Appendix 2-E - Model Documentation

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Executive Summary

This report presents a preliminary version of the model documentation for the Shasta Watershed Groundwater Model (SWGM) v 1.0; this is the first available integrated hydrological model that represents the entire Shasta Valley watershed. This documentation highlights key model components and describes the planned modifications considered for future updates of the SWGM. Many of these modifications and enhancements are already under development requiring the technical team to balance the need to document key model inputs or assumptions and the ongoing refinement of the SWGM. This effort to document an evolving model has therefore required the technical team to incorporate place holders pending further information. Any updates to parametrization, parameter values, or additional observations will be published in SWGM v1.1. SWGM v1.1 is expected to be released October 2021.

As an important note for the review of the GSP, the model has been actively used only to provide a representation of the water budget of the entire watershed and of the groundwater basin for historical, and current conditions and for future climate change scenarios. All key GSP decision up to this point, including the development of Sustainable Management Criteria (SMCs), have been made using available observed data and not on simulated results from the SWGM. The Advisory Committee that collaborated with the technical team throughout the past three years strongly recommended that the GSP clearly state that the development of the SWGM has been an achievement but, due to the limited time and the limited data availability, the uncertainty in the model is currently too significant to be reasonably used to drive critical decision making for the GSP. The extensive data gap section (Appendix 3-A) and the description of the SMCs in Chapter 3 explain in detail which data will be collected over the next five years to allow the development of a more robust model. For the 5-year GSP update, we envision new definitions of the SMCs that rely on observed data in addition to simulated model results and future scenarios.

A brief history of the development of all the model components is summarized here. The technical team started working on data collection and evaluation in 2018. Following this preliminary assessment, we followed these steps:

- Development of the 3-dimensional geological model: analysis and geolocation of about 1500 well-logs throughout the valley, development of the geological model which serves as the basis for the groundwater model layer definition;
- Development of the crop-demand soil water budget model (Davids Engineering, Appendix 2-I);
- Extensive coordination with the State Water Resource Control Board (SWRCB) environmental flows project technical team to ensure that atmospheric inputs including precipitation, potential evapotranspiration, and temperature align to the extent possible;
- Development of a surface water hydrology model reflecting key elements including precipitation as rain or snow, snow accumulation, snowmelt, and surface runoff using the PRMS software with preliminary sensitivity analysis and calibration;
- Development of the Hydrogeological Conceptual Model;
- Groundwater model (based on MODFLOW) with preliminary sensitivity analysis and calibration; and
- Preliminary coupling in GSFLOW, but not currently used because of runtime limitations.

The PRMS surface water model is expected to be refined and enhanced significantly in coming iterations as additional data and datasets become available. Time series datasets derived from an array of planned stream gages is expected to allow for the validation of surface water flows derived from a currently poorly understood combination of precipitation as rain or snow, snow melt, and spring flow. In the absence of a comprehensive and defensible hydrologic feature or hydrography dataset, the modeled representation of stream channels and springs was derived using a digital elevation model (DEM) and Advisory Committee input. This placeholder dataset is expected to be revised and enhanced using a combination of continued stakeholder outreach, validation using satellite imagery, and potentially additional instrumentation. Streambed location and geometry is expected to revisited and revised with high resolution Light Detection and Ranging (LiDAR) elevation data provided by the SWRCB.

The spatial and temporal dynamics of snowpack hydrology within the Shasta Watershed are currently a notable data limitation with significant variability observed at snow pillows across the region and limited understanding of glacier melt on Mt. Shasta. Future DWR snow surveys are expected to allow for refinement of the snow module within PRMS to more effectively simulate the accumulation and subsequent melting of snowpack across the Shasta Watershed. Additional novel resources in the field of snowpack hydrology, including snowpack modeling from UC Santa Barbara's Snow Hydrology Research Group is also expected to allow for the refinement of the snowpack in PRMS.

The first iteration of the SWGM includes a series to atmospheric time series datasets that were developed by Paradigm Environmental, the technical team of consultants developing a parallel model for the SWRCB's environmental flows project. An extensive effort was made to coordinate with the SWRCB's technical team through a series of meetings and follow up conversations allowing for the sharing of model inputs but not yet model input documentation. The SWGM technical team has included a short conceptual overview outlining the origin and development of these datasets and how they were incorporated into the PRMS model in the absence of comprehensive documentation from Paradigm Environmental or a SWRCB environmental flows project work product to reference. The refinement of atmospheric inputs is expected to be a key component of SWGM revisions through a combination of on the ground observed conditions and remote sensing datasets derived from satellites. Key areas of focus are expected to be the spatial and temporal variability of precipitation and temperature as it drives the rain, snow, and snowmelt elements of the model.

