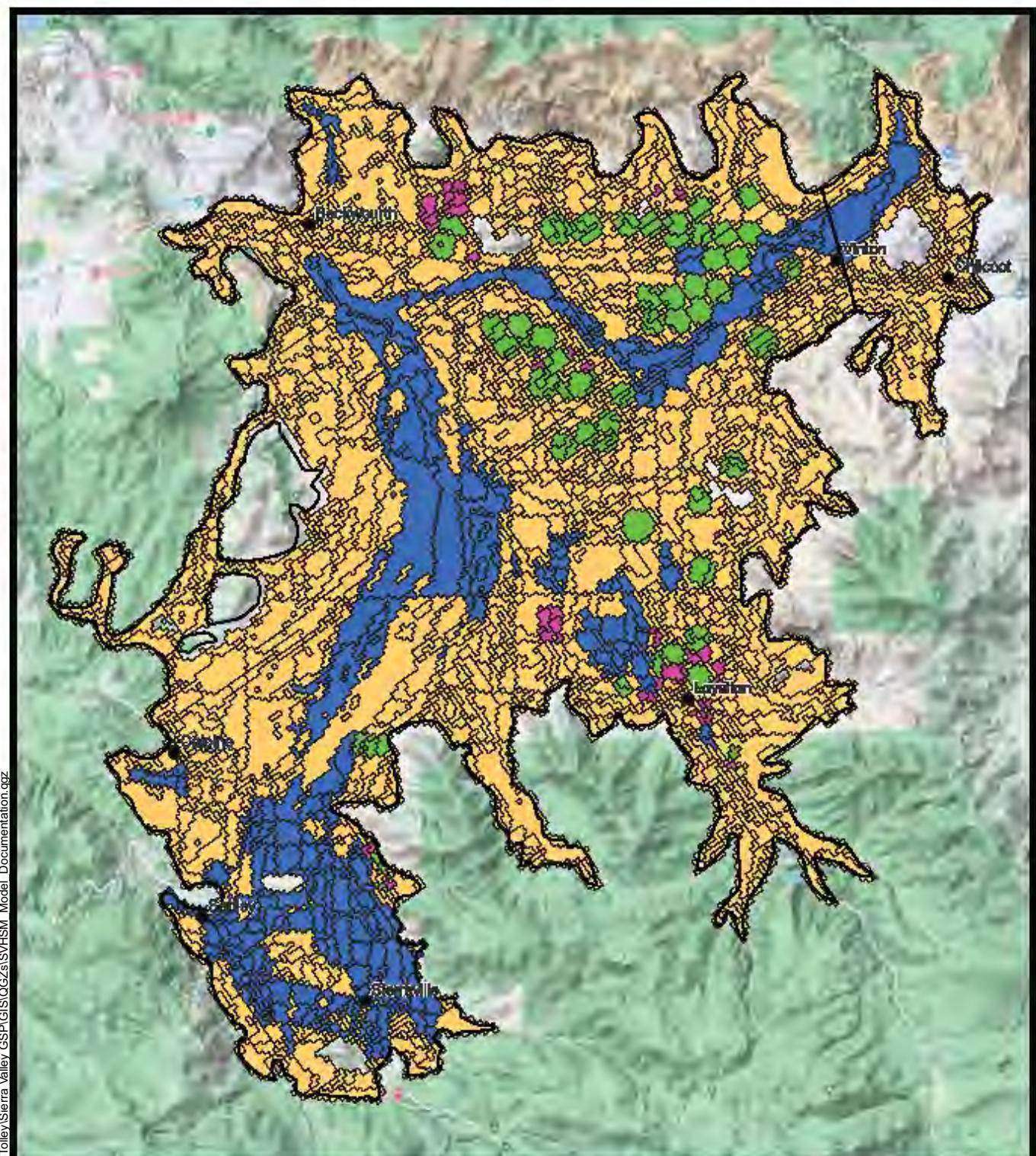
0 2 4 mi



Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. Landuse changes slightly during simulation

SVHSM Documentation
SWBM Landcover



Explanation

SWBM Irrigation Type

- Flood
- Wheel Line
- Center Pivot
- Non-Irrigated

- Groundwater Basin
- City or Town

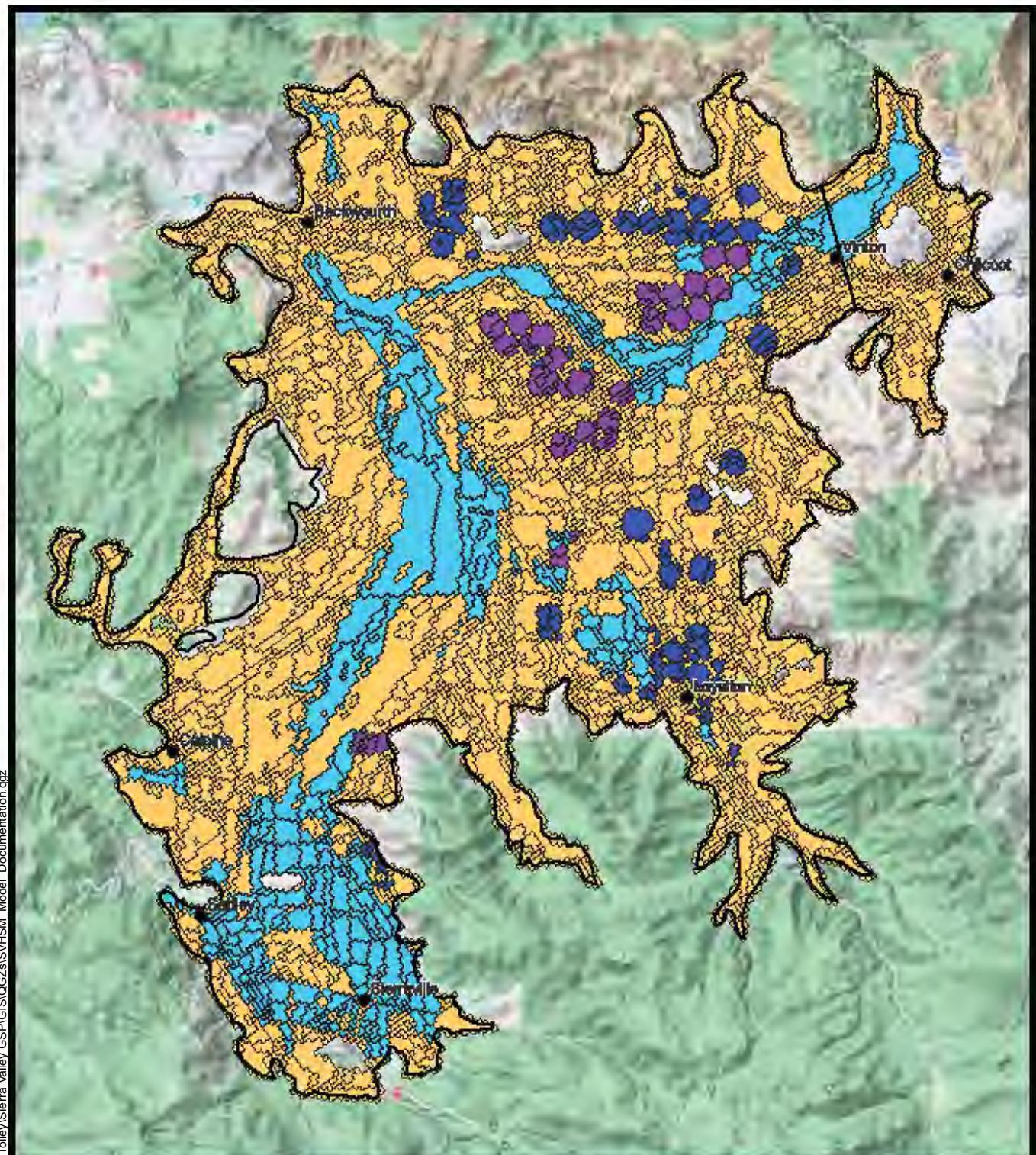
0 2 4 mi



Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. Some fields converted from wheel line to center pivot during simulation

SVHSM Documentation
SWBM Irrigation Type



Explanation

SWBM Irrigation Water Source

- Surface-Water
- Groundwater
- Mixed
- 'Non-Irrigated'

Groundwater Basin

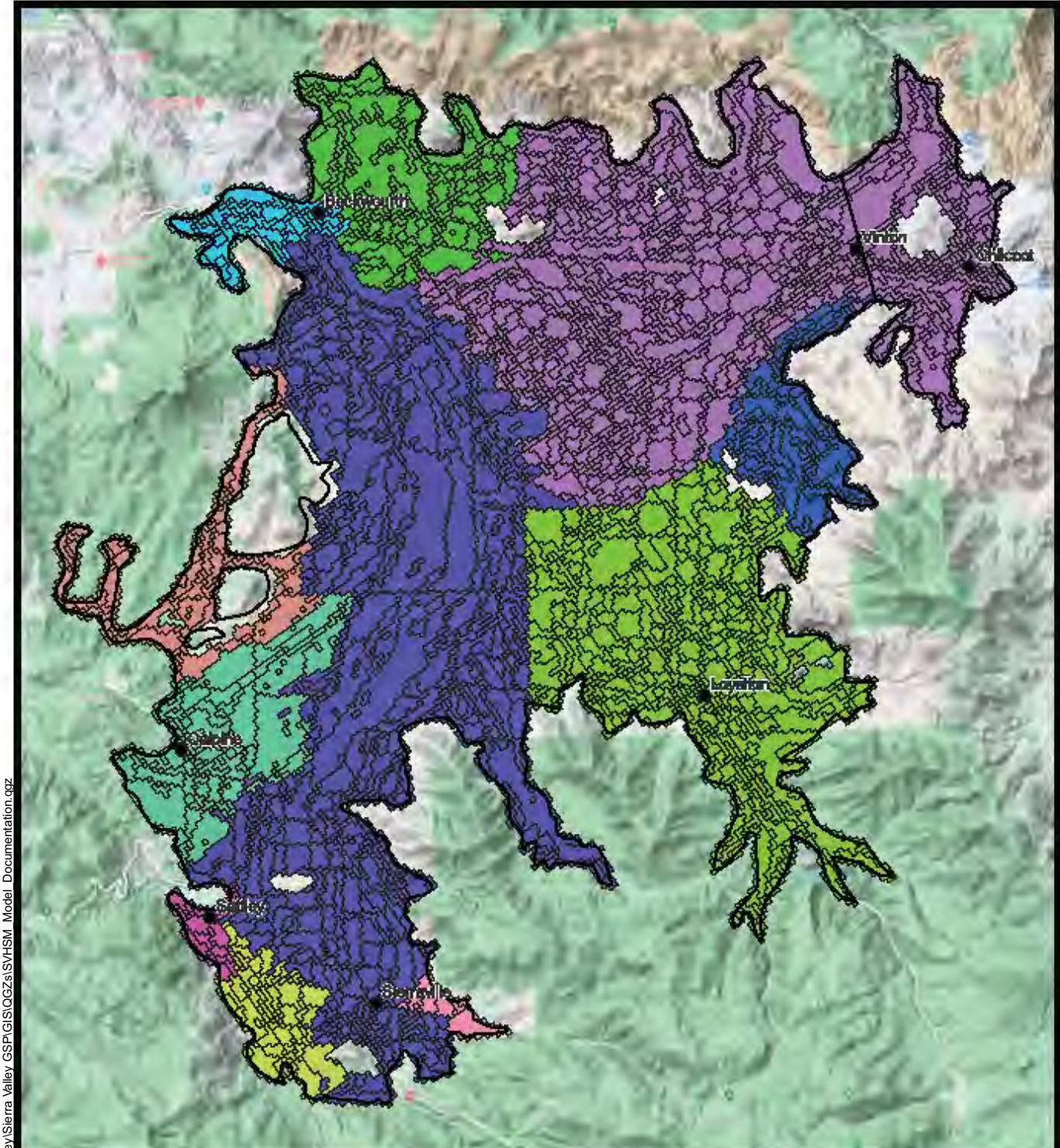
- City or Town

0 2 4 ml



Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. Mixed fields use surface water when available, then switch to groundwater



Explanation

SWBM Surface Water Accounting Units
Cold Stream
Hamlin Creek
Turner Creek
Fletcher Creek
Carman Creek
Big Grizzly Creek

Mapes Creek
Little Last Chance Creek
Chance Creek
Correco Canyon
Bear Valley-Smithneck Creek
Lemon Creek

Groundwater Basin
 City or Town

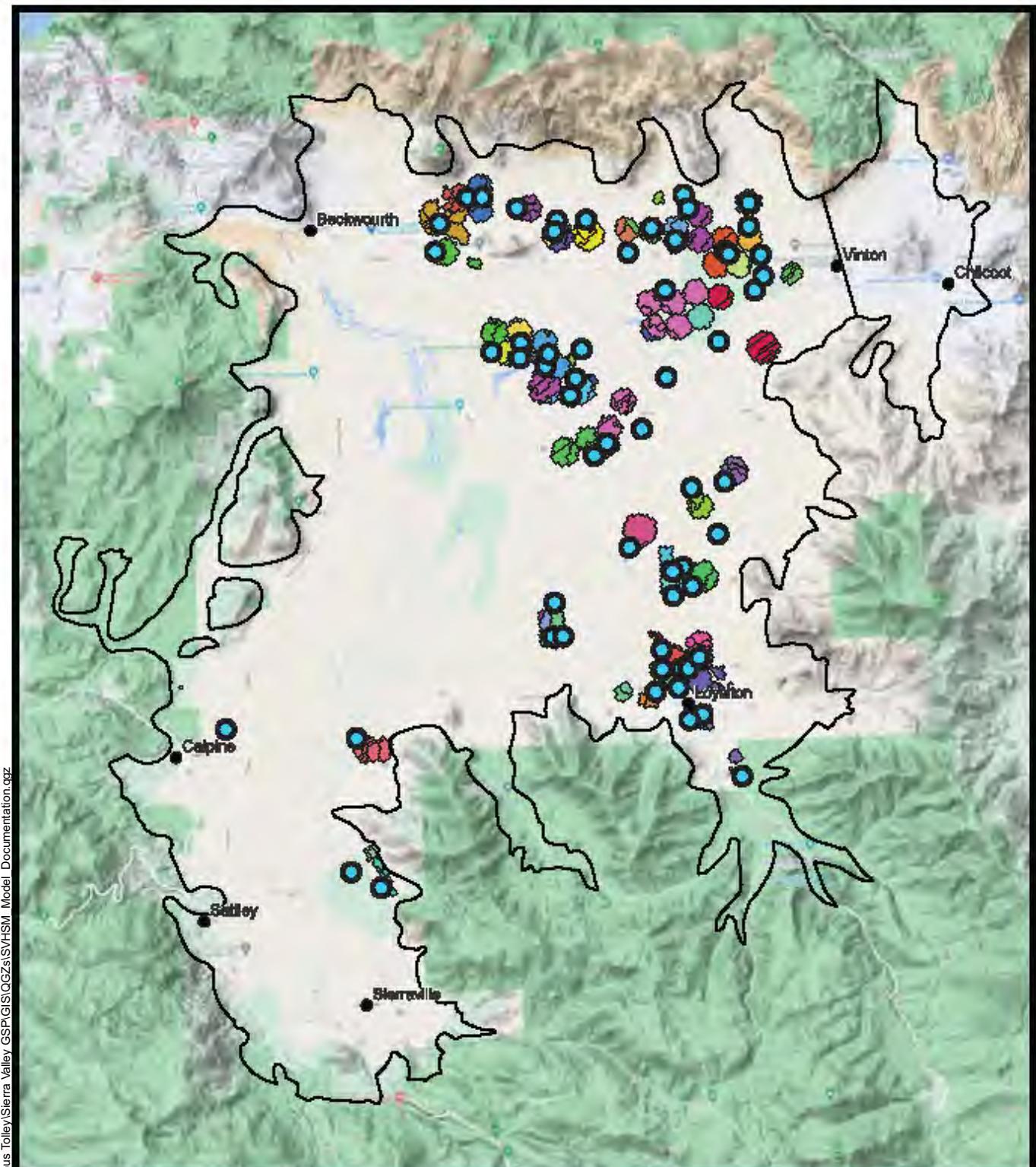
0 1 2 mi



Notes:
 1. SWBM fields shown are mapped to MODFLOW grid.



SVHSM Documentation
SWBM Surface Water Accounting Units



Explanation

- Groundwater Irrigated Field
- Groundwater Basin
- Agricultural Irrigation Well
- City or Town

Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. Fields colored according to assigned well.

0 1 2 mi



SVHSM Documentation
SWBM Groundwater Irrigation Wells and Fields



The current version of the SWBM assumes that a field is irrigated with a single well, which, based on conversations with growers, is not always accurate. However, this would primarily affect the distribution of pumping, and not the total volumes simulated by the SWBM. This effect is small, as pumping volumes for wells are known and therefore specified for the majority of the simulation period (see Section XX - MODFLOW GW PUMPING).

The water holding capacity for each field was determined using the weighted average value found in the SSURGO database (Figure 5-8) multiplied by the rooting depth of the landcover (Table 5-1) and area of the field. Recharge only occurs when the moisture content of a field exceeds its holding capacity. Therefore, fields with greater water holding capacity can contribute more water to vegetation demands in the absence of irrigation, but also require storms of greater precipitation magnitude or intensity to generate groundwater recharge.

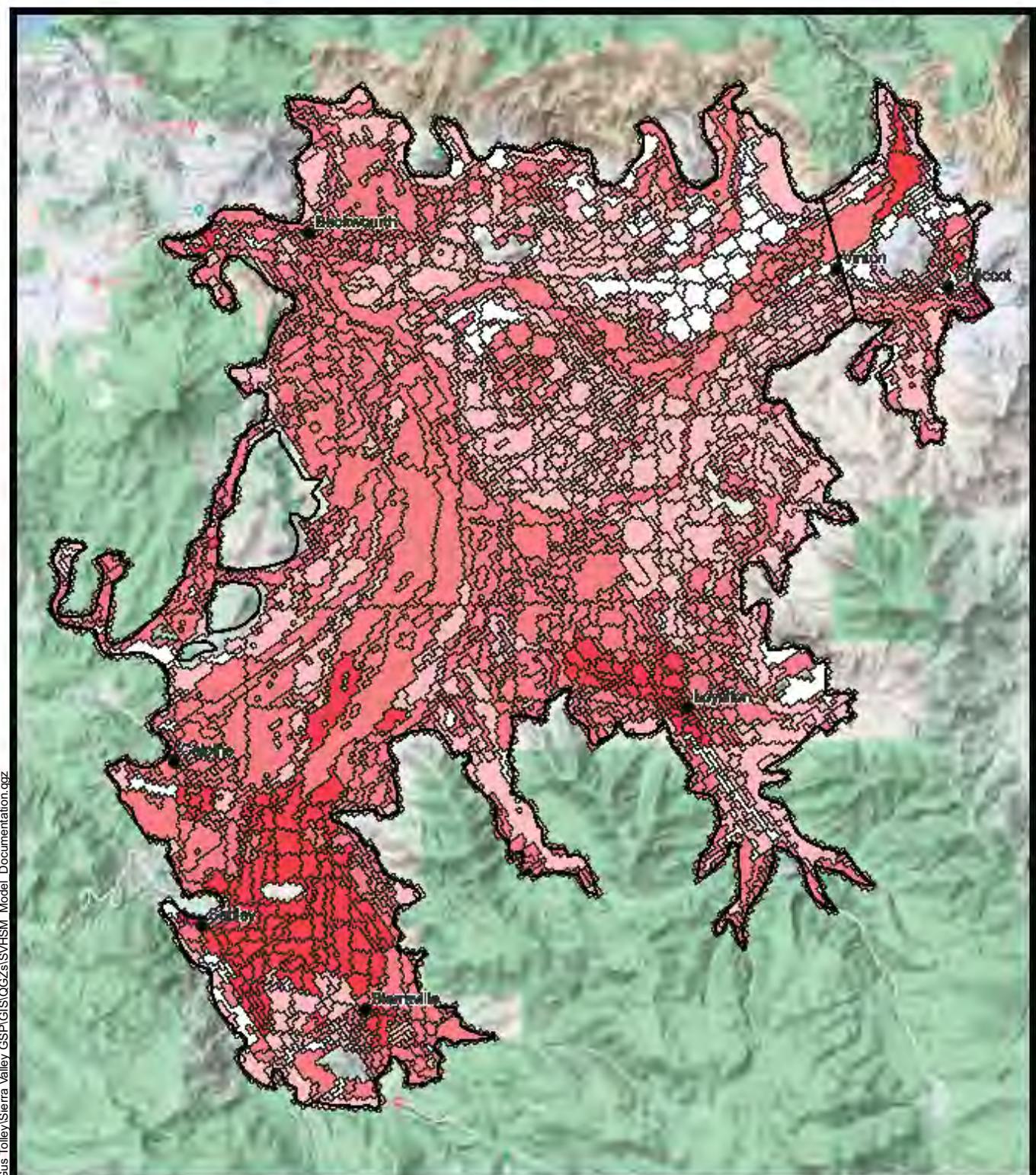
Infiltration excess (Hortonian) runoff that occurs during intense precipitation events can be estimated in the SWBM. This prevents overestimation of recharge in the model and improves surface-water representation. The maximum infiltration rate can be specified for each field using the parameter *max_infil_rate* in the **polygons_table.txt** input file. This runoff can be routed to a specific SFR segment in MODFLOW by specifying the segment number for the *runoff_ISEG* parameter in the same file. As this feature was added relatively late during model development, a constant value of 0.157 inches per day (in/d) (0.004 meters per day [m/d]) was used for all fields.

5.1.4 Crop Coefficients

The SWBM uses the crop coefficient (K_c) method to estimate water demand of crops and vegetation. The crop coefficient is a scaling factor applied to the ET_0 . Values were chosen based on published literature or from previous experience gained in the Scott Valley, which has similar crop types and management practices as the Sierra Valley. The variable *kc_mult* is available in the SWBM for uniformly scaling variable K_c values.

A seasonal average K_c value of 0.9 was used for alfalfa and pasture, as opposed to a variable K_c that reflects different ET rates depending on the crop development stage. This was done because K_c values for pasture do not vary much over the growing season, and detailed information about management practices that affect alfalfa K_c values (e.g., cutting schedules) vary significantly depending on the year and grower. The growing season for alfalfa occurred from April 1 through October 15 each year, and from March 15 through October 31 for pasture. A constant K_c value of 1.2 was used for the water landcover type.

Variable K_c values were used for the grain and native vegetation landcover types. This was done instead of using seasonal average crop coefficients because the K_c values are much less dependent on grower-specific management practices. Grain K_c values range from 0 to 1.15 during April 1 through July 20, and native vegetation values range from 0 to 0.8 during March 1 through December 31 (Figure 5-9).



C:\Users\500\Sierra Valley GSP Dropbox\Gus Tolley\Sierra Valley GSP\GIS\GZs\SVHSM Model Documentation.giz

Explanation

SWBM Water Holding Capacity (%)

0 - 5
5 - 10
10 - 15
15 - 20

Groundwater Basin

City or Town

0 1 2 mi



Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. Volumetric capacity defined by multiplying water holding capacity by effective root depth and field area.

SVHSM Documentation
SWBM Soil Water Holding Capacity

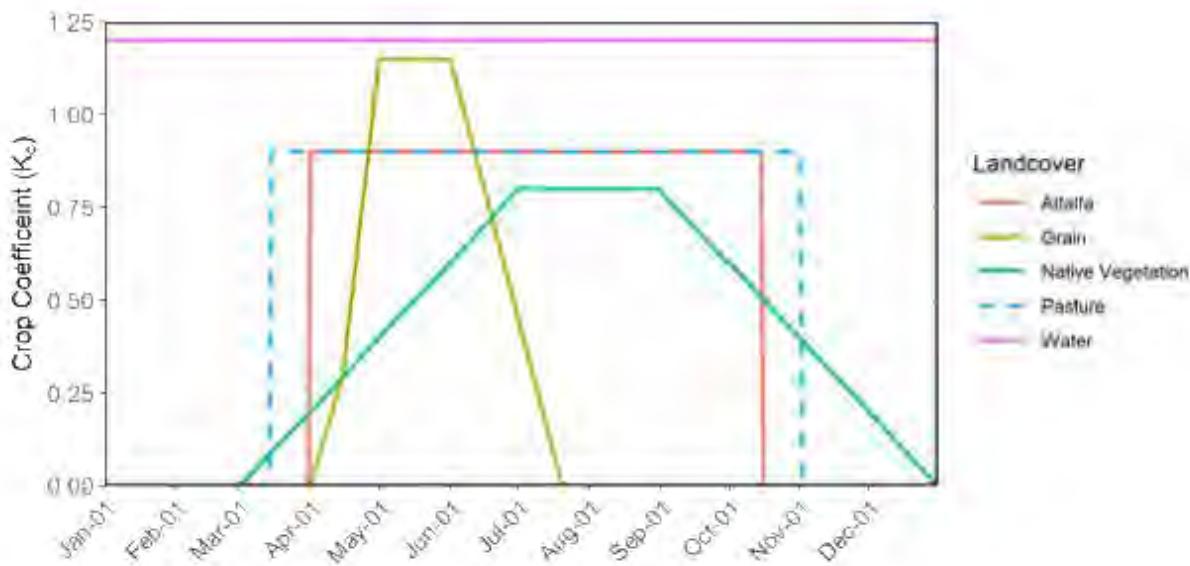


Figure 5-9. Crop coefficient (K_c) values by landcover type.

5.1.5 Surface Water Inflows

Surface water inflows entering the groundwater basin were estimated using the PRMS submodel (see Section 4.2.1) with the exception of Cold Stream, Big Grizzly Creek, and Little Last Chance Creek. Cold Stream flows are augmented by imported water from the Little Truckee River. These imports are measured by the Watermaster on a daily basis and were added to the natural inflows estimated by PRMS. Flows in Big Grizzly Creek and Little Last Chance Creek are regulated by reservoir releases operated by DWR. Flow data for these two streams were provided on a daily or monthly basis by the Watermaster, with releases subdivided into various categories (e.g., streamflow maintenance, water supply contract, and spill). These were converted into an “irrigation inflow” and “non-irrigation inflow” categorization. Only water categorized as “irrigation inflow” can be used for surface water irrigation. Applied surface water irrigation is removed from the boundary inflows, with remaining flows passed on to the streamflow routing (SFR2) package in MODFLOW. All surface water diversions are assumed to take place at the margins of the groundwater basin where inflows are specified due to lack of detailed streamflow diversion data within the groundwater basin.

Annual streamflow is highly variable, ranging from about 35 to 360 thousand acre-feet per year (TAF/yr) (Figure 5-10). Surface water available for irrigation made up about 69 to 91% of total inflows, and averaged about 82% of total inflows over the 21-year simulation period. These streamflow estimates may change in the future if further calibration is performed on the PRMS model.

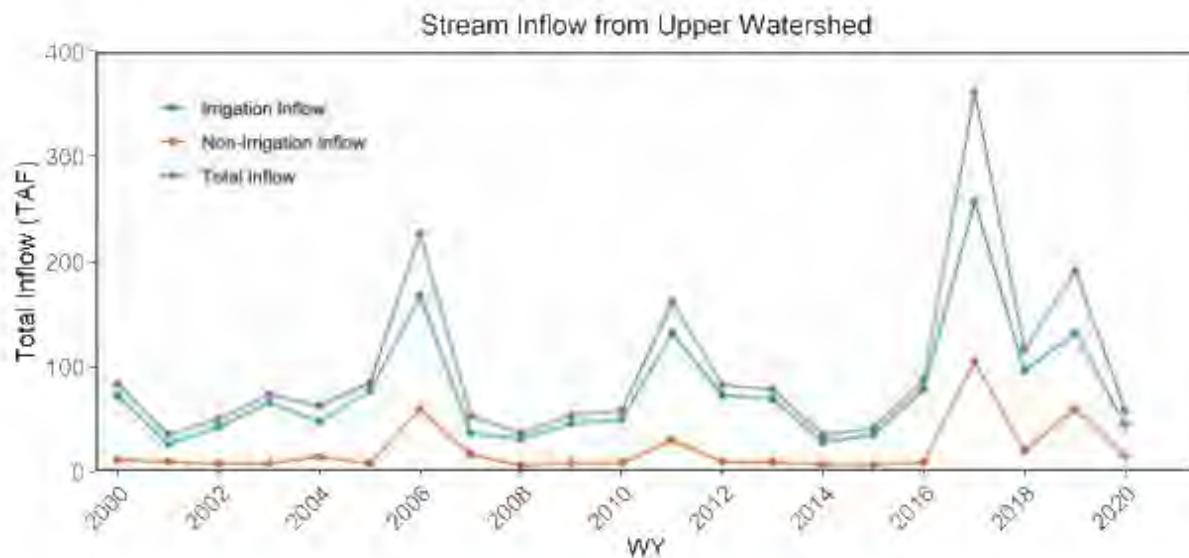


Figure 5-10. Annual surface water inflows input to the SWBM.

5.1.6 Specified Groundwater Pumping

The Sierra Valley is one of the few basins in California where agricultural groundwater pumping is metered. Because groundwater pumping is commonly one of the largest fluxes within an agricultural groundwater basin, this provides an additional dataset with which to calibrate SVHSM, as well as significantly reduces uncertainty of model results for the historical simulation period (WY 2000-2020). Agricultural and municipal pumping volumes in the SWBM can be specified for any well on a monthly basis in **ag_well_specified_volume.txt** and **muni_well_specified_volume.txt**, respectively. Specified pumping volumes define irrigation application rates for fields associated with a well.

Annual groundwater pumping volumes were provided by the District for agricultural production wells from 2003 to 2020 (Table 5-3). Municipal water suppliers in the valley provided monthly extraction data from 2005 to 2020. Annual agricultural pumping volumes fluctuate significantly depending on the water year type and management factors (e.g., well maintenance). Reported agricultural groundwater pumping volumes during the simulation period range from about 4,700 to 13,600 acre-feet per year (AFY). Municipal groundwater extractions show a much smaller proportion of total groundwater pumped and much less interannual variation, with reported values ranging from 195 to 652 AFY. The reported value of 195 AFY in 2005 appears to be missing extraction data from one or more wells based on data from other years. Municipal pumping data from the Sierra County Water Works District #1 (Calpine) was provided from 2009 to 2017, but not included in SVHSM because the wells are located outside of the groundwater basin boundary and screened exclusively in bedrock. Annual production volumes for these wells are less than 60 AFY, so their omission is not expected to be significant.

Table 5-3. Specified pumping volumes.

Year	Agricultural Pumping Volume (AF)	Municipal Groundwater Pumping Volume ¹ (AF)	Total Groundwater Pumping Volume (AF)
2003	6,956	650 ^a	7,606
2004	9,023	613 ^a	9,636
2005	6,406	195	6,601
2006	6,276	328	6,604
2007	8,198	409	8,607
2008	7,690	652	8,342
2009	4,748	650	5,398
2010	9,827	613	10,440
2011	5,049	544	5,592
2012	9,173	605	9,778
2013	12,121	642	12,763
2014	12,075	589	12,663
2015	13,609	492	14,101
2016	10,515	575	11,090
2017	6,973	374	7,347
2018	7,934	362	8,296
2019	7,474	406	7,879
2020	8,217	453	8,670

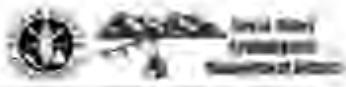
1. Excludes Calpine municipal groundwater pumping.

a. Records not available; estimated volume.

Annual total volume for each irrigation well was distributed throughout the growing season according to the proportion of growing season ET_0 that occurred during the month. For example, if 16% of total growing season ET_0 in 2004 occurred during the month of June, then 16% of the 2004 measured pumping volume was assumed to occur during that month.

5.2 SWBM Outputs

The daily water budgets estimated by the SWBM are upscaled to monthly periods for output to smooth out timing discrepancies between the model and real-world conditions caused by lack of detailed management information (e.g., knowledge of specific irrigation timing for a given field).



These are available for each field in linear and volumetric units. Some formatted input files (e.g., groundwater pumping, recharge, streamflow) to the groundwater-surface-water model (Section 7) are written directly by the SWBM. This allows for the SWBM and groundwater-surface water model to be calibrated as a single model. Tabulated water budgets from the SWBM submodel of SVHSM can be found in Appendix B.

5.2.1 Evapotranspiration (ET)

ET calculated by the SWBM is the product of the ET_0 , the K_c , and the SWBM scaling factor (kc_mult). This processes is water limited, meaning that it only occurs when water is available for a given field. Figure 5-11 shows the spatially distributed annual average ET over the 21 year simulation period. Annual average ET within the groundwater basin boundary ranged from 0 to 34.5 in/yr (0 to 875 mm/yr) depending on landcover and if the field was irrigated or not. These rates are consistent with previously published values for the region (Hanson and others, 2010; Tolley and others, 2019).

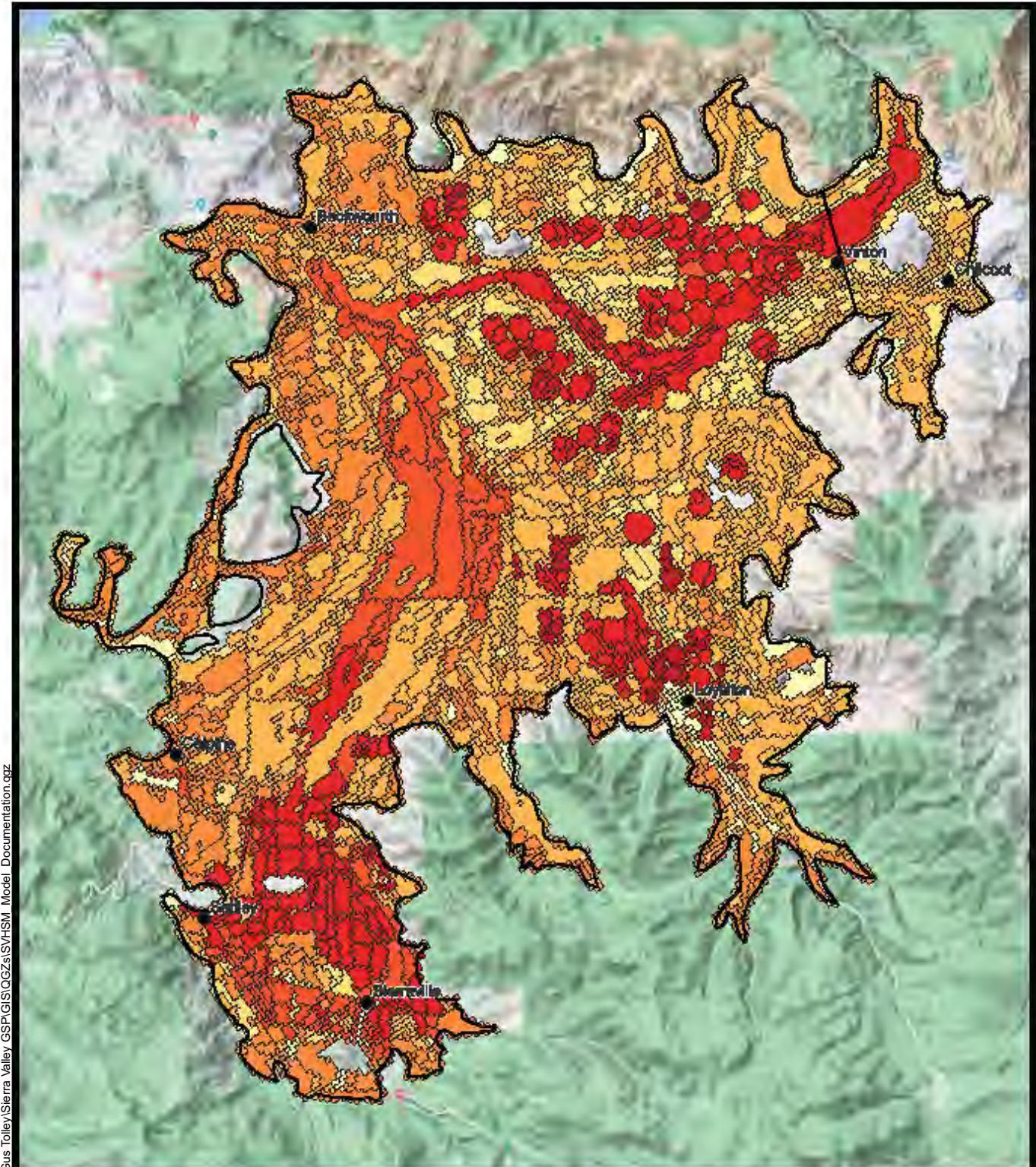
5.2.2 Irrigation

The SWBM tracks surface water and groundwater irrigation applied to each field. Average annual surface water irrigation rates ranged from 0 to 17.3 in/yr (0 to 439 mm) over the 21-year simulation period (Figure 5-12). The highest surface water application rates estimated by the model are located in the eastern portion of the basin, where soils are generally sandier and have lower capillary storage compared to the more silt and clay rich soils on the western side of the valley. Surface water used for irrigation is subtracted from the stream inflows entering the groundwater basin to ensure that water is not double counted as remaining streamflows are passed on to the MODFLOW submodel of SVHSM.

Groundwater irrigation simulated by the SWBM occurs almost exclusively in the eastern portion of the valley (Figure 5-13). Annual average application rates of groundwater range from about 6 to 27 inches. The combination of high water demand for alfalfa and the inability to apply irrigation water around cutting times results in deficit irrigation (applying less water than crop demand) over the season. Some of this deficit is met by seasonal reduction of soil-moisture storage.

5.2.3 Groundwater Pumping

Groundwater pumping is the portion of applied irrigation that is not sourced from surface water and specified extractions from municipal wells. All fields simulated in the SWBM are assigned a well, with one well able to service multiple fields. Applied groundwater irrigation is aggregated on a monthly basis by well for input to the groundwater-surface water model. Specified municipal pumping is not used by the SWBM and is simply passed through the model and included in groundwater-surface water model input file generated.



Explanation

Average Annual ET
(in/yr)

0 - 5	20 - 25
5 - 10	25 - 30
10 - 15	30 - 34.5
15 - 20	

Groundwater Basin

City or Town

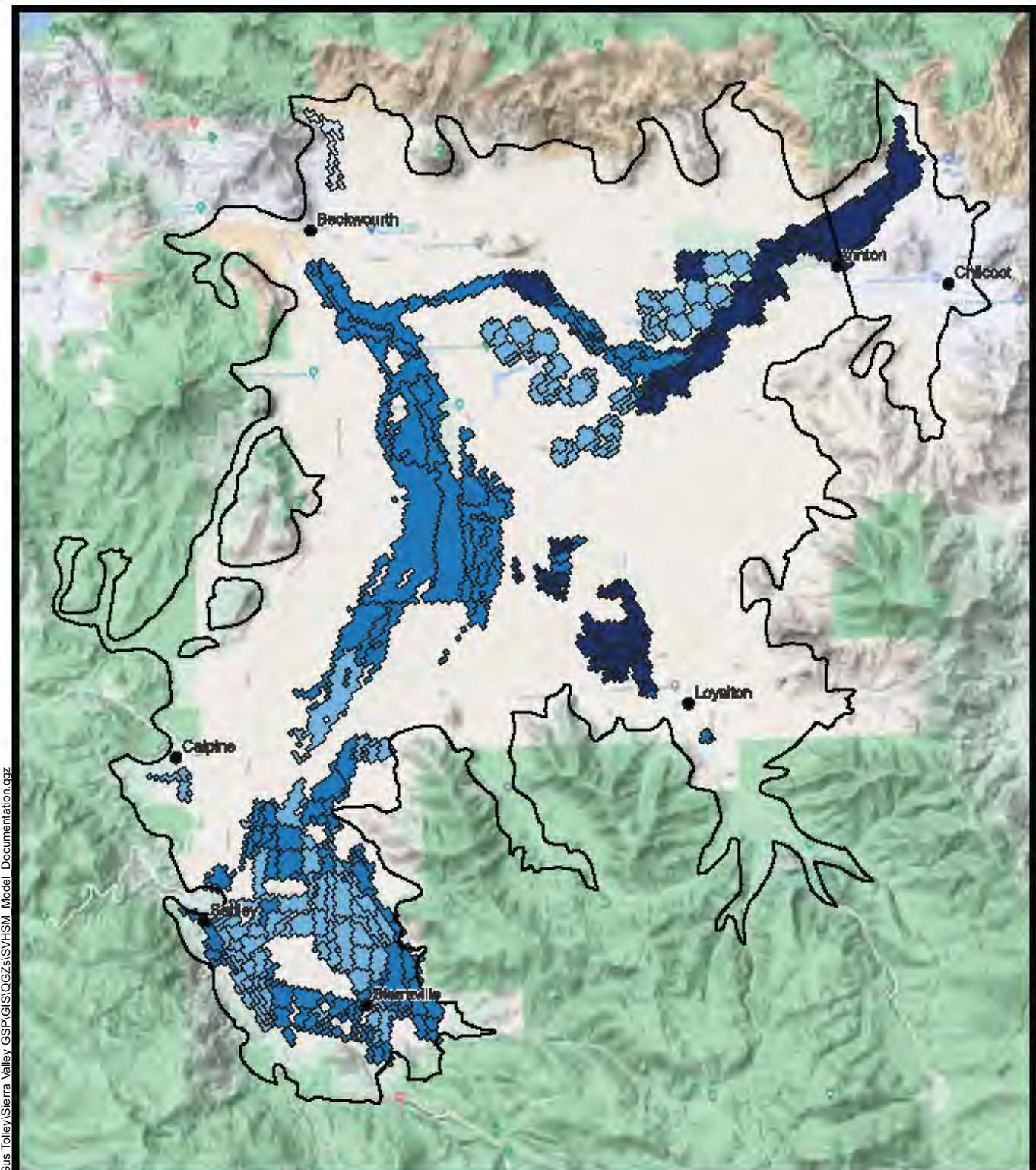
0 1 2 mi



Notes:

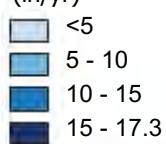
1. SWBM fields shown are mapped to MODFLOW grid.
2. 21 year average (WY2000-2020)

SVHSM Documentation
SWBM Average Annual ET



Explanation

Average Surface Water Irrigation
(in/yr)



□ Groundwater Basin
● City or Town

0 1 2 m N

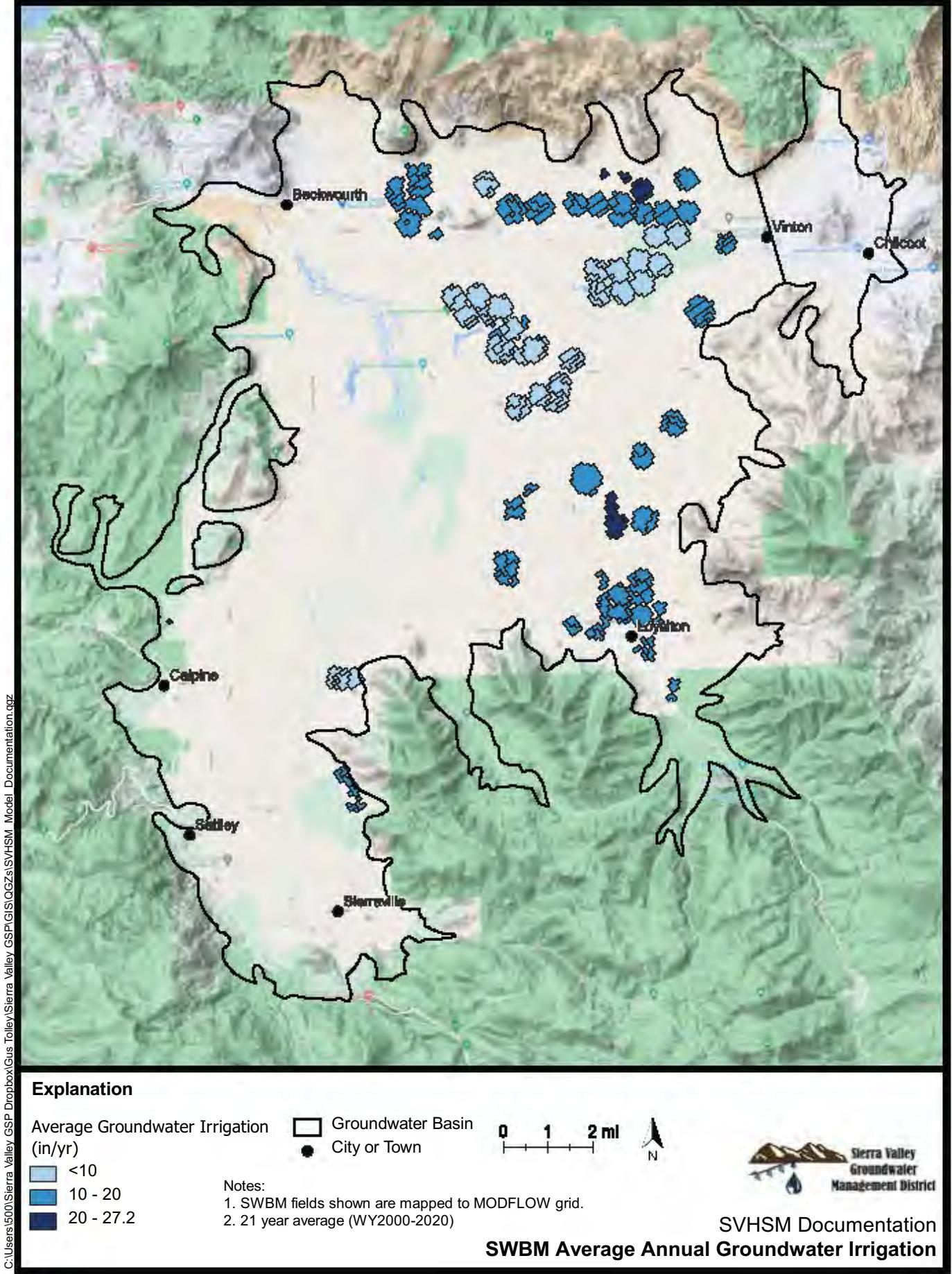
Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. 21 year average (WY2000-2020)



SVHSM Documentation

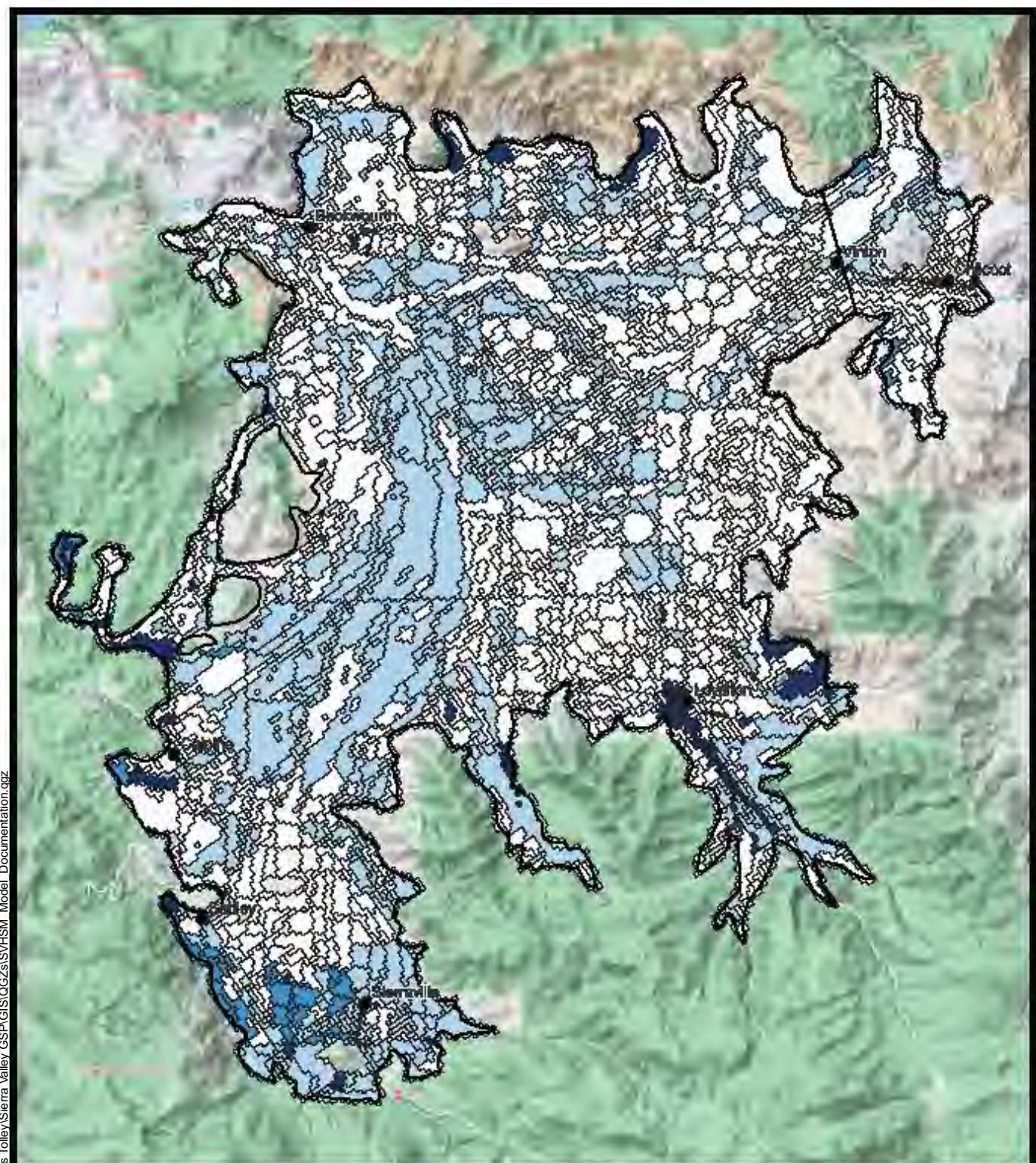
SWBM Average Annual Surface Water Irrigation





5.2.4 Recharge

Soil moisture that exceeds the field capacity (gravity drainage threshold) for a given field is assumed to recharge groundwater. Figure 5-14 shows the average annual recharge estimated by the SWBM over the 21-year simulation period. Values range from less than 0.1 inch to 8.5 in/yr (0 to 215 mm/yr). Fields with the highest recharge rates are typically those assigned the urban/barren landcover class, as ET is assumed to be negligible, or flood irrigated pasture. Alfalfa/grain fields irrigated with center pivots typically have the lowest average recharge rates.