Summary of ongoing and future improvements

SWGM v1.0 should be considered a preliminary effort to characterize the Shasta Watershed. Data from continuous groundwater sensors, increased number of stream gages, and agricultural water usage will provide updates to the calibrated values of the system. There are a number of updates that are under consideration for the base model:

- Updates to glacier melt and snow dynamics on Mount Shasta. Updates to the PRMS code, v 5.2, include a more robust characterization of glacier dynamics. Increased data collection on precipitation, solar radiation, air temperature, and other climate variables should also be included in PRMS updates.
- Geologic updates to include fracture flow within basalt geology.
- Hydrogeologic updates to refine anisotropy, storage, and model layer thicknesses.
- Agricultural demands should be internally calculated within the code. Both Ag package within GSFLOW and FMP package with OWHM are possible codes that can be used.
- Update to stream morphology using LiDAR data from SWRCB.
- Representation of the canal network using SFR.
- Update the model simulation period through 2021 to include new continuous groundwater level data collected as part of the GSP.
- Surface water diversions can be dynamically linked with priorities to the SFR package to meet surface water demand.

Introduction / Background

The Shasta Watershed Groundwater Model (SWGM) was developed to calculate historical and projected water budgets and to improve understanding of long-term trends in groundwater levels. The SWGM is a loosely coupled groundwater-surface water interaction model. The groundwater is simulated through USGS' Modular Groundwater Flow Model (MODFLOW) (Harbaugh 2005), climate variables and surface water flows are simulated through the Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2008) with the addition of a Daily Root Zone Simulation

Model (RSRZ) providing input for irrigated lands (Davids Engineering 2013). The SWGM simulates the entire Shasta Valley HUC8 Watershed (Watershed) with the Bulletin 118 Groundwater Basin located within the domain.

The SWGM was developed to meet the requirements of the Sustainable Groundwater Management Act (SGMA) (Cal. Water Code, Division 6, Part 2.74).

Purpose and Scope

Development of SWGM was done to assist in the development of a water balance within the Shasta Valley Groundwater Sustainability District. In order to estimate subsurface inflows into the District, the entire Watershed is modeled. This iteration of the model should still be considered preliminary. Inflows and outflows within the watershed are accounted for to degree that time and budget allowed. Updates to the model should be conducted as additional data are gathered from the region.

Description of Study Area

Model Software Summary

The SWGM is a combination of multiple models interacting to simulate the entire HUC8 Shasta Watershed. Three models are used to estimate all of the flow components herein. The three models are a Daily Root Zone Simulation Model (RZSM) developed by Davids Engineering, a Precipitation-Runoff Modeling System (PRMS), and MODFLOW-OWHM.

RSRZ

Davids Engineering developed a Daily Root Zone Simulation Model (RSRZ) that calculates the root zone water budget based on the water budget components Figure 1. The RSRZ uses precipitation and evapotranspiration as the driving water budget model inputs, and root zone water balance parameters based on crop and soil type that impact the soil moisture storage. The RSRZ model relies on remote sensing-based estimates of evapotranspiration model derived from imagery collected by LandSat satellties, Parameter-elevation Regressions on Independent Slopes Model (PRISM) rainfall data developed by Oregon State University[1], and root zone parameters based on the crop and soil types (Davids Engineering 2013). The Daily root zone dynamics were modeled from January 1989 to December 2018. Daily water budget components were then upscaled to monthly values by taking the sum of each water budget component (e.g. evapotranspiration). These monthly values were extracted and incorporated into the MODFLOW models as *Applied Water* and *Deep Percolation* which respectively represent the amount of groundwater pumping for cells where irrigation occurs and the amount of groundwater recharge to the aquifer. Complete details of the Daily Root Zone Simulation Model can be found in Chapter 2 Appendix E.