Explanation

Average Groundwater Recharge
(in/yr)

□ Groundwater Basin
● City or Town

0 1 2 mi
N

0 - 2
2 - 4
4 - 6
6 - 8.5

Notes:

1. SWBM fields shown are mapped to MODFLOW grid.
2. 21 year average (WY2000-2020)



SVHSM Documentation
SWBM Average Annual Groundwater Recharge



6.0 3D Geologic Model (Leapfrog Works)

During the initial stages of GSP development in the Sierra Valley, several comments were made by stakeholders about incorporating geologic features (e.g., faults) into the model that may influence groundwater flow within the valley. The desire to represent these features and the lack of consistent stratigraphic layering in previously published geologic cross sections by Kenneth D. Schmidt and Associates (2003 and 2005) prompted the development of a 3D geologic model. The software Leapfrog Works (<https://www.sequent.com/products-solutions/leapfrog-works/>) with the hydrogeology extension was chosen, which allows for powerful 3D visualization, explicit separation of data and geologic interpretations, efficient model updates, the ability to export geologic models as MODFLOW input files, and the ability to import MODFLOW results into Leapfrog Works for 3D visualization purposes. While a license for the software is required to develop and make changes to a model, visualization and exploration of an existing model is available at no cost. The 3D geologic model developed for SVHSM is available at the SVGMD website (<https://www.sierravalleygmd.org/>).

Formatted Leapfrog Works input files were generated using a pre-processing script developed in R that extracts required data from the DMS. As new wells and/or lithology data are added to the database, the 3D geologic model can be updated as needed.

6.1 3D Geologic Model Inputs

All available and applicable subsurface datasets for the groundwater basin were used in the development of the 3D geologic model of the groundwater basin. The primary datasets were geologic logs from wells drilled in the basin, geologic maps, and geophysical studies. Data from these sources were used to develop the bedrock contact surface and sediment distribution within the basin. Leapfrog Works accomplishes this by creating contact surfaces between categorical geologic units and interpolating between them using the radial basis function (RBF) method to create volumes. Spatial variability and knowledge of depositional process are accounted for by applying a variogram (mathematical model that describes the spatial continuity of the data) to a given categorical geologic unit (e.g., sands and gravels) during volume creation. This allows for general process knowledge (e.g., silts and clays are more laterally expansive than sands and gravels) to be incorporated into the 3D geologic model. The model domain was defined by the DWR Bulletin 118 basin boundary.

6.1.1 Faults

A total of 10 different faults are represented in the 3D geologic submodel of SVHSM (Figure 6-1). The faults were identified from the [USGS fault and fold database](#), geologic maps of the Sierra Valley (DWR, 1963; CGS, 1962 and 1992; Grose, 2000a, 2000b, and 2000c; Grose and Mergner, 2000), and USGS geophysical studies (Jackson and others, 1961; Gold and others, 2013). Locations and names (when available) of faults in the valley can differ depending on the source. An effort was made to amalgamate all available data from geologic maps, geophysical studies, and well logs, as well as to standardize the naming convention to reduce confusion



moving forward. Therefore, names and locations of faults presented in this report may differ from previously published material.

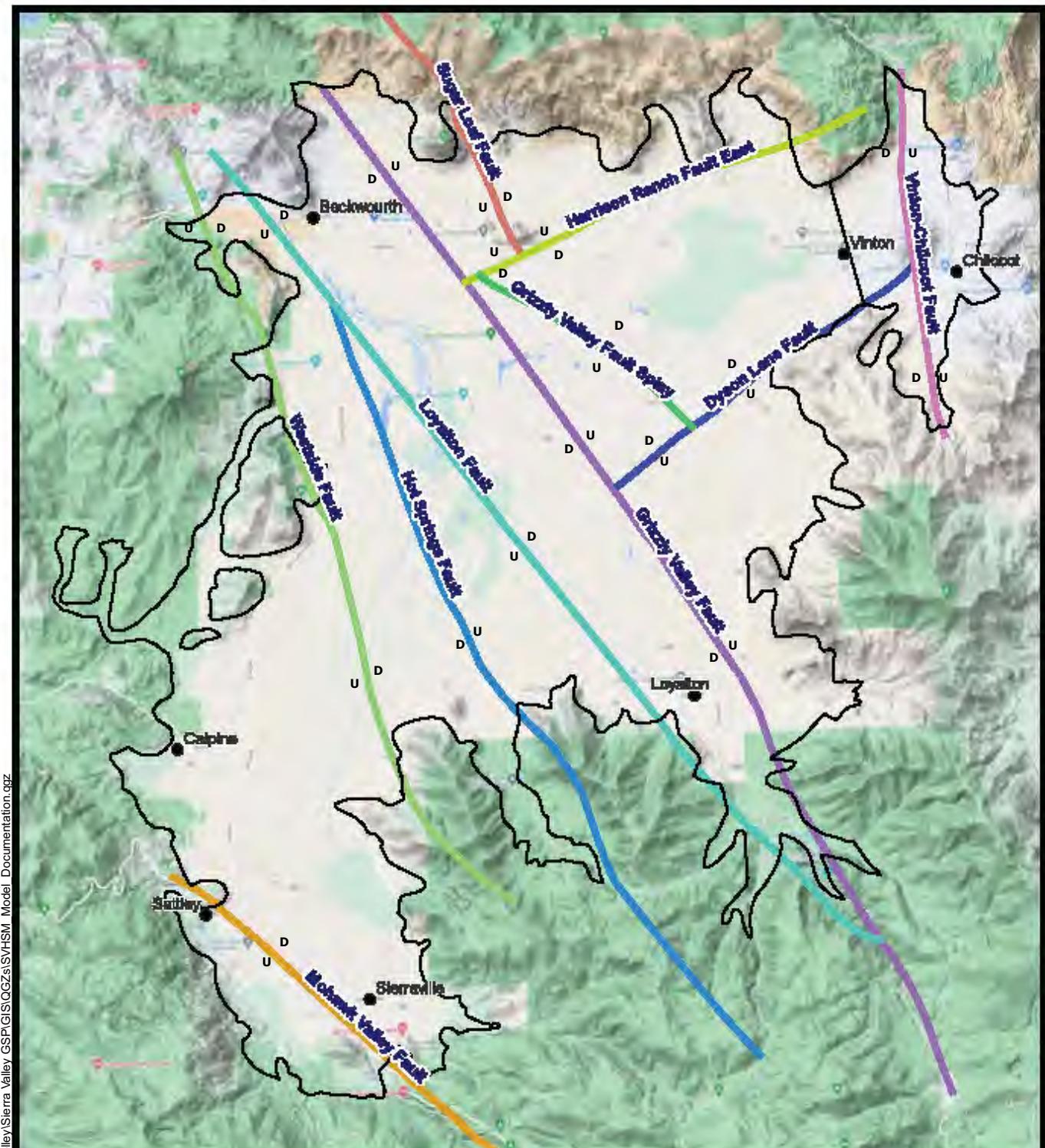
All faults in the model are currently represented as vertical (dip angle of 90°) based on previous descriptions and geophysical surveys. Displacement was generally only provided on a relative basis (upthrown and downthrown sides of the fault indicated). A description of vertical displacement was available from a geologic description of the Mohawk Valley Fault (Sawyer and others, 1995) and for the Grizzly Valley Fault Splay based on seismic reflection data (Gold and others, 2013). Vertical offset for all other faults was estimated by observed bedrock contacts in well logs and professional judgement, which results in a high degree of uncertainty. The USGS is currently conducting a seismic geophysical study of the basin, and an airborne electromagnetic (AEM) survey conducted by DWR is expected in 2022. Results from these studies may provide more information on faults in the basin which could be incorporated into future model updates.

6.1.2 Wells

A total of 439 wells within and immediately adjacent to the groundwater basin boundary (Figure 6-2) were identified from multiple publicly available databases (e.g., SGMA Data Viewer, CASGEM, GeoTracker), reports, or provided directly to the project team by SVGMD. A large proportion of the wells identified a location accuracy of approximately 2,640 feet (805 m), as the coordinates reported were the centroid of the section the well is located within as opposed to the actual location of the well. Location data for these wells was refined using the non-redacted information in the well log such as address, parcel number, or driller's map, when available. This typically reduced the location uncertainty to within a few hundred feet, and generally improved representation of the subsurface distribution of sediments.

6.1.3 Bedrock Units and Contacts

Bedrock in SVHSM was defined as the suite of non-sedimentary units present in the basin. This includes the Jurassic metavolcanic and metasedimentary rocks present before the emplacement of the Sierra Nevada batholith, the Cretaceous granitic and granodioritic intrusions of the Sierra Nevada batholith, and the late Tertiary volcanic rocks associated with tectonic extension that formed Sierra Valley. The hydrogeologic conceptual model (HCM) developed for the basin has the late Tertiary volcanics primarily erupting onto the existing granite and granodiorite, as opposed to alluvial and fluvial sediments. While distinct geologically, the non-sedimentary units were assumed to have similar hydrologic properties.



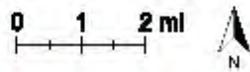
Explanation

Faults

- Dyson Lane Fault
- Grizzly Valley Fault
- Grizzly Valley Fault Splay
- Harrison Ranch Fault East
- Hot Springs Fault
- Loyalton Fault

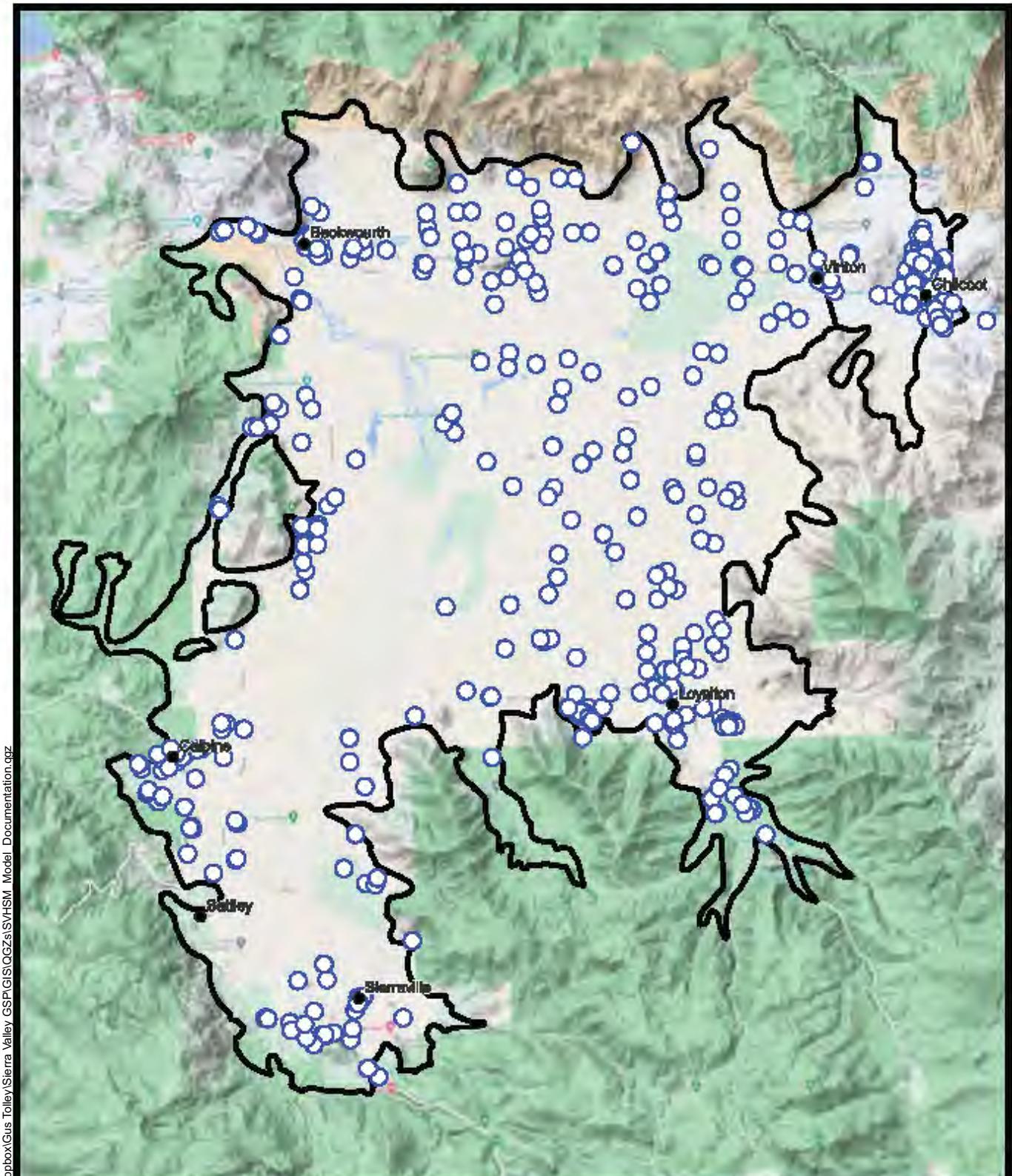
- Mohawk Valley Fault
- Sugar Loaf Fault
- Vinton-Chilcoot Fault
- Westside Fault

- Groundwater Basin
- City or Town



Notes:
1. D and U indicate relative downthrown and upthrown sides of the fault, respectively

SVHSM Documentation
3D Geologic Model Faults



Sources: DWR Well Completion Report Database; CASGEM; GeoTracker; SGMA Data Viewer; SVGMD

Explanation

- Well with Lithology Data
- City or Town
- Groundwater Basin
(DWR Bulletin 118)

0 1 2 mi



SVHSM Documentation
Wells with Lithology Data



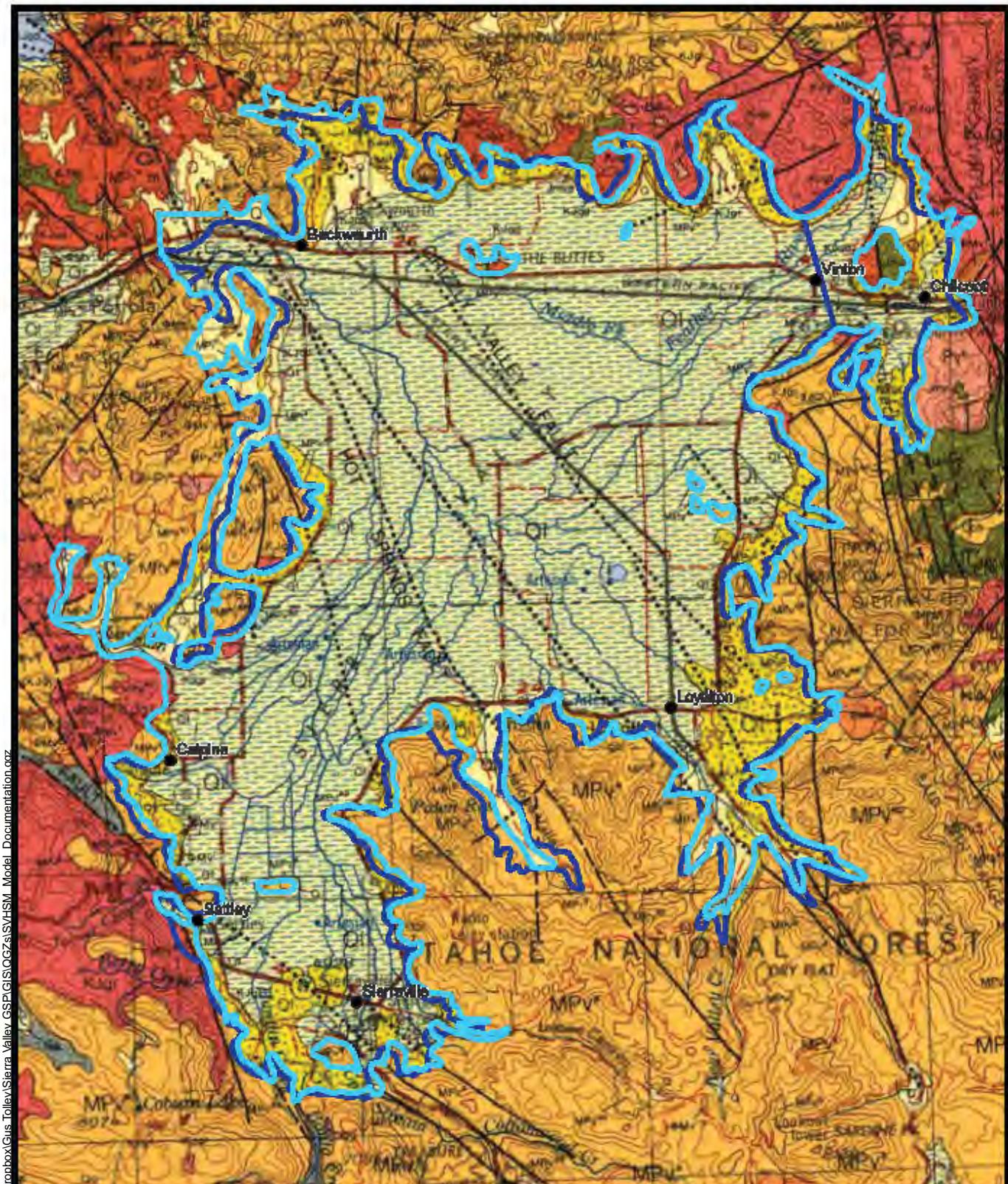
Bedrock contacts within and around the perimeter of the groundwater basin were determined based on the multiple geologic maps available for the basin. Although there is general agreement between the DWR Bulletin 118 groundwater basin boundary and the perimeter of the bedrock contacts used in the 3D geologic model (Figure 6-3), there are some areas where the two show disagreement (e.g., Antelope Creek canyon in the south and near the northwest boundary of the basin). This indicates that the Sierra Valley groundwater basin could benefit from a basin boundary adjustment in the future to better align the physical and jurisdictional boundaries of the groundwater basin.

Leapfrog Works handles geologic cross-cutting relationships by requiring the user to specify the relative age of each geologic unit and the type of contact surface between them. The contact surface between bedrock and aquifer sediments in SVHSM was represented using the “erosional” contact surface, meaning that sediment volumes took precedence over bedrock volumes. Slope of the bedrock contact into the groundwater basin was assumed to be similar to the topographic slope of the surrounding mountains. This was implemented in the 3D geologic model by adding “structural discs” around the perimeter of the basin. Bedrock contacts were also added manually as needed using “3D polylines” to satisfy geologic principles and interpretations based on well log and geophysical data. These are easily distinguishable within the Leapfrog Works software, and can be modified in the future if more data become available.

6.1.4 Aquifer Units and Contacts

Sedimentary lithology data from well logs was condensed into five hydrogeologic groups: (1) sand and gravel, (2) silty clayey sand and gravel, (3) sandy gravelly silt and clay, (4) silt and clay, and (5) volcanic tuff. The first two groups represent the coarse aquifer units, which make up the most productive portions of the aquifer. The third and fourth groups represent finer-grained sediments that are either poorly productive portions of the aquifer system or act as hydrologic flow barriers (aquitards). The last group was created to account for volcanic tuff that was reported in a few well logs. This classification system resulted in 3,652 geologic intervals that were used to generate contact surfaces and volumes within Leapfrog Works.

Due to the heterogeneous distribution of aquifer sediments in the basin, contacts in the 3D geologic model were represented using the “intrusion” contact surface type in Leapfrog Works. This contact type allows for units that are not laterally continuous across the model domain, which is more consistent with the HCM. Variograms based on well data with each fault block, as well as ellipsoid ratios (relative extent) with values from 60 to 80 in the x and y directions, were applied during the generation of the contact surfaces. Coarser units were defined as being the youngest so they would take precedence over finer units during volume generation. The option to specify a background lithology in Leapfrog Works was not used in order to better comprehend and visualize lithology data gaps. This resulted in the generation of a sixth “Unknown” sedimentary unit.



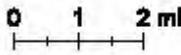
C:\Users\500\Sierra Valley GSP Dropbox\Gus Tolley\Sierra Valley GSP\GIS\GZs\SVHSM Model Documentation.00z

Explanation

- Modeled Bedrock Contact
- Groundwater Basin (DWR Bulletin 118)
- City or Town

Notes:

1. Bedrock contacts based on multiple data sources



Source: California Geological Survey (1992)



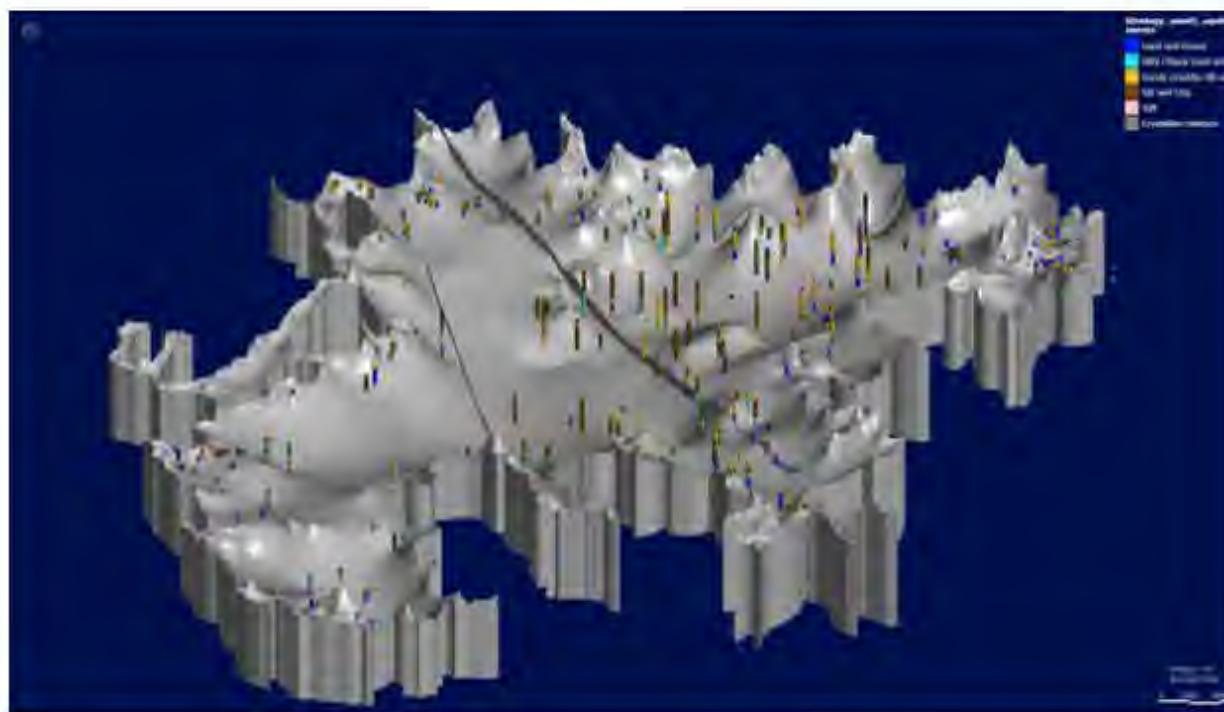
SVHSM Documentation
3D Geologic Model Bedrock Contacts

6.2 Outputs

Outputs from the 3D geologic model are contact surfaces between each of the simulated units and resulting volumes. The hydrogeology extension provides the ability to map the categorical aquifer sediments onto the MODFLOW grid. Parameter values required by MODFLOW such as hydraulic conductivity, storage coefficients, etc., can then be assigned to the aquifer sediment categories. This allows for heterogeneity to be accounted for without over parameterizing the model.

6.2.1 Bedrock Surface

Figure 6-4 shows the bedrock surface geometry used in SVHSM. Depth to bedrock is generally shallowest along the margins of the valley and greatest near the center. Maximum depth to bedrock in SVHSM is estimated to be about 1,530 feet (466 m) near the Lost Marbles Ranch (intersection of Dyson Lane and Marble Hot Spring road) based on geophysical data (Gold and others, 2013). Bedrock outcrops within the valley are present at various locations and are likely remnant topographic highs or volcanic features.



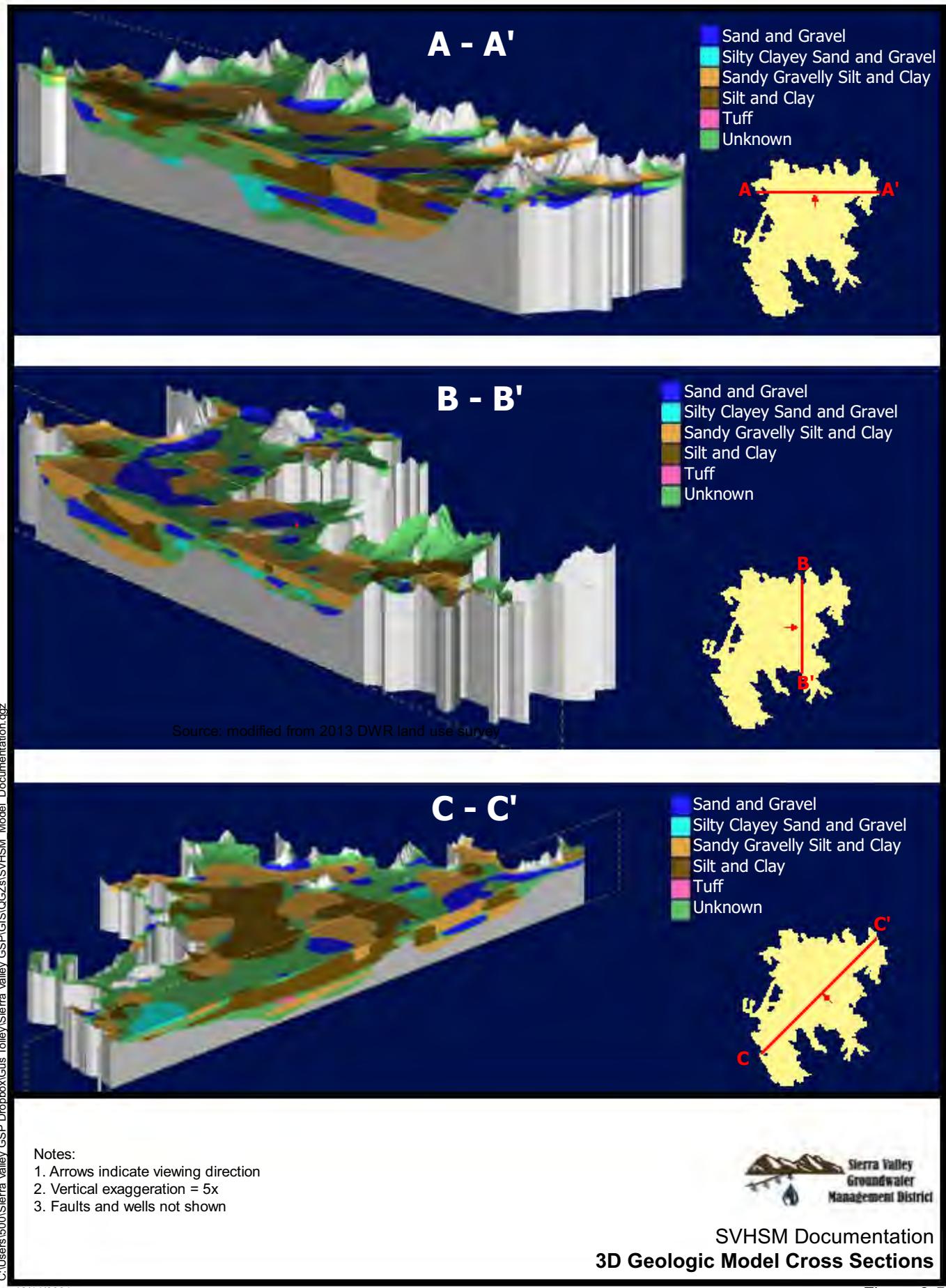


portion of the depositional history. The unknown volume makes up over one-third of the total model volume, indicating that some areas of the model have significant data gaps.

Table 6-1. SVHSM 3D geologic model lithology unit volumes.

ID	Lithology	Volume		Percentage	
		m ³	mi ³	km ³	(%)
1	Sand and Gravel	5.80E+09	1.4	5.8	7%
2	Silty Clayey Sand and Gravel	3.69E+09	0.9	3.7	4%
3	Sandy Gravelly Silt and Clay	1.78E+10	4.3	17.8	20%
4	Silt and Clay	3.06E+10	7.3	30.6	35%
5	Tuff	1.76E+08	0	0.2	0%
6	Unknown	3.01E+10	7.2	30.1	34%
<i>Total</i>		8.81E+10	21.1	88.1	100%

Several cross sections of the 3D model at various angles are shown in Figure 6-5. In general, there is much better subsurface characterization on the east side of the basin compared to the west side, largely due to the limited number and shallower depth of wells found on the west side. The model indicates the presence of a shallow unconfined aquifer and a deep confined aquifer on the northeastern portion of the basin in the vicinity of most of the agricultural production wells. Water levels in the area also indicate the presence of an upper and lower aquifer. Although a laterally continuous confining layer has not been observed, silt and clay units in some areas are estimated to be up to about 860 feet (262 m) thick and laterally extensive enough to provide confining conditions. Water levels collected from multiple depth completion wells (e.g., DMW 2 and DMW 3) indicate that the hydrologic connection between the upper and lower aquifer units on the west side of the basin may vary spatially, but cannot be confirmed in the 3D geologic model due to data sparsity in that area.





7.0 Groundwater-Surface-Water Model (MODFLOW)

Groundwater heads and streamflow within the groundwater basin are simulated using the USGS 3D finite-difference code MODFLOW (Harbaugh, 2005). The Newton formulation (MODFLOW-NWT) (Niswonger and others, 2011) is used, as it better handles drying and rewetting of model cells compared to other versions. The MODFLOW One-Water Hydrologic Flow Model (MF-OWHM v2.0) (Boyce and others, 2020) executable was used to run MODFLOW-NWT as improvements were made to the underlying code that improved run times and output formatting.

The MODFLOW model domain (Figure 7-1) is 216 rows, 243 columns, and 12 layers rotated by 35 degrees counter clockwise around 727096.781207E, 4368418.236840N (NAD 83 UTM Zone 10 N). The grid rotation was to align the principal axes in the groundwater model with the Loyalton and Grizzly Valley faults. Horizontal discretization is 150 m the x and y directions and 37 to 69 m in the y direction, for a total of 105,929 active model cells.

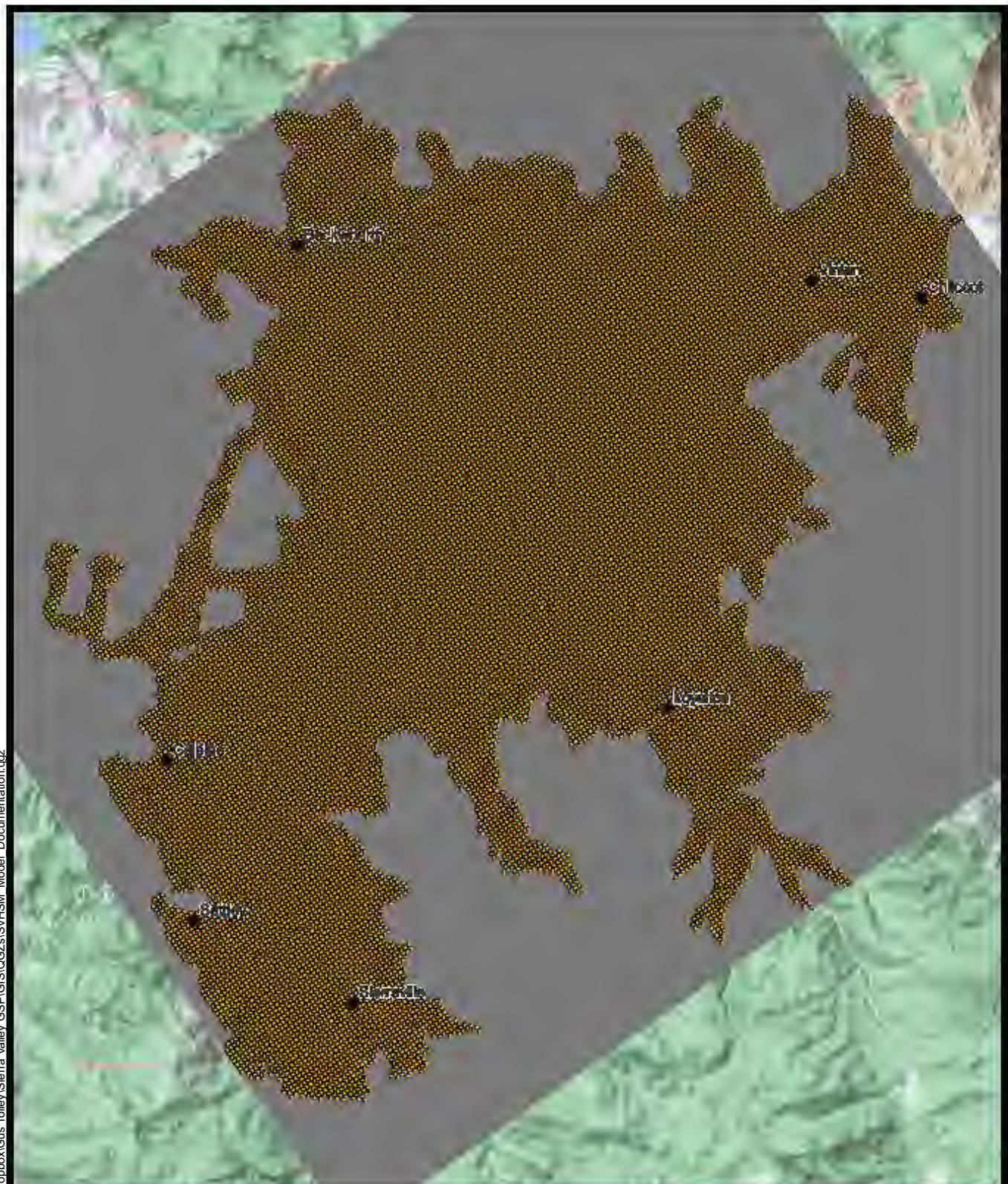
MODFLOW uses a stress period and time step scheme for solving conditions that change with time (transient model). Stress periods are intervals for which boundary conditions (i.e., things that “drive” the model) are specified. Time steps define the interval over which the numerical solution takes place and are always equal to or less than stress periods. SVHSM uses monthly stress periods and daily time steps. This means that boundary conditions (e.g., recharge, pumping, stream inflow) are specified using monthly average values, with groundwater elevations (heads) and streamflow calculated on a daily basis. The historical simulation period is from October 1, 1999 through September 30, 2020.

7.1 MODFLOW Inputs

Inputs to the MODFLOW submodel of SVHSM are specified on a monthly basis, with many inputs being outputs from the other submodels discussed above. Required input files that are not directly written by other submodels or need modifications are generated using a pre-processing script developed in R. This documents a large portion of the workflow for converting the conceptual model of the aquifer system into a numerical simulation, and decreases the time required to update the model in the future.

7.1.1 Hydraulic Properties

The 3D geologic model (see Section 6) was used to define the distribution of hydraulic property zones in the model. Figures 7-2a through 7-2l show the distribution of hydraulic property zones for each model layer. Zones 1 through 6 corresponded with the lithologies represented in the 3D geology model. Zones 7 and 8 are used to represent alteration zones caused by movement of the Loyalton Fault and Grizzly Valley Fault, respectively. These two fault zones are only present in layers 4 through 12, and do not extend to the surface. This was done to reflect the limited movement along the fault the upper sediments have experienced compared to the lower sediments, as the lower sediments were deposited earlier and have more time to accumulate displacement.



Explanation

MODFLOW Grid

● City or Town

Active

 Inactive

0 1 2 ml

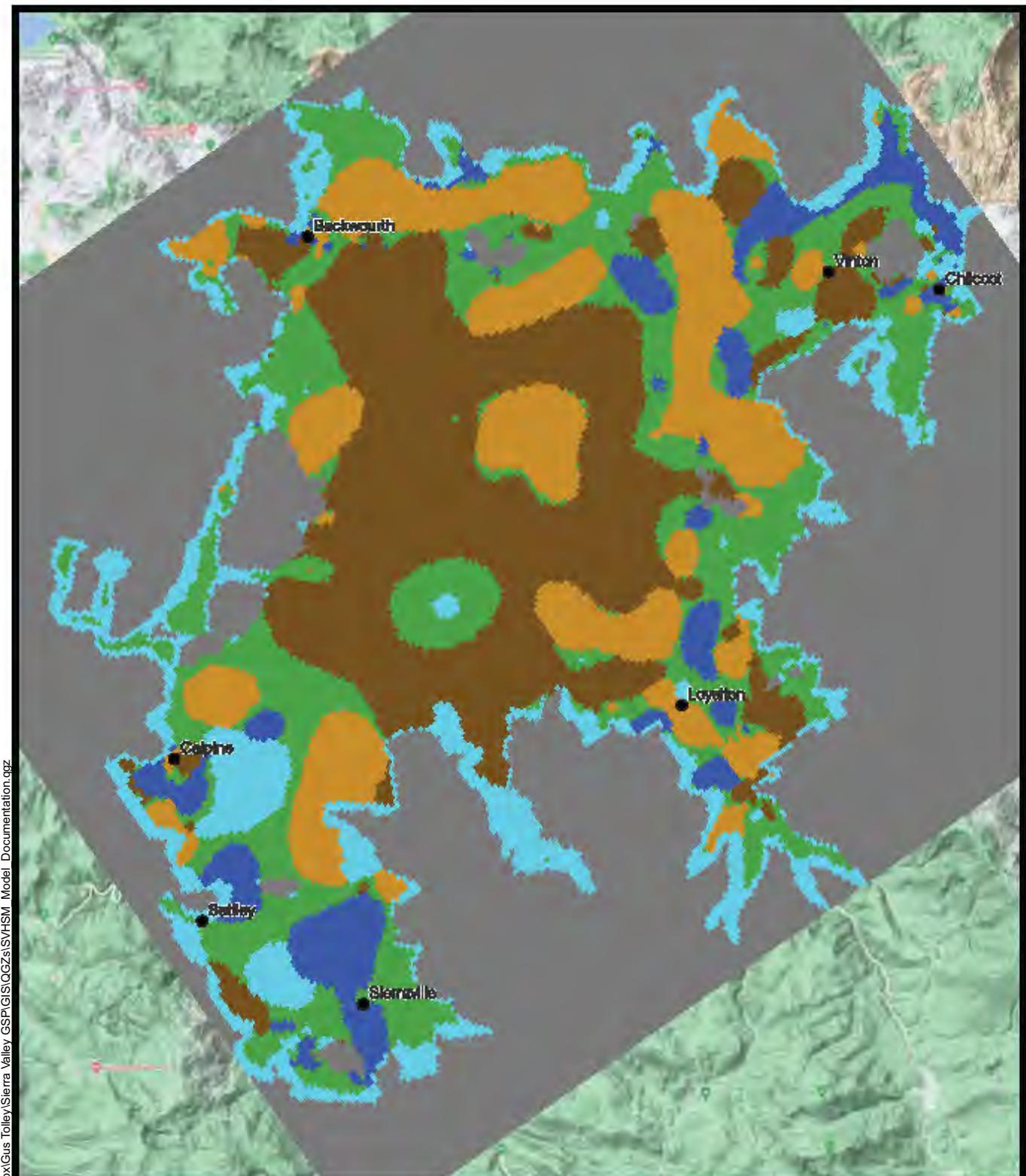
N

Notes:

Notes:



SVHSM Documentation **MODFLOW Domain**



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

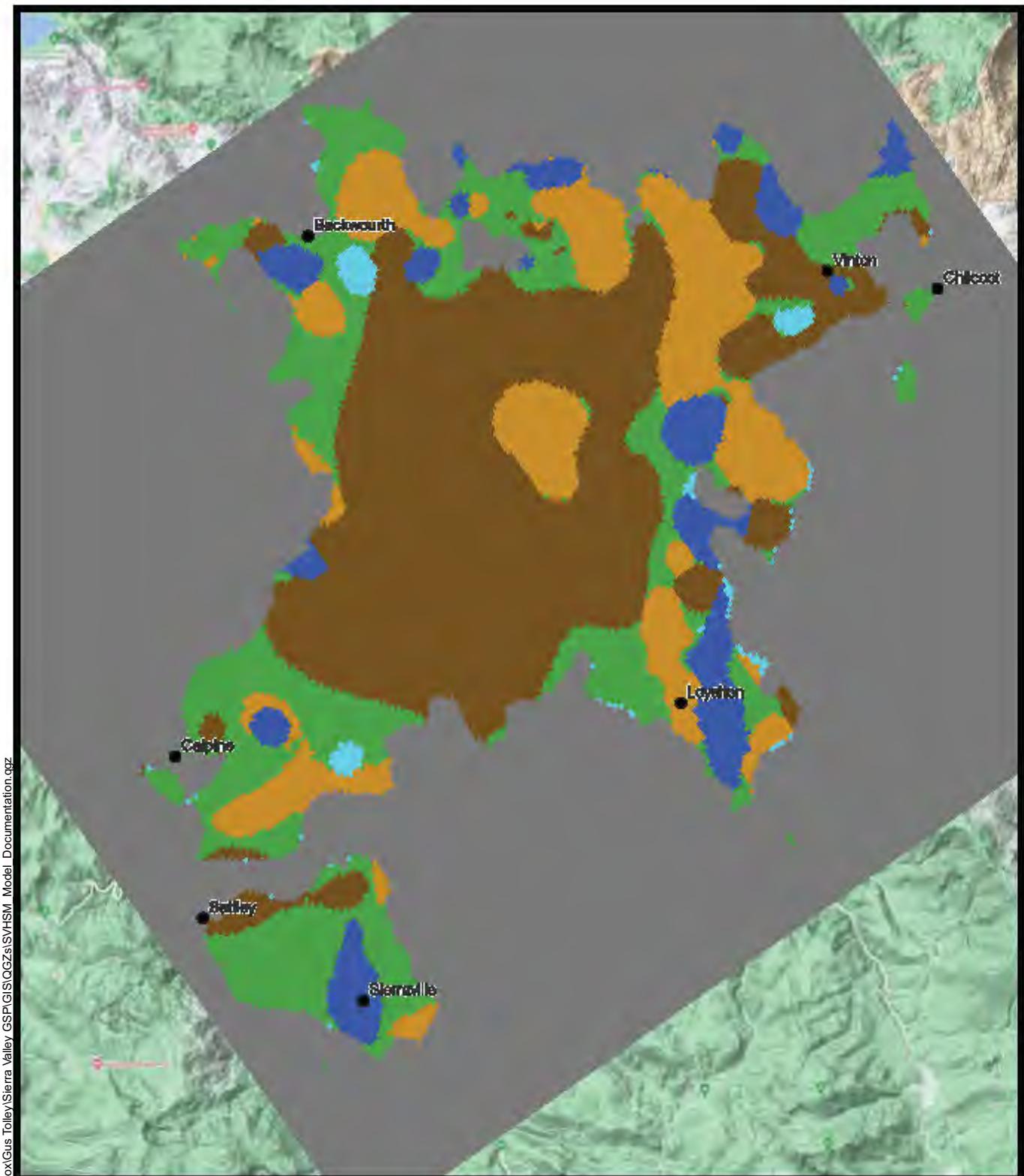
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 1)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

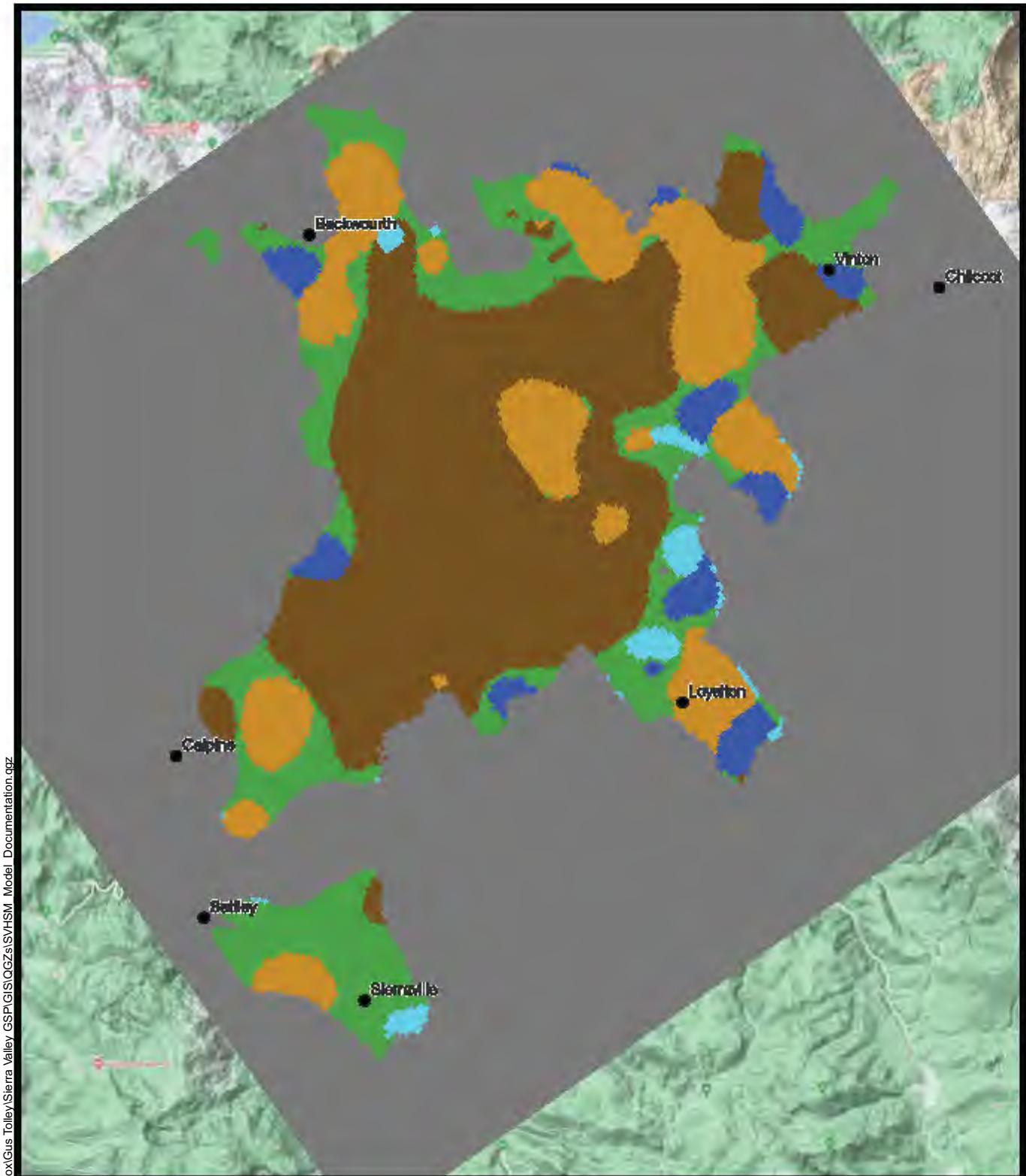
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 2)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

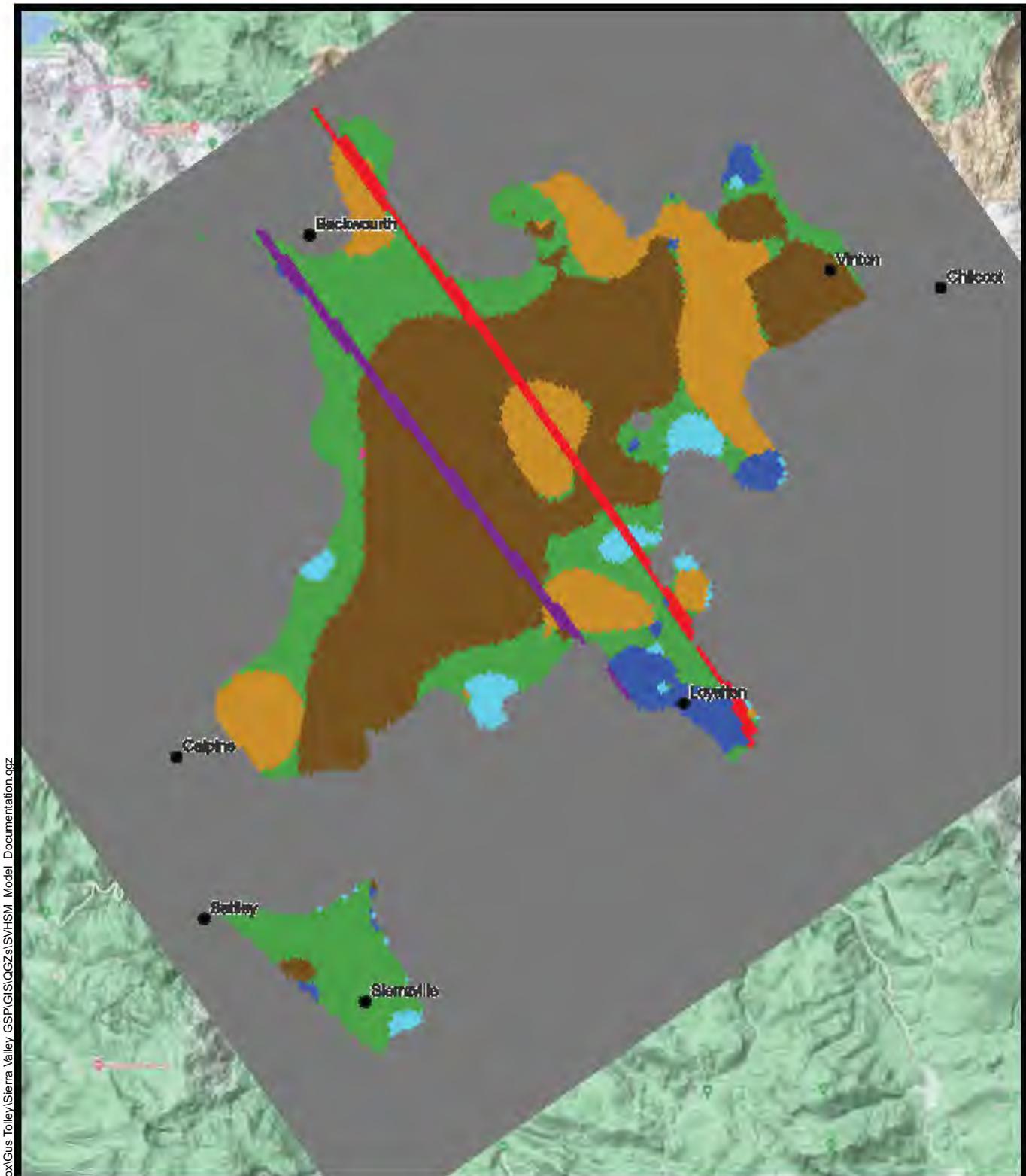
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 3)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

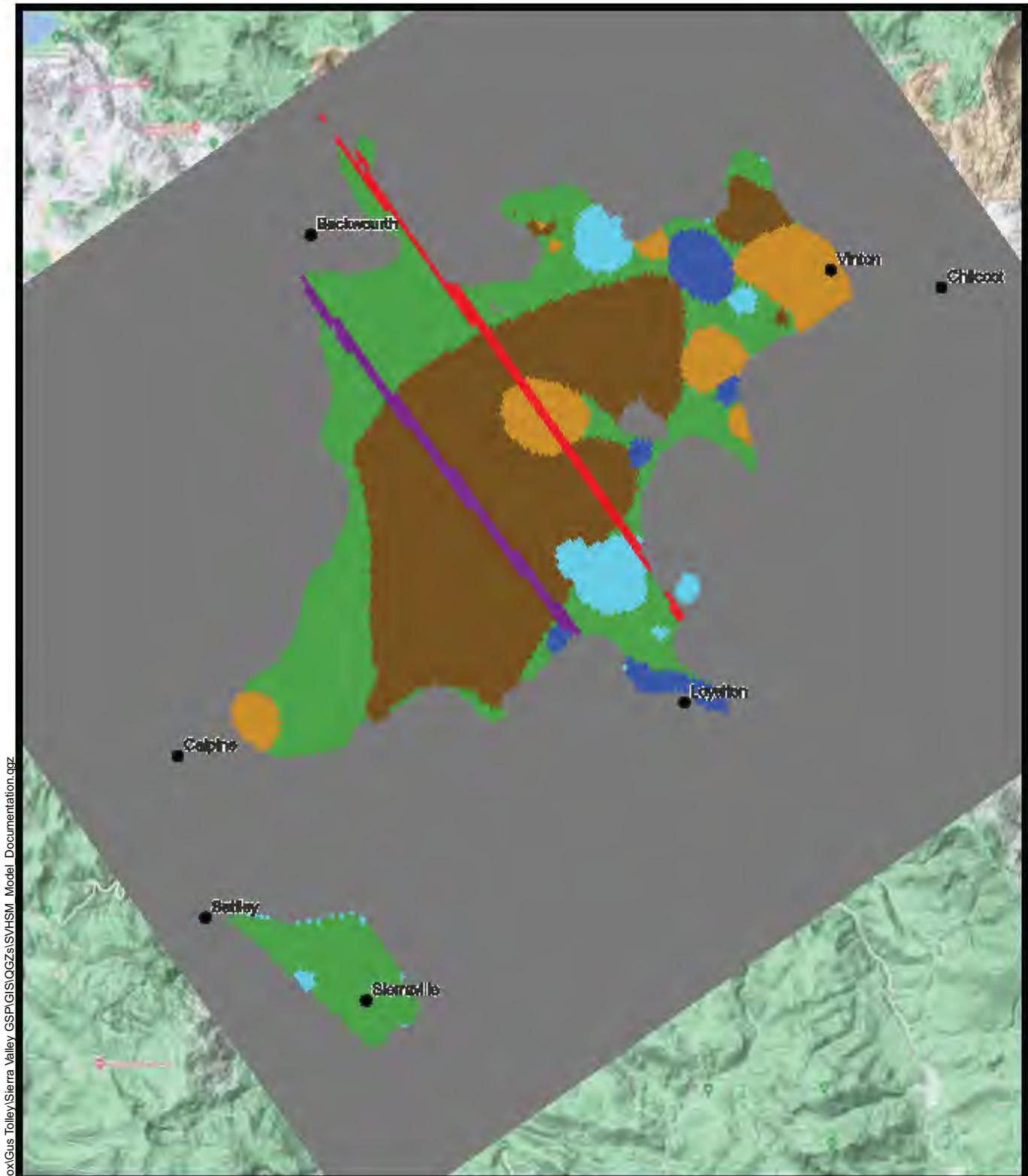
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 4)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

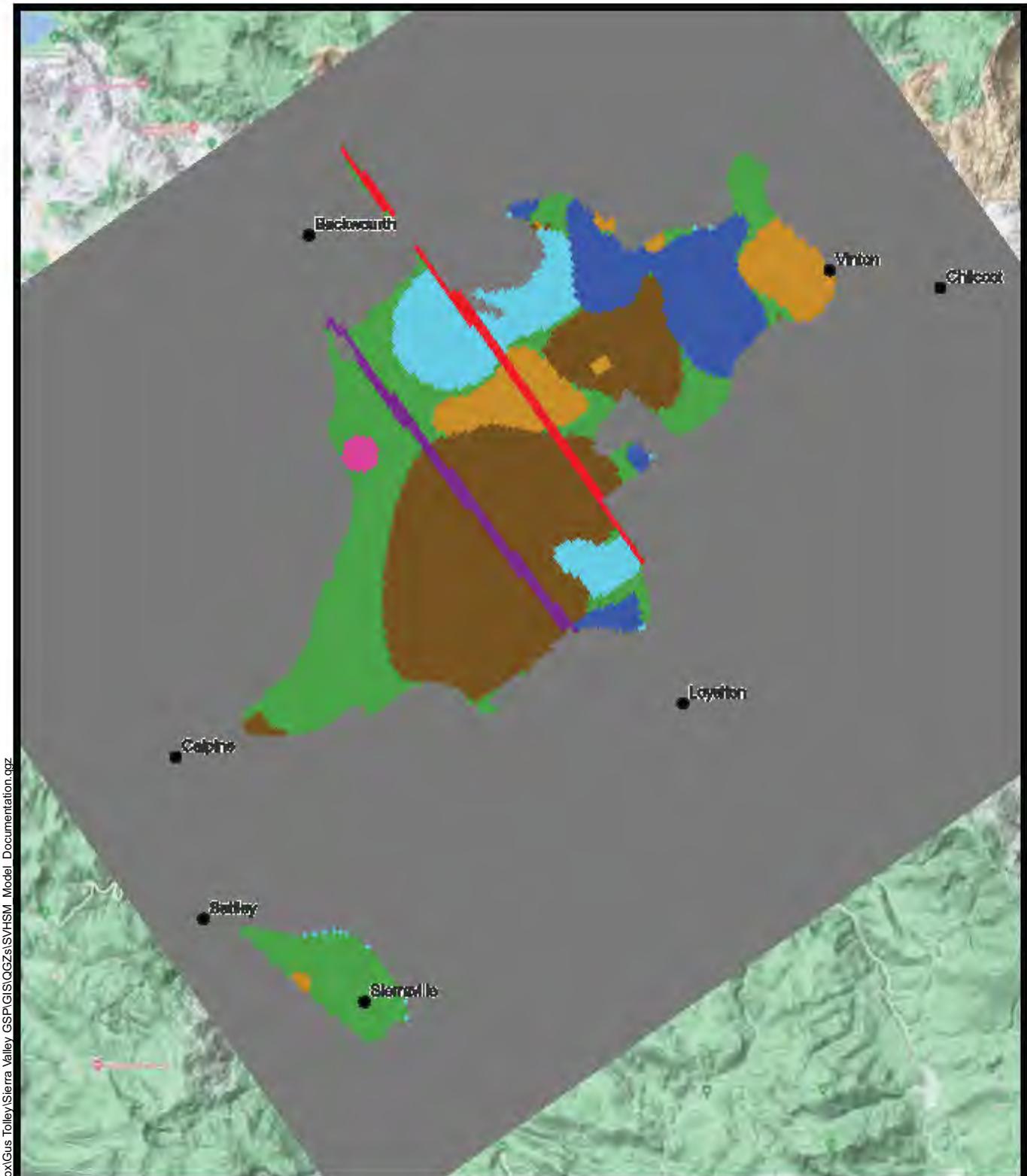
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 5)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

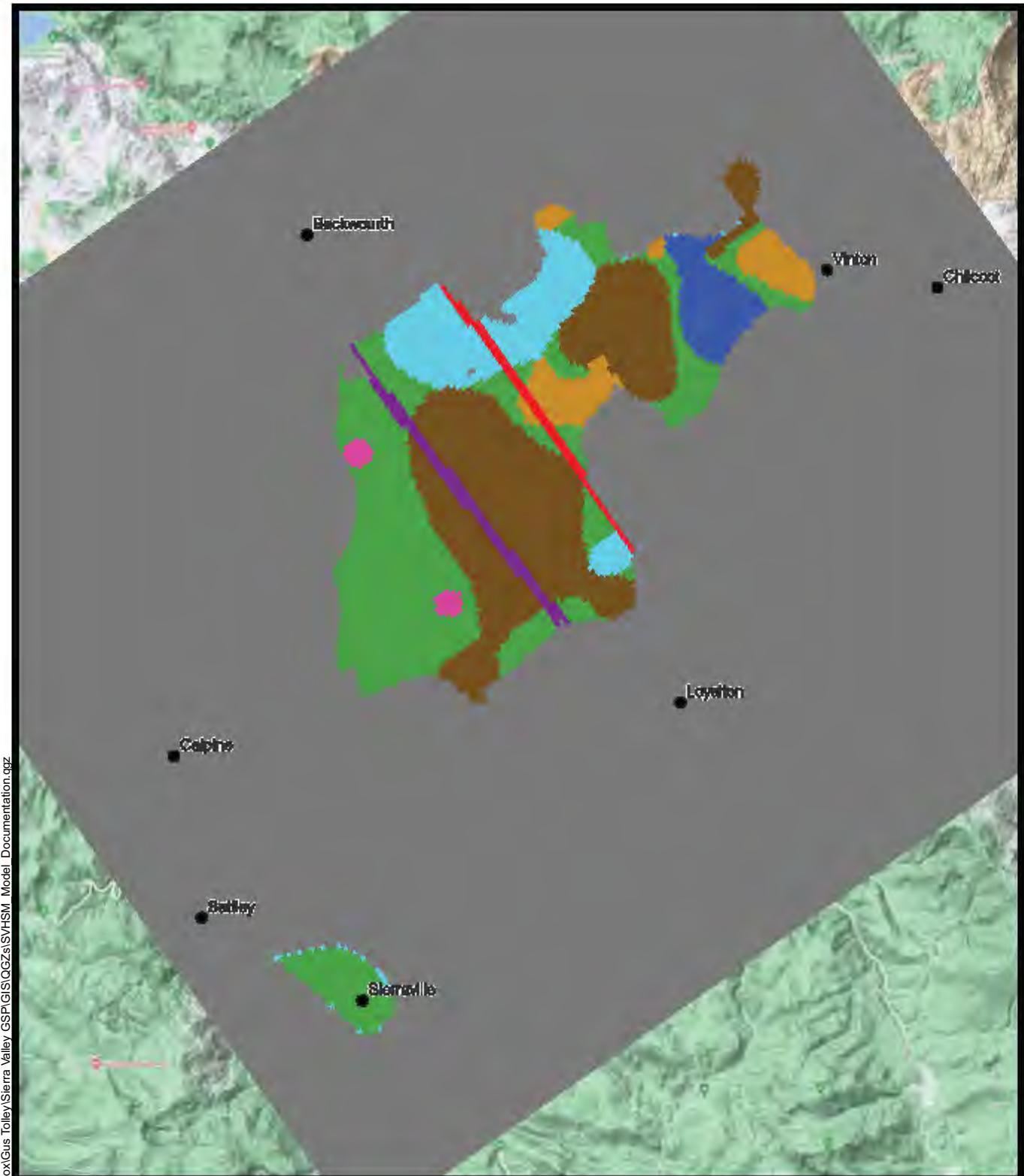
- 5 - Tuff
- 6 - Unknown
- 7 - Loyalton Fault
- 8 - Grizzly Valley Fault
- Inactive

● City or Town
 0 1 2 mi
 N



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 6)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

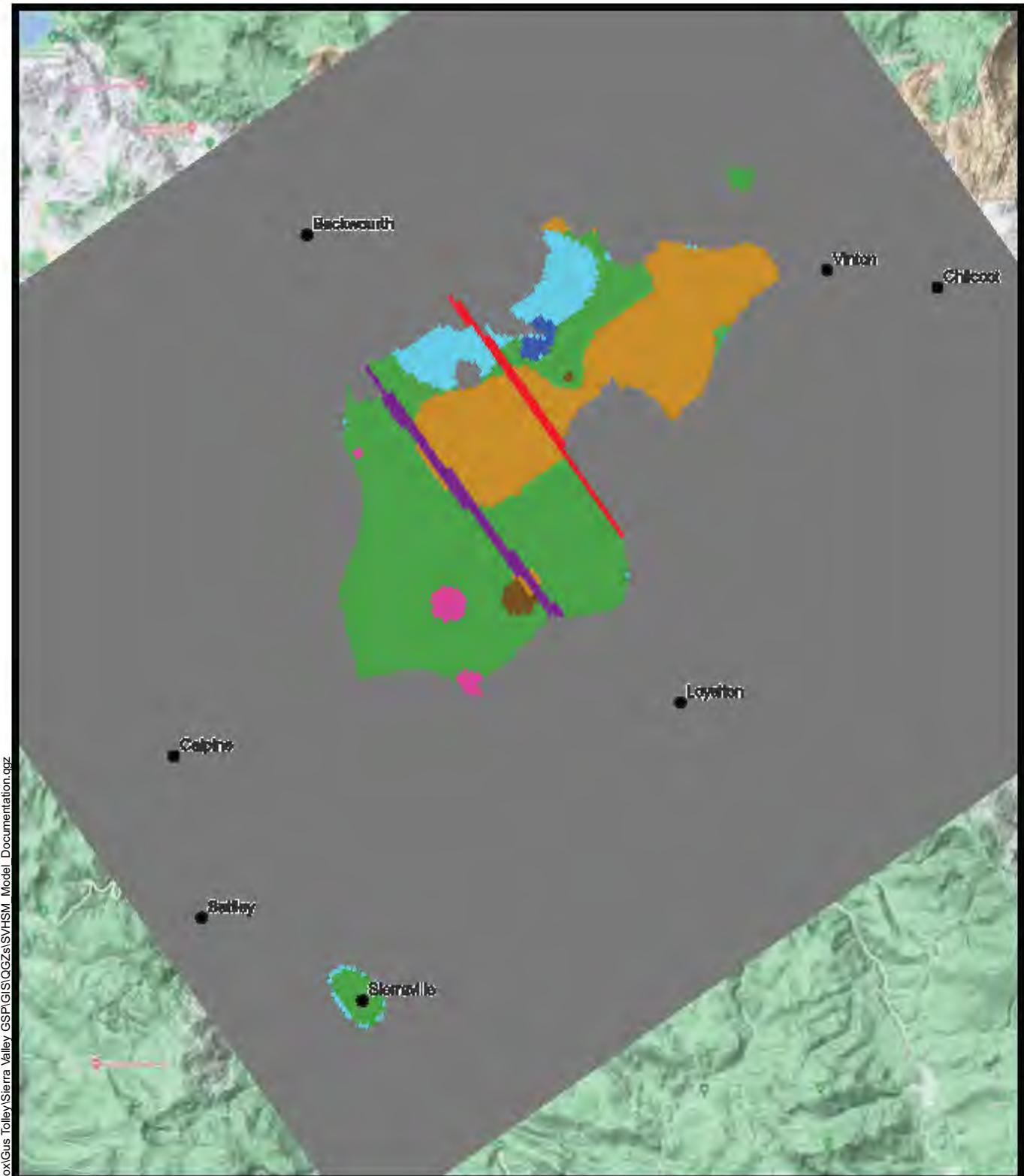
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 7)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

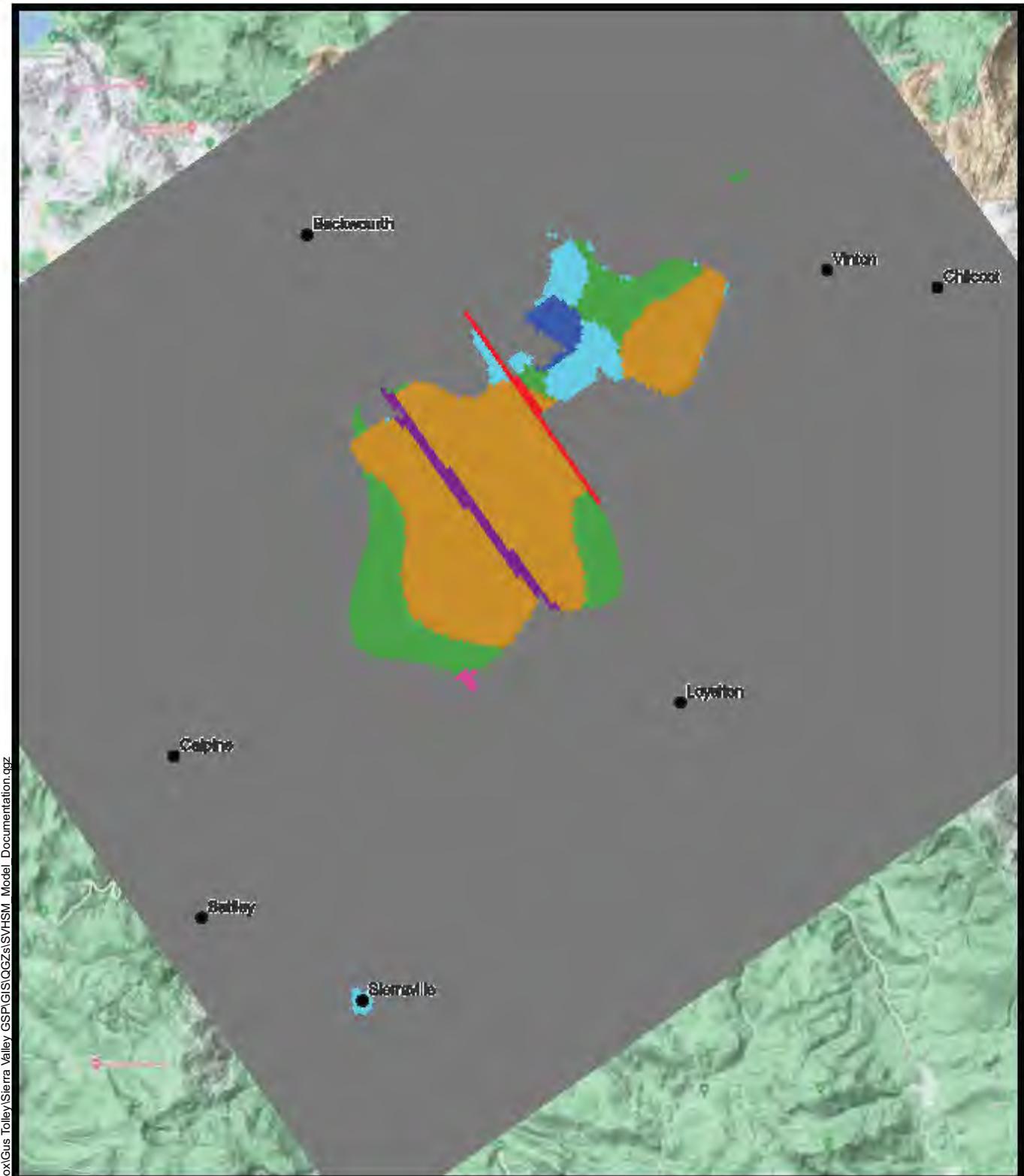
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 8)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

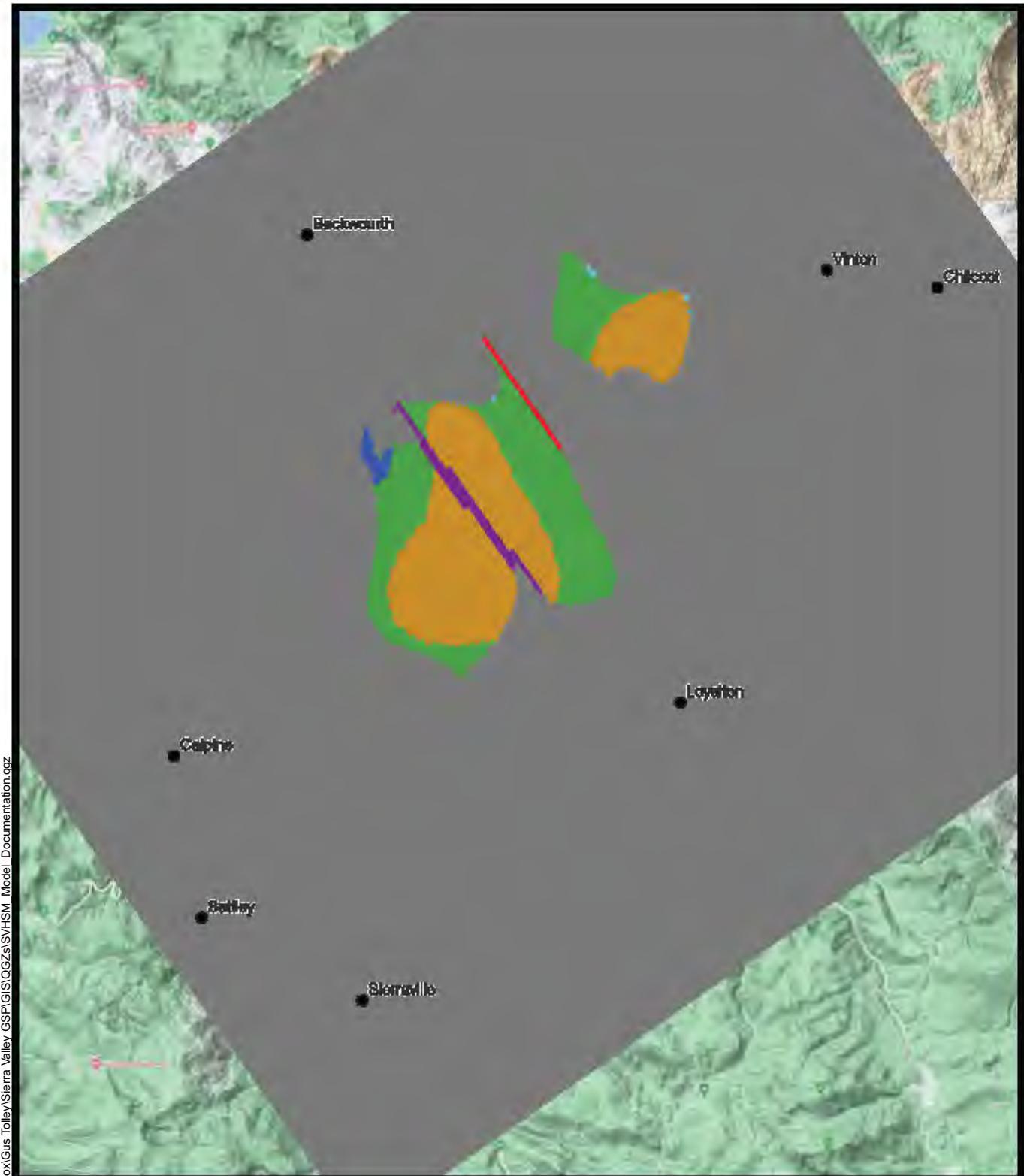
- 5 - Tuff
- 6 - Unknown
- 7 - Loyalton Fault
- 8 - Grizzly Valley Fault
- Inactive

● City or Town
 0 1 2 mi
 N



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 9)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

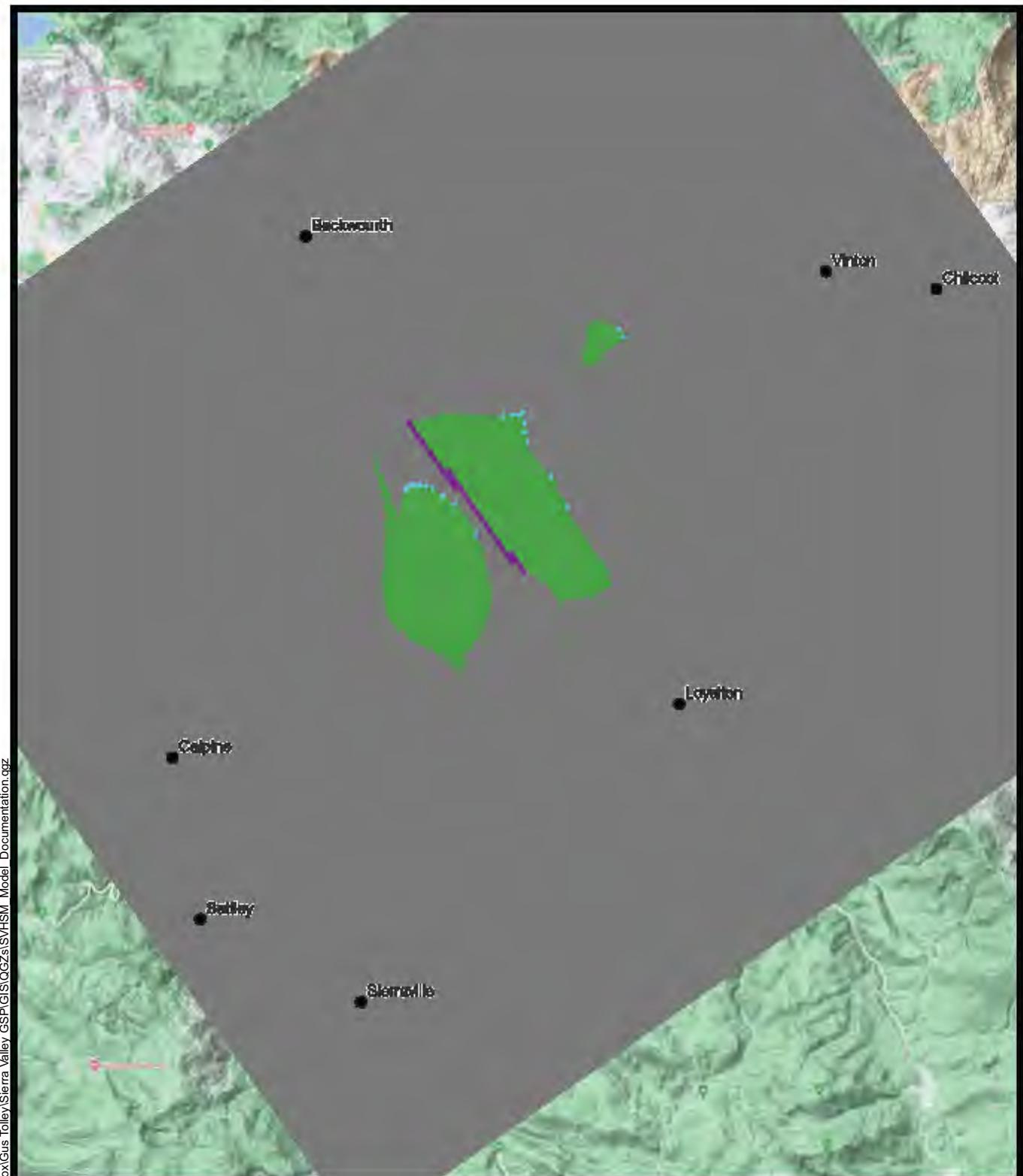
● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 10)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

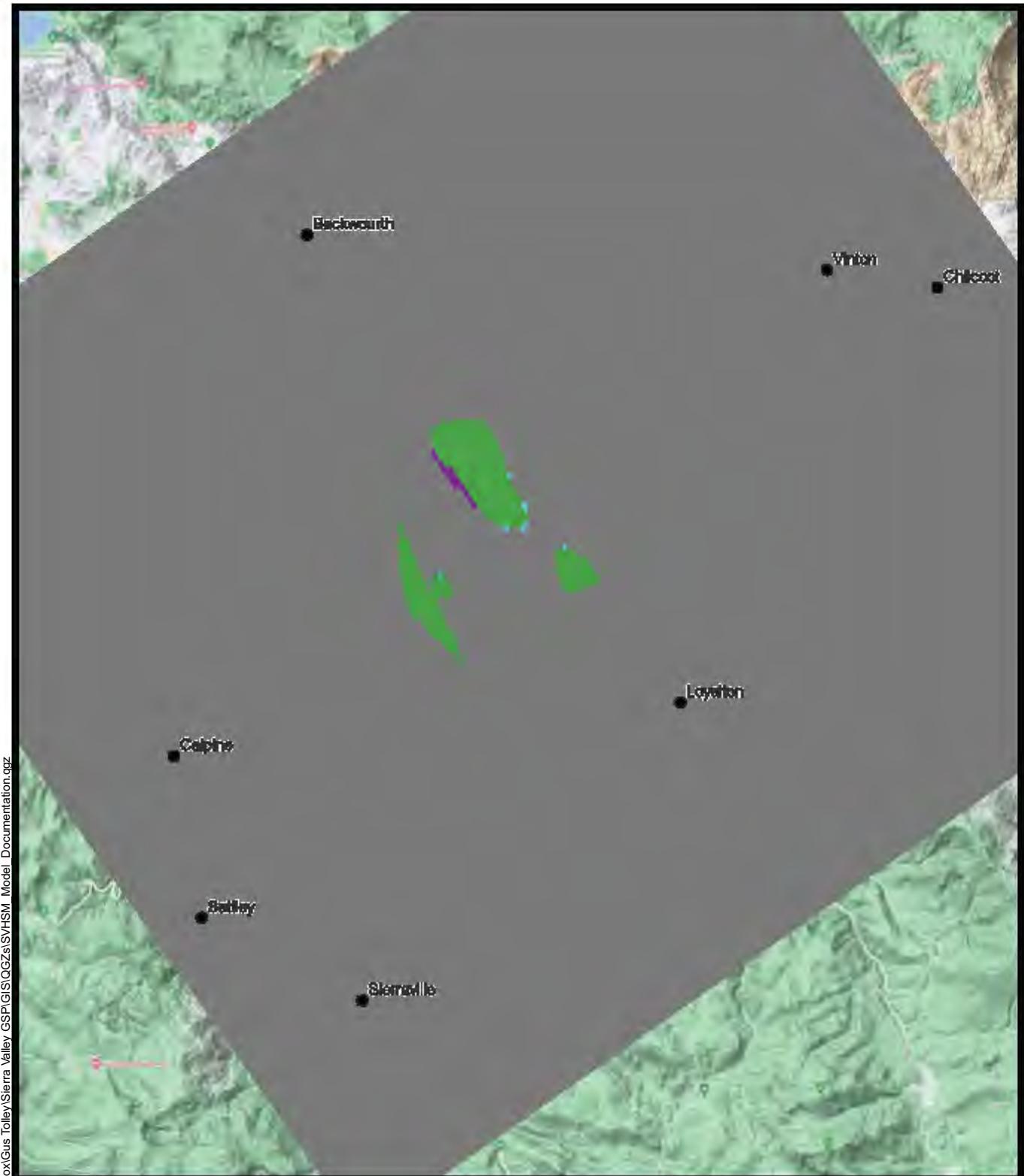
City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 11)



Explanation

Hydraulic Property Zone

- 1 - Sand and Gravel
- 2 - Silty Clayey Sand and Gravel
- 3 - Sandy Gravelly Silt and Clay
- 4 - Silt and Clay

5 - Tuff

6 - Unknown

7 - Loyalton Fault

8 - Grizzly Valley Fault

Inactive

● City or Town

0 1 2 mi



SVHSM Documentation

MODFLOW Hydraulic Property Zones (Layer 12)



The hydraulic property zones are used to assign numerical values for horizontal hydraulic conductivity (*HK*), horizontal anisotropy (*HANI*), vertical anisotropy (*VANI*), specific yield (*SY*), and specific storage (*SS*). These parameters control groundwater flow and storage in the MODFLOW model. Calibrated parameter values for each zone can be found in Section 8.XX.X.

The upper three layers of the model are specified as convertible layer types (*LAYTYP*), which represent the upper aquifer as unconfined (0). The remaining model layers (4 through 12) are specified as confined. A “Quasi-Three-Dimensional” (Quasi-3D) confining bed was placed between the third and fourth layers of the model in order to better match observed heads and head differences between the upper and lower aquifers. This confining bed restricts vertical flow between layers, and allows for thin aquitards to be represented without adding additional layers (computational expense).

7.1.2 Groundwater Pumping

Agricultural and municipal groundwater pumping in SVHSM is simulated using the multi-node well (MNW2) (Konikow and others, 2010) package due to the presence of long screen intervals for agricultural irrigation wells that spanned multiple model layers. Wells without screen information were assumed to be screened from 10 feet below ground surface to the total well depth. If well depth was unknown, then it was assumed to be 800 feet. Total well depth is missing from about 28% of simulated wells, and screen depth information is missing from about 51% of high capacity pumping wells. Assumptions made in the absence of this data are more likely to bias well and screen depths shallow.

Groundwater inputs to the MODFLOW submodel are estimated by the SWBM or specified by the user. For more details, see Section 5.

7.1.3 Evapotranspiration (ET)

The majority of ET simulated in SVHSM is handled by the SWBM submodel. However, the current version of the SWBM does not simulate direct uptake from shallow groundwater by vegetation. Due to prevalence of wetlands and shallow depth to water in some areas of the groundwater basin, representation of ET directly from the shallow groundwater aquifer was desired. The evapotranspiration segments (ETS) (Banta, 2000) package was used to simulate ET losses from the shallow aquifer. Groundwater that comes within a specified distance of the land surface, referred to as the extinction depth (*ETSX*) is subject to ET in SVHSM. A maximum flux rate (*ETSR*) is specified at the land surface, which decreases linearly to a value of zero at the extinction depth. For example, if the groundwater elevation in a model cell is halfway between the land surface and the extinction depth, then the ET rate at that cell for that time step is 50% of the specified maximum rate.



7.1.4 Mountain Front Recharge (MFR)

Mountain front recharge (MFR) is represented in the groundwater-surface-water submodel using a specified flux boundary applied to selected cells in layers 1-10. Model cells along the perimeter of the active area in each of these layers were chosen and assigned to one of six MFR segments (Figure 7-3). The MFR parameters found in the **SVHSM.pval** input file (e.g., *MFR_1*) represent the total volumetric flux (units of m^3/day) that enters the model across each MFR segment boundary. This flux is distributed between the selected model cells based on lithology. Currently, the MFR flux is constant for each stress period and distributed equally to cells with coarser lithologies (hydraulic property zones 1, 2, 6, 7, and 8); cells with lower conductivities (hydraulic property zones 1, 2, and 5) are excluded from MFR.

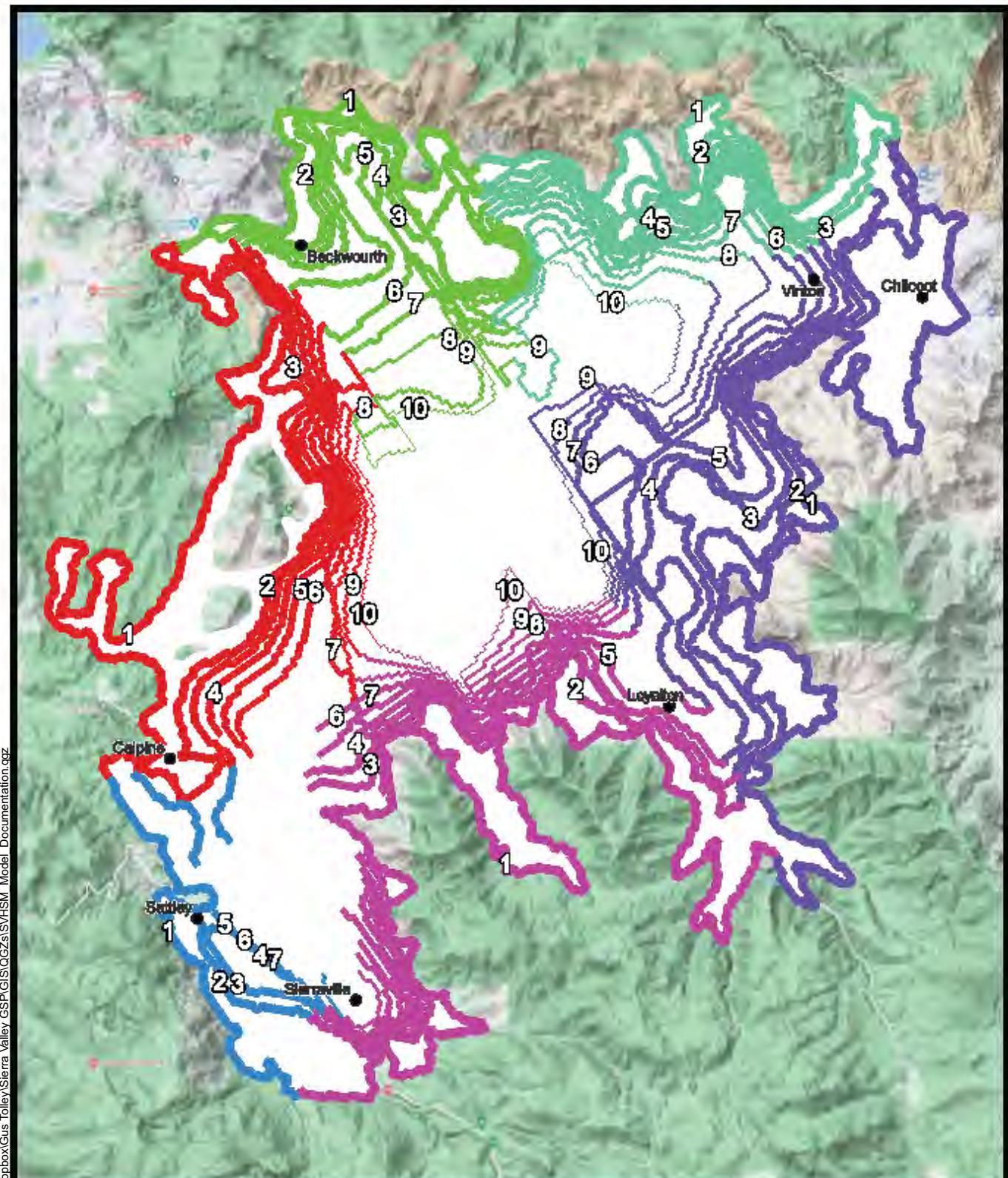
The model development timeline only allowed for limited model calibration, so a detailed evaluation of different representations of MFR could not be completed. For example, MFR may vary intra-annually, inter-annually, or experience a time-lagged cross correlation with recharge in the upper watershed estimated by the PRMS submodel. Evaluation of these conceptualizations would require much more detailed parameterization, computational expense, and analysis, but may ultimately provide greater understanding of watershed-scale recharge processes operating in the basin.

7.1.5 Surface Water

The streamflow routing (SFR2) (Niswonger and Prudic, 2005) package is used to represent surface water flow and interactions between surface water and groundwater within the groundwater basin boundary. The SFR package uses a segment and reach classification system, where reaches are the portion of a stream contained within a given model cell and segments are continuous collections of reaches that define how flow is routed through the system. Physical properties of the streambed can be defined for each specific reach, or be linear interpolated along the segment using specified values for the beginning and end. Typically, segments are defined by the intersection of streams with the model boundary or other surface water features (e.g., confluence of two streams).

Flow rates are specified for each stress period at the margin of the basin where streams enter Sierra Valley. The flows are routed through a stream network specified by the user using one of several available methods. Exchanges between groundwater and surface water are treated as either a general head boundary (i.e., flux is dependent on water levels) or a constant flux boundary if groundwater levels drop below the bottom of the streambed in that model cell.

The surface-water network in the Sierra Valley is a complex system of low-gradient, interconnected natural stream channels and unlined canals. This complex network was condensed into 51 stream segments based on available data and stakeholder feedback that represent the major surface water features in the valley. From a modeling perspective, groundwater-surface-water exchange processes are the same for a natural streambed as an unlined canal, so no differentiation was made between the two in the model (Figure 7-4). Specification of diversion information is required at seven locations where a stream segment splits (bifurcates) into two downstream segments.



Explanation

MFR Segment

- MFR 4
- MFR 1
- MFR 2
- MFR 3

- MFR 5
- MFR 6

City or Town

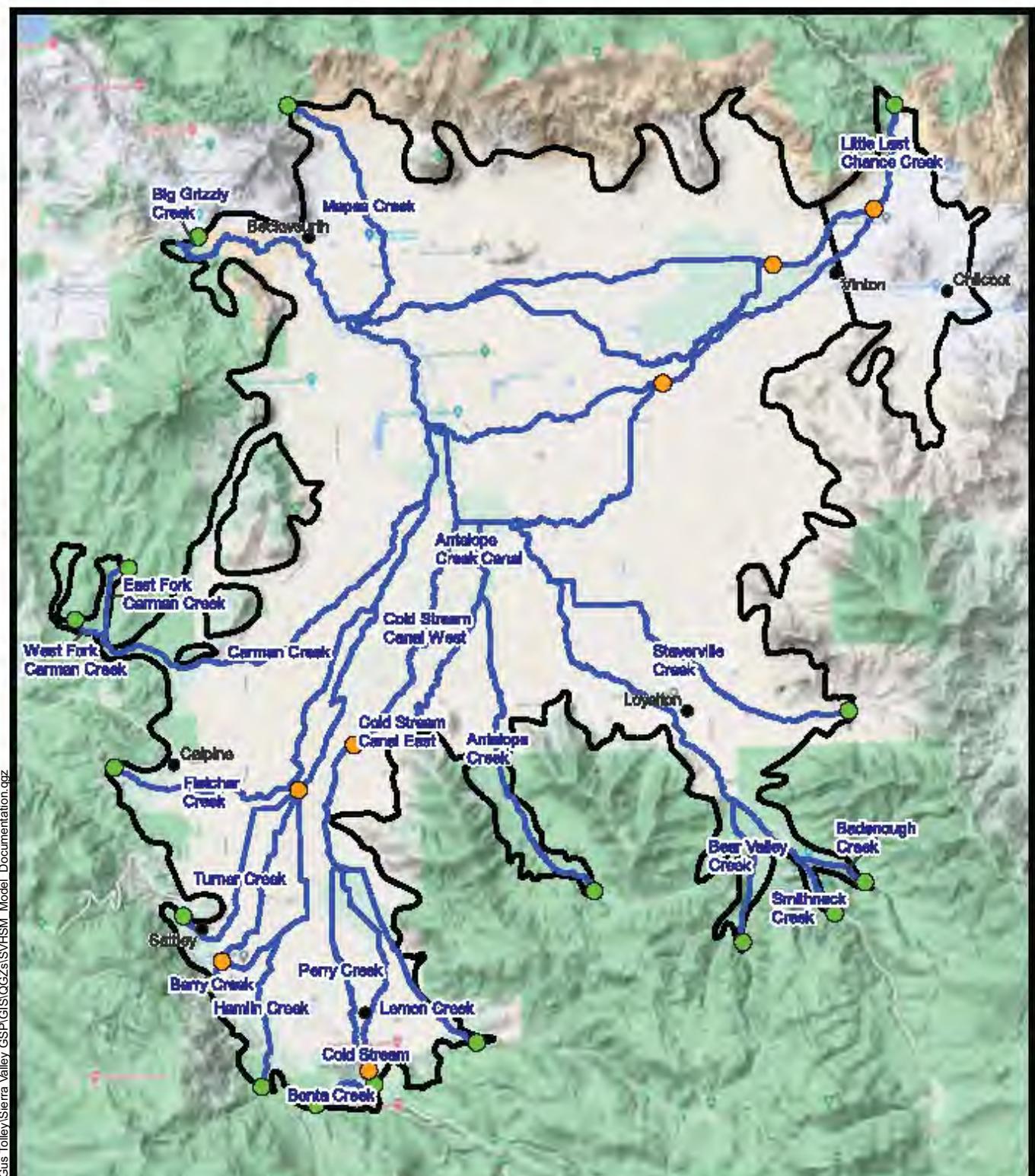
0 1 2 mi

Notes:

1. Annotations indicate model layer
2. Thinner lines denote deeper model layers



SVHSM Documentation
MODFLOW Mountain Front Recharge



Explanation

- City or Town
- Specified Inflow Location
- Specified Diversion Location
- Stream/Canal
- Groundwater Basin (SFR)

Source: USGS National Hydrography Dataset (2020)



SVHSM Documentation
MODFLOW Stream Network



Due to a lack of detailed diversion information within the valley, flow from the upstream segment was evenly split between the two downstream segments.

Flows are routed through the network using Manning's equation. Solution of this equation requires physical parameters related to the slope, geometry, and roughness of the streambed for be specified for every reach in the segment, as well as a numerical boundary condition for the stream segment itself. Streambed slope was calculated for each reach using elevations extracted from the digital elevation model (DEM) at the centroids of each reach and the distance between them along the stream channel. Channel geometry is assumed to be rectangular with stream widths defined using aerial imagery. Channel roughness for all segments was set to 0.035, which is appropriate for cultivated areas with mature field crops (Chow, 2009). Inflow rates are specified for each stream where it enters the groundwater basin for every stress period (month) during the simulation to satisfy the numerical boundary condition requirement. Stream inflows to SFR are those input to the SWBM minus any surface water irrigation.

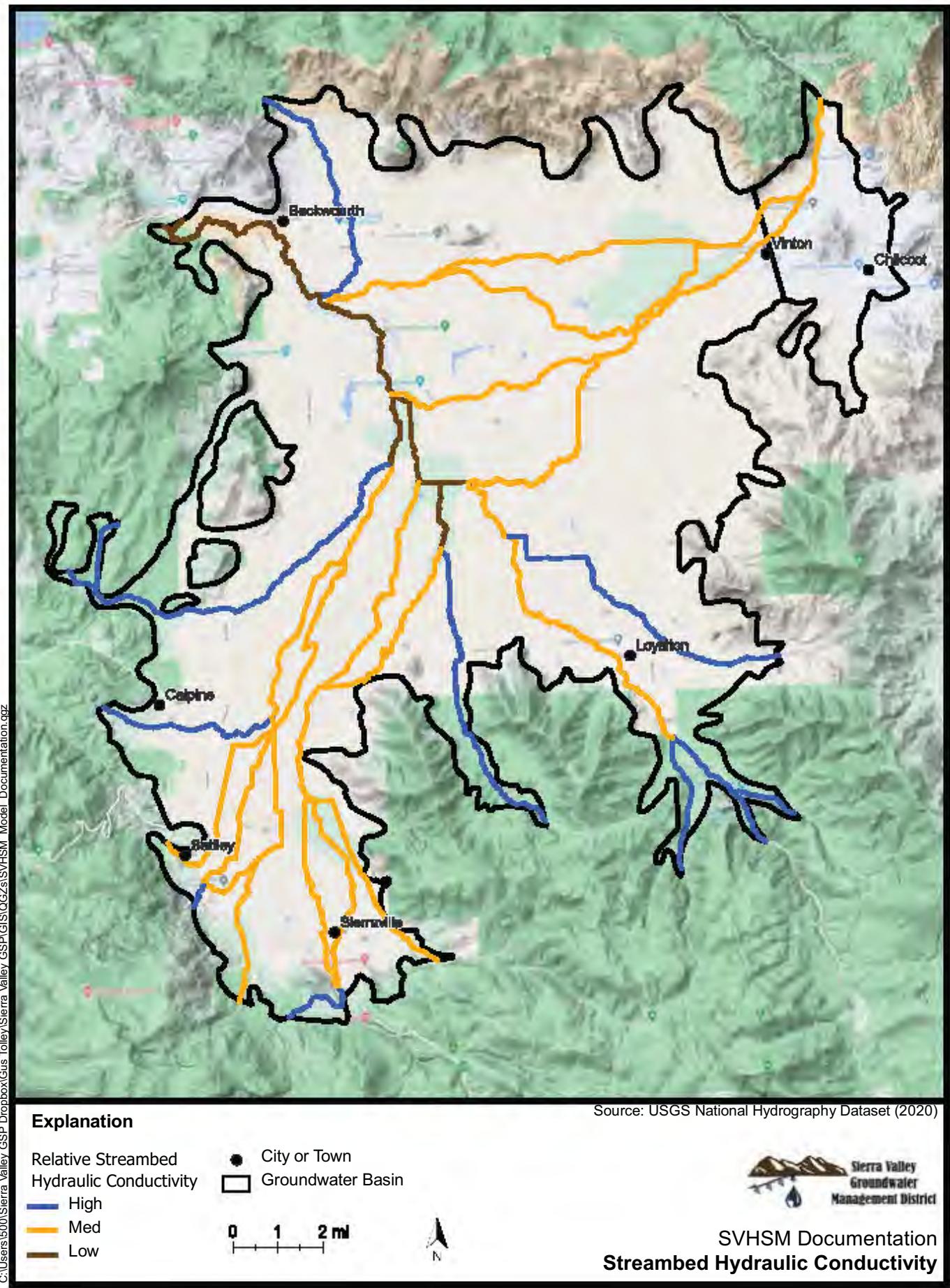
Relative streambed hydraulic conductivities were assigned to each reach (Figure 7-5) that, together with stream and groundwater elevations, control groundwater-surface water exchanges. High streambed conductivity results in strong communication between the groundwater and surface water system, while low streambed conductivity restricts exchanges between the two. Generally, streambed hydraulic conductivity is highest along the margins of the valley and decreases toward the center and outlet of the valley.

7.2 MODFLOW Outputs

Outputs from the MODFLOW submodel of SVHSM include detailed water budget, groundwater elevation, and streamflow data. Frequency of MODFLOW simulation output is specified by the user in the output control file (**SVHSM.oc**); it can vary depending on the output data type and be as detailed as every time step or as coarse as a summary of the entire simulation. Simulated output in SVHSM is generally saved at the end of each month (stress period), except for streamflow data at specified gage locations where output is saved on a daily basis. This frequency was chosen as it allows for evaluation of intra-annual changes while keeping output files to a manageable size.

7.2.1 Groundwater Elevations

Groundwater elevations, also referred to as groundwater heads, are saved at every active cell in the model domain at intervals specified by the user in the output control file. In SVHSM, heads are printed at the end of every stress period (month). Due to the large number of active model cells and stress periods, this file (**SVHSM.hds**) is written into a binary format to reduce the file size and therefore cannot be viewed in a text editor directly like most of the other model input and output files. The file **Read_MODFLOW_heads.R** included in the model post processing R script library on the project repository (<https://github.com/gustolley/SVHSM>) can be used to translate the binary file into an ASCII format that can be read by standard text editors.





Groundwater elevations can be extracted for the entire model domain for a specific stress period, or as a time series for all layers at a specific row-column location. Other freely available options for reading the groundwater elevation data include the USGS software ModelMuse (<https://www.usgs.gov/software/modelmuse-graphical-user-interface-groundwater-models>), Python scripts (<https://github.com/modflowpy/flopy>), or other R scripts (<https://rdrr.io/cran/inlmisc/>).

The other location groundwater heads in the model are saved in the head observation (HOBS) package output file (**SVHSM_HOB_out.dat**). Data written to this file are simulated and observed groundwater elevations at the corresponding location and time of observations provided in the HOBS input file (SVHSM.hob) and are used to evaluate model performance (see Section 8). The file can be viewed with a standard text editor.

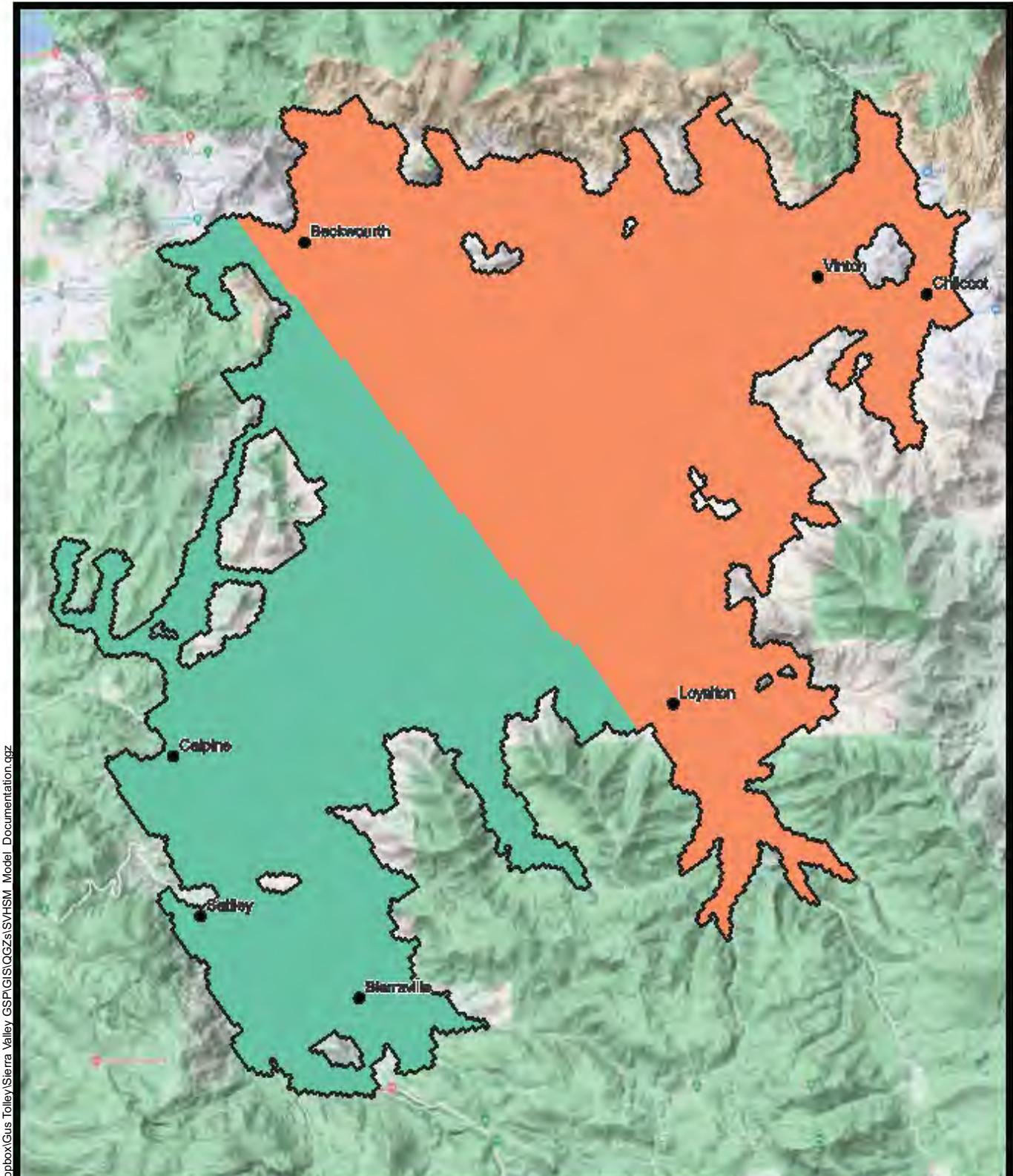
7.2.2 Water Budgets

MODFLOW tracks the movement (flux) of water into, within, and out of the model domain which allows for development of detailed water budgets. Summary water budgets for the entire model are printed at intervals specified by the user in the output control file. Fluxes are grouped according to the physical process represented in the model, such as groundwater pumping, recharge, and change in storage.

Water budgets are printed to several different output files. A model summary of cumulative flux volumes and daily flux rates for the time step specified in the output control file are printed to the listing file (**SVHSM.Ist**). For SVHSM, this means that cumulative volumetric water budgets are printed at the end every month along with the flux rates for the last day of each month. A new feature in MF-OWHM v2.0 is the ability to print water budgets for every time step directly to a spreadsheet formatted file. This is done by specifying a filename for the *BUDGETDB* parameter in the options list at the beginning of the basic package (BAS or BAS6) input file (**SVHSM.bas**). In SVHSM, this file is named **MODFLOW_Budget.dat**. Both the listing file and the spreadsheet formatted budget file can be viewed with standard text editors.

Cell-specific fluxes are written to the cell-by-cell budget file (**SVHSM.cbb**) at intervals specified by the user in the output control file. In SVHSM, these fluxes are saved for the last day in each month and can be used to evaluate water budgets for specific portions of the model, as opposed to the summary (global) budgets exported to the listing file and spreadsheet formatted budget file. This is done by specifying zones within the model domain and using the **ZONEBUDGET** program (<https://www.usgs.gov/software/zonebudget-program-computing-subregional-water-budgets-modflow-groundwater-flow-models>) to extract the saved flux rates.

Two different zonations were created to evaluate water budgets spatially in SVHSM. The first separates the eastern and western portions of the groundwater basin separated by the Loyalton Fault (Figure 7-6). The second uses the same east-east differentiation but also subdivides the eastern portion of the basin into an upper and lower zone; the upper zone is defined as the top three layers of the model. The values extracted using ZONEBUDGET are flux rates for the time step during which they are printed, as opposed to the volumetric fluxes saved in the global water budgets.



Explanation

Budget Zone
■ Eastside
■ Westside

● City or Town
■ Active MODFLOW
Domain Boundary

Notes:
1. Active cells in Layer 1 shown

0 1 2 mi



SVHSM Documentation
Water Budget Zones



While most fluxes are generally constant during the stress period (e.g., pumping and recharge), some fluxes are dependent on water levels (e.g., groundwater-surface water exchange and ET), which can change over the stress period. The flux rate for a given budget component saved at the end of the month may not be the same as that at the beginning of the month, which can potentially result in significant extrapolation errors if converted to monthly volumes. Therefore, ZONEBUDGET results are presented with rate units as opposed to volume units used in the global water budgets.

7.2.3 Streamflow

Streamflow simulated using the SFR package in MODFLOW can be exported several different ways. Commonly, time-series data at a specific location are desired in order to compare simulated streamflow with observations from a stream gage. The streamflow gaging (GAGE) package in MODFLOW allows the user to specify SFR reaches where outputs are saved for every time step. The current version of SVHSM only has a single model gage located at the most downstream reach in the surface water network (Figure 7-4), with results saved to **SVHSM_streamflow_MFFR.dat**. This represents the Middle Fork Feather River gage near Portola (MFP) (<http://stratus.water.ca.gov/dynamicapp/QueryF?s=MFP>) operated by DWR. While the simulated location of the gage is approximately 0.8 mile (1.3 km) upstream of the actual location, streamflow at both locations is assumed to be similar as no tributaries enter between the two and groundwater-surface water exchanges are expected to be minor given the short distance. Files produced by the gage package can be viewed with any standard text editor.

Results for all simulated reaches are also printed at intervals specified by the user in the output control file. In SVHSM, SFR results are printed at the end of every stress period (month) to **SVHSM_Streamflow_Global.dat**. This provides a snapshot in time of conditions for the entire streamflow network. A new feature in MF-OWHM v2.0 is the ability to export detailed streamflow data for the entire surface water network at every time step directly to a spreadsheet formatted file. This is done by specifying a filename for the *DBFILE* parameter in the options list at the beginning of the SFR package input file (**SVHSM.sfr**). In SVHSM, this file is named **SFR_out.dat**. Although both reach budget files can be viewed with a standard text editor, they are they are considerably large (3-6GB file size) and therefore may take considerable time to open.

8.0 Sensitivity Analysis and Calibration

A numerical model can generally be partitioned into two development categories:

(1) parameterization and (2) numerical value assignment to the parameterization.

Parameterization in the context of integrated hydrologic models is the establishment of the physical framework, or structure, and what/how different real-world hydrologic processes are to be simulated. Structural components of SVHSM are discussed in Sections 4 through 7, and generally include things like how the subsurface sediment distribution is represented, how different boundary conditions (e.g., pumping, streams, MFR) are distributed throughout the



model domain, and specific hydrologic processes are represented within the numerical model. Some structural model elements have a relatively high degree of certainty because they can be easily observed (e.g., topography, landcover, stream locations). Others can vary with location due to differences in data density (e.g., subsurface sediment distribution), and some have a high degree of uncertainty because they cannot be directly observed (e.g., MFR).

Once the model parameterization has been prescribed, numerical values for physical properties or boundary condition fluxes must be assigned in order to solve the system of equations posed by the numerical model. For example, eight lithology categories were used to represent the subsurface in SVHSM. The distribution of these categories in each layer is how the model was parameterized, but physical values that represent hydraulic conductivity, anisotropy, and storage must be assigned to each of these categories. Parameter values are rarely a fixed (scalar) number but instead occur over a likely range (distribution). Hydraulic conductivity is commonly used to demonstrate this, as naturally occurring values range over eight orders of magnitude. Additional information such as the sediment type being represented can be used to constrain the range to within a few orders of magnitude, but that still covers a wide range of possible values.

Sensitivity analysis and calibration are two tools that are used to assess model parameterization and define optimum parameter values. Sensitivity analysis is used to evaluate which parameters have the greatest impact on simulated results by comparing changes in simulated output when parameter values are adjusted. Model calibration, also known as inverse modeling, is the process of adjusting parameter values so that the difference between simulated and observed values is minimized. Both methods can inform parameterization and parameter value assignment, and can be performed manually or using automated software.

8.1 Methods

Sensitivity analysis and calibration of SVHSM was performed manually for the PRMS submodel while an automated method was used for the SWBM and MODFLOW submodels. Manual methods were chosen for the PRMS model, as the input file structure makes it difficult to automate with a reasonable number of parameters. In addition, the lack of streamflow data would likely result in what is referred to as an “underdetermined” problem, where the number of knowns (observations) is less than the number of unknowns (parameters). Therefore, the effort required to develop the input files required for PRMS to be evaluated with automated methods was not considered to be an efficient use of the limited time available. This may change in the future if additional observations are collected within the PRMS model domain area.

Sensitivity analysis and calibration of the SWBM and MODFLOW submodels of SVHSM was performed using the universal inverse modeling software suite UCODE_2014 (Poeter and others, 2005 and 2014) (<https://igwmc.mines.edu/ucode-2/>) which compares measured observations (e.g., groundwater elevations, streamflow rates, pumping volumes) with simulated equivalents in the model. Residuals, or the differences between simulated equivalents and measured observations, are aggregated into a single value referred to as the objective function



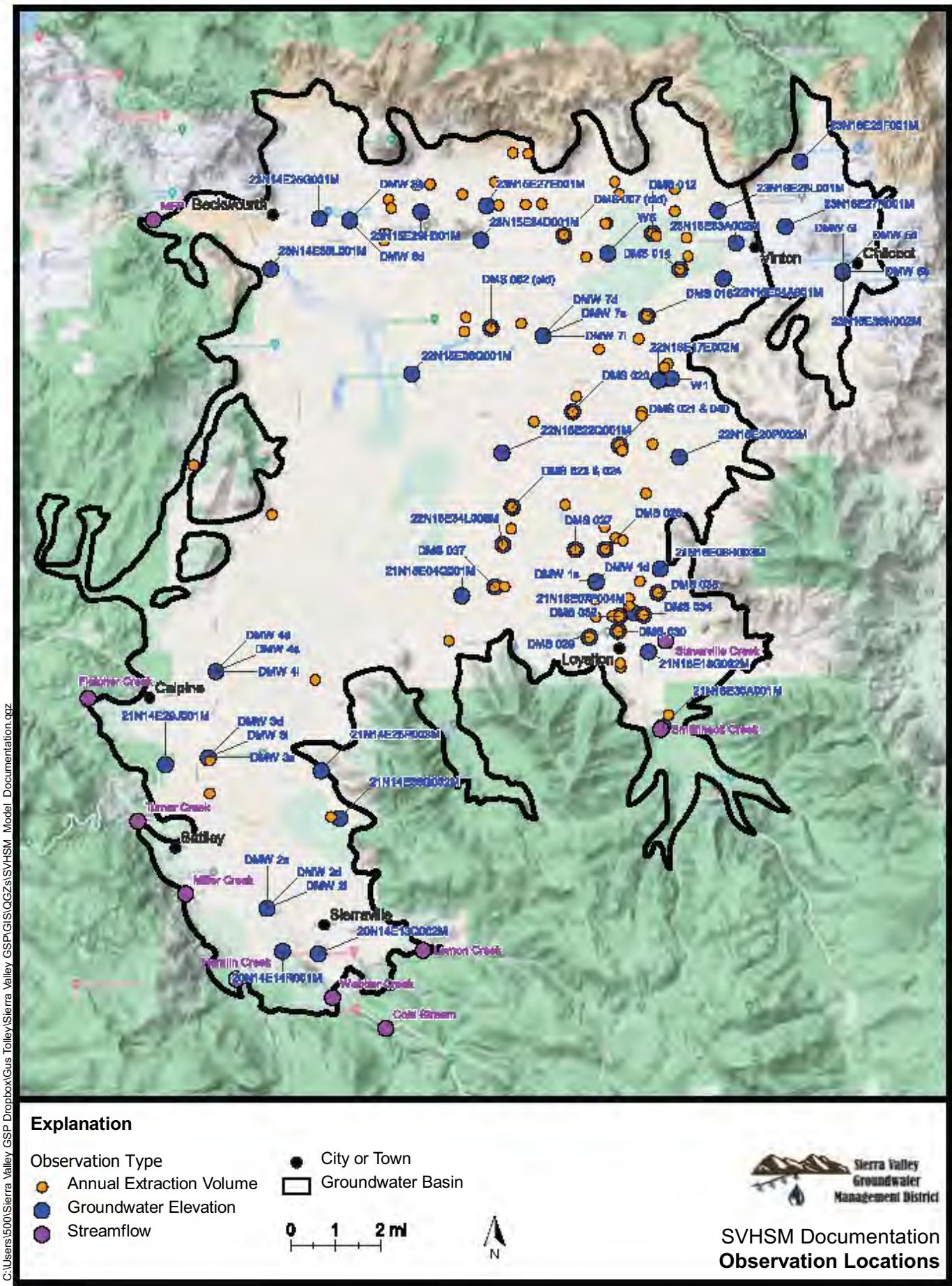
which represents a numerical valuation of the overall mismatch between the two for the entire model. A reduction of the objective function value generally means the model is a better representation of the system, as it is producing similar conditions to those observed. Because most physical aquifer properties do not vary with time, once optimum parameter values for a historical time period have been identified, future conditions can be estimated by altering the model boundary conditions appropriately.

The forward-difference perturbation technique available in UCODE_2014 was used to perform sensitivity analysis on 79 identified parameters. Parameter values were increased one at a time by 1% from their starting values. Initial parameter values were chosen based on previously published values and expert judgement. Parameter sensitivity is fit-independent for linear models, meaning that the same sensitivities are calculated whether or not parameter values are at their optimum value. For highly nonlinear models, parameter sensitivities can change depending on the choice of initial values (Tolley and others, 2019) even when model structure is not altered. Inclusion of groundwater-surface water interactions generally adds nonlinearity to a numerical model. Unfortunately, the project timeline did not allow for evaluation of model nonlinearity so a linear model was assumed. Evaluation of the degree of nonlinearity of SVHSM could be conducted using UCODE_2014 as part of future sensitivity analysis and calibration efforts.

Selected model parameters based on the sensitivity analysis results were then adjusted automatically using the parameter optimization mode in UCODE_2014 in an attempt to minimize the objective function and therefore provide the best match between observed and simulated values. Convergence was met when either parameter values did not vary by more than 1% ($TolPar = 0.01$), or the objective function did not change by more than 1% for three consecutive iterations ($TolSOSC = 0.01$).

8.2 Observations

Observations used to develop the objective function include water levels, streamflow, and annual groundwater pumping (Figure 8-1). Weights are applied to each residual to (1) convert all observations into similar units so they can be squared and summed together and (2) reflect the observation certainty. More accurate observations are given greater weight, which increases their influence on the objective function value.



8.2.1 Streamflow

Instantaneous streamflow observations collected intermittently from nine tributaries near the margin of the groundwater basin (Figure 8-1) were used to manually calibrate the PRMS submodel of SVHSM.

Daily streamflow observations from the Middle Fork Feather River near Portola (MFP) (<http://cdec4gov.water.ca.gov/dynamicapp/QueryF?s=MFP>) gage (Figure 8-1) were used to calibrate the SWBM and MODFLOW submodels of SVHSM. Flow data at this gage were available from September 8, 2006 through October 1, 2018, and represent total surface water outflow from the groundwater basin. A total of 500 streamflow observations were randomly selected from this dataset (Figure 8-2) and grouped into low flow (<10 cfs), medium flow (10 to 100 cfs), and high flow (>100 cfs) categories with 100, 300, and 100 observations, respectively. The selected observations are generally distributed through the entire time period for which data are available.

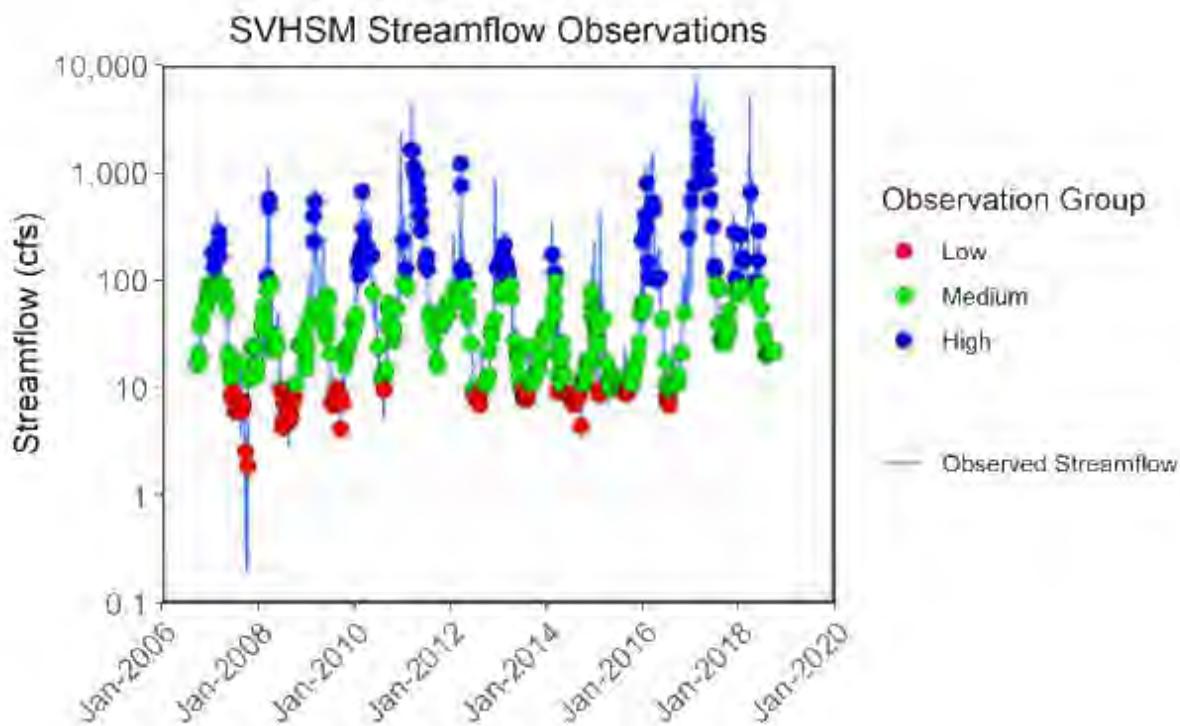


Figure 8-2. Streamflow observations used for sensitivity analysis and calibration.

Streamflow observation weights were determined using the coefficient of variation method, which allows the user to specify a confidence interval for the observation expressed as a percentage. The observation weight is a function of the coefficient of variation and the observation value. A lower coefficient of variation assigned to an observation indicates greater trust in that observation. The low, medium, and high streamflow categories were assigned



coefficients of variation equal to 10%, 20%, and 40%, respectively, to reflect increasing uncertainty in estimated streamflow as flow rates increase.

8.2.2 Groundwater Elevations

A total of 4,112 groundwater elevation observations from 63 observation wells (Figure 8-1) were used to calibrate the SWBM and MODFLOW submodels of SVHSM. Based on available well construction information, 24 observation wells (38%) associated with 1,279 observations (31%) were screened in two or more model layers. Head contributions from these multi-layer observations were assumed to be equal, meaning that the average simulated value from all layers the well was screened within was used as the simulated equivalent. Head observation weights were defined using an assumed measurement error variance of 1 m². Head observations are contained in the UCODE_2014 input file *SVHSM.headobs*.

8.3 Results

Limited sensitivity analysis and calibration efforts performed due to the accelerated project timeline. Despite this limited effort, results presented below show that the model performs reasonably well. Additional calibration efforts are likely to improve model performance even further.

8.3.1 Sensitivity Analysis

Although a formal sensitivity analysis was not performed on the PRMS submodel of SVHSM, parameter sensitivity was observed during the manual calibration efforts. The parameters related to temperature lapse rates (*tmax_lapse* and *tmin_lapse*), which control how temperatures are adjusted for elevation, appeared to significantly affect hydrograph timing. The two parameters controlling downslope routing of gravity reservoir storage (*slowcoef_lin* and *slowcoef_sq*) were also identified as having a significant effect on hydrograph shape and timing. Parameters that represent the groundwater system of the upper watershed and control groundwater-surface water interactions in PRMS such as *gwflow_coef*, *gwsink_coef*, and *gwstor_init* were important for controlling baseflow entering streams. Most of these parameters are applied to the entire basin, or were adjusted uniformly across the basin as part of manual calibration efforts. More detailed evaluation of these parameters at the sub-watershed (stream catchment) scale may improve model representation of streamflows generated from the upper watershed portion of the basin.

Formal sensitivity analysis was performed on 79 parameters (Table 8-1) in the SWBM and MODFLOW submodels of SVHSM using UCODE_2014. Composite scaled sensitivities for the 25 most sensitive parameters are shown in Figure 8-3, with more sensitive parameters indicated by greater value. The most sensitive parameter identified in the analysis was the vertical hydraulic conductivity of the quasi-3D confining bed (*CB_3*) present at the bottom of the third model layer, which means that changes to the value of this parameter results in the greatest change in model results. This parameter affects groundwater heads throughout the model domain, so the high degree of sensitivity is not unexpected.

Table 8-1. Summary of parameters evaluated in SWBM and MODFLOW submodels during sensitivity analysis.

SVHSM Submodel	Parameter Type	Parameter Group	Parameter Names	Description
SWBM	Effective Rooting Depth	SWBM	RD_Alf_Irr, RD_Grn_Irr, RD_Pstr_Irr, RD_NatVeg, RD_Baren, RD_Water, RD_Alf_NI, RD_Grn_NI, RD_Pstr_NI	Total depth that plants can access soil moisture from. Accounts for root depth and capillary movement of water into root zone
	Effective Irrigation Efficiency	SWBM	Fld_IE_Alf, Fld_IE_Grn, Fld_IE_Pstr, WL_IE_Alf, WL_IE_Grn, WL_IE_Pstr, CP_IE_Alf, CP_IE_Grn, CP_IE_Pstr	Ratio of crop water uptake to applied water.
	Crop Coefficient (Kc) Scaling Factor	SWBM	KcMltAlfIrr, KcMltGnIrr, KcMltPstrIrr, KcMltNatVeg, KcMltWater, KcMltAlfNI, KcMltGnNI, KcMltPstrNI	Scaling factor that allows crop coefficients to be adjusted uniformly. Allows for single parameter to adjust crop coefficients that vary over time.
	Hydraulic Conductivity	Kx	Kx_1, Kx_2, Kx_3, Kx_4, Kx_5, Kx_6, Kx_7, Kx_8	Sediment hydraulic conductivity along rows.
	Horizontal Anisotropy	Hani	HANI_1, HANI_2, HANI_3, HANI_4, HANI_5, HANI_6, HANI_7, HANI_8	Scaling factor that adjusts aquifer hydraulic conductivity along columns based on Kx value.
	Vertical Anisotropy	Kvar	KVAR_1, KVAR_2, KVAR_3, KVAR_4, KVAR_5, KVAR_6, KVAR_7, KVAR_8	Scaling factor that adjusts vertical hydraulic conductivity of aquifer based on Kx value.
	Specific Yield	Sy	Sy_1, Sy_2, Sy_3, Sy_4, Sy_5, Sy_6, Sy_7, Sy_8	Unconfined aquifer storage coefficient
	Specific Storage	Ss	Ss_1, Ss_2, Ss_3, Ss_4, Ss_5, Ss_6, Ss_7, Ss_8	Confined aquifer storage coefficient
	Mountain Front Recharge	MFR	MFR_1, MFR_2, MFR_3, MFR_4, MFR_5, MFR_6	Flux of water into model from surrounding bedrock.
	Quasi-3D Confining Bed	Q3DCB	CB_3	Vertical hydraulic conductivity of Quasi-3D confining layer.
MODFLOW	Streambed Hydraulic Conductivity	SFR	BedK_1, BedK_2, BedK_3	Hydraulic conductivity of sediments in stream channels.
	Manning Roughness Coefficient	SFR	Manning_n_1, Manning_n_2, Manning_n_3	Coefficient that defines how easily water can flow through a channel.

Notes:

1. Alf = alfalfa; Grn = grain hay; Pstr = pasture; NatVeg = native vegetation; IE = irrigation efficiency; Fld = flood irrigated; WL = wheel line irrigated; CP = center pivot irrigated; Irr = Irrigated; NI = non-irrigated

2. Numbers in parameter name indicate property zone (Kx, Hani, Kvar, Sy, and Ss), MFR segment (MFR), model layer (Q3DCB), or streamflow channel property segments (SFR).

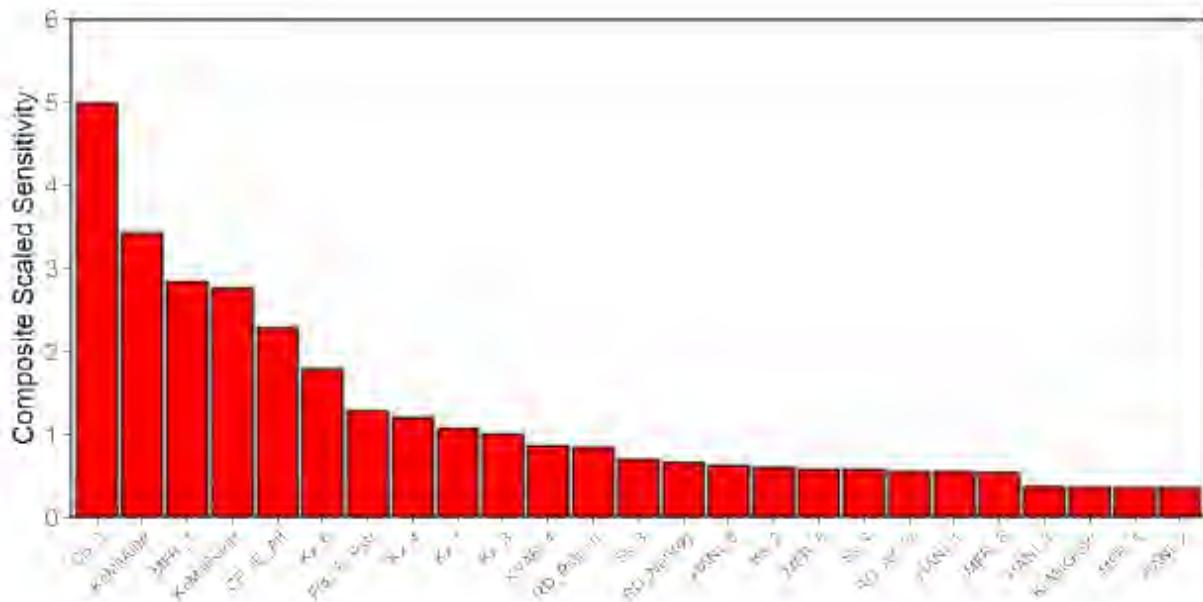
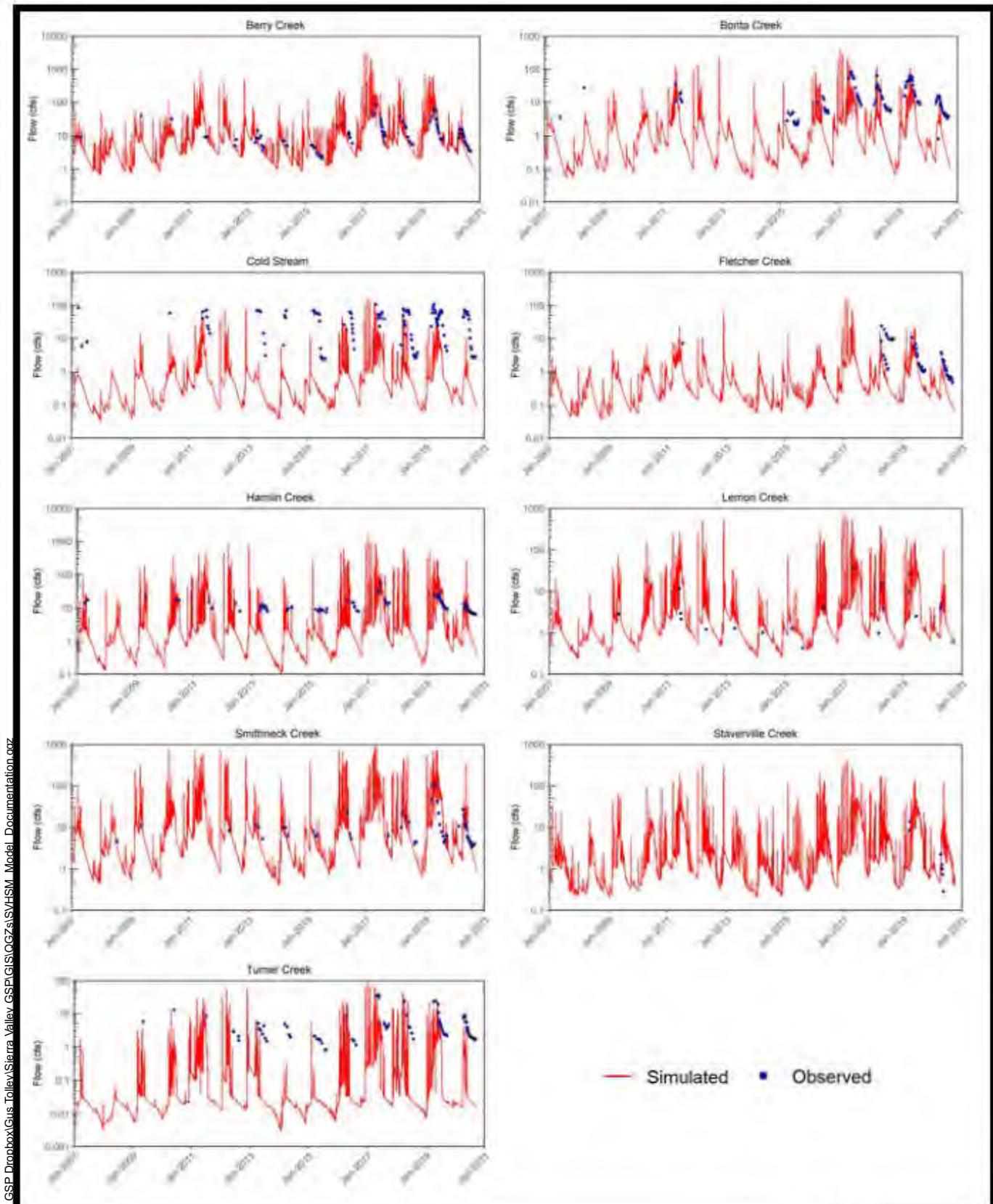


Figure 8-3. Sensitivity analysis results for the 25 most sensitive model parameters in the SWBM and MODFLOW submodels of SVHSM.

Sensitive SVHSM parameters are found in both the SWBM and MODFLOW submodels, indicating that processes represented in each are important for recreating observed groundwater and streamflow conditions. In the SWBM, the crop coefficient factors and irrigation efficiencies for alfalfa ($KcMltAlfIrr$ and CP_IE_Alf) and pasture ($KcMltPstrIrr$ and Fld_IE_Pstr) were the most sensitive. Like the MODFLOW quasi-3D confining bed parameter, these SWBM parameters affect a large portion of the model domain and, therefore, multiple observations. Other sensitive MODFLOW parameters include the MFR flux (MFR_1) into the southwest portion of the model domain (see Figure 7-3) and the hydraulic conductivity (K_x) for aquifer property zones 6, 4, 1, and 3. Eight parameters (Sy_5 , Sy_7 , Sy_8 , MFR_2 , RD_Barren , RD_Water , Fld_IE_Grn , and $KcMltWater$) were determined to be insensitive, meaning that changes in their values did not result in changes to the model output. This is because either the parameters occupy only a small portion of the model domain (e.g., Sy_5) or there are limited nearby observations (e.g., MFR_2).

8.3.2 Calibration

Manual calibration results of the PRMS submodel of SVHSM are shown in Figure 8-4. In general, agreement between simulated and observed flows is moderate but highly stream dependent. For example, there is strong agreement for Berry Creek, Lemon Creek, and Smithneck Creek but poor agreement for Cold Stream, Hamlin Creek, and Turner Creek. However, the lack of streamflow observations, particularly during the winter months, makes it difficult to fully ascertain the level of model performance.



— Simulated • Observed

Notes:

1. Smitneck Creek is a combination of Smitneck, Bear Valley, and Badenough creeks due to gage location.



SVHSM Documentation
PRMS Streamflow Calibration Results



When agreement is poor, the model appears to be capturing the general shape of the hydrograph, but either the timing or magnitude of flow is incorrect. This suggests that the PRMS submodel would benefit from detailed subwatershed-scale calibration efforts, as parameters that are currently assumed to be constant for the entire watershed (e.g., groundwater contributions) may vary across stream catchments. Furthermore, spatially distributed parameters were only adjusted during the manual calibration using scaling factors that applied to the entire model domain; adjustment of these parameters at the catchment scale is likely necessary to improve model performance.

During calibration of the SWBM and MODFLOW submodels of SVHSM, it was discovered that groundwater heads were equilibrating in the upper and lower layers of the model regardless of parameter values despite widespread distribution of low conductivity sediments (hydraulic property zones 3 and 4 and possibly 6). This was inconsistent with observations, especially those from nested wells located on the eastern side of the groundwater basin that showed a strong vertical gradient between the upper and lower portions of the aquifer system. Therefore, it was decided this was likely a structural error in the model and a quasi-3D confining bed was added to the bottom of layer 3 (CB_3) to restrict flow between the upper and lower model layers.

The addition of the quasi-3D confining bed generally improved model results and produced vertical gradients similar to those observed. However, this addition was made relatively late during the calibration process and the project timeline did not allow for an additional round of sensitivity analysis and calibration runs. The calibration results presented below use the version of the model with the quasi-3D confining bed and parameter values (see Appendix D) from a previous calibration run without the confining bed present.

Agreement between observed groundwater elevations and those simulated by the model is generally good (Figure 8-5). Linear regression of simulated and observed heads produces a slope of 1.09 with a correlation coefficient (R^2) of 0.87. Residuals, or the difference between observed and simulated values, are shown for each well in Figure 8-6. Some wells show very strong agreement (small magnitude residuals) between observations and simulated equivalents, while water levels in other wells are consistently overpredicted or underpredicted. Wells with the highest magnitude residuals tend to be irrigation (DMS) wells.

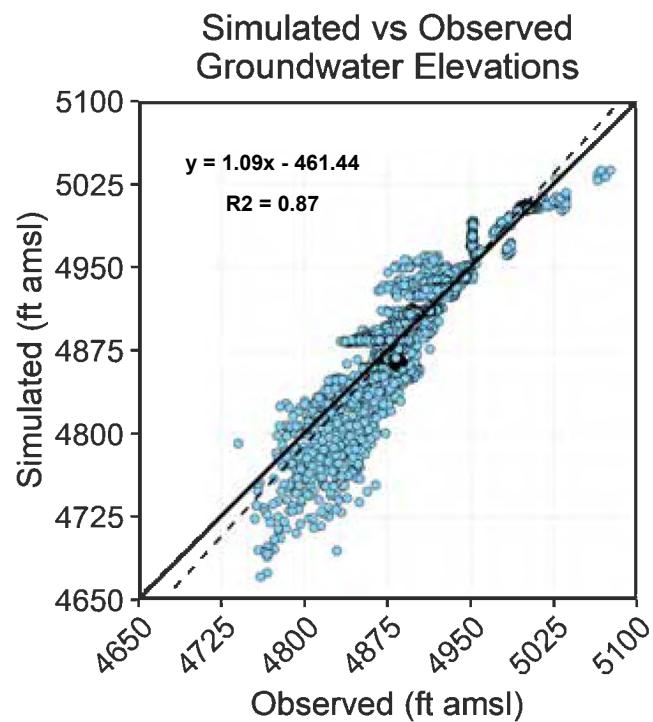


Figure 8-5. Simulated vs observed groundwater elevations. Solid line is one-to-one line. Dashed line shows linear regression of the data.

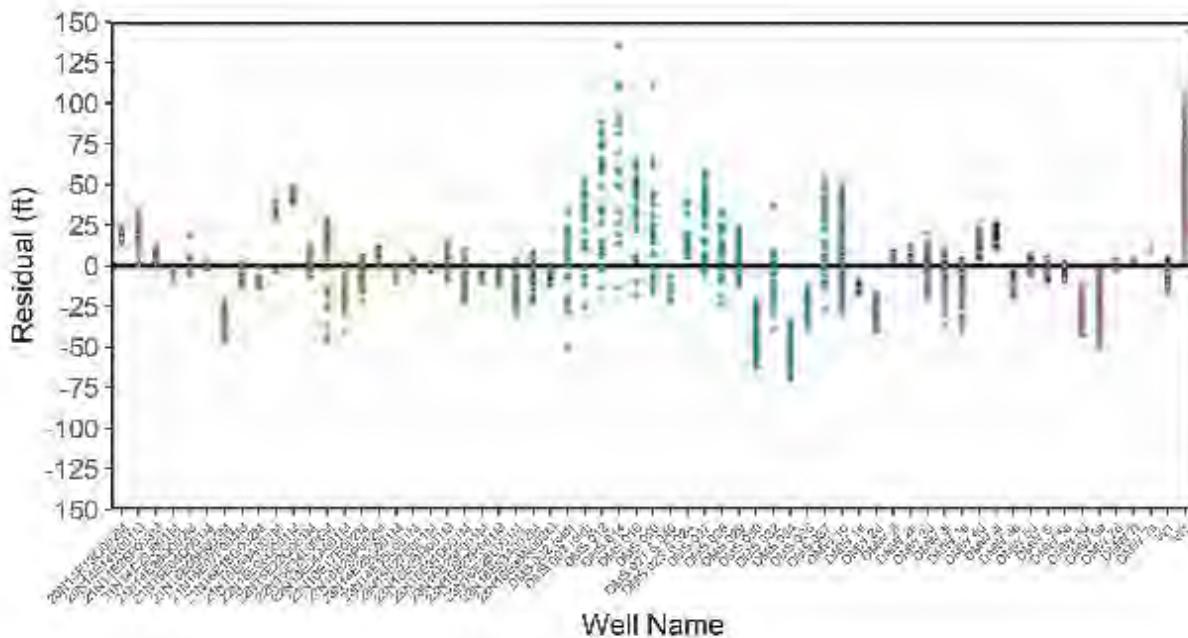
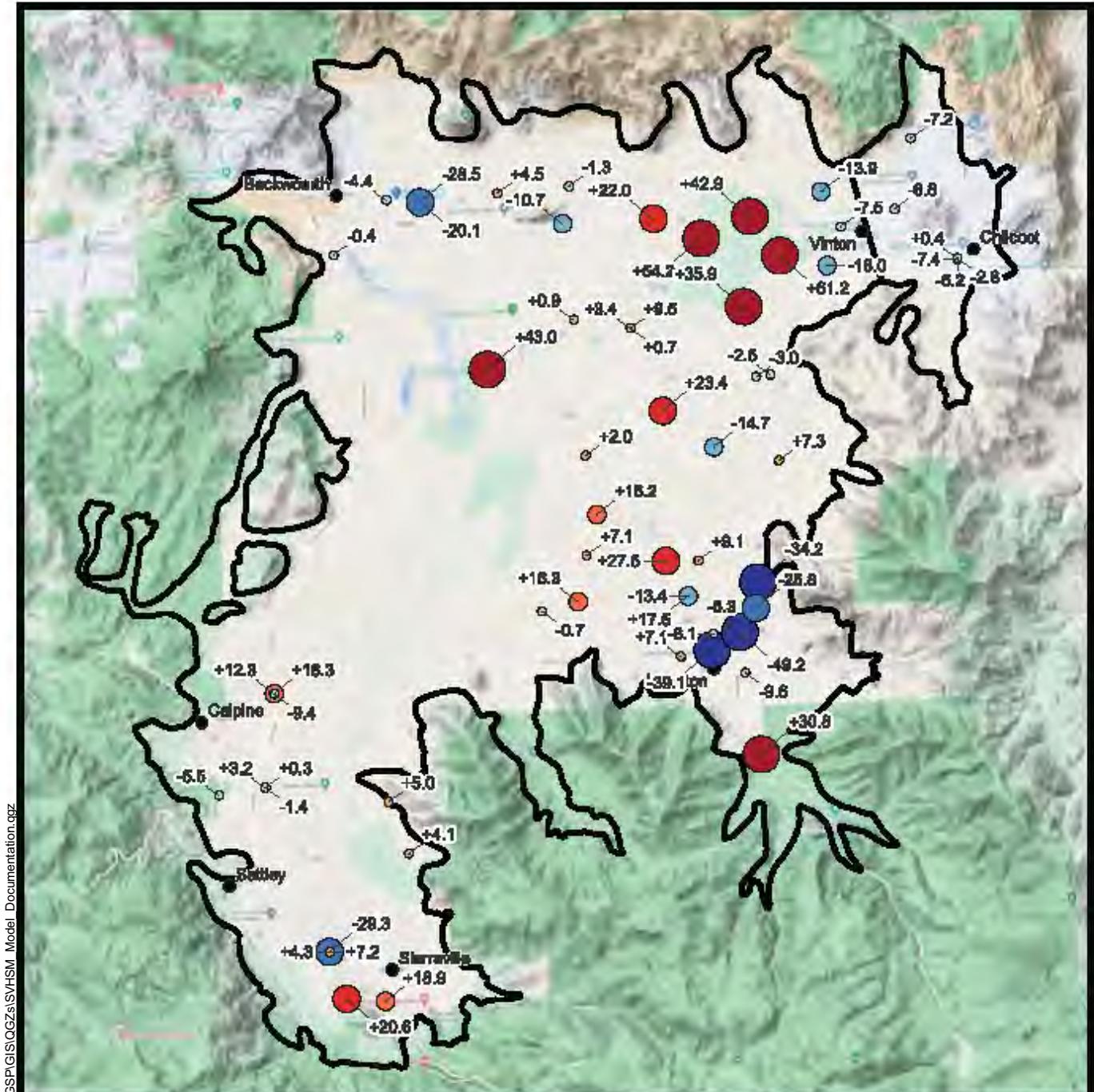


Figure 8-6. Agreement between simulated and observed groundwater levels varies by well. Small residual values indicate greater agreement between observations and simulated results. Residuals with the largest magnitudes tend to be from irrigation (DMS) wells.

Spatial distribution of average, minimum and maximum groundwater head residuals are shown in Figures 8-7 through 8-9. In general, the model appears to be doing a satisfactory job of representing groundwater elevations for most of the model domain. Approximately 26% of simulated heads are within 5 feet, 49% are within 10 feet, and 71% are within 20 feet of observed water levels. Two areas that show the greatest average model error in groundwater heads are the northeast portion of the valley where a large portion of groundwater pumping occurs, and to the northeast of Loyalton.

Selected hydrographs for wells located throughout the valley and at different depths are shown in Figure 8-10. While groundwater elevations and trends are generally captured at most wells, the hydrographs show the complex behavior of the aquifer system such as observed seasonal water level fluctuations up to 100 feet. Even though known extraction volumes were used to specify pumping rates for the majority of the simulation period, it appears that some pumping was either neglected or attributed to the wrong well as evidenced by the model not capturing significant drawdown events (e.g., 22N16E17E002M and DMW 3s). Wells that appeared to be poorly represented based on analysis of residuals (e.g., DMS 037 and W5) show that while the magnitude of simulated groundwater elevation is incorrect, the general trend of the hydrograph is captured by the model. This indicates that significant improvement in the representation of groundwater elevations would likely be achieved with a more thorough calibration effort than was possible to due project timeline constraints.



Explanation

Average Head Residual (ft)



● City or Town
□ Groundwater Basin

0 1 2 mi

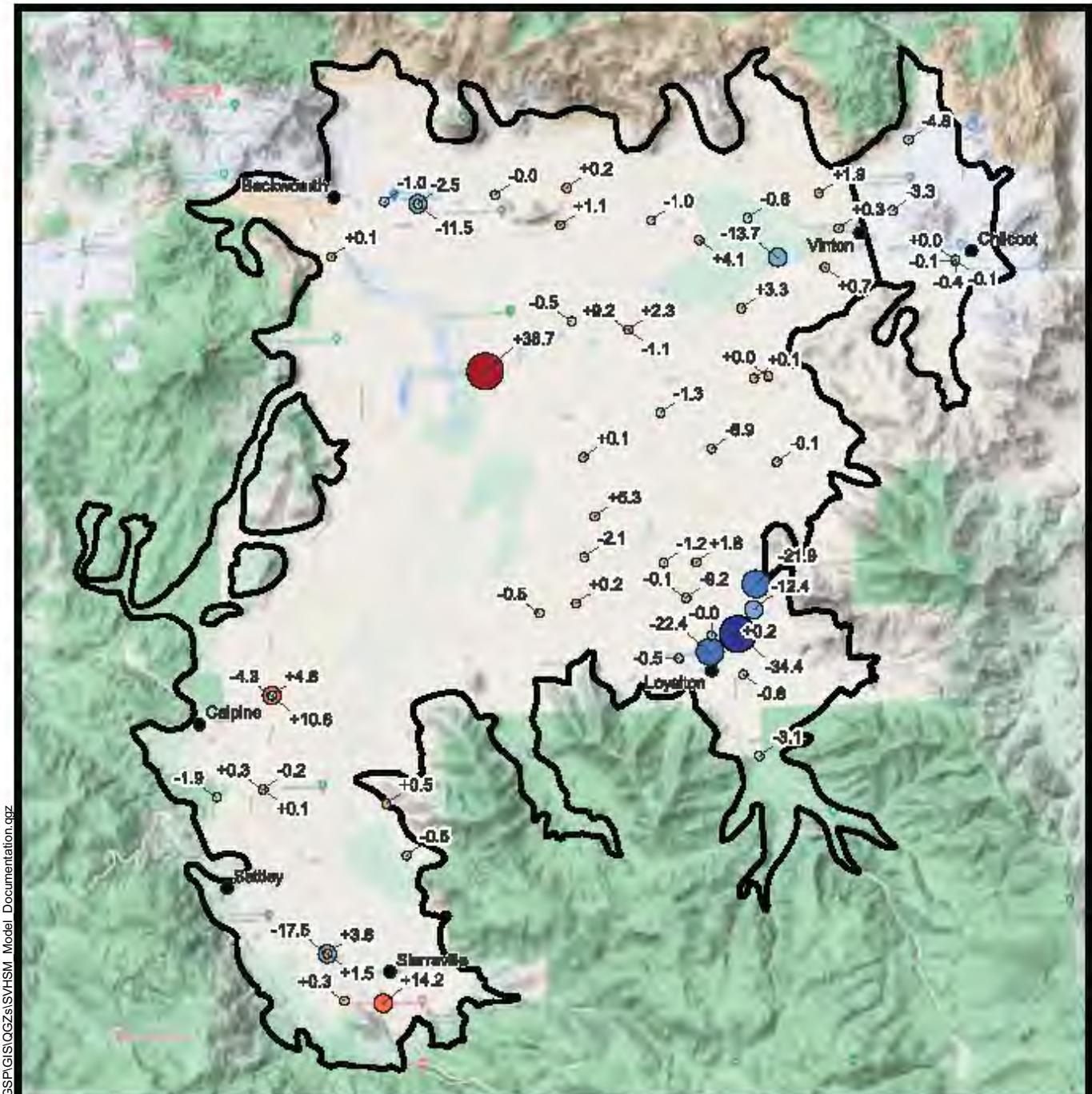


Notes:

1. Negative residual indicates overestimation of groundwater elevation
2. Positive residual indicates underestimation of groundwater elevation
3. Labels indicate residual value
4. Multiple residuals at same location indicates nested monitoring well



SVHSM Documentation
Average Groundwater Head Residuals



Explanation

Minimum Head Residual (ft)



● City or Town

□ Groundwater Basin

0 1 2 mi

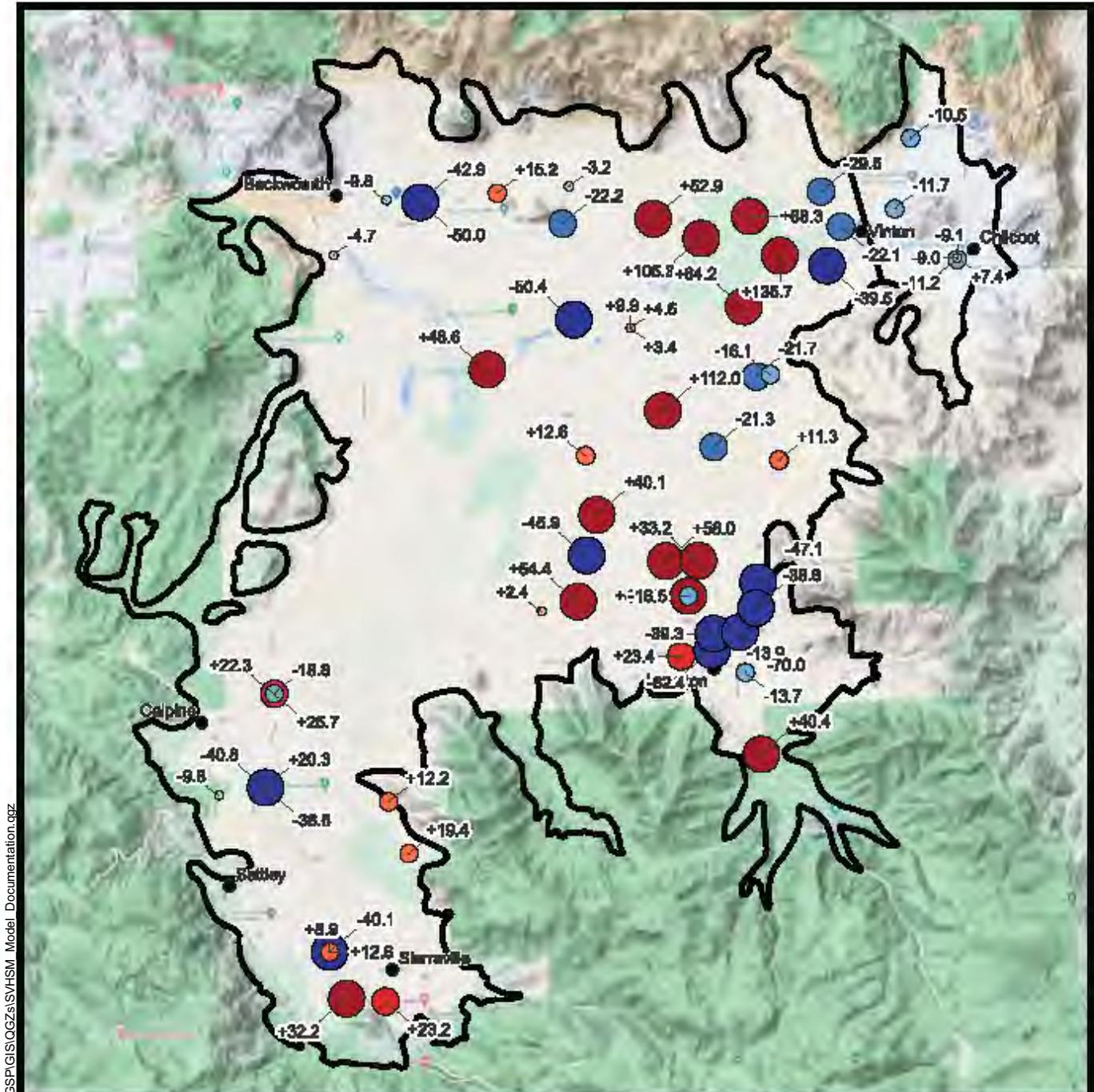


Notes:

1. Negative residual indicates overestimation of groundwater elevation
2. Positive residual indicates underestimation of groundwater elevation
3. Labels indicate residual value
4. Multiple residuals at same location indicates nested monitoring well



SVHSM Documentation
Minimum Groundwater Head Residuals



Explanation

Maximum Head Residuals (ft)



● City or Town

□ Groundwater Basin

0 1 2 mi



Notes:

1. Negative residual indicates overestimation of groundwater elevation
2. Positive residual indicates underestimation of groundwater elevation
3. Labels indicate residual value
4. Multiple residuals at same location indicates nested monitoring well



SVHSM Documentation
Maximum Groundwater Head Residuals

Comparison of simulated streamflow to observed values at gages was done both graphically and using a modified version of the Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970). An NSE of 1.0 indicates the model perfectly matches observations, while a value of 0.0 means the model is no more accurate than predicting the mean value. Streamflow data were log-transformed because they span more than 3 orders of magnitude and large variance can produce high NSE values even if model fit is relatively poor (Jain and Sudheer, 2008). Therefore, NSE values presented here are conservative.

Surface water outflow from the Middle Fork Feather River is moderately well represented with the current parameterization of SVHSM (Figure 8-11) with an NSE of 0.65. Model mismatch during high runoff events is expected, as the duration of these is typically on the order of days, whereas SVHSM boundary conditions are specified on a monthly time scale. Simulated streamflow appears to be biased slightly high during the summer months.

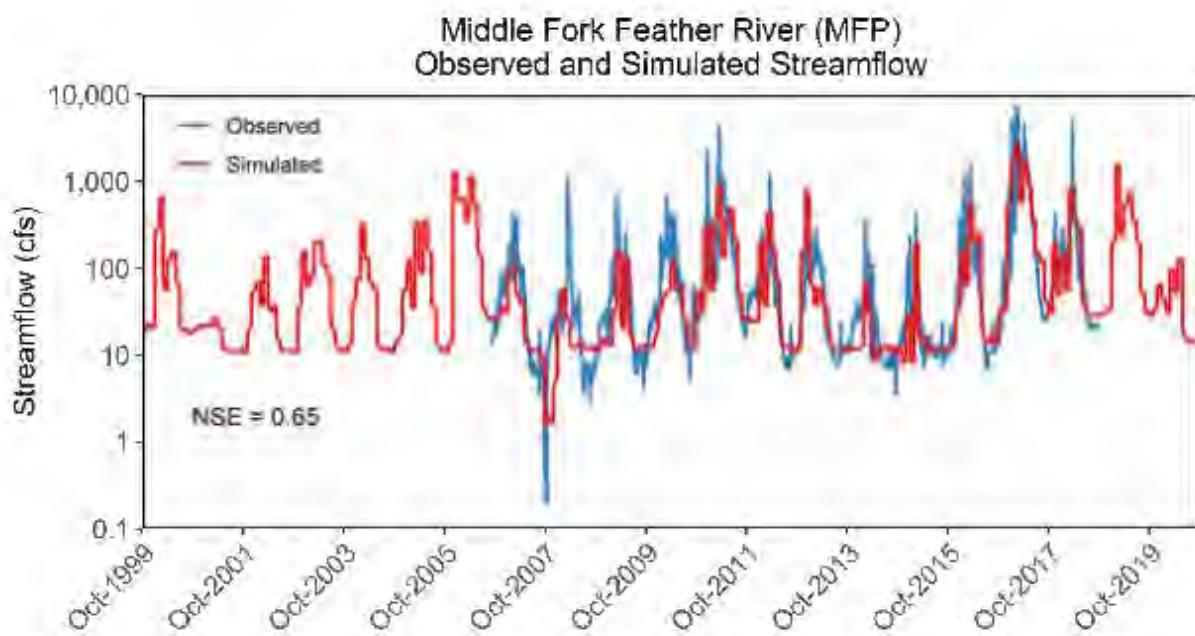


Figure 8-11. Surface water outflow from the basin via the Middle Fork Feather River is satisfactorily represented in SVHSM. NSE = Nash-Sutcliffe efficiency.

This may be due to overestimation of groundwater discharge to surface water near the gage, underestimation of stream leakage within the groundwater basin, misrepresentation of reservoir releases from Lake Davis via Big Grizzly Creek, which enters just above the gage, or a combination thereof.



9.0 Water Budgets

One of the key outputs of SVHSM are water budgets, which account for the movement of water into, within, and out of one of the three main hydrologic subsystems (i.e., land surface, surface water, and groundwater) that occurs during the simulation period. SVHSM simulates conditions from October 1, 1999 through September 30, 2020. We have defined the historical period to be WY 2000 through 2015, and the current period to be the most recent five years (WY 2016 through 2020) for which data were available. Projected future water budgets that incorporate anticipated climate change effects were also evaluated for a 50-year planning horizon.

9.1 Historical Water Budgets

The historical annual surface water budget for the Basin is shown with water year types in Figure 9-1, summarized with average, minimum, and maximum flows in Table 9-1. The water budget reveals a wide range of surface water conditions that depend on the water year type. During dry, normal, and wet years, surface water fluxes within the Basin average about 58,000 AFY, 106,000 AFY, and 357,000 AFY, respectively.

The historical annual land surface water budget for the Basin is shown with water year types in Figure 9-2, summarized with average, minimum, and maximum flows in Table 9-2. The water budget reveals a wide range of conditions that depend on the water year type. During dry, normal, and wet years, land surface water fluxes within the Basin average about 166,000 AFY, 219,000 AFY, and 380,000 AFY, respectively.

The historical annual groundwater budget for the Basin is shown with water year types in Figure 9-3, summarized with average, minimum, and maximum flows in Table 9-3. The water budget reveals a wide range of conditions that depend on the water year type. During dry, normal, and wet years, groundwater fluxes within the Basin average about 25,000 AFY, 32,000 AFY, and 50,000 AFY, respectively.

The relative contributions of recharge attributed to the valley floor area versus the mountain-front area vary depending on the water year type. This is because valley floor recharge rates are calculated using the SWBM, while mountain-front recharge is largely unknown and currently simulated as a constant inflow (about 3,700 AFY) to the basin based on limited model calibration. During dry years, valley floor recharge varies between about 2,000 and 20,000 AFY. During normal years, valley floor recharge varies between about 8,000 and 38,000 AFY. During wet years, valley floor recharge is much greater, varying between about 32,000 and 68,000 AFY.

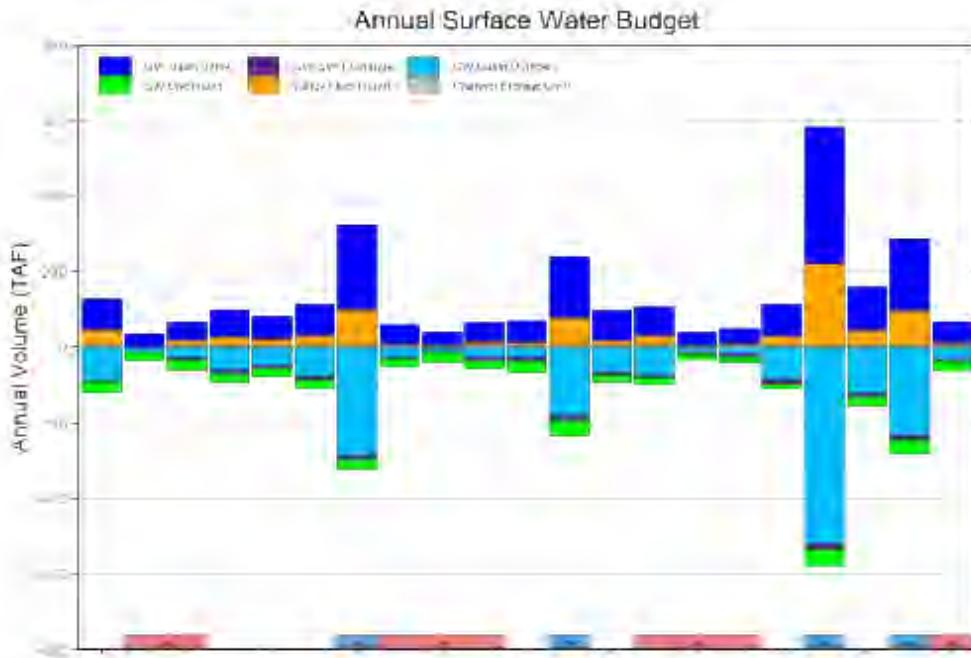


Figure 9-1. Historical and current annual surface water budget.

Table 9-1. Historical (WY 2001-2015) surface water budget summary.

Annual Flow (AFY)				
Flow	Component	Average	Minimum	Maximum
Inflow	Stream Flow	75,400	34,700	226,700
	Valley Floor Runoff	22,400	1,100	97,600
	Subtotal	97,800	36,600*	324,300*
Outflow	Stream Flow (MFFR)	-62,800	-11,900	-285,300
	SW Diversions	-25,000	-15,300	-43,300
	Subtotal	-87,800	-29,400*	-314,100*
Inflow/Outflow	GW Exchange	-7,000	-900	-13,600

Notes:

- Values represent water years 2001 through 2015. WY 2000 excluded to remove influence of assumed initial conditions.
- MFFR: Middle Fork Feather River
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.

* Column arithmetic not applicable since values may come from different years and violate mass balance. Mass-conservative values shown.

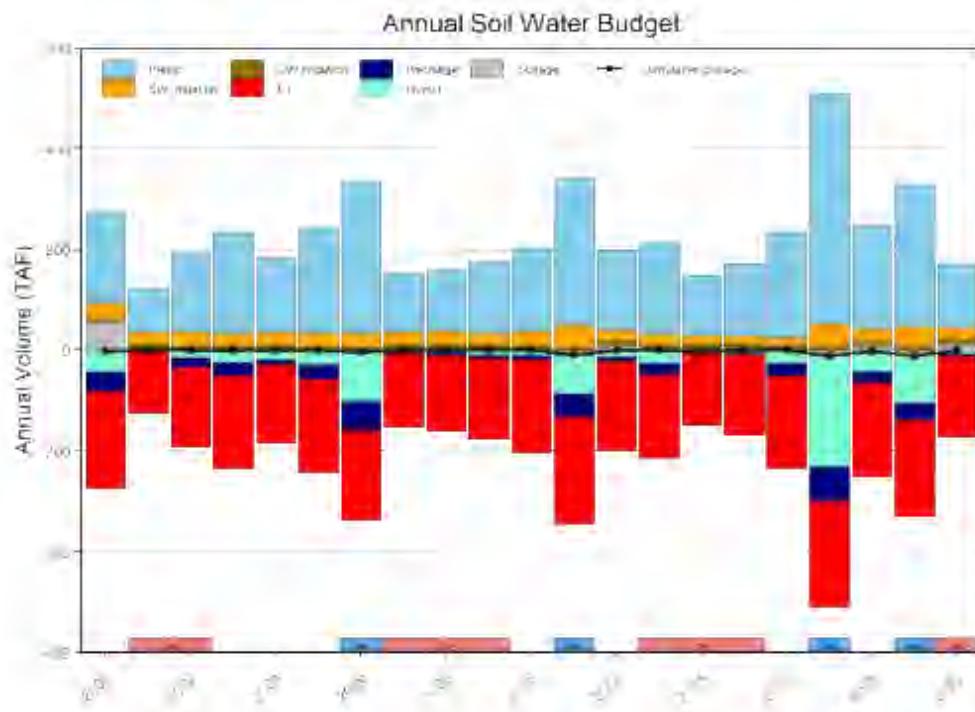


Figure 9-2. Historical and current annual land surface water budget.

Table 9-2. Historical (WY 2001-2015) land surface water budget summary.

Flow	Component	Annual Flow (AFY)		
		Average	Minimum	Maximum
Inflow	Precipitation	170,400	88,800	302,000
	Irrigation (from SW)	25,000	15,300	43,300
	Irrigation (from GW)	8,900	5,100	12,100
	Subtotal	204,300	121,800*	343,200*
Outflow	Evapotranspiration (Irrigated Fields)	-69,400	-57,700	-85,600
	Evapotranspiration (Non-Irrigated Fields)	-37,700	-26,200	-48,600
	Evapotranspiration (Native Vegetation)	-58,800	-36,800	-77,800
	Recharge (to GW)	-16,200	-2,400	-57,100
	Runoff	-22,400	-1,100	-97,600
	Subtotal	-204,500	-124,200*	-333,900*
Change in Storage		-100	-9,600*	9,200*

Notes:

- Values represent water years 2001 through 2015. WY 2000 excluded to remove influence of assumed initial conditions.
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.

* Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.

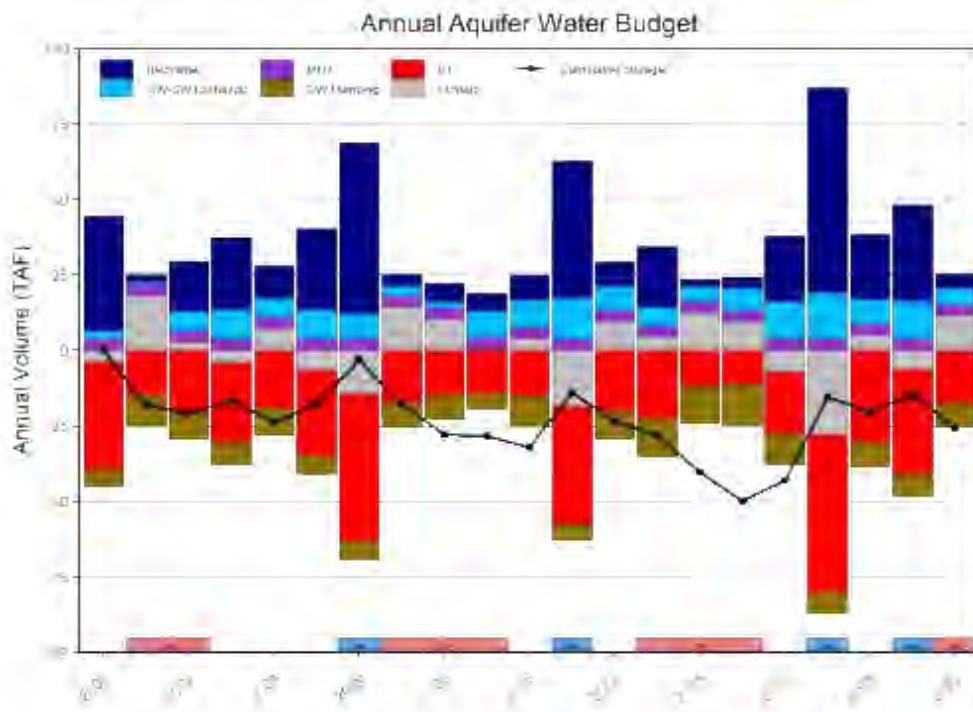


Figure 9-3. Historical and current annual groundwater budget.

Table 9-3. Historical (WY 2001-2015) groundwater budget summary.

Flow	Component	Annual Flow (AFY)		
		Average	Minimum	Maximum
Inflow	Recharge (Valley Floor)	16,100	2,400	56,900
	Recharge (Mountain Front)	3,700	3,700	3,700
		Subtotal	19,800	6,100
Outflow	Evapotranspiration	-21,800	-11,000	-48,500
	Pumping (Agricultural)	-8,600	-5,200	-12,900
	Pumping (Municipal)	-500	-200	-700
		Subtotal	-30,900	-19,300*
Inflow/Outflow	Stream Exchange	7,400	2,100	13,600
		Change in Storage	-3,300	-18,200*
				18,000*

Notes:

- Values represent water years 2001 through 2015. WY 2000 excluded to remove influence of assumed initial conditions.
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.
- Increasing storage reported as a positive value, decreasing storage reported as a negative value.
- * Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.



At the Basin scale, more surface water enters the groundwater basin than leaves via discharge from the MFFR. Fluxes of surface water into the groundwater system are largest for average and wet years following dry periods (e.g., 2016 and 2017), when groundwater levels are low and surface water can easily percolate into the subsurface. It should be noted that some groundwater does discharge to the Middle Fork Feather River, but these flows are small compared to the amount of stream percolation that occurs in the central and upper parts of the Basin. Underflow out of the groundwater basin is considered to be negligible, and therefore not simulated.

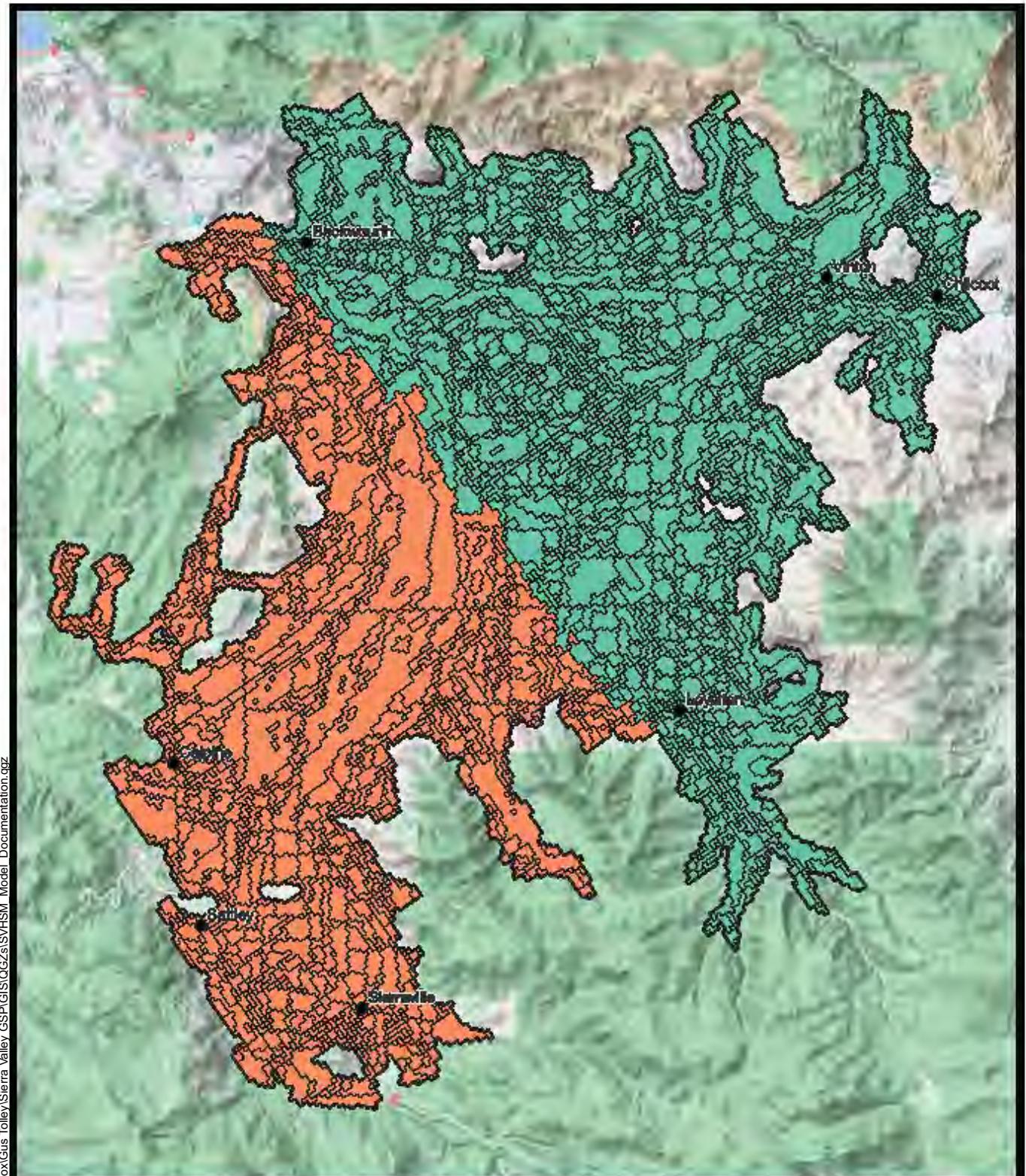
ET is typically the largest outflow component from the groundwater system. Rates are highly correlated with water year type. The volume of water lost to ET during dry, average, and wet years in the Basin is about 16,000 AFY, 24,000 AFY, and 44,000 AFY, respectively.

Groundwater pumping is the second largest outflow from the aquifer and generally decreases as water year types become wetter. Groundwater pumping during dry, average, and wet water years was about 9,900 AFY, 8,500 AFY, and 6,800 AFY, respectively.

Results from SVHSM can be used to quantify fluxes between different portions of the groundwater basin. Zonal results are presented as the average daily flux for each water year due to how the data is exported from the model and file size limitations. Although these rates can only be used to estimate annual flux volumes for each zone, they are useful for comparing relative flux rates for each zone.

Two different zonal comparisons are presented below. One compares the eastside and westside portions of the basin (Figure 9-4), believed to be hydrogeologically separated by the Loyalton and Grizzly Valley Faults. The second subdivides the eastside portion of the basin into an upper and lower aquifer zone. The upper aquifer is defined as the first three layers of SVHSM and ranges from the upper 120 feet to 330 feet of the model. Zonal comparison plots have units of average daily rate, as opposed to units of volume used in the basin-wide plots. The flux rate (units of volume/time) for the last day of each month were averaged within a water year. This is due to how data is exported from SVHSM and computer storage limitations given the high number of model cells and time-steps. While the units may differ, they offer similar functionality as the volume unit plots.

Net recharge rates and corresponding changes in groundwater storage rates are shown for the westside and eastside Basin areas in Figure 9-5. Similar interannual patterns are observed for both the eastside and westside portions on the basin. The main difference between the two zones is that the eastside portion of the basin has much greater magnitudes when net recharge is negative (i.e., outputs are greater than inputs for that year). As a result, the eastside portion of the basin has experienced a simulated storage reduction of approximately 21,600 acre-ft (60 acre-ft/day * 360 days) over the 21-year simulation, or an overdraft on the order of 1,000 AFY. Storage in the westside portion appears to be in a dynamic equilibrium. This is due to the significantly greater groundwater pumping volume that occurs on the eastside of the basin compared to the westside (Figure 9-6).



Explanation

Budget Zone

East Side

West Side

City or Town

Groundwater Model Domain Boundary

0 1 2 mi



SVHSM Documentation
MODFLOW Groundwater Budget Zones

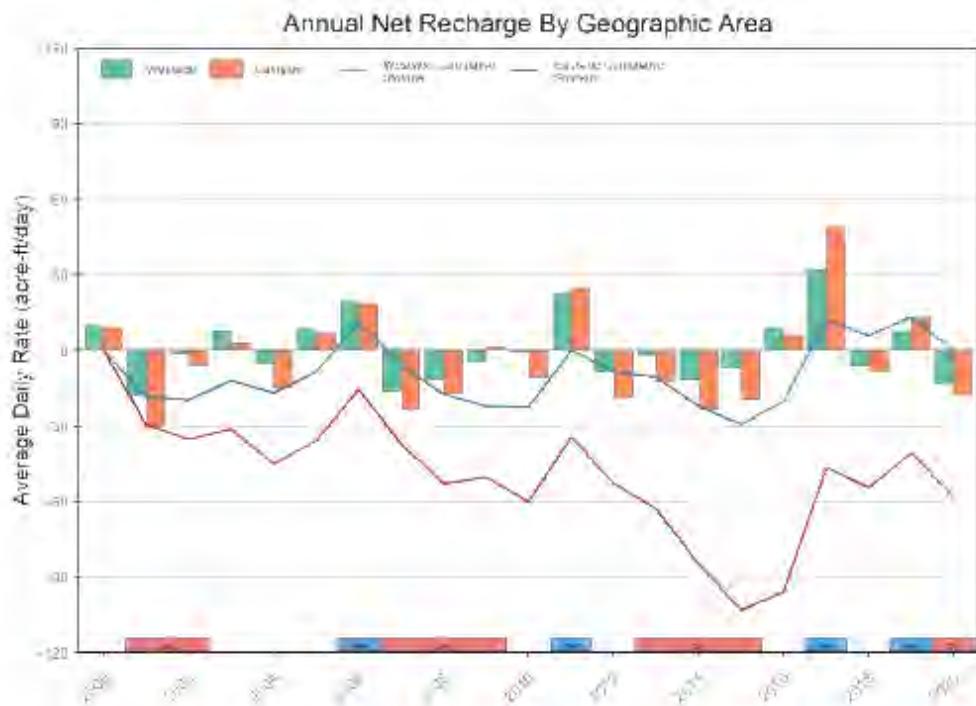


Figure 9-5. Historical and current annual net recharge rates by geographic area.

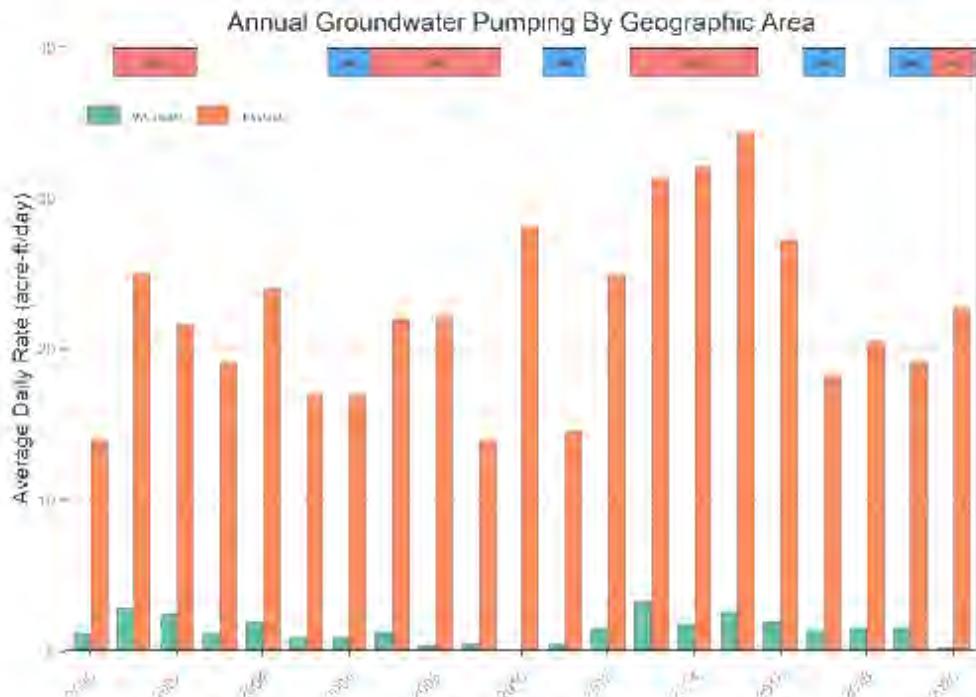
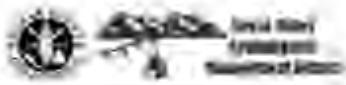


Figure 9-6. Historical and current annual pumping rates by geographic area.



Comparison of net recharge for the eastside upper and lower aquifer zones is shown in Figure 9-7. Rates differ substantially between the eastside upper and lower aquifers, with the upper aquifer showing a much greater range of net recharge values compared to the lower. Storage for both aquifer zones has decreased during the 21-year simulation, although simulated change in storage is lower for the upper aquifer compared to the lower. This is likely due to the upper aquifer having a smaller volume compared to the lower combined with similar simulated groundwater pumping in each zone (Figure 9-8). It should be noted that total well depth is missing from about 28% of simulated wells, and screen depth information is missing from about 51% of high capacity pumping wells. Assumptions made in the absence of these data are more likely to bias well and screen depths shallow. Therefore, a greater fraction of total groundwater pumping may be occurring in the lower aquifer.

In the context of observed long-term groundwater levels and the historical water budget, the Basin has historically operated with a small amount of overdraft, specifically on the eastside of the basin. Groundwater budget deficits occur during drought periods (i.e., dry and critical water years), and do not quite fully recover during subsequent wet periods. The amount of overdraft is relatively small compared to the overall water budget and suggests that recharge enhancement may be possible through management actions. The Basin sustainable yield has been estimated at about 6,000 to 7,000 AFY (Bachand and Carlton, 2020), consistent with SVHSM results. Historical groundwater pumping records indicate about 8,500 AFY water demand on average, resulting in an annual deficit of approximately 1,500 to 2,500 AFY.

9.2 Current Water Budgets

Current water budget conditions are represented by the five most recent water years (WY 2016-2020). This period represents a transition in observed climate conditions from the peak of the drought (i.e., 2016) and towards less dry conditions (i.e., 2017 through 2019), corresponding to a partial recovery of groundwater levels in the Basin.

Current (in addition to historical) water budgets for the surface water, land surface, and groundwater subsystems are shown in Figures 9-1 through 9-3, respectively, and are summarized in Tables 9-4 through 9-6. The number of above normal or wet year(s) recently has the Basin. Although the historical average deficit rate of 1,500 AFY is less than the current average 10,000 AFY surplus, these changes in groundwater in storage do not completely offset one another, because the historical average represents a significantly longer duration (and therefore volume) than the current average change in storage (i.e., 15 years versus five years). This is why tracking changes in groundwater in storage as the cumulative (total) of annual changes in storage is useful for comparing different time periods. The current estimated rate of recovery of groundwater in storage is similar to rates of recovery that occurred in the past, prior to full recovery of groundwater levels.



Figure 9-7. Historical and current annual net recharge by aquifer zone.

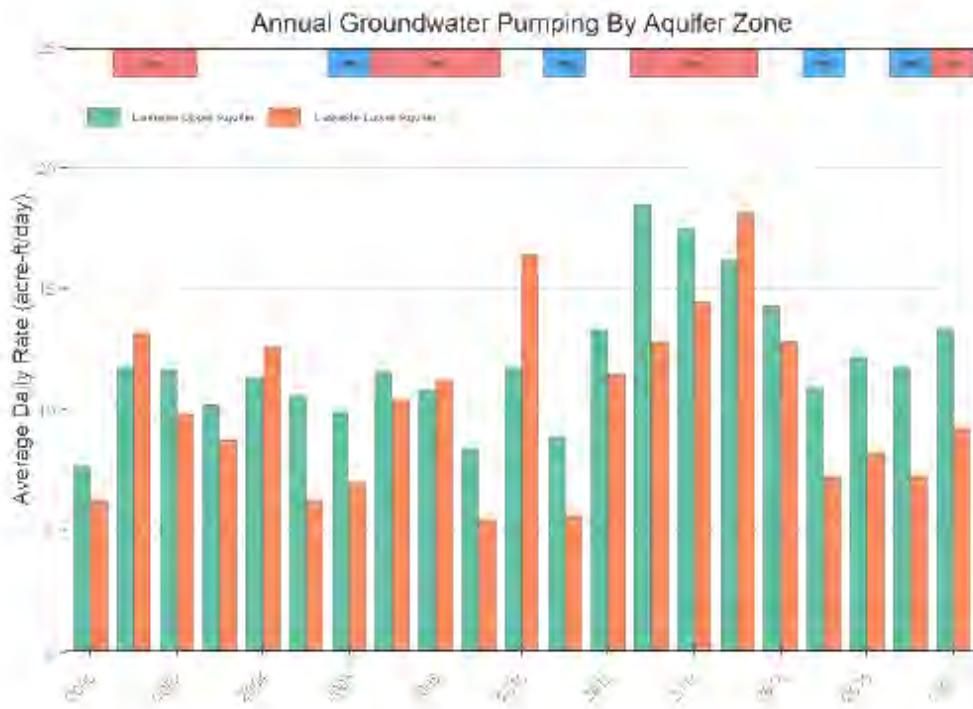


Figure 9-8. Historical and current annual groundwater pumping by aquifer zone.

Table 9-4. Current (WY 2016-2020) surface water budget summary.

		Annual Flow (AFY)		
Flow	Component	Average	Minimum	Maximum
Inflow	Stream Flow	163,200	58,600	362,300
	Valley Floor Runoff	77,600	7,100	219,000
	Subtotal	240,800	65,700*	581,300*
Outflow	Stream Flow (MFFR)	-196,700	-32,500	-517,900
	SW Diversions	-30,300	-15,200	-46,100
	Subtotal	-227,000	-56,600*	-564,000*
Inflow/Outflow	GW Exchange	-10,800	-5,500	-15,300

Notes:

- Values represent water years 2016 through 2020.
- MFFR: Middle Fork Feather River
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.

* Column arithmetic not applicable since values may come from different years and violate mass balance. Mass-conservative values shown.

Table 9-5. Current (WY 2016-2020) land surface water budget summary.

		Annual Flow (AFY)		
Flow	Component	Average	Minimum	Maximum
Inflow	Precipitation	257,500	127,000	457,600
	Irrigation (from SW)	30,300	15,200	46,100
	Irrigation (from GW)	7,900	6,500	10,100
	Subtotal	295,700	161,100*	510,200*
Outflow	Evapotranspiration (Irrigated Fields)	-78,100	-68,000	-89,600
	Evapotranspiration (Non-Irrigated Fields)	-43,000	-35,000	-49,100
	Evapotranspiration (Native Vegetation)	-67,100	-52,700	-73,400
	Recharge (to GW)	-29,700	-4,700	-68,400
	Runoff	-77,600	-7,100	-219,000
	Subtotal	-295,500	-171,900*	-499,400*
Change in Storage		300	-10,800*	10,700*

Notes:

- Values represent water years 2016 through 2020.
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.

* Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.

Table 9-6. Current (WY 2016-2020) groundwater budget summary.

Flow	Component	Annual Flow (AFY)		
		Average	Minimum	Maximum
Inflow	Recharge (Valley Floor)	29,600	4,700	68,100
	Recharge (Mountain Front)	3,700	3,700	3,700
		Subtotal	33,300	8,400
Outflow	Evapotranspiration	-31,000	-17,100	-52,200
	Pumping (Agricultural)	-8,000	-6,800	-10,200
	Pumping (Municipal)	-400	-400	-600
		Subtotal	-39,400	-25,500*
Inflow/Outflow	Stream Exchange	10,800	5,500	15,300
		Change in Storage	-1,300	-27,700*
				11,300*

Notes:

- Values represent water years 2016 through 2020.
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY.
- Increasing storage reported as a positive value, decreasing storage reported as a negative value.
- * Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.

9.3 Projected Future Water Budgets

SVHSM was used to estimate water budgets for the 50-year (WY 2021-2070) planning and implementation horizon required by SGMA using the change factors from four future climate scenarios provided by DWR. These scenarios are described in greater detail in the climate change guidance provided by DWR (2018a), and are summarized in Table 9-7. Change factors are provided for precipitation, reference ET, and stream flow on a monthly basis for historical datasets. Future climate and stream flow inputs were generated using the following steps:

1. Identify historical water years with precipitation and reference ET data, as well as DWR climate change factors (WY 1990-2011 for Sierra Valley). Surface water inflows are only available from WY 2000-2011.
2. Future 50-year (WY 2021-2070) planning and implementation horizon was created by randomly sampling years from WY 2000-2011. For example, WY 2005 was used to represent WY 2050. Several iterations were performed, and the dataset with the most similar statistical distribution to the historical data was selected. For historical water years where surface water inflow data was unavailable, average inflows based on the projected water year type (i.e., dry, average, and wet) were used.
3. Values of precipitation, reference ET, and streamflow for a future month were multiplied by the change factor for the historical month used to represent it.



Table 9-7. Summary of future climate scenarios.

Abbreviation	Scenario	Description
2030	2030 (near future)	Central tendency of the ensemble general circulation models (GCMs).
2070	2070 (late future)	Central tendency of the GCMs.
2070DEW	2070 (late future)	Drier with extreme warming (2070 DEW) conditions (extreme scenario, single GCM: HadGEM2-ES with representative concentration pathway [RCP] 8.5)
2070WMW	2070 (late future)	Wetter with moderate warming (2070 WMW) conditions (extreme scenario, single GCM: CNRM-CM5 with RCP 4.5)

It is important to note that the projected water budget is based on assumptions of events that may occur in the future, and is not intended to represent a prediction of future conditions. Instead, the projected water budgets are constructed to simulate “what-if” scenarios that incorporate uncertainty and evaluate the Agency’s ability to operate the Basin sustainably over the 50-year planning and implementation horizon required by SGMA.

Cumulative inputs of precipitation, reference ET, and stream inflow for the 50-year future simulation are shown for the four climate change scenarios as well as the unmodified historical inputs in Figure 9-9. In general, future climate is projected to produce greater precipitation, but with less runoff due to increased ET. Average changes from historical values for each month (Figure 9-10) show projected increases in precipitation occur during the winter months, with the majority of increased ET occurring during the growing season (April through October). Reduced streamflow inputs during the spring and early summer are from projected reductions in winter snowpack.

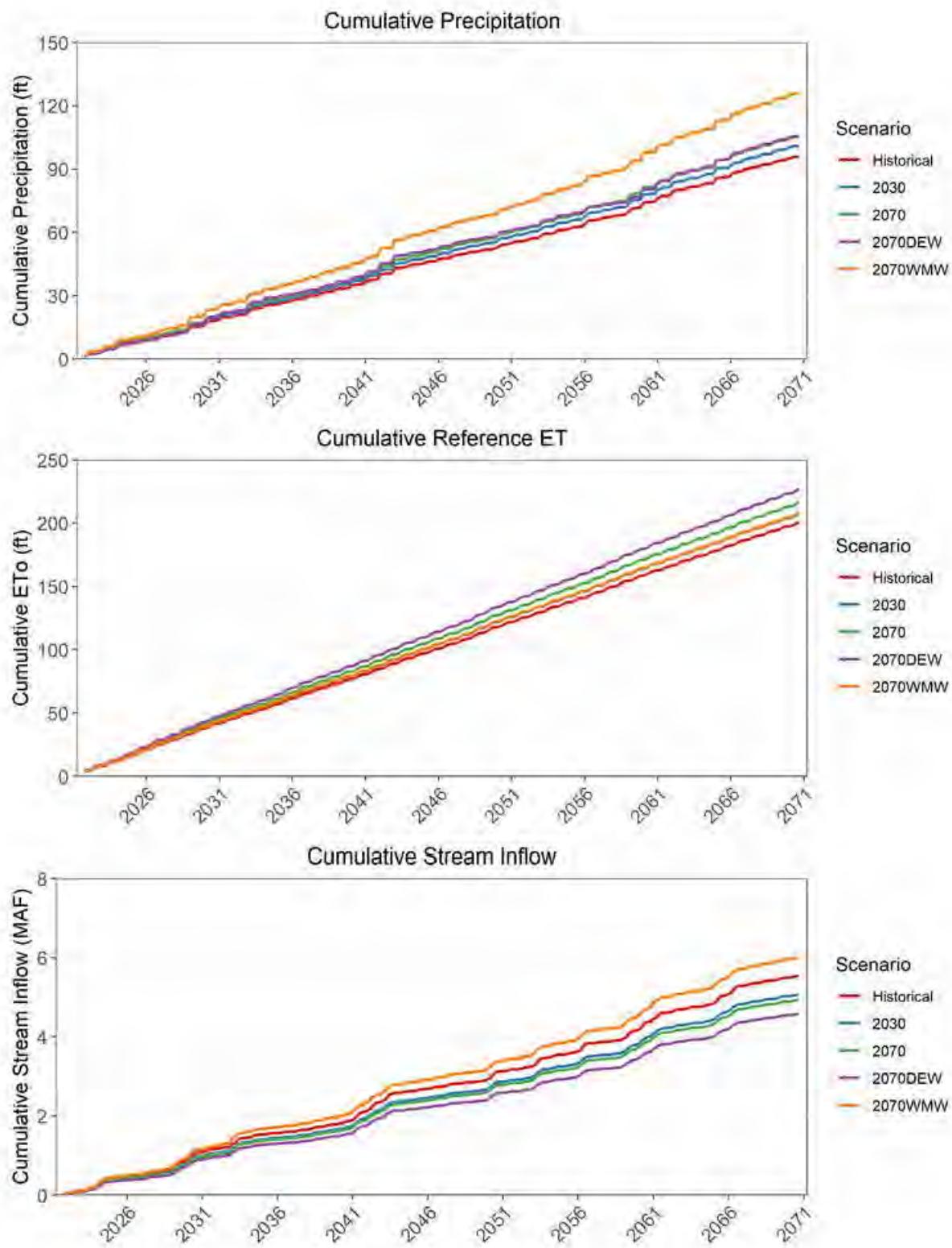


Figure 9-9. Cumulative inputs from simulated climate change scenarios.

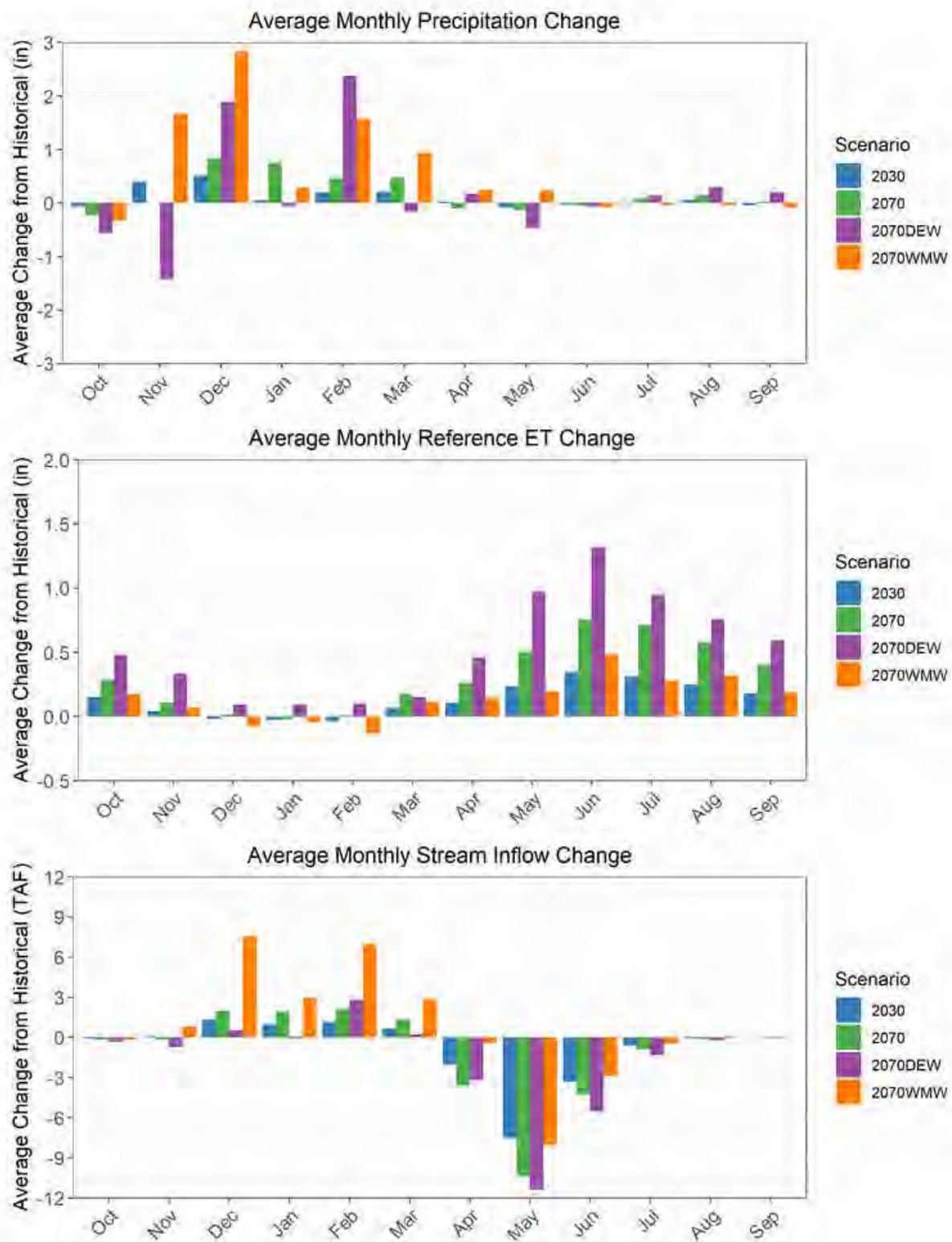


Figure 9-10. Average change from historical inputs by month using DWR climate change factors.

Sierra Valley has experienced a small population decline between 2010 and 2019, so changes in future water demand are only expected to occur due to greater crop water demand from increased reference ET. Future groundwater pumping is estimated using SVHSM, and assumes similar land use patterns as those observed historically. Figure 9-11 shows the estimated and observed annual groundwater pumping volumes from WY 2003-2020. In general, historical pumping is well represented by SVHSM and provides confidence in estimated future pumping. Future municipal groundwater pumping was assumed to be the same as historical.

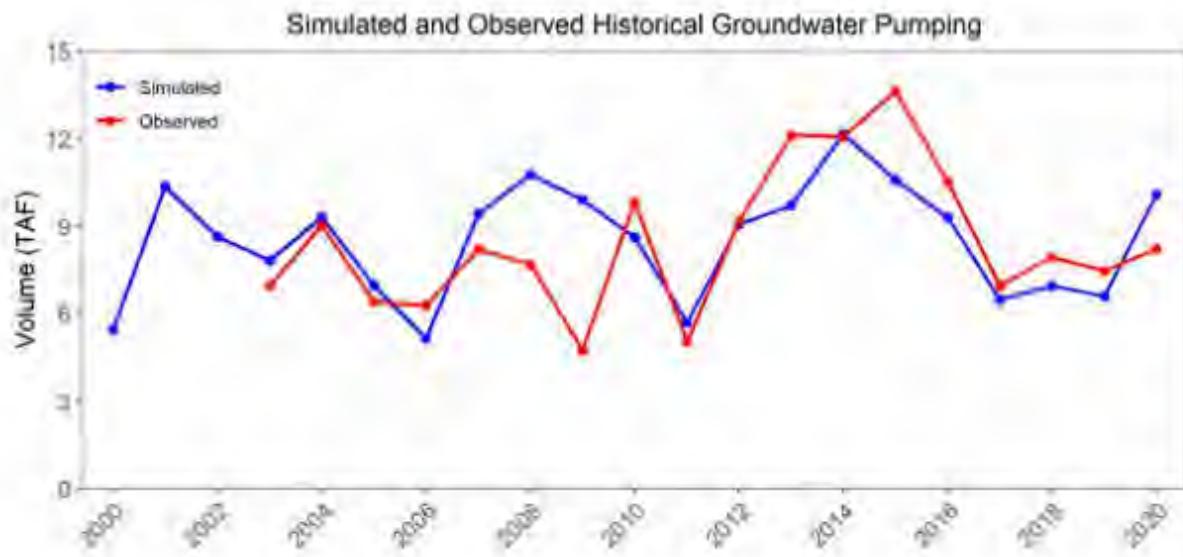


Figure 9-11. Historical groundwater pumping is well represented for most years by the SWBM submodel of SVHSM.

Projected agricultural groundwater demand ranges from 5,500 to 16,600 AFY, with average annual pumping ranging from 8,700 to 11,000 AFY in the four climate change scenarios (Figure 9-12). This corresponds to an increase in average annual groundwater pumping ranging from 200 to 2,500 AFY, compared to the observed historical average of 8,500 AFY.

Projected surface water inputs to Sierra Valley are shown in Figure 9-13. Annual inflows range from 27,800 to 270,600 AFY across all four scenarios. Annual average surface water inflows range from 91,500 to 120,100 AFY, which represents a change of -5,000 to +23,400 AFY from the historical annual average of 96,700 AFY.

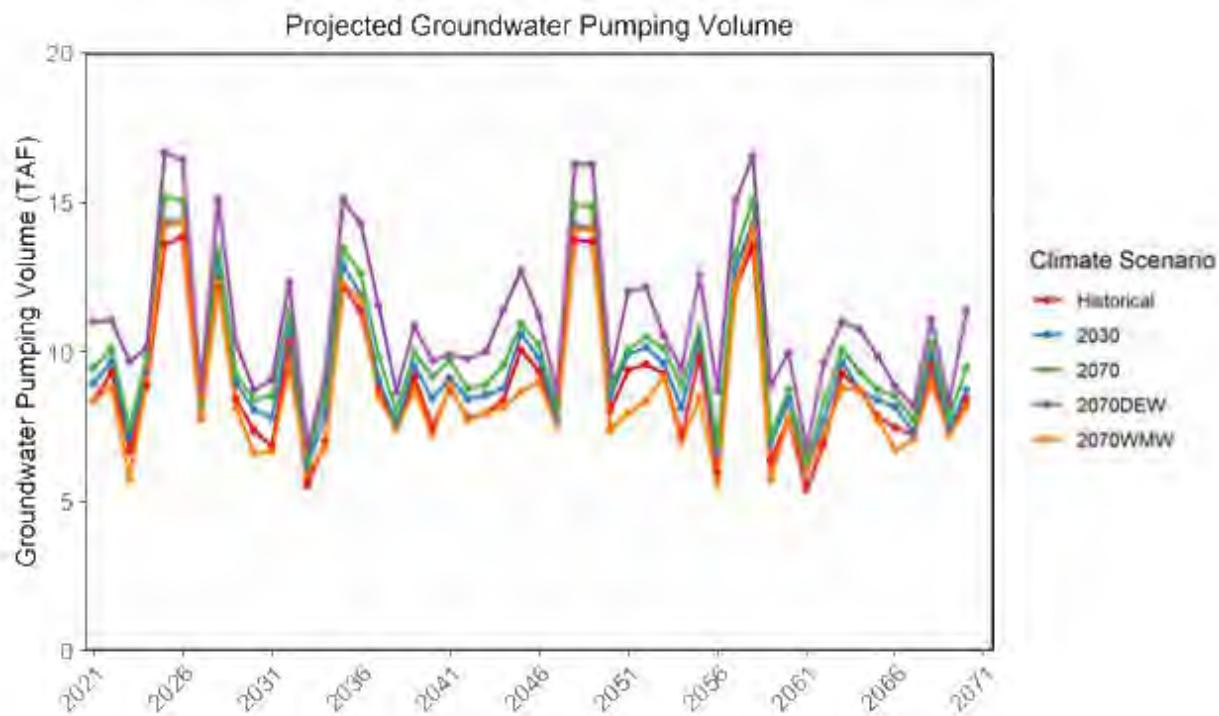


Figure 9-12. Estimated future groundwater pumping.

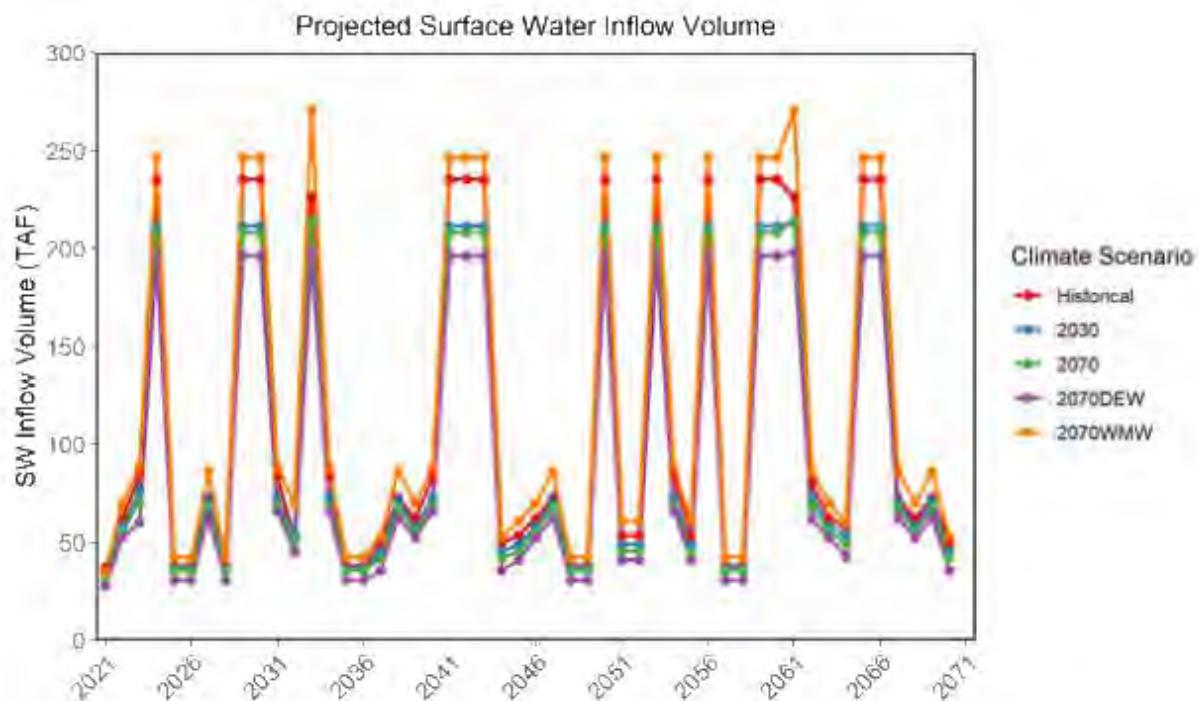


Figure 9-13. Estimated future surface water inflows to the Sierra Valley groundwater basin.



Surface water subsystem budgets over the 50-year (WY 2021-2070) planning and implementation horizon for each climate change scenario are shown in Figure 9-14 and summarized in Table 9-8. Tabulated water budgets are presented in Appendix 2-8. As mentioned in Section 2.2.3.5.3, average annual inflows range from 5,000 to 23,400 AFY when compared to the historical annual average of 96,700 AFY. Average annual surface water irrigation volumes range from 29,600 to 30,500 AFY across all scenarios, which represents a decrease of approximately 0 to 3% compared to annual estimated historical surface water irrigation volume. Surface water outflows from the MFFR are projected to increase on average between 0 and 57,000 AFY on average across all scenarios, largely due to increased valley floor runoff from increased storm intensity.

Projected future land surface (soil zone) water budgets for the groundwater basin are shown in Figure 9-15 and summarized in Table 9-9. In general, both the magnitude and variance of the annual average of the budget components increase. This means that more water moves through the system on average, but interannual variability also increases. In other words, wet years are projected to be wetter and dry years are projected to be drier, with fewer years that would be considered “average.” Results from the SWBM indicate that overall groundwater recharge for the basin is projected to increase by about 5,800 to 16,700 AFY, while groundwater irrigation is projected to increase approximately 100 to 2,500 AFY.

Projected future water budgets for the groundwater subsystem are shown in Figure 9-16 and summarized in Table 9-10. Groundwater pumping is projected to increase from about 0 to 2,300 AFY on average due to increased ET. However, projected increases in recharge due to increased precipitation offset increased pumping demand. Long-term changes in storage are projected to range from -500 to +100 AFY, which is a reduction from the -1,300 AFY simulated by SVHSM for WY 2001-2020. Figure 9-17 shows the time series of cumulative change in storage since the beginning of the model run for each future climate scenario. Changes in storage recover for the 2070WMW and 2030 scenarios during the latter 15 years of the future simulation following a simulated dry period that lasts for about 7 years. Partial recovery is observed for the 2070 and 2070DEW scenarios.

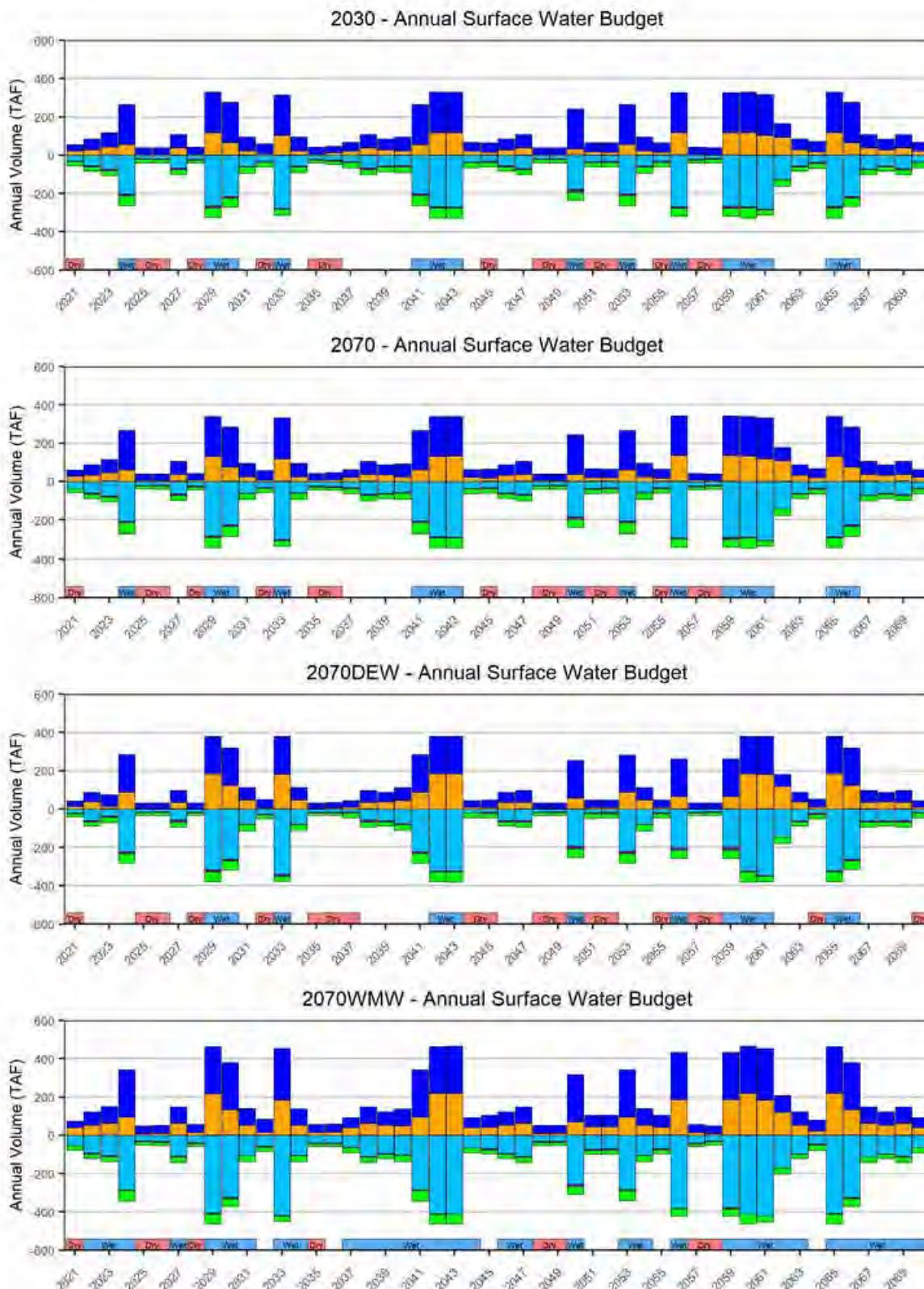


Figure 9-14. Projected future surface water budgets.

Table 9-8. Summary of projected surface water budgets.

Scenario	Flow	Component	Annual Flow (AFY)		
			Average	Minimum	Maximum
2030	Inflow	Stream Flow	102,700	36,600	213,600
		Runoff	41,400	3,300	132,500
		Subtotal	144,100	39,900	346,100
	Outflow	Stream Flow (MFFR)	-105,200	-16,500	-280,700
		SW Diversions	-30,600	-16,300	-52,200
		Subtotal	-135,800	-32,800	-332,900
	Inflow/Outflow	GW Exchange	-7,200	-900	-15,900
2070	Inflow	Stream Flow	100,000	35,700	214,300
		Runoff	47,400	3,700	132,500
		Subtotal	147,400	39,400	346,800
	Outflow	Stream Flow (MFFR)	-110,200	-18,200	-300,100
		SW Diversions	-30,300	-14,500	-52,700
		Subtotal	-140,500	-32,700	-352,800
	Inflow/Outflow	GW Exchange	-5,900	1,000	-13,900
2070DEW	Inflow	Stream Flow	92,800	30,900	198,100
		Runoff	55,700	1,900	184,400
		Subtotal	148,500	32,800	382,500
	Outflow	Stream Flow (MFFR)	-111,700	-13,300	-347,300
		SW Diversions	-29,800	-14,300	-51,600
		Subtotal	-141,500	-27,600	-398900
	Inflow/Outflow	GW Exchange	-7,000	100	-15,800
2070WMW	Inflow	Stream Flow	121,800	42,500	270,600
		Runoff	77,100	6,900	218,000
		Subtotal	198,900	49,400	488,600
	Outflow	Stream Flow (MFFR)	-162,900	-27,700	-422,900
		SW Diversions	-29,900	-15,300	-53,600
		Subtotal	-192,800	-43,000	-476,500
	Inflow/Outflow	GW Exchange	-4,700	1,300	-11,800

Notes:

- Values represent projections for WY 2022-2070. WY 2021 excluded to remove influence of assumed initial conditions.
- MFFR: Middle Fork Feather River
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Annual flow values (in acre-feet per year [AFY]) are rounded to the nearest 100 AFY; therefore, a discrepancy of 100 AFY may occur.

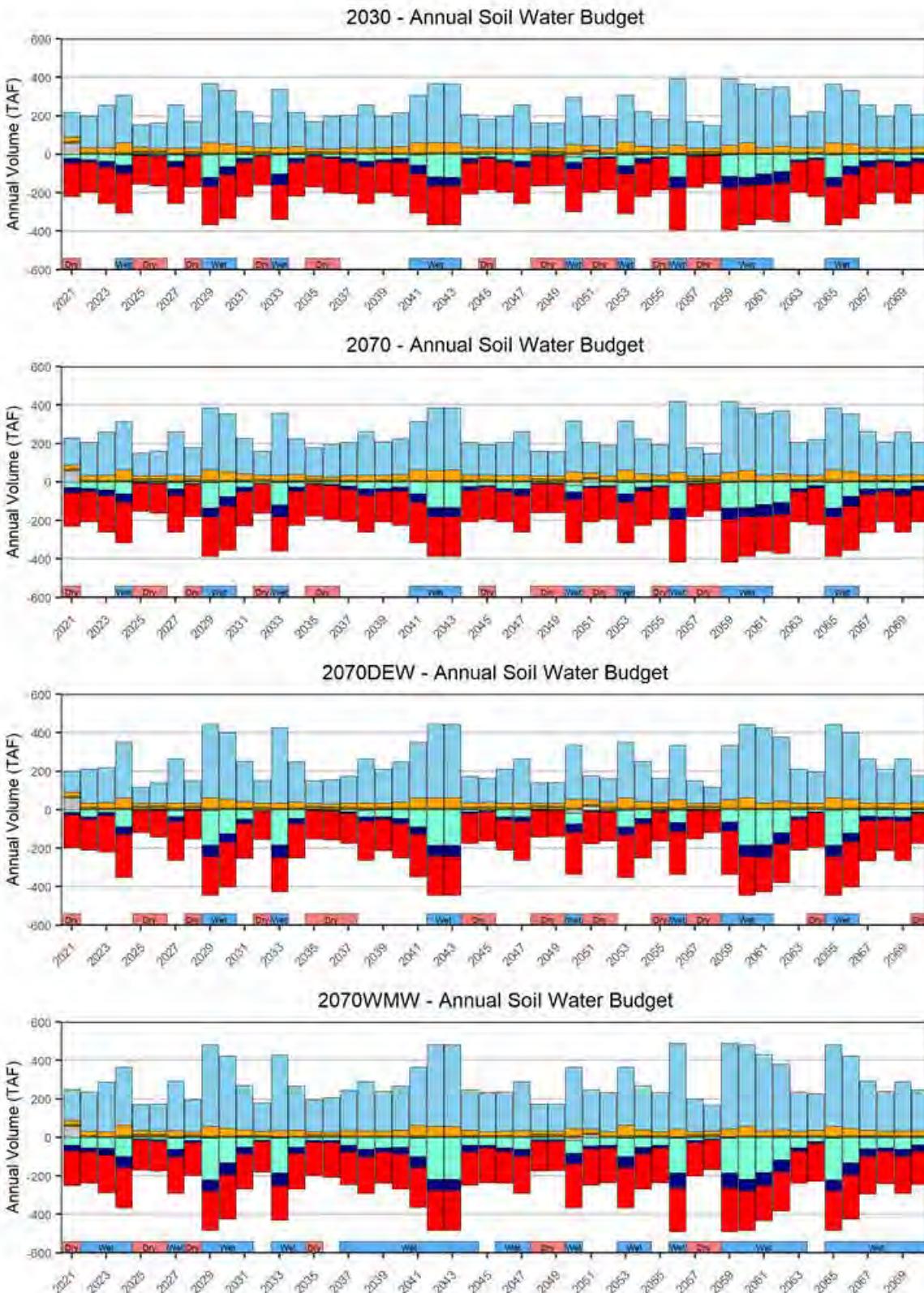


Figure 9-15. Projected future land surface (soil zone) water budgets.

Table 9-9. Summary of projected land surface water budgets.

Scenario	Flow	Component	Annual Flow (AFY)		
			Average	Minimum	Maximum
2030	Inflow	Precipitation	207,900	118,000	345,500
		Irrigation (from SW)	30,600	16,300	52,200
		Irrigation (from GW)	9,500	5,900	14,800
	Outflow	Subtotal	248,000	140,200	412,500
		Evapotranspiration (Irrigated Fields)	-78,100	-63,300	-101,300
		Evapotranspiration (Non-Irrigated Fields)	-38,900	-32,200	-51,500
		Evapotranspiration (Native Vegetation)	-63,100	-47,900	-77,400
		Recharge to GW	-26,300	-3,800	-59,400
	Change in Storage	Runoff	-41,400	-3,300	-118,000
		Subtotal	-247,800	-150,500	-407,600
		Change in Storage	200	-13,500*	12,300*
2070	Inflow	Precipitation	216,600	117,700	368,700
		Irrigation (from SW)	30,300	14,500	52,700
		Irrigation (from GW)	10,100	6,200	15,600
	Outflow	Subtotal	257,000	138,400	437,000
		Evapotranspiration (Irrigated Fields)	-78,800	-61,400	-103,600
		Evapotranspiration (Non-Irrigated Fields)	-39,200	-31,800	-52,000
		Evapotranspiration (Native Vegetation)	-63,900	-47,400	-79,600
		Recharge to GW	-27,600	-4,000	-61,000
	Change in Storage	Runoff	-47,400	-3,700	-132,500
		Subtotal	-256,900	-148,300	-428,700
		Change in Storage	100	-17,000*	15,700*
2070DEW	Inflow	Precipitation	217,700	86,800	392,000
		Irrigation (from SW)	29,800	14,300	51,600
		Irrigation (from GW)	11,200	6,700	17,200
	Outflow	Subtotal	258,700	107,800	460,800
		Evapotranspiration (Irrigated Fields)	-78,400	-53,400	-106,300
		Evapotranspiration (Non-Irrigated Fields)	-38,400	-24,400	-52,700
		Evapotranspiration (Native Vegetation)	-60,900	-34,800	-75,700
		Recharge to GW	-25,300	-2,200	-65,500
	Change in Storage	Runoff	-55,700	-1,900	-184,400
		Subtotal	-258,700	-116,700	-484,600
		Change in Storage	0	-17,100*	16,300*
2070WMW	Inflow	Precipitation	260,500	136,000	445,700
		Irrigation (from SW)	29,900	15,300	53,600
		Irrigation (from GW)	8,800	5,300	14,800
	Outflow	Subtotal	299,200	156,600	514,100
		Evapotranspiration (Irrigated Fields)	-79,000	-64,000	-101,600
		Evapotranspiration (Non-Irrigated Fields)	-40,800	-33,700	-56,300
		Evapotranspiration (Native Vegetation)	-65,900	-55,000	-81,700
		Recharge to GW	-36,200	-5,600	-79,200
	Change in Storage	Runoff	-77,100	-6,900	-218,000
		Subtotal	-299,000	-165,200	-536,800
		Change in Storage	200	-15,400*	13,800*

Notes:

- WY 2021 excluded to remove influence of assumed initial conditions
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Values are rounded to the nearest 100 AFY
- Increasing storage reported as a positive value, decreasing storage reported as a negative value.
- * Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.

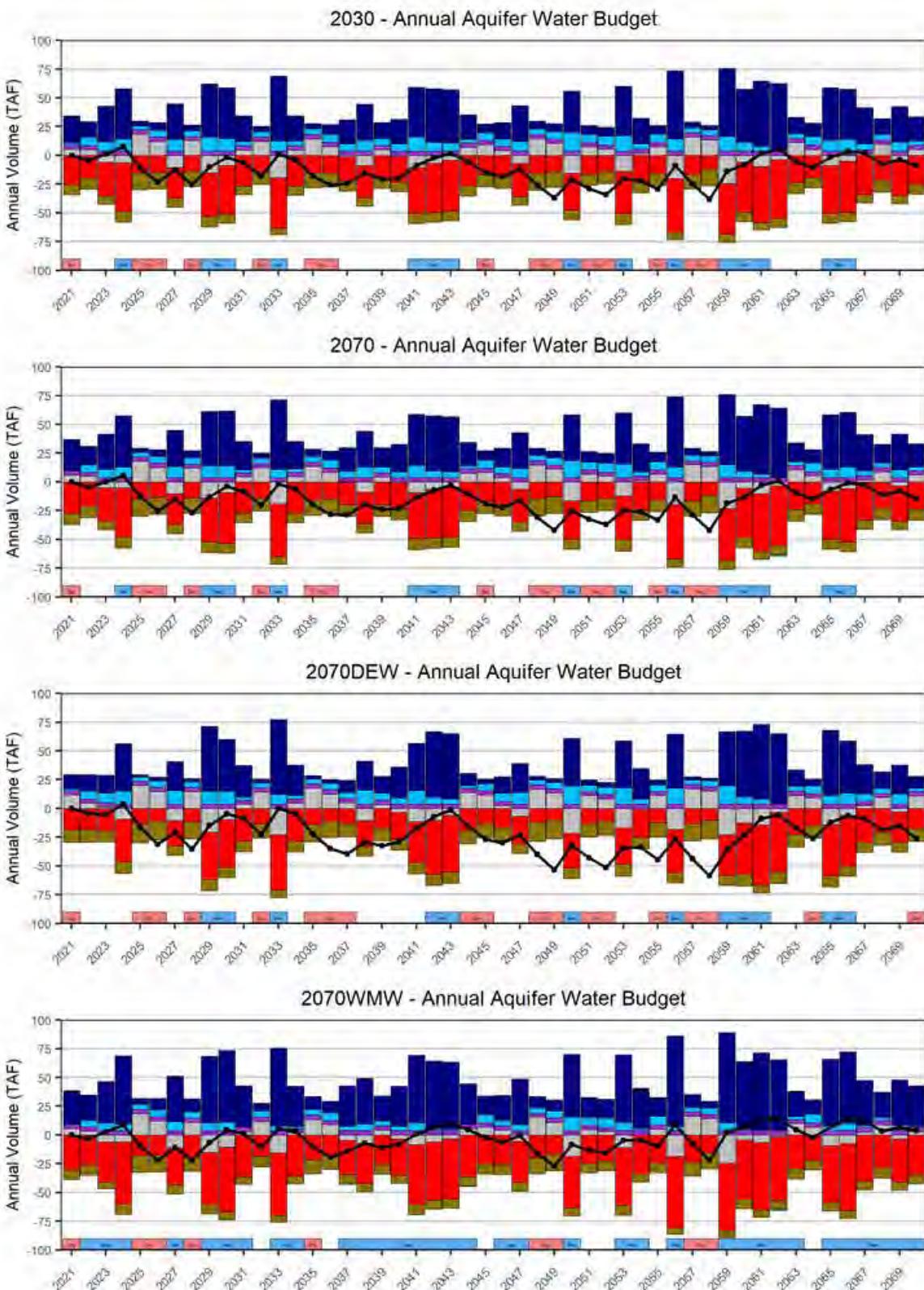


Figure 9-16. Projected future groundwater budgets.

Table 9-10. Summary of projected groundwater budgets.

Scenario	Flow	Component	Annual Flow (AFY)			
			Average	Minimum	Maximum	
2030	Inflow	Recharge (Valley Floor)	26,200	3,800	59,200	
		Recharge (Mountain Front)	3,700	3,700	3,700	
		Subtotal	29,900	7,500	29,900	
	Outflow	Evapotranspiration	-27,900	-12,300	-51,200	
		Pumping (Wells)	-9,500	-6,100	-14,400	
		Subtotal	-37,400	-18,400	-65,600	
	Inflow/Outflow	Stream Exchange	7,200	900	15,900	
		Change in Storage	-200	-18,500*	24,400*	
	2070	Inflow	Recharge (Valley Floor)	27,500	4,000	60,800
			Recharge (Mountain Front)	3,700	3,700	3,700
			Subtotal	31,200	7,700	64,500
		Outflow	Evapotranspiration	-28,300	-12,000	-52,400
			Pumping (Wells)	-10,000	-6,300	-15,200
			Subtotal	-38,300	-18,300	-67,600
		Inflow/Outflow	Stream Exchange	5,900	-1,000	13,900
			Change in Storage	-500	-17,800*	22,500*
2070DEW	Inflow	Recharge (Valley Floor)	25,200	2,200	65,300	
		Recharge (Mountain Front)	3,700	3,700	3,700	
		Subtotal	28,900	5,900	69,000	
	Outflow	Evapotranspiration	-25,500	-10,200	-52,200	
		Pumping (Wells)	-11,100	-6,800	-16,700	
		Subtotal	-36,600	-17,000	-68,900	
	Inflow/Outflow	Stream Exchange	7,000	-100	15,800	
		Change in Storage	-500	-20,000*	22,900*	
2070WMW	Inflow	Recharge (Valley Floor)	36,100	5,600	79,000	
		Recharge (Mountain Front)	3,700	3,700	3,700	
		Subtotal	39,800	29,900	82,700	
	Outflow	Evapotranspiration	-35,700	-15,500	-62,300	
		Pumping (Wells)	-8,800	-5,500	-14,300	
		Subtotal	-44,500	-21,000	-76,600	
	Inflow/Outflow	Stream Exchange	4,700	-1,300	11,800	
		Change in Storage	100	-18,500*	24,600*	

Notes:

- Values represent projections for WY 2022-2070. WY 2021 excluded to remove influence of assumed initial conditions.
- Inflows are represented by positive values; outflows are represented by negative values.
- Minimum and maximum values represent the smallest and largest magnitudes of annual flows, respectively.
- Increasing storage reported as a positive value, decreasing storage reported as a negative value.

* Column arithmetic not applicable since values come from different years which violates mass balance. Mass-conservative values shown.

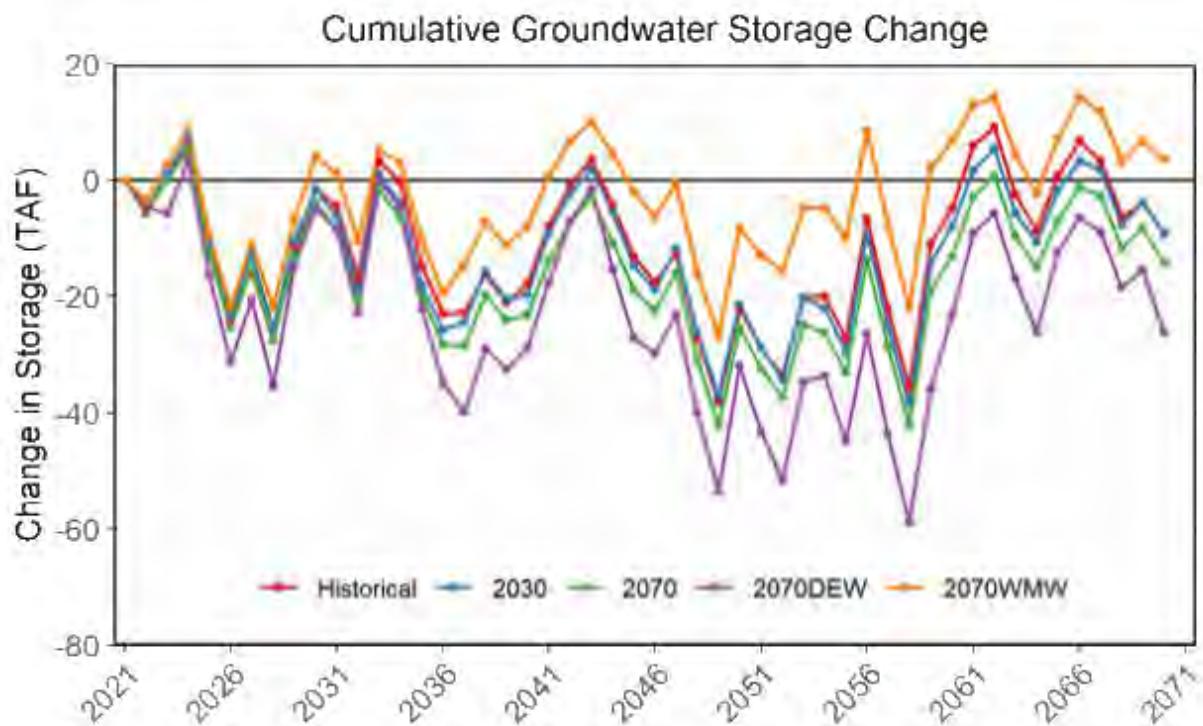


Figure 9-17. Projected change in groundwater storage from future climate scenarios.

Comparison of cumulative change in groundwater storage rates between the eastside and westside portions of the basin (Figure 9-18) shows similar interannual patterns between the two zones, but the magnitude of change is much greater for the eastside. Annual average change in storage rates range from about -0.1 to -1.6 acre-feet per day for the westside, compared to about -0.8 to -2.7 acre-feet per day for the eastside of the basin. Both sides of the basin exhibit the same pattern in storage rate changes as that observed in the basin wide change in storage volume (Figure 9-17).

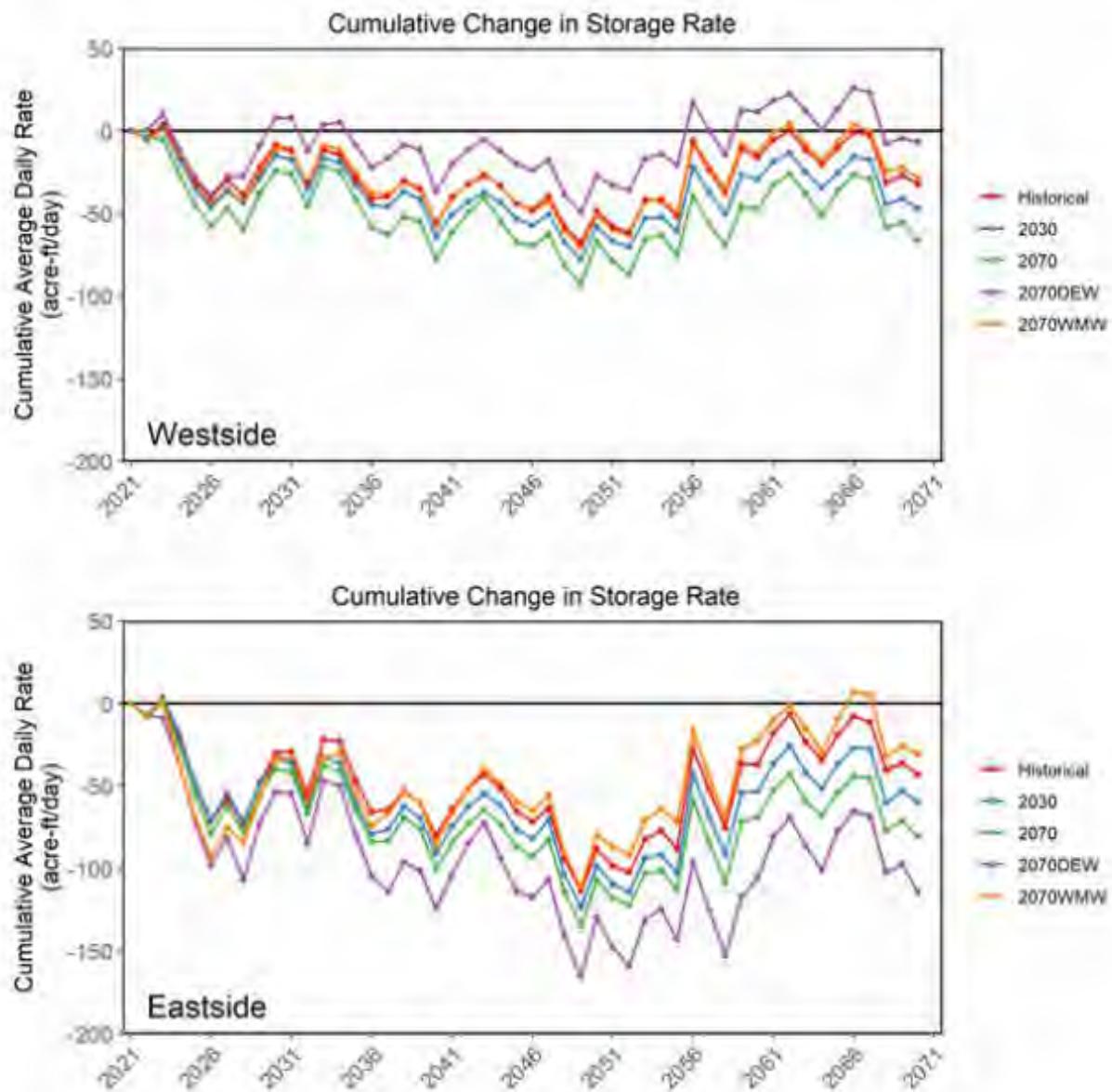


Figure 9-18. Eastside portion of the basin projected to experience greater declines in groundwater storage than the westside in the future.

Differences in cumulative changes in storage rates are much more apparent when comparing the eastside upper aquifer to the eastside lower aquifer (Figure 9-19). The eastside upper aquifer follows a similar interannual pattern to that observed when comparing the eastside of the basin to the westside, or looking at the change in volumetric storage for the groundwater basin as a whole. In contrast, changes in eastside lower aquifer storage are much more subdued on an interannual basis. Recovery of storage following the seven-year dry period is not observed in the eastside lower aquifer for any of the scenarios, although the 2070WMW scenario does

come close. This indicates that groundwater levels in the eastside lower aquifer would continue to decline if current groundwater management practices were continued in the future.

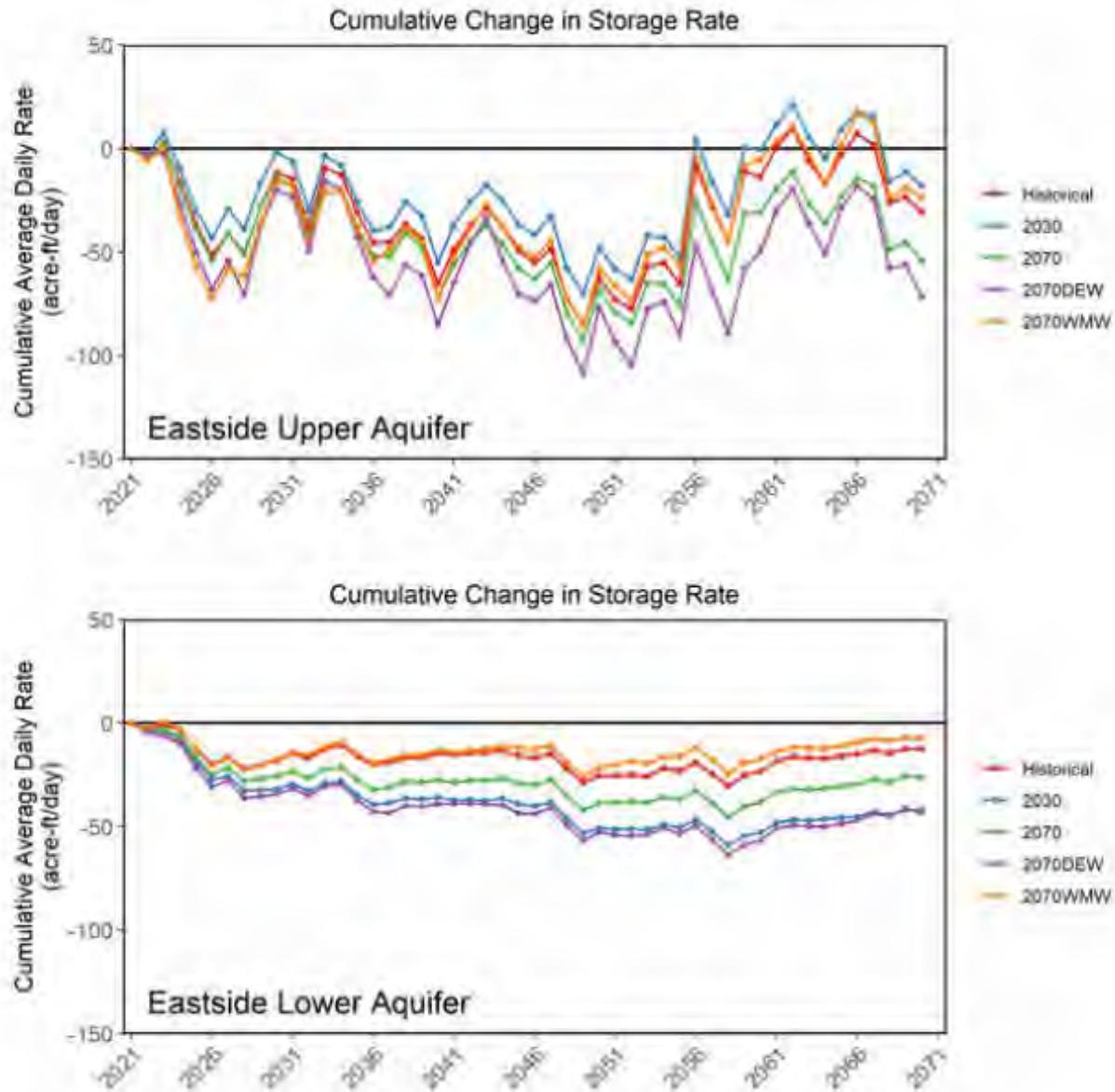


Figure 9-19. Continued declines in groundwater storage are expected for the eastside lower aquifer in the absence of management changes.



10.0 Future Work

Overall, representation of the Sierra Valley watershed hydrogeologic system by SVHSM is moderate to good despite limited time available for calibration efforts. The model captures the most salient intra- and inter-annual trends observed in available groundwater, surface water, and pumping data, making it a valuable tool for the basin moving forward. Additional calibration efforts are expected to greatly improve model results and are highly recommended. The following subsections suggest future data collection and model calibration efforts to focus on, in no particular order, based on understanding gained during initial model development and calibration.

10.1 Collection of Additional Streamflow Data

Flow data for streams that enter the groundwater basin along the margin of Sierra Valley are limited both spatially and temporally. Only 11 of the 17 (65%) streams where inflows to Sierra Valley are simulated by the PRMS submodel of SVHSM have flow data associated with them. Two of these streams are Little Last Chance Creek and Big Grizzly Creek for which daily or monthly totals are reported. However, flow in these streams is controlled by reservoir releases, and is therefore not suitable for calibration purposes. The remaining streams have a total number of flow observations that range from 7 to 124, which represents 0.09% to 1.6% of the SVHSM simulation period.

No flow data are available for streams that flow within Sierra Valley at a location sufficiently far enough away from the margins of the basin. While some flow observations are technically located within the valley, they are near enough to the margin that they have been associated with flow entering the valley, and are therefore used to specify stream inflow boundary conditions required for the SFR package the in MODFLOW submodel of SVHSM. The only surface water calibration data within the groundwater basin are streamflow data observed at the Middle Fork Feather River (MFP) gage, which represents total surface water outflow from the basin. Without additional streamflow data from locations within the valley, more detailed evaluation of model performance in the context of surface water flows and groundwater-surface water interactions cannot be performed.

Collection of flow data for streams that enter along the margin of Sierra Valley and flow within the groundwater basin is recommended in order to provide calibration points for SVHSM. Due to the high frequency of variation in surface water flows, data should be collected at a minimum of every two weeks, but preferably on a daily basis in order to identify periods of baseflow, snowmelt runoff, and storm runoff. Pressure transducers placed in streambeds are a relatively affordable method of estimating streamflow at sub-daily time intervals, and their deployment should be considered as part of future data collection efforts.



10.2 Collection of Additional Lithology Data

Information about aquifer geometry and sediment distribution is generally lacking on the western side of the valley. This is largely due to the preponderance of surface water use resulting in few groundwater wells with available well logs (see Figure 6-2). The USGS is currently conducting a seismic geophysical study of the basin, and an AEM survey conducted by DWR is expected in 2022. Both of these may provide additional geologic insight for this portion of the basin. Siting of future monitoring wells should prioritize this area if possible. In general, new wells drilled within the groundwater basin should have the lithology logs added to the DMS so their data can be incorporated into future model updates.

10.3 More Frequent Collection of Pumping Volume Data

Sierra Valley benefits from requiring flow meters to be installed on high-capacity (>100 gpm) wells. The availability of this dataset was extremely helpful during model development, and greatly reduced one of the largest sources of uncertainty in groundwater models developed in agricultural groundwater basins. Metered volumes are currently collected on an annual basis, with reads taken at the beginning and end of the growing season. Because SVHSM operates with monthly stress periods, the measured annual pumping volume must be distributed across the growing season months (see Section 5.1.6), which adds to model uncertainty.

Performing additional flow meter reads at the beginning/end of each month during the growing season would allow for a more accurate temporal distribution of groundwater pumping from each well. Because this additional data collection would likely result in a significant amount of effort for SVGMD staff, and therefore additional cost, we propose that these additional meter reads be performed voluntarily by growers. SVGMD staff would still perform meter reads at the beginning and end of the growing season to confirm total annual production volumes, and any intra-seasonal meter reads could be provided to SVGMD staff by growers at this time. This would facilitate the collection of higher resolution groundwater pumping volumes that would improve model performance without requiring an appreciable increase in SVGMD staff workload.

10.4 Subbasin Specific Calibration of PRMS

During manual calibration of the PRMS submodel of SVHSM, it was hypothesized that model performance may be improved if some parameters assigned to the entire model domain (e.g., *gwflow_coef*, *gwsink_coef*) were instead distributed spatially. Additionally, spatially distributed parameters may benefit from adjustment on a subbasin scale, as opposed to applying scaling factors to the entire model domain as was done in this instance due to time constraints. This would allow for different streamflow responses to similar climatic inputs that may result from physical differences in the basin due to geology, landcover, soil texture, etc. Additional streamflow data collection recommended in Section 10.1 would expand the number of subbasin streams to which this calibration effort could be applied.



10.5 Testing Alternative Representations of Confining Layer(s)

Due to the limited time available for model calibration, testing alternative representations of the confining layer(s) between the upper and lower aquifers was not possible. The current representation using a quasi-3D confining bed, while greatly improving model results, does have some significant limitations. It is applied across the entire model domain and the vertical conductivity can only be a single value. Given the large spatial extant and lithologic heterogeneity observed in the basin, the presence of a continuous confining layer present across the entire aquifer system is unlikely. However, it is clear that some type of confining layer (or layers) exists for a significant portion of the basin based on observed vertical head gradients. Therefore, future calibration efforts should explore alternative representations of this confining layer, especially since the quasi-3D confining bed in the current version of SVHSM was identified as the most sensitive parameter.

10.6 Testing Alternative Representations of Mountain Front Recharge

Due to the limited time available for model calibration, testing alternative representations of MFR was not possible. The current representation parameterizes MFR spatially, but not temporally. Future calibration efforts should explore the effects of varying MFR on an intra- and/or interannual basis. Additionally, further exploration of the spatial distribution of MFR and its control on simulated results should be considered.

11.0 References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. 1998. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome, 300(9), D05109.
http://www.avwatermaster.org/filingdocs/195/70653/172618e_5xAGWAX8.pdf

Bachand and Associates, Carlton Hydrology. 2020. Groundwater relationships to pumping, precipitation and geology in high-elevation basin, Sierra Valley, CA. For Feather River Land Trust (FRLT) in fullfillment of Deliverable #1: Groundwater Report.

Banta, E.R., 2000. MODFLOW-2000: The US Geological Survey Modular Ground-water Model-- documentation of Packages for Simulating Evapotranspiration with a Segmented Function (ETS1) and Drains with Return Flow (DRT1) (No. 466). US Department of the Interior, US Geological Survey. <https://pubs.usgs.gov/of/2000/0466/report.pdf>

Bohm, B. 2016. Sierra Valley Aquifer Delineation and Ground Water Flow. Available from:
<http://www.sierravalleygmd.org/files/95dd7ff5b/Sierra+Valley+Aquifer+Delineation+and+GW+Flow+-+Bohm+-+12-27-16.pdf>

Boyce, S.E., Hanson, R.T., Ferguson, I., Schmid, W., Henson, W.R., Reimann, T., Mehl, S.W. and Earll, M.M., 2020. One-Water Hydrologic Flow Model: A MODFLOW based conjunctive-



use simulation software (No. 6-A60). US Geological Survey.
<https://pubs.er.usgs.gov/publication/tm6A60>

California Department of Water Resources (DWR). 1963. Northeastern Counties Investigation, Volume 2, Plates. California Department of Water Resources. Bulletin 98.

California Department of Water Resources (DWR). 1983. Sierra Valley Ground Water Study. Northern District Memorandum Report. California Department of Water Resources. Bulletin 118-80.

California Department of Water Resources (DWR). 2018. CA Bulletin 118 Groundwater Basins. Available at
https://gis.water.ca.gov/arcgis/rest/services/Geoscientific/i08_B118_CA_GroundwaterBasins/FeatureServer

California Geological Survey (CGS). 1962. Geologic Map of California: Chico Sheet. Olaf P. Jenkins Edition. California Department of Conservation, Division of Mines and Geology.

California Geological Survey (CGS). 1992. Regional Geologic Map Series: Chico Quadrangle. Map No. 7A (Geology). California Department of Conservation, Division of Mines and Geology.

Chow, T.V. 2009. Open-Chennal Hydraulics. Blackburn Press, Illustrated Edition. p. 680.
https://www.amazon.com/dp/1932846182/ref=cm_sw_em_r_mt_dp_5CJ2B2HG988TCSZFJ2W7_encoding=UTF8&psc=1

Dib, A., Ceyhan, S., Ishida, K., Kavvas, M.L., Jang, S., Ohara, N. 2016. Final Report on the Upper Middle Fork Project. Report to Plumas County, p. 412.

Durrell, C. 1959. Tertiary Stratigraphy of the Blairsden Quadrangle, Plumas County, California. Calif. Univ., Dept. Geol. Sci. Bull., V. 34, No. 3, p. 161-192.

Foglia, L., McNally, A., Hall, C., Ledesma, L., & Hines, R., 2013a. Scott Valley Integrated Hydrologic Model: Data collection, analysis, and water budget (Technical report). Davis: University of California. <https://ucanr.edu/sites/groundwater/files/165395.pdf>

Foglia, L., McNally, A., & Harter, T., 2013b. Coupling a spatiotemporally distributed soil water budget with stream-depletion functions to inform stakeholder-driven management of groundwater-dependent ecosystems. Water Resources Research, 49, 7292– 7310.
<https://doi.org/10.1002/wrcr.20555>

Gardner, M., Morton, C., Huntington, J., Niswonger, R., Henson, W., 2018. Input data processing tools for the integrated hydrologic model GSFLOW. Environmental Modelling & Software, 109. <https://doi.org/10.1016/j.envsoft.2018.07.020>

Gold, R.D., Stephenson, W.J., Odum, J.K., Briggs, R.W., Crone, A.J. and Angster, S.J., 2013. Concealed Quaternary strike-slip fault resolved with airborne lidar and seismic reflection: The Grizzly Valley fault system, northern Walker Lane, California. Journal of Geophysical Research: Solid Earth, 118(7), pp.3753-3766. <https://doi.org/10.1002/jgrb.50238>



Grose, T.L.T. 2000a. Geologic Map of the Portola 15' Quadrangle, Plumas County, California. DMG Open-File Report 2000-22. California Department of Conservation, Division of Mines and Geology.

Grose, T.L.T. 2000b. Geologic Map of the Sierraville 15' Quadrangle, Sierra and Plumas Counties, California. DMG Open-File Report 2000-24. California Department of Conservation, Division of Mines and Geology.

Grose, T.L.T. 2000c. Geologic Map of the Loyalton 15' Quadrangle, Lassen, Plumas and Sierra Counties, California. DMG Open-File Report 2000-25. California Department of Conservation, Division of Mines and Geology.

Grose, T.L.T. and Mergner, M. 2000. Geologic Map of the Chilcoot 15' Quadrangle, Lassen and Plumas Counties, California. DMG Open-File Report 2000-23. California Department of Conservation, Division of Mines and Geology.

Harbaugh, A.W., 2005. MODFLOW-2005, the US Geological Survey modular ground-water model: the ground-water flow process (pp. 6-A16). Reston, VA: US Department of the Interior, US Geological Survey. <https://www.usgs.gov/software/modflow-2005-usgs-three-dimensional-finite-difference-ground-water-model>

Hanson, B., Orloff, S., Bali, K., Sanden, B. and Putnam, D., 2010. Irrigating alfalfa with limited water supplies. Upgrading Technology and Infrastructure in a Finance-Challenged Economy, p.347.

Jackson, W.H., Shawe, F.R., Pakiser, L.C. 1961. Gravity Study of the Structural Geology of Sierra Valley, California. In *Short papers in the geologic and hydrologic sciences, articles 1-146: Chapter B in Geological Survey research 1961*. USGS Professional paper 424-B, p. B-254 - B-256. <https://doi.org/10.3133/pp424B>

Jain, S.K. and Sudheer, K.P., 2008. Fitting of hydrologic models: a close look at the Nash-Sutcliffe index. Journal of hydrologic engineering, 13(10), pp.981-986. [https://doi.org/10.1061/\(ASCE\)1084-0699\(2008\)13:10\(981\)](https://doi.org/10.1061/(ASCE)1084-0699(2008)13:10(981))

Jennings, C.W., Strand, R.G., and Rogers, T.H., 1977, Geologic map of California: California Division of Mines and Geology, scale 1:750,000. <https://mrdata.usgs.gov/geology/state/state.php?state=CA>

Kenneth D. Schmidt and Associates. 2003. Technical Report on 1998-2003 Hydrogeologic Evaluation for Sierra Valley. Prepared for Sierra Valley Groundwater Management District, Sierraville, California. p. 176.

Kenneth D. Schmidt and Associates. 2005. Technical Report on 2003-2005 Hydrogeologic Evaluation for Sierra Valley. Prepared for Sierra Valley Groundwater Management District, Sierraville, California. p. 104.

Konikow, L.F., Hornberger, G.Z., Halford, K.J., and Hanson, R.T., 2009, Revised multi-node well (MNW2) package for MODFLOW ground-water flow model: U.S. Geological Survey Techniques and Methods 6-A30, 67 p. <https://pubs.usgs.gov/tm/tm6a30/>



Leavesley, G.H., Lichty, R.W., Troutman, B.M., and Saindon, L.G. 1983. Precipitation-runoff modeling system—User's manual: U.S. Geological Survey Water Resources Investigation Report 83-4238, 207 p. <https://pubs.er.usgs.gov/publication/wri834238>

Markstrom, S. L., Niswonger, R. G., Regan, R. S., Prudic, D. E., & Barlow, P. M. 2008. GSFLOW-Coupled Ground-water and Surface-water FLOW model based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Ground-Water Flow Model (MODFLOW-2005). US Geological Survey techniques and methods, 6, 240.

Markstrom, S. L., Regan, R. S., Hay, L. E., Viger, R. J., Webb, R. M., Payn, R. A., & LaFontaine, J. H. 2015. PRMS-IV, the precipitation-runoff modeling system, version 4. US Geological Survey Techniques and Methods, 6, B7. <https://pubs.er.usgs.gov/publication/tm6B7>

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, 10(3), pp.282-290. [https://doi.org/10.1016/0022-1694\(70\)90255-6](https://doi.org/10.1016/0022-1694(70)90255-6)

Natural Resources Conservation Service (NRCS), 2016. Sierra Valley Conservation Partnership Project. Awarded 2016. <https://www.nrcs.usda.gov/wps/portal/nrcs/detail/ca/programs/farmbill/rcpp/?cid=nrcseprd1295237>

Niswonger, R.G., Panday, S. and Ibaraki, M., 2011. MODFLOW-NWT, a Newton formulation for MODFLOW-2005. US Geological Survey Techniques and Methods, 6(A37), p.44. <https://pubs.usgs.gov/tm/tm6a37/>

Niswonger, R.G. and Prudic, D.E., 2005. Documentation of the Streamflow-Routing (SFR2) Package to include unsaturated flow beneath streams-A modification to SFR1 (No. 6-A13). US Geological Survey. <https://pubs.er.usgs.gov/publication/tm6A13>

Poeter, E.P., Hill, M.C., Banta, E.R., Mehl, Steffen, and Christensen, Steen, 2005, UCODE_2005 and Six Other Computer Codes for Universal Sensitivity Analysis, Calibration, and Uncertainty Evaluation: U.S. Geological Survey Techniques and Methods 6-A11, 283p. As updated in Feb 2008. https://igwmc.mines.edu/wp-content/uploads/sites/117/2018/11/UCODE_2005_User_Manual.pdf

Poeter, Eileen P., Mary C. Hill, Dan Lu, Claire R. Tiedeman, and Steffen Mehl, 2014, UCODE_2014, with new capabilities to define parameters unique to predictions, calculate weights using simulated values, estimate parameters with SVD, evaluate uncertainty with MCMC, and More: Integrated Groundwater Modeling Center Report Number: GWMI 2014-02. https://igwmc.mines.edu/wp-content/uploads/sites/117/2018/11/UCODE_2014_User_Manual-version02.pdf

Sawyer, T.L., Page, W.D., and Hemphill-Haley, M.A., 1995, Southern Mohawk Valley fault zone at the Calpine trench site, in Page, W.D., ed., Quaternary Geology along the boundary between Modoc Plateau, southern Cascade Mountains, and northern Sierra Nevada:



Friends of the Pleistocene 1995 Pacific Cell field trip guidebook.
https://earthquake.usgs.gov/eqc/fault/show_report_AB_archive.cfm?fault_id=25§ion_id=a

Soil Survey Staff, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at <https://sdmdataaccess.sc.egov.usda.gov>. Accessed 9/29/2020.

SVGMD, 2019. Personal communications between Bachand et al. (2020) and Kristi Jamason. February 2019.

Tolley, D., Foglia, L. and Harter, T., 2019. Sensitivity Analysis and Calibration of an Integrated Hydrologic Model in an Irrigated Agricultural Basin With a Groundwater-Dependent Ecosystem. *Water Resources Research*, 55(9), pp.7876-7901.

U.S. Geological Survey (USGS) Gap Analysis Project (GAP), 2016, GAP/LANDFIRE National Terrestrial Ecosystems 2011: U.S. Geological Survey data release, <https://doi.org/10.5066/F7ZS2TM0>

U.S. Geological Survey, 2019, USGS TNM Hydrography (NHD), accessed November 11, 2020 at URL <https://hydro.nationalmap.gov/arcgis/rest/services/nhd/MapServer>.

Vestra. 2005. Sierra Valley Watershed Assessment. Prepared for Sierra Valley Resource Conservation District. April. Available from:
http://featherriver.org/db/files/212_FINAL_SIERRAVALLEY_WATERHSED_ASSESSMENT_T.pdf

Wilson, J.L. and Guan, H., 2004. Mountain-block hydrology and mountain-front recharge. Groundwater recharge in a desert environment: The Southwestern United States, 9, pp.113-137. <https://www.rosemonteis.us/sites/default/files/references/wilson-guan-2004.pdf>

Appendix A

PRMS Water Budget

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
1989	10	3.381	0.463	3.09	0.295
1989	11	2.215	0.607	4.214	0.113
1989	12	0	0.356	3.502	0.08
1990	1	2.298	0.248	5.17	0.098
1990	2	3.458	0.201	8.054	0.082
1990	3	0.972	0.802	7.702	0.136
1990	4	1.256	1.938	6.238	0.261
1990	5	2.214	1.354	6.049	0.541
1990	6	0.146	1.678	3.866	0.195
1990	7	0	1.005	2.423	0.102
1990	8	0	0.497	1.627	0.048
1990	9	0.769	0.403	1.772	0.037
1990	10	0.278	0.461	1.414	0.03
1990	11	0.619	0.234	1.674	0.026
1990	12	0.516	0.161	1.926	0.023
1991	1	0	0.214	1.64	0.015
1991	2	0.909	0.65	1.814	0.024
1991	3	7.623	0.609	7.786	0.494
1991	4	0.232	1.397	5.797	0.213
1991	5	1.274	1.277	5.127	0.193
1991	6	0	1.158	3.484	0.111
1991	7	0.357	1.025	2.373	0.135
1991	8	1.047	1.045	2.038	0.088
1991	9	0.331	0.575	1.566	0.042
1991	10	2.178	0.436	3.086	0.064
1991	11	1.901	0.687	3.988	0.087
1991	12	1.465	0.268	4.861	0.075
1992	1	0.227	0.251	4.618	0.046
1992	2	2.854	0.586	6.441	0.136
1992	3	0.781	1.164	5.457	0.142
1992	4	0.284	1.365	3.894	0.106
1992	5	0	0.906	2.569	0.095
1992	6	0.322	0.634	1.943	0.066
1992	7	0	0.591	1.125	0.035
1992	8	0.595	0.439	1.116	0.026

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
1992	9	0	0.334	0.663	0.018
1992	10	2.447	0.46	2.533	0.041
1992	11	0	0.572	1.813	0.04
1992	12	8.532	0.11	9.866	0.132
1993	1	8.053	0.08	17.446	0.105
1993	2	6.662	0.185	23.476	0.157
1993	3	1.857	0.801	22.652	1.406
1993	4	1.097	1.485	18.324	2.846
1993	5	0.836	1.686	13.455	2.808
1993	6	1.456	1.874	9.559	2.455
1993	7	0	1.416	6.391	1.016
1993	8	0.282	1.046	4.554	0.54
1993	9	0	0.594	3.397	0.165
1993	10	1.192	0.884	3.244	0.125
1993	11	1.137	0.27	3.786	0.066
1993	12	1.613	0.258	4.768	0.092
1994	1	0.129	0.371	4.251	0.054
1994	2	3.538	0.353	7.024	0.137
1994	3	1.338	1.244	6.2	0.296
1994	4	0.113	1.234	4.512	0.124
1994	5	1.567	1.427	4.034	0.229
1994	6	0	0.857	2.776	0.101
1994	7	0	0.676	1.762	0.097
1994	8	0	0.365	1.157	0.051
1994	9	0.504	0.229	1.26	0.029
1994	10	0.406	0.467	1.053	0.028
1994	11	3.986	0.23	4.557	0.084
1994	12	1.835	0.177	5.708	0.136
1995	1	9.981	0.278	13.328	1.469
1995	2	0.742	0.614	12.533	0.29
1995	3	10.992	0.752	15.633	5.961
1995	4	2.234	1.421	14.065	1.33
1995	5	3.051	1.663	11.411	2.916
1995	6	1.143	1.788	8.665	1.27
1995	7	0.475	1.561	5.958	0.974
1995	8	0	0.969	4.148	0.349
1995	9	0	0.521	3.12	0.142
1995	10	0	0.377	2.387	0.059
1995	11	0.36	0.214	2.267	0.043
1995	12	4.197	0.395	5.346	0.303
1996	1	6.81	0.395	10.735	0.403

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
1996	2	7.7	0.525	13.094	3.694
1996	3	2.973	1.007	12.023	1.843
1996	4	3.231	1.881	10.129	2.212
1996	5	4.63	1.591	9.305	2.886
1996	6	0	1.716	6.305	0.497
1996	7	0	1.172	4.294	0.301
1996	8	0	0.634	3.101	0.158
1996	9	0.328	0.389	2.665	0.078
1996	10	0.876	0.43	2.81	0.062
1996	11	2.933	0.495	4.877	0.115
1996	12	12.461	0.346	13.395	2.759
1997	1	11.192	0.248	18.947	4.159
1997	2	0.191	0.33	17.721	0.302
1997	3	0.386	0.99	15.693	0.681
1997	4	0.256	1.501	13.328	0.469
1997	5	0.153	1.459	10.24	1.097
1997	6	1.127	1.55	7.808	1.358
1997	7	0	1.23	5.464	0.594
1997	8	0	0.794	3.973	0.29
1997	9	0.314	0.503	3.34	0.125
1997	10	1.209	0.854	3.315	0.101
1997	11	1.255	0.32	3.981	0.055
1997	12	1.427	0.237	4.864	0.073
1998	1	4.07	0.275	8.093	0.175
1998	2	6.711	0.351	12.854	0.882
1998	3	3.079	0.88	13.306	0.972
1998	4	1.02	1.535	11.537	0.475
1998	5	1.9	1.293	10.398	0.994
1998	6	0.159	1.574	7.674	0.702
1998	7	0	1.314	5.314	0.544
1998	8	0	0.833	3.863	0.219
1998	9	2.149	0.948	4.547	0.199
1998	10	0.543	0.968	3.766	0.073
1998	11	3.869	0.516	6.709	0.152
1998	12	1.792	0.177	7.603	0.186
1999	1	5.385	0.258	11.858	0.356
1999	2	6.718	0.352	15.976	1.512
1999	3	1.625	0.803	15.344	0.635
1999	4	1.302	1.412	14.077	0.548
1999	5	0	1.371	11.241	0.783
1999	6	0	1.336	8.363	0.912

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
1999	7	0	1.223	5.844	0.751
1999	8	0.276	0.892	4.486	0.312
1999	9	0	0.512	3.541	0.102
1999	10	1.217	0.513	3.889	0.082
1999	11	0.969	0.658	3.913	0.06
1999	12	0.212	0.253	3.638	0.044
2000	1	7.017	0.319	9.666	0.354
2000	2	5.674	0.542	12.508	1.472
2000	3	0.111	1.046	10.519	0.272
2000	4	1.295	1.656	9.106	0.45
2000	5	0.732	1.312	7.384	0.57
2000	6	0.205	1.224	5.429	0.469
2000	7	0	0.868	4.018	0.162
2000	8	0	0.585	3.039	0.092
2000	9	0	0.268	2.493	0.044
2000	10	1.146	0.32	3.087	0.042
2000	11	0.618	0.281	3.244	0.035
2000	12	0.42	0.301	3.215	0.029
2001	1	0.553	0.174	3.476	0.023
2001	2	1.859	0.244	4.993	0.024
2001	3	1.441	1.204	4.875	0.098
2001	4	1.608	1.343	4.741	0.095
2001	5	0	1.113	3.259	0.078
2001	6	0	0.655	2.352	0.044
2001	7	0	0.434	1.733	0.032
2001	8	0	0.263	1.334	0.03
2001	9	0.415	0.188	1.466	0.023
2001	10	0.519	0.26	1.654	0.015
2001	11	3.335	0.427	4.421	0.065
2001	12	4.884	0.225	8.437	0.227
2002	1	1.929	0.218	9.314	0.235
2002	2	0.905	0.499	9.131	0.155
2002	3	2.227	0.899	9.614	0.3
2002	4	0.734	1.531	8.095	0.218
2002	5	0.229	1.17	6.496	0.21
2002	6	0	1.127	4.688	0.267
2002	7	0	0.931	3.207	0.191
2002	8	0	0.506	2.346	0.067
2002	9	0	0.25	1.839	0.037
2002	10	0	0.165	1.476	0.025
2002	11	4.385	0.492	4.856	0.173

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2002	12	6.656	0.307	10.241	0.415
2003	1	1.106	0.51	9.764	0.326
2003	2	0.959	0.468	9.403	0.266
2003	3	1.755	1.229	8.863	0.488
2003	4	3.315	1.296	9.552	0.691
2003	5	0.159	1.59	7.206	0.39
2003	6	0.173	1.245	5.254	0.43
2003	7	0.347	1.096	3.831	0.291
2003	8	1.369	1.285	3.438	0.155
2003	9	0	0.537	2.595	0.056
2003	10	0.114	0.386	2.086	0.038
2003	11	0.732	0.306	2.328	0.035
2003	12	5.666	0.266	7.322	0.137
2004	1	1.786	0.202	8.38	0.118
2004	2	4.426	0.392	11.391	0.527
2004	3	0.796	1.317	9.483	0.534
2004	4	0	1.412	7.1	0.312
2004	5	0.717	1.18	5.728	0.381
2004	6	0	1.04	4.094	0.187
2004	7	0	0.809	2.857	0.098
2004	8	0	0.451	2.089	0.054
2004	9	0	0.205	1.65	0.034
2004	10	2.563	0.403	3.563	0.064
2004	11	1.612	0.53	4.382	0.064
2004	12	4.135	0.249	7.909	0.093
2005	1	3.913	0.17	11.398	0.051
2005	2	0.592	0.343	11.433	0.052
2005	3	4.344	0.852	13.201	1.121
2005	4	0.796	1.584	10.973	0.616
2005	5	2.335	1.78	9.201	1.499
2005	6	0.569	1.547	6.855	0.686
2005	7	0	1.388	4.5	0.446
2005	8	0	0.747	3.211	0.146
2005	9	0.261	0.401	2.709	0.064
2005	10	0.207	0.376	2.258	0.045
2005	11	1.093	0.217	2.92	0.04
2005	12	13.083	0.431	10.099	4.83
2006	1	4.053	0.337	11.163	1.543
2006	2	3.55	0.513	11.497	1.82
2006	3	3.481	0.508	12.383	1.097
2006	4	4.674	1.853	11.057	3.025

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2006	5	0.29	1.588	8.138	0.789
2006	6	0.172	1.321	5.926	0.482
2006	7	0	1.028	4.181	0.258
2006	8	0	0.558	3.152	0.119
2006	9	0	0.288	2.535	0.06
2006	10	0.216	0.277	2.216	0.042
2006	11	1.843	0.479	3.361	0.05
2006	12	1.367	0.248	4.272	0.051
2007	1	0.728	0.272	4.419	0.07
2007	2	5.068	0.554	8.361	0.194
2007	3	0.69	1.163	7.053	0.222
2007	4	0.556	1.613	5.373	0.144
2007	5	0.29	1.113	4.069	0.119
2007	6	0.342	0.915	3.137	0.082
2007	7	0	0.643	2.223	0.049
2007	8	0	0.33	1.691	0.031
2007	9	0.107	0.164	1.489	0.02
2007	10	1.204	0.633	1.927	0.031
2007	11	0.178	0.235	1.777	0.02
2007	12	2.063	0.122	3.631	0.025
2008	1	5.262	0.114	8.413	0.12
2008	2	2.439	0.329	10.076	0.136
2008	3	0.435	0.696	9.31	0.129
2008	4	0	1.216	7.703	0.105
2008	5	0.331	1.323	6.178	0.163
2008	6	0	1.253	4.303	0.2
2008	7	0	0.974	2.85	0.126
2008	8	0	0.539	2	0.048
2008	9	0	0.238	1.542	0.03
2008	10	0.554	0.322	1.603	0.027
2008	11	2.04	0.683	2.756	0.06
2008	12	1.726	0.198	4.163	0.026
2009	1	1.13	0.273	4.891	0.04
2009	2	2.942	0.371	7.156	0.113
2009	3	3.931	0.693	9.092	0.534
2009	4	0	1.433	6.888	0.182
2009	5	2.026	1.806	5.803	0.687
2009	6	0.514	1.271	4.321	0.252
2009	7	0	0.914	2.955	0.091
2009	8	0	0.466	2.162	0.053
2009	9	0	0.24	1.685	0.035

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2009	10	1.951	0.794	2.59	0.066
2009	11	0.625	0.439	2.599	0.039
2009	12	2.713	0.12	5.06	0.028
2010	1	3.253	0.257	7.735	0.102
2010	2	2.384	0.432	9.185	0.162
2010	3	2.092	0.814	9.647	0.243
2010	4	3.37	1.377	10.447	0.561
2010	5	0.937	1.38	9.003	0.379
2010	6	0	1.603	6.436	0.433
2010	7	0	1.226	4.337	0.411
2010	8	0	0.695	3.15	0.124
2010	9	0	0.378	2.441	0.053
2010	10	4.527	1.194	5.187	0.29
2010	11	2.771	0.582	6.819	0.12
2010	12	6.887	0.272	12.035	0.703
2011	1	0.575	0.272	11.346	0.241
2011	2	3.809	0.24	14.161	0.242
2011	3	7.8	0.584	17.775	2.718
2011	4	0.72	1.267	15.59	0.712
2011	5	1.195	1.304	13.348	1.271
2011	6	1.739	1.833	10.336	2.056
2011	7	0	1.61	6.943	1.087
2011	8	0	1.034	4.948	0.444
2011	9	0.562	0.796	4.095	0.229
2011	10	1.371	1.08	3.919	0.126
2011	11	0.914	0.361	4.145	0.067
2011	12	0	0.169	3.715	0.047
2012	1	5.328	0.317	7.817	0.608
2012	2	0.946	0.435	7.599	0.157
2012	3	5.061	0.776	9.742	1.422
2012	4	1.807	1.942	8.032	0.747
2012	5	0.509	1.434	6.17	0.314
2012	6	0.318	1.197	4.686	0.17
2012	7	0.372	1.006	3.598	0.113
2012	8	0	0.605	2.656	0.067
2012	9	0.104	0.321	2.193	0.043
2012	10	1.05	0.398	2.642	0.039
2012	11	6.478	0.654	7.704	0.546
2012	12	7.128	0.29	11.045	2.558
2013	1	0.298	0.161	10.149	0.26
2013	2	0.13	0.318	9.326	0.154

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2013	3	0.619	1.132	8.049	0.246
2013	4	0.306	1.555	6.124	0.199
2013	5	1.047	1.261	5.307	0.192
2013	6	0	0.982	3.867	0.129
2013	7	0	0.698	2.801	0.092
2013	8	0.18	0.407	2.304	0.045
2013	9	0.464	0.349	2.211	0.035
2013	10	0.577	0.3	2.316	0.029
2013	11	0.239	0.333	2.09	0.025
2013	12	0.638	0.213	2.406	0.022
2014	1	1.588	0.378	3.507	0.036
2014	2	4.658	0.795	6.686	0.312
2014	3	1.606	1.348	6.169	0.197
2014	4	0.317	1.555	4.423	0.108
2014	5	0.713	1.104	3.632	0.099
2014	6	0	0.768	2.574	0.057
2014	7	0.541	0.666	2.231	0.037
2014	8	1.685	1.439	2.242	0.073
2014	9	0.799	0.495	2.402	0.036
2014	10	0.517	0.835	1.969	0.032
2014	11	1.17	0.311	2.74	0.031
2014	12	4.01	0.43	5.682	0.22
2015	1	0	0.568	4.627	0.098
2015	2	4.161	0.911	6.792	0.561
2015	3	0.151	1.347	4.88	0.148
2015	4	1.117	1.211	4.304	0.117
2015	5	1.252	1.188	3.908	0.147
2015	6	0.809	1.419	2.938	0.1
2015	7	1.279	1.354	2.57	0.08
2015	8	0.675	0.916	2.116	0.05
2015	9	0	0.329	1.644	0.027
2015	10	1.64	1.074	2.068	0.048
2015	11	2.098	0.367	3.637	0.061
2015	12	4.258	0.248	7.093	0.196
2016	1	3.969	0.327	9.56	0.571
2016	2	0.794	0.732	8.444	0.386
2016	3	4.357	1.307	9.111	1.492
2016	4	1.725	2.003	7.5	0.652
2016	5	2.44	1.762	6.66	0.89
2016	6	0.159	1.51	4.658	0.188
2016	7	0	0.914	3.292	0.093

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2016	8	0	0.501	2.451	0.058
2016	9	0	0.235	1.969	0.038
2016	10	5.75	0.884	6.213	0.295
2016	11	0.934	0.804	5.538	0.191
2016	12	6.21	0.331	8.684	1.918
2017	1	13.838	0.16	18.046	3.229
2017	2	13.295	0.335	22.269	7.414
2017	3	2.287	0.771	20.871	1.802
2017	4	4.529	1.535	17.207	5.265
2017	5	0.703	1.67	13.101	2.049
2017	6	0.147	1.542	9.588	1.351
2017	7	0	1.306	6.73	0.943
2017	8	0.535	1.094	5.053	0.651
2017	9	0.994	0.824	4.62	0.243
2017	10	0.414	0.635	4.026	0.071
2017	11	5.384	0.668	7.771	0.559
2017	12	0.303	0.382	6.882	0.187
2018	1	2.373	0.565	7.744	0.358
2018	2	0.698	0.469	7.404	0.125
2018	3	7.14	0.649	11.452	1.787
2018	4	1.853	1.873	9.244	1.263
2018	5	2.104	1.652	8.211	0.787
2018	6	0.42	1.708	6.115	0.277
2018	7	0	1.112	4.415	0.187
2018	8	0	0.532	3.456	0.114
2018	9	0	0.265	2.898	0.056
2018	10	0.273	0.288	2.65	0.042
2018	11	1.688	0.219	3.933	0.04
2018	12	1.364	0.232	4.862	0.049
2019	1	7.787	0.317	11.119	0.723
2019	2	13.331	0.217	21.885	1.585
2019	3	2.042	0.656	21.062	1.374
2019	4	1.18	1.874	17.26	2.166
2019	5	1.894	1.492	14.215	2.408
2019	6	0	1.773	10.092	1.51
2019	7	0	1.347	7.142	0.961
2019	8	0	0.936	5.314	0.414
2019	9	1.072	0.66	5.178	0.181
2019	10	0.403	0.73	4.458	0.08
2019	11	0.817	0.286	4.705	0.05
2019	12	4.705	0.28	8.481	0.204

Year	Month	Precip (inches)	ET (inches)	Storage (inches)	Runoff (inches)
2020	1	0.926	0.403	8.383	0.143
2020	2	0	0.611	7.375	0.079
2020	3	3.006	0.64	9.459	0.059
2020	4	1.277	1.735	8.373	0.23
2020	5	1.196	1.563	6.956	0.519
2020	6	0.152	1.211	5.241	0.234
2020	7	0	0.889	3.907	0.124
2020	8	0	0.509	3.081	0.069
2020	9	0	0.237	2.62	0.036

Appendix B

SWBM Water Budget

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
1999	10	13,573	1,480	28	-19,814	-135	-266	5,133	0
1999	11	14,336	0	0	-2,381	-331	-70	-11,554	0
1999	12	5,944	0	0	-427	-206	0	-5,311	0
2000	1	67,108	0	0	-8	-8,472	-15,006	-43,623	0
2000	2	52,494	0	0	-9	-24,188	-24,545	-3,751	0
2000	3	3,981	0	0	-9,308	-3,784	0	9,111	0
2000	4	13,150	131	27	-25,053	-903	-1,265	13,913	0
2000	5	7,293	3,495	277	-36,619	-139	0	25,693	0
2000	6	1,398	12,137	1,190	-41,954	-25	0	27,253	0
2000	7	0	7,306	2,002	-36,712	0	0	27,404	0
2000	8	0	4,897	1,809	-16,397	0	0	9,691	0
2000	9	1,464	1,461	139	-5,871	-14	0	2,821	0
2000	10	14,494	691	35	-8,455	-274	-115	-6,377	0
2000	11	9,487	0	0	-1,651	-134	-164	-7,539	0
2000	12	5,906	0	0	-383	-170	-17	-5,336	0
2001	1	7,557	0	0	-7	-242	-47	-7,260	0
2001	2	17,526	0	0	-10	-540	-169	-16,807	0
2001	3	15,323	0	0	-9,991	-485	-427	-4,421	0
2001	4	14,853	2,705	1,057	-23,600	-483	-158	5,625	0
2001	5	0	8,920	1,981	-37,161	0	0	26,260	0
2001	6	0	4,793	2,351	-22,162	0	0	15,018	0
2001	7	96	2,292	2,485	-6,535	0	0	1,663	0
2001	8	0	2,531	2,288	-5,428	0	0	609	0
2001	9	3,591	668	157	-5,282	-54	-37	958	0
2001	10	5,133	315	60	-1,592	-54	-105	-3,758	0
2001	11	37,309	0	0	-2,025	-427	-778	-34,078	0
2001	12	49,778	0	0	-353	-3,193	-2,528	-43,705	0
2002	1	18,307	0	0	-8	-3,402	-3,058	-11,839	0
2002	2	8,742	0	0	-13	-3,343	-1,104	-4,281	0
2002	3	24,104	0	0	-9,056	-5,794	-7,142	-2,112	0
2002	4	7,781	71	604	-22,660	-195	-17	14,416	0
2002	5	2,999	4,694	1,289	-37,083	-60	0	28,161	0
2002	6	0	11,458	2,014	-41,152	0	0	27,680	0
2002	7	1,037	7,071	2,422	-32,636	-6	0	22,112	0

Year	Month	Volume (AF)						
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage
2002	8	0	2,998	2,073	-10,520	0	0	5,449
2002	9	0	1,070	171	-3,006	0	0	1,766
2002	10	0	468	54	-927	0	0	404
2002	11	47,443	0	0	-1,306	-269	-1,358	-44,510
2002	12	65,315	0	0	-380	-6,032	-7,450	-51,453
2003	1	11,257	0	0	-8	-5,213	-1,450	-4,587
2003	2	10,171	0	0	-12	-4,326	-2,336	-3,496
2003	3	17,921	0	0	-8,187	-3,641	-6,896	803
2003	4	30,078	1	184	-18,723	-4,335	-3,942	-3,262
2003	5	3,574	767	765	-37,348	-82	0	32,324
2003	6	1,604	8,937	1,936	-46,991	-21	0	34,535
2003	7	3,280	9,277	2,658	-39,350	-21	0	24,156
2003	8	10,331	4,166	2,068	-25,041	-172	-77	8,726
2003	9	735	1,399	155	-7,488	-5	0	5,204
2003	10	1,112	600	63	-1,664	-35	0	-75
2003	11	11,005	0	0	-1,792	-229	-104	-8,880
2003	12	57,340	0	0	-360	-1,196	-1,785	-54,000
2004	1	19,491	0	0	-7	-1,548	-1,773	-16,162
2004	2	42,534	0	0	-10	-5,969	-13,310	-23,245
2004	3	8,598	0	0	-11,195	-1,855	-1,571	6,024
2004	4	465	709	476	-26,708	-3	0	25,061
2004	5	5,294	7,085	1,692	-37,349	-108	-2	23,387
2004	6	904	9,858	2,081	-36,430	-5	0	23,593
2004	7	0	3,888	2,670	-27,846	0	0	21,288
2004	8	0	2,126	2,173	-6,582	0	0	2,283
2004	9	1,899	1,194	165	-4,972	-15	0	1,729
2004	10	27,421	723	56	-5,267	-292	-548	-22,093
2004	11	20,130	0	0	-1,710	-281	-387	-17,752
2004	12	40,787	0	0	-285	-1,060	-2,954	-36,488
2005	1	36,238	0	0	-5	-6,464	-6,837	-22,932
2005	2	10,644	0	0	-9	-6,055	-605	-3,976
2005	3	41,799	0	0	-7,519	-10,736	-16,086	-7,458
2005	4	8,969	0	171	-21,887	-1,048	-190	13,985
2005	5	17,149	373	427	-32,889	-959	-743	16,642
2005	6	4,895	6,029	1,444	-41,738	-69	-1	29,441
2005	7	0	12,407	2,421	-43,050	0	0	28,222
2005	8	139	5,146	2,303	-24,669	-1	0	17,081
2005	9	2,753	1,407	142	-8,558	-37	0	4,293
2005	10	4,489	670	50	-4,984	-86	0	-140
2005	11	13,978	0	0	-1,874	-298	-131	-11,675

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
2005	12	127,443	0	0	-281	-3,744	-29,143	-94,276	0
2006	1	37,740	0	0	-9	-14,166	-17,600	-5,965	0
2006	2	31,975	0	0	-13	-10,499	-18,913	-2,550	0
2006	3	38,729	0	0	-6,078	-17,629	-13,327	-1,695	0
2006	4	43,630	0	0	-20,458	-10,598	-18,484	5,909	0
2006	5	2,582	220	340	-39,249	-33	0	36,141	0
2006	6	1,434	8,509	1,124	-42,885	-20	0	31,837	0
2006	7	0	10,101	1,959	-36,917	0	0	24,857	0
2006	8	0	6,649	1,516	-20,627	0	0	12,462	0
2006	9	0	2,643	159	-5,867	0	0	3,064	0
2006	10	2,383	877	41	-4,357	-42	0	1,098	0
2006	11	21,768	0	0	-1,925	-439	-236	-19,169	0
2006	12	15,964	0	0	-410	-358	-160	-15,036	0
2007	1	6,538	0	0	-8	-134	-270	-6,125	0
2007	2	46,381	0	0	-10	-2,275	-3,364	-40,732	0
2007	3	6,628	0	0	-10,086	-221	-165	3,844	0
2007	4	7,545	303	1,050	-24,962	-161	-71	16,296	0
2007	5	2,696	8,606	1,575	-41,050	-61	-4	28,237	0
2007	6	2,414	6,558	1,987	-34,611	-49	-6	23,706	0
2007	7	0	3,520	2,402	-14,130	0	0	8,208	0
2007	8	0	2,764	2,227	-6,396	0	0	1,406	0
2007	9	3,870	1,020	141	-6,284	-29	0	1,282	0
2007	10	14,743	537	22	-13,219	-243	-118	-1,722	0
2007	11	3,705	0	0	-1,861	-90	-8	-1,747	0
2007	12	21,532	0	0	-405	-419	-279	-20,429	0
2008	1	50,219	0	0	-7	-1,832	-1,728	-46,653	0
2008	2	22,377	0	0	-12	-2,352	-2,501	-17,512	0
2008	3	4,884	0	0	-8,609	-1,257	-63	5,045	0
2008	4	513	351	1,296	-27,774	-7	0	25,620	0
2008	5	3,804	8,063	1,654	-35,409	-57	0	21,946	0
2008	6	0	9,103	2,594	-35,755	0	0	24,059	0
2008	7	0	4,685	2,686	-17,116	0	0	9,745	0
2008	8	0	3,049	2,336	-6,296	0	0	912	0
2008	9	0	937	178	-2,483	0	0	1,368	0
2008	10	5,549	721	40	-5,437	-137	-16	-720	0
2008	11	22,343	0	0	-1,855	-263	-442	-19,782	0
2008	12	18,861	0	0	-458	-402	-227	-17,774	0
2009	1	10,195	0	0	-9	-358	-129	-9,699	0
2009	2	27,403	0	0	-12	-1,615	-1,355	-24,421	0
2009	3	38,096	0	0	-9,508	-2,916	-7,459	-18,212	0

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
2009	4	1,937	276	1,130	-26,399	-43	0	23,099	0
2009	5	13,916	6,972	1,662	-42,972	-299	-88	20,809	0
2009	6	4,755	8,357	1,906	-34,293	-75	-1	19,351	0
2009	7	0	3,835	2,710	-30,180	0	0	23,634	0
2009	8	599	2,392	2,267	-7,305	-4	0	2,052	0
2009	9	775	611	187	-3,297	-5	0	1,729	0
2009	10	19,835	669	39	-10,028	-121	-501	-9,893	0
2009	11	7,048	0	0	-2,505	-148	-71	-4,324	0
2009	12	27,948	0	0	-223	-492	-465	-26,768	0
2010	1	29,833	0	0	-6	-1,046	-1,387	-27,394	0
2010	2	21,626	0	0	-11	-2,084	-2,062	-17,468	0
2010	3	21,640	0	0	-9,604	-2,139	-2,413	-7,484	0
2010	4	30,476	20	494	-22,401	-2,011	-3,079	-3,499	0
2010	5	7,664	1,479	1,062	-36,198	-132	-27	26,151	0
2010	6	756	8,144	2,184	-46,008	-5	0	34,929	0
2010	7	0	12,057	2,592	-36,112	0	0	21,464	0
2010	8	0	4,585	2,071	-17,158	0	0	10,502	0
2010	9	0	1,274	173	-4,745	0	0	3,298	0
2010	10	44,631	2,222	12	-16,223	-348	-1,048	-29,246	0
2010	11	30,920	0	0	-2,297	-596	-964	-27,064	0
2010	12	68,161	0	0	-386	-6,610	-15,062	-46,103	0
2011	1	5,622	0	0	-8	-2,936	-1,367	-1,312	0
2011	2	34,009	0	0	-13	-9,469	-17,156	-7,370	0
2011	3	75,261	0	0	-6,470	-24,905	-40,051	-3,834	0
2011	4	9,114	1	50	-22,990	-547	-53	14,426	0
2011	5	9,072	1,067	319	-35,011	-183	-7	24,743	0
2011	6	11,915	6,984	1,106	-42,299	-158	-119	22,572	0
2011	7	0	12,791	2,250	-42,207	0	0	27,166	0
2011	8	0	13,242	1,846	-27,227	0	0	12,140	0
2011	9	5,489	7,008	119	-16,850	-76	-23	4,333	0
2011	10	14,229	1,601	19	-15,305	-164	-251	-129	0
2011	11	10,137	0	0	-1,998	-275	-31	-7,833	0
2011	12	202	0	0	-480	-7	0	285	0
2012	1	48,304	0	0	-4	-427	-1,859	-46,014	0
2012	2	9,973	0	0	-13	-778	-484	-8,697	0
2012	3	51,129	0	0	-8,147	-5,131	-10,383	-27,469	0
2012	4	15,684	76	225	-25,905	-1,017	-483	11,421	0
2012	5	3,325	3,680	1,376	-43,255	-68	-1	34,942	0
2012	6	2,692	7,692	2,237	-43,133	-53	-5	30,571	0
2012	7	3,164	3,981	2,691	-28,324	-42	-11	18,542	0

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
2012	8	0	2,733	2,341	-6,846	0	0	1,772	0
2012	9	869	1,283	180	-4,157	-6	0	1,831	0
2012	10	10,243	757	65	-5,733	-155	-158	-5,018	0
2012	11	70,575	0	0	-2,117	-742	-3,197	-64,519	0
2012	12	70,979	0	0	-473	-11,997	-20,448	-38,061	0
2013	1	4,453	0	0	-6	-3,397	-769	-281	0
2013	2	1,132	0	0	-14	-881	0	-237	0
2013	3	7,488	0	0	-9,782	-2,640	-1,329	6,263	0
2013	4	2,925	444	465	-29,135	-99	0	25,400	0
2013	5	7,521	7,300	1,387	-39,107	-135	-22	23,057	0
2013	6	1,091	7,115	2,188	-37,729	-13	0	27,348	0
2013	7	214	3,470	2,970	-28,025	-1	0	21,372	0
2013	8	1,255	1,890	2,482	-8,806	-17	0	3,196	0
2013	9	4,614	505	150	-6,657	-93	-23	1,505	0
2013	10	5,735	457	52	-1,812	-91	-91	-4,250	0
2013	11	3,694	0	0	-2,309	-85	-29	-1,271	0
2013	12	6,129	0	0	-354	-107	-91	-5,576	0
2014	1	14,073	0	0	-3	-136	-324	-13,610	0
2014	2	40,838	0	0	-15	-875	-1,526	-38,422	0
2014	3	16,238	0	0	-9,126	-833	-408	-5,870	0
2014	4	3,872	1,906	1,514	-28,261	-64	-30	21,063	0
2014	5	5,400	6,911	2,357	-38,723	-58	-87	24,201	0
2014	6	0	3,437	3,100	-27,893	0	0	21,356	0
2014	7	5,274	1,571	2,757	-10,523	-63	-23	1,007	0
2014	8	12,553	1,580	2,204	-16,994	-103	-167	928	0
2014	9	6,800	628	159	-6,306	-138	-31	-1,112	0
2014	10	5,879	366	59	-7,833	-135	-6	1,670	0
2014	11	14,771	0	0	-1,593	-270	-185	-12,722	0
2014	12	40,496	0	0	-277	-706	-978	-38,536	0
2015	1	0	0	0	-9	-4	-27	41	0
2015	2	36,950	0	0	-17	-1,513	-3,821	-31,599	0
2015	3	1,426	0	0	-11,074	-346	-6	10,000	0
2015	4	10,205	781	1,254	-28,152	-180	-104	16,196	0
2015	5	8,998	5,688	1,840	-34,050	-150	-57	17,733	0
2015	6	5,263	3,744	2,781	-40,605	-58	-12	28,888	0
2015	7	12,277	1,824	2,257	-24,491	-148	-28	8,309	0
2015	8	4,708	2,130	2,222	-9,885	-54	-63	943	0
2015	9	1,272	721	163	-3,589	-16	0	1,448	0
2015	10	16,207	614	40	-15,047	-181	-305	-1,327	0
2015	11	24,600	0	0	-1,908	-343	-436	-21,913	0

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
2015	12	42,812	0	0	-367	-918	-1,597	-39,929	0
2016	1	38,956	0	0	-6	-3,373	-5,709	-29,869	0
2016	2	10,051	0	0	-14	-4,420	-467	-5,151	0
2016	3	41,539	0	0	-8,648	-9,548	-15,419	-7,924	0
2016	4	16,572	2	404	-27,401	-1,246	-1,048	12,717	0
2016	5	17,123	387	953	-36,164	-1,727	-931	20,360	0
2016	6	1,033	7,714	2,427	-44,996	-16	0	33,838	0
2016	7	0	4,018	2,648	-36,050	0	0	29,383	0
2016	8	577	1,797	2,650	-11,985	-4	0	6,965	0
2016	9	0	654	180	-2,902	0	0	2,068	0
2016	10	57,561	2,664	33	-11,252	-503	-1,449	-47,054	0
2016	11	12,596	0	0	-2,457	-421	-320	-9,398	0
2016	12	61,813	0	0	-419	-3,670	-14,189	-43,535	0
2017	1	124,865	0	0	-7	-20,280	-87,862	-16,716	0
2017	2	117,208	0	0	-12	-25,190	-89,798	-2,207	0
2017	3	23,974	0	0	-7,461	-8,693	-8,697	876	0
2017	4	38,509	0	0	-23,652	-9,326	-16,676	11,145	0
2017	5	4,891	1,241	525	-44,653	-103	-17	38,116	0
2017	6	1,368	9,110	1,648	-43,836	-26	0	31,736	0
2017	7	0	14,398	2,627	-39,240	0	0	22,214	0
2017	8	4,549	12,302	1,570	-21,434	-37	0	3,050	0
2017	9	10,268	6,359	92	-17,609	-134	-13	1,039	0
2017	10	4,856	1,646	45	-9,513	-75	-64	3,105	0
2017	11	60,526	0	0	-1,708	-591	-2,058	-56,169	0
2017	12	3,694	0	0	-440	-357	-33	-2,863	0
2018	1	24,556	0	0	-9	-2,651	-3,236	-18,660	0
2018	2	8,810	0	0	-14	-2,761	-745	-5,290	0
2018	3	70,669	0	0	-8,167	-12,839	-32,560	-17,103	0
2018	4	16,655	0	25	-23,717	-2,012	-1,986	11,035	0
2018	5	16,521	252	553	-38,761	-172	-241	21,848	0
2018	6	2,736	8,455	2,084	-46,527	-51	-14	33,317	0
2018	7	0	6,531	2,329	-38,416	0	0	29,555	0
2018	8	0	5,853	1,750	-15,660	0	0	8,057	0
2018	9	0	3,014	171	-5,410	0	0	2,225	0
2018	10	3,579	1,184	35	-5,304	-61	-23	589	0
2018	11	18,627	0	0	-384	-346	-248	-17,649	0
2018	12	15,424	0	0	-376	-265	-236	-14,547	0
2019	1	70,657	0	0	-9	-2,067	-8,518	-60,063	0
2019	2	118,127	0	0	-9	-16,611	-77,955	-23,553	0
2019	3	22,196	0	0	-8,022	-10,227	-6,545	2,598	0

Year	Month	Volume (AF)							
		Precip	SW Irrigation	GW Irrigation	ET	Recharge	Runoff	Storage	Error
2019	4	10,568	2	10	-24,269	-2,147	-1,232	17,067	0
2019	5	15,372	411	244	-36,436	-240	-32	20,682	0
2019	6	0	8,896	1,840	-45,797	0	0	35,061	0
2019	7	0	12,390	2,472	-37,158	0	0	22,297	0
2019	8	0	12,315	1,898	-22,661	0	0	8,448	0
2019	9	9,815	5,138	96	-14,819	-194	-61	25	0
2019	10	3,933	1,309	31	-11,038	-54	-59	5,877	0
2019	11	10,328	0	0	-612	-233	-93	-9,390	0
2019	12	47,299	0	0	-314	-717	-1,244	-45,024	0
2020	1	10,103	0	0	-8	-719	-470	-8,906	0
2020	2	1,265	0	0	-17	-170	0	-1,078	0
2020	3	30,901	0	0	-6,908	-2,206	-4,656	-17,130	0
2020	4	10,910	514	822	-29,235	-477	-503	17,970	0
2020	5	9,475	3,633	1,697	-36,537	-122	-118	21,972	0
2020	6	1,949	9,318	2,354	-38,855	-14	0	25,249	0
2020	7	292	4,650	2,832	-26,147	-2	0	18,374	0
2020	8	547	3,362	2,169	-7,077	-4	0	1,002	0
2020	9	0	1,270	182	-3,320	0	0	1,869	0

Appendix C

MODFLOW Water Budget

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
1999	10	134	-1185	311	324	-49	116	-349
1999	11	329	-881	301	455	-16	-189	0
1999	12	204	-749	311	267	-15	-18	0
2000	1	8452	-2429	311	1331	-20	-7645	0
2000	2	24143	-6236	291	-1391	-17	-16790	0
2000	3	3778	-9627	311	-402	-8	5953	5
2000	4	899	-3634	301	950	-43	1530	3
2000	5	138	-3161	311	1277	-296	1731	0
2000	6	25	-2663	301	761	-1192	2769	1
2000	7	0	-2074	311	-264	-1985	4012	1
2000	8	0	-1713	311	-165	-1798	3372	7
2000	9	14	-1356	301	-156	-177	1375	1
2000	10	272	-1191	311	-94	-52	755	1
2000	11	133	-756	301	288	-12	47	0
2000	12	169	-785	311	92	-15	228	0
2001	1	241	-951	311	33	-16	384	2
2001	2	536	-1177	281	90	-16	286	1
2001	3	483	-1872	311	625	-19	474	2
2001	4	480	-1638	301	199	-1040	1698	0
2001	5	0	-1637	311	-87	-1956	3370	1
2001	6	0	-1338	301	-68	-2302	3405	-2
2001	7	0	-1228	311	-66	-2421	3382	-21
2001	8	0	-1126	311	-65	-2236	3091	-24
2001	9	54	-941	301	16	-198	768	0
2001	10	54	-869	311	135	-84	453	0
2001	11	424	-647	301	942	-20	-1001	-2
2001	12	3185	-931	311	870	-20	-3415	0
2002	1	3396	-1947	311	745	-30	-2479	-4
2002	2	3334	-3009	281	397	-30	-973	0
2002	3	5772	-4250	311	1461	-29	-3274	-9
2002	4	193	-2163	301	899	-612	1382	1
2002	5	60	-1892	311	1194	-1296	1624	0
2002	6	0	-1513	301	384	-2024	2852	0

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2002	7	6	-1315	311	-63	-2412	3441	-32
2002	8	0	-1121	311	-65	-2067	2886	-56
2002	9	0	-957	301	-51	-255	962	0
2002	10	0	-805	311	-7	-103	604	0
2002	11	267	-669	301	1447	-23	-1326	-3
2002	12	6021	-1759	311	1512	-31	-6054	0
2003	1	5198	-3342	311	431	-24	-2578	-3
2003	2	4313	-3871	281	687	-22	-1389	0
2003	3	3623	-3937	311	1806	-640	-1169	-5
2003	4	4302	-3013	301	1619	-657	-2567	-15
2003	5	82	-2553	311	1169	-1130	2115	-6
2003	6	21	-2048	301	919	-1441	2204	-43
2003	7	21	-1639	311	177	-1642	2704	-67
2003	8	170	-1333	311	81	-1327	2028	-69
2003	9	5	-1144	301	-61	-442	1321	-20
2003	10	35	-1002	311	-3	-289	937	-11
2003	11	227	-604	301	364	-30	-258	0
2003	12	1189	-567	311	847	-28	-1754	-2
2004	1	1545	-1154	311	452	-28	-1129	-3
2004	2	5955	-3129	291	1683	-24	-4777	-1
2004	3	1846	-3629	311	1379	-874	956	-10
2004	4	3	-2022	301	1080	-1077	1704	-10
2004	5	107	-1842	311	860	-1462	1994	-32
2004	6	5	-1419	301	-123	-1697	2890	-43
2004	7	0	-1318	311	-64	-1959	2959	-70
2004	8	0	-1131	311	-61	-1619	2440	-60
2004	9	15	-982	301	-56	-503	1213	-13
2004	10	289	-834	311	392	-265	104	-3
2004	11	279	-572	301	637	-23	-623	-1
2004	12	1056	-659	311	888	-23	-1577	-4
2005	1	6446	-1593	311	503	0	-5667	0
2005	2	6036	-3759	281	-453	0	-2108	-3
2005	3	10693	-7830	311	2169	-553	-4805	-15
2005	4	1039	-3150	301	1238	-667	1213	-25
2005	5	950	-2873	311	2629	-879	-204	-66
2005	6	69	-2330	301	1326	-1116	1609	-141
2005	7	0	-1928	311	679	-1459	2160	-236
2005	8	1	-1504	311	-118	-1355	2443	-223
2005	9	37	-1175	301	-24	-258	1100	-19
2005	10	85	-1021	311	8	-176	785	-8

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2005	11	296	-816	301	437	-16	-202	0
2005	12	3732	-1193	311	3463	-15	-6298	0
2006	1	14111	-4879	311	-78	-20	-9445	0
2006	2	10461	-7550	281	660	-17	-3836	-2
2006	3	17567	-9885	311	-242	-398	-7355	-1
2006	4	10549	-9491	301	1926	-638	-2662	-15
2006	5	33	-4997	311	1669	-1089	3996	-76
2006	6	20	-2996	301	790	-1246	3005	-126
2006	7	0	-2317	311	-94	-1440	3379	-161
2006	8	0	-1893	311	-211	-1266	2914	-145
2006	9	0	-1562	301	-165	-282	1700	-8
2006	10	42	-1255	311	-150	-164	1217	2
2006	11	435	-978	301	412	-12	-158	0
2006	12	355	-886	311	178	-15	57	0
2007	1	133	-1135	311	348	-16	360	1
2007	2	2270	-1813	281	1168	-16	-1892	-1
2007	3	220	-2214	311	847	-739	1560	-15
2007	4	160	-1761	301	666	-900	1496	-38
2007	5	61	-1810	311	100	-1455	2718	-76
2007	6	48	-1482	301	-65	-1575	2643	-130
2007	7	0	-1404	311	-62	-1758	2773	-140
2007	8	0	-1263	311	-60	-1601	2482	-131
2007	9	29	-1018	301	-59	-355	1076	-25
2007	10	241	-881	311	132	-209	396	-11
2007	11	89	-704	301	271	-20	63	0
2007	12	415	-670	311	319	-20	-356	-1
2008	1	1825	-892	311	665	-30	-1882	-1
2008	2	2348	-1946	291	565	-30	-1232	-3
2008	3	1254	-2144	311	213	-639	986	-19
2008	4	7	-1518	301	216	-945	1924	-16
2008	5	57	-1339	311	-30	-1212	2169	-43
2008	6	0	-1260	301	-14	-1564	2450	-87
2008	7	0	-1170	311	-39	-1636	2421	-113
2008	8	0	-1081	311	-47	-1551	2259	-109
2008	9	0	-905	301	54	-451	979	-20
2008	10	136	-768	311	69	-265	509	-8
2008	11	261	-599	301	918	-23	-858	0
2008	12	398	-614	311	443	-31	-509	-2
2009	1	356	-732	311	326	-24	-239	-1
2009	2	1610	-1183	281	801	-22	-1493	-6

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2009	3	2906	-2374	311	2456	-387	-2927	-14
2009	4	42	-1559	301	820	-570	955	-11
2009	5	297	-1824	311	2246	-877	-204	-51
2009	6	74	-1216	301	625	-796	947	-65
2009	7	0	-1185	311	30	-1079	1866	-56
2009	8	4	-1027	311	58	-934	1519	-68
2009	9	5	-926	301	61	-343	878	-24
2009	10	120	-820	311	456	-165	94	-5
2009	11	146	-684	301	508	-30	-241	0
2009	12	488	-337	311	499	-28	-934	0
2010	1	1042	-683	311	648	-28	-1291	0
2010	2	2081	-1586	281	705	-24	-1457	0
2010	3	2130	-2219	311	1184	-884	-531	-8
2010	4	1992	-1992	301	2300	-1046	-1569	-15
2010	5	131	-1655	311	1388	-1483	1285	-24
2010	6	5	-1534	301	1177	-1949	1910	-91
2010	7	0	-1365	311	608	-2334	2649	-131
2010	8	0	-1091	311	62	-1980	2601	-98
2010	9	0	-937	301	69	-442	982	-27
2010	10	345	-933	311	1814	-219	-1319	0
2010	11	592	-799	301	948	-23	-1022	-2
2010	12	6589	-1856	311	1610	-23	-6631	0
2011	1	2925	-2574	311	305	-24	-944	-1
2011	2	9426	-4809	281	1137	-20	-6032	-18
2011	3	24796	-11689	311	414	-384	-13453	-6
2011	4	543	-5057	301	402	-575	4376	-9
2011	5	182	-2868	311	1909	-797	1256	-8
2011	6	157	-2960	301	2457	-950	963	-32
2011	7	0	-2635	311	1585	-1220	1915	-44
2011	8	0	-1878	311	651	-1131	2005	-42
2011	9	75	-1444	301	250	-197	1018	3
2011	10	163	-1227	311	463	-111	402	1
2011	11	272	-861	301	413	-23	-104	0
2011	12	6	-844	311	357	-24	194	1
2012	1	425	-1274	311	1724	-26	-1163	-4
2012	2	776	-1466	291	488	-22	-68	0
2012	3	5117	-4029	311	2254	-729	-2937	-12
2012	4	1007	-2781	301	1480	-1057	1045	-4
2012	5	67	-2221	311	1015	-1629	2411	-45
2012	6	53	-1544	301	-95	-1858	3085	-58

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2012	7	42	-1384	311	-14	-2116	3114	-47
2012	8	0	-1190	311	-35	-1828	2684	-58
2012	9	6	-1021	301	33	-317	998	0
2012	10	154	-938	311	183	-209	500	0
2012	11	737	-917	301	2385	-23	-2484	0
2012	12	11953	-3169	311	1503	-39	-10559	0
2013	1	3380	-2842	311	-284	-31	-535	0
2013	2	877	-3135	281	237	-22	1763	2
2013	3	2624	-2912	311	855	-1082	201	-3
2013	4	99	-2000	301	723	-1540	2376	-41
2013	5	134	-1652	311	521	-2014	2609	-92
2013	6	13	-1376	301	-34	-2280	3259	-116
2013	7	1	-1305	311	13	-2708	3467	-221
2013	8	17	-1140	311	51	-2325	2934	-152
2013	9	93	-956	301	73	-449	938	0
2013	10	90	-835	311	120	-278	592	0
2013	11	84	-640	301	331	-22	-54	0
2013	12	106	-446	311	267	-27	-213	-1
2014	1	135	-829	311	553	-24	-147	-1
2014	2	872	-1183	281	1728	-21	-1680	-3
2014	3	830	-1479	311	1198	-964	99	-4
2014	4	63	-1289	301	484	-1443	1841	-43
2014	5	57	-1165	311	24	-2099	2814	-57
2014	6	0	-1031	301	4	-2526	3144	-109
2014	7	62	-979	311	101	-2513	2926	-91
2014	8	103	-946	311	222	-2142	2381	-71
2014	9	137	-819	301	95	-382	666	-2
2014	10	134	-690	311	69	-240	416	0
2014	11	268	-545	301	503	-27	-499	0
2014	12	701	-448	311	1486	-23	-2031	-3
2015	1	4	-721	311	692	-24	-263	-1
2015	2	1510	-1460	281	2469	-26	-2778	-4
2015	3	345	-1379	311	862	-1286	1144	-2
2015	4	178	-1153	301	877	-1641	1402	-35
2015	5	149	-1044	311	253	-1921	2194	-58
2015	6	58	-1017	301	94	-2746	3253	-57
2015	7	147	-932	311	143	-2561	2820	-72
2015	8	53	-872	311	138	-2434	2732	-71
2015	9	16	-715	301	72	-669	986	-9
2015	10	180	-666	311	317	-427	280	-4

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2015	11	340	-483	301	824	-27	-954	0
2015	12	914	-463	311	1351	-28	-2089	-4
2016	1	3365	-985	311	2016	-29	-4679	0
2016	2	4406	-2774	291	1065	-25	-2964	-1
2016	3	9498	-5223	311	2845	-775	-6662	-6
2016	4	1230	-2906	301	1694	-1256	918	-20
2016	5	1707	-2348	311	2178	-1453	-438	-44
2016	6	16	-1473	301	-83	-1940	3114	-64
2016	7	0	-1254	311	50	-2220	3052	-61
2016	8	4	-1109	311	65	-2150	2817	-63
2016	9	0	-893	301	62	-428	957	-2
2016	10	499	-845	311	1491	-209	-1247	-1
2016	11	419	-777	301	1187	-22	-1111	-3
2016	12	3659	-1512	311	2777	-24	-5213	-2
2017	1	20190	-3785	311	132	-25	-16823	0
2017	2	25088	-8978	281	-1014	-23	-15354	0
2017	3	8650	-12177	311	543	-518	3189	-3
2017	4	9286	-8933	301	2604	-717	-2553	-11
2017	5	102	-5146	311	2672	-1206	3265	-2
2017	6	25	-3429	301	1942	-1345	2489	-16
2017	7	0	-2858	311	1384	-1678	2808	-32
2017	8	37	-2270	311	1224	-1278	1950	-25
2017	9	133	-1608	301	367	-196	1005	3
2017	10	74	-1406	311	80	-143	1087	4
2017	11	587	-1099	301	1618	-20	-1389	-2
2017	12	356	-998	311	373	-21	-22	0
2018	1	2647	-1965	311	759	-20	-1735	-3
2018	2	2758	-2937	281	215	-19	-301	-1
2018	3	12795	-8074	311	1712	-621	-6126	-2
2018	4	1994	-4306	301	1616	-864	1254	-5
2018	5	171	-3090	311	1815	-1259	2041	-11
2018	6	50	-2096	301	146	-1577	3123	-53
2018	7	0	-1777	311	-21	-1763	3177	-72
2018	8	0	-1499	311	29	-1508	2607	-60
2018	9	0	-1274	301	38	-309	1245	0
2018	10	60	-1058	311	124	-178	741	1
2018	11	343	-859	301	429	-22	-193	0
2018	12	262	-662	311	294	-23	-183	0
2019	1	2061	-1354	311	1779	-25	-2778	-6
2019	2	16542	-4759	281	614	-24	-12655	0

Year	Month	Volume (AF)						
		Recharge	ET	MFR	GW-SW Exchange	GW Pumping	Storage	Error
2019	3	10179	-8765	311	230	-543	-1415	-2
2019	4	2130	-4624	301	1988	-837	1032	-10
2019	5	238	-3707	311	2759	-1112	1502	-8
2019	6	0	-3252	301	2183	-1527	2249	-45
2019	7	0	-2631	311	1559	-1618	2319	-60
2019	8	0	-1871	311	404	-1454	2554	-57
2019	9	193	-1397	301	187	-259	976	1
2019	10	53	-1215	311	123	-180	910	3
2019	11	231	-934	301	462	-25	-35	0
2019	12	713	-784	311	774	-27	-988	-1
2020	1	717	-1037	311	329	-24	-298	-1
2020	2	170	-1570	291	288	-23	846	3
2020	3	2203	-2311	311	887	-675	-420	-5
2020	4	473	-2057	301	967	-1098	1385	-30
2020	5	121	-1975	311	1539	-1273	1222	-54
2020	6	14	-1547	301	91	-1577	2664	-53
2020	7	2	-1431	311	61	-1896	2851	-103
2020	8	4	-1210	311	68	-1568	2317	-79
2020	9	0	-1086	301	64	-50	771	0

Appendix D

SWBM and MODFLOW Parameter Values

SHVSM Submodel	Parameter						
	Group	Type	Description	Name	Value	Units	
SWBM	SWBM	Effective Rooting Depth	Total depth that plants can access soil moisture from. Accounts for root depth and capillary movement of water into root zone.	RD_Alf_Irr	1.97E+01	ft	
				RD_Grn_Irr	6.56E+00	ft	
				RD_Pstr_Irr	6.56E+00	ft	
				RD_NatVeg	9.84E+00	ft	
				RD_Barren	0.00E+00	ft	
		Effective Irrigation Efficiency		RD_Water	6.56E+00	ft	
				RD_Alf_NI	1.97E+01	ft	
				RD_Grn_NI	6.56E+00	ft	
				RD_Pstr_NI	6.56E+00	ft	
	MODFLOW	Kx	Sediment hydraulic conductivity along rows.	Fld_IE_Alf	7.00E-01	-	
				Fld_IE_Grn	7.00E-01	-	
				Fld_IE_Pstr	7.00E-01	-	
				WL_IE_Alf	1.25E+00	-	
				WL_IE_Grn	1.25E+00	-	
				WL_IE_Pstr	1.00E+00	-	
MODFLOW	MODFLOW	Kx	Horizontal Anisotropy	Scaling factor that allows crop coefficients to be adjusted uniformly. Allows for single parameter to adjust crop coefficients that vary over time.	CP_IE_Alf	1.35E+00	-
					CP_IE_Grn	1.35E+00	-
					CP_IE_Pstr	1.15E+00	-
					KcMltAlfIrr	9.60E-01	-
					KcMltGrnIrr	9.60E-01	-
					KcMltPstrIrr	9.60E-01	-
					KcMltNatVeg	9.60E-01	-
					KcMltWater	9.60E-01	-
	MODFLOW	Hani	Scaling factor that adjusts aquifer hydraulic conductivity along columns based on Kx value.	Kx_1	3.20E+01	ft/day	
					Kx_2	1.64E+01	ft/day
					Kx_3	6.56E-01	ft/day
					Kx_4	3.22E-02	ft/day
					Kx_5	3.28E-03	ft/day
					Kx_6	3.76E+00	ft/day
					Kx_7	3.28E+00	ft/day
					Kx_8	3.28E+00	ft/day
	MODFLOW	Hani	Scaling factor that adjusts aquifer hydraulic conductivity along columns based on Kx value.	HANI_1	1.00E+00	-	
					HANI_2	1.00E+00	-
					HANI_3	1.00E+00	-
					HANI_4	1.00E+00	-
					HANI_5	1.00E+00	-
					HANI_6	1.00E+00	-
					HANI_7	1.00E+02	-
					HANI_8	1.00E+02	-

SHVSM Submodel	Parameter					
	Group	Type	Description	Name	Value	Units
MODFLOW	Kvar	Vertical Anisotropy	Scaling factor that adjusts vertical hydraulic conductivity of aquifer based on Kx value.	KVAR_1	1.00E+00	-
				KVAR_2	5.00E+00	-
				KVAR_3	2.00E+01	-
				KVAR_4	5.00E+01	-
				KVAR_5	1.00E+00	-
				KVAR_6	2.00E+00	-
				KVAR_7	1.00E+00	-
				KVAR_8	1.00E+00	-
	Sy	Specific Yield	Unconfined aquifer storage coefficient.	Sy_1	1.50E-01	-
				Sy_2	1.00E-01	-
				Sy_3	6.00E-02	-
				Sy_4	3.00E-02	-
				Sy_5	1.00E-03	-
				Sy_6	4.00E-02	-
				Sy_7	2.00E-01	-
				Sy_8	2.00E-01	-
	Ss	Specific Storage	Confined aquifer storage coefficient.	Ss_1	3.28E-06	1/ft
				Ss_2	3.28E-05	1/ft
				Ss_3	6.56E-05	1/ft
				Ss_4	6.56E-04	1/ft
				Ss_5	3.28E-05	1/ft
				Ss_6	3.28E-05	1/ft
				Ss_7	3.28E-04	1/ft
				Ss_8	3.28E-04	1/ft
	MFR	Mountain Front Recharge	Flux of water into model from surrounding bedrock.	MFR_1	4.09E+00	AF/day
				MFR_2	0.00E+00	AF/day
				MFR_3	9.80E-01	AF/day
				MFR_4	1.10E+00	AF/day
				MFR_5	2.56E+00	AF/day
				MFR_6	1.31E+00	AF/day
				CB_3	4.76E-05	ft/day
				BedK_1	3.28E+00	ft/day
	SFR	Streambed Hydraulic Conductivity	Hydraulic conductivity of sediments in stream channels.	BedK_2	3.28E-01	ft/day
				BedK_3	3.28E-02	ft/day
				Manning_n_1	3.50E-02	-
		Manning Roughness Coefficient	Coefficient that defines how easily water can flow through a channel.	Manning_n_2	3.50E-02	-
				Manning_n_3	3.50E-02	-