Davids Engineering developed a Daily Root Zone Simulation model that uses remote sensing based evapotranspiration model using LandSat, PRISM rainfall data from Oregon State[2], and root zone parameters based on the crop and soil types (Davids Engineering 2013). The Daily RSRZ was ran from January 1989 to December 2018 and provided the calculated *Applied Water* and

[1] PRISM website: http://prism.oregonstate.edu/
[2] PRISM website: http://prism.oregonstate.edu/

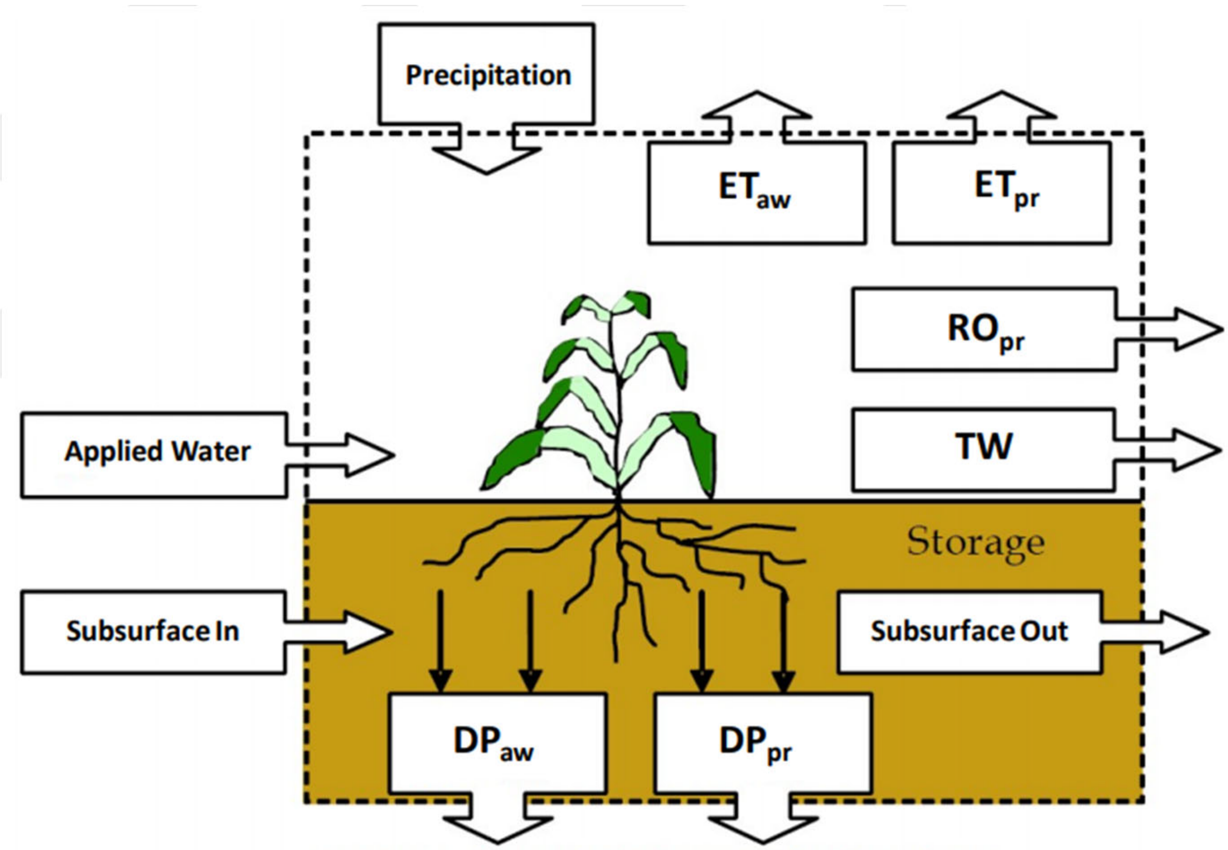

Figure 1: Conceptualization of Fluxes of Water Into and Out of the Crop Root Zone

Deep Percolation which respectively represent the amount of groundwater pumping for irrigated cells and the amount of groundwater recharge to the aquifer. The daily water budget components were then upscaled to monthly values by taking the sum of each water budget component (e.g. Evapotranspiration). Complete details of the Daily Root Zone Simulation Model can be found in Chapter 2 Appendix E.

PRMS

PRMS is a surface water hydrology model focused on simulating a watershed's response to climatic processes such as precipitation, evaporation, and evapotranspiration. The first iteration of PRMS was released by USGS in 1983 in the FORTRAN programming language where model inputs were incorporated with punch cards and outputs were summarized by line printers. USGS has released five iterations of the model with recent revisions focused on streamlining the integrating PRMS with other computational tools such as USGS' MODFLOW. The surface water component of USGS' coupled Groundwater and Surface Water FLOW (GSFLOW) model developed for the Shasta GSP is the most recent publicly available iteration of PRMS, PRMS-V or version 5, released in late May of 2019. PRMS is comprehensively documented and supported by USGS with a dedicated webpage, release notes, and installation instructions. The PRMS version 4 User's Manual (PRMS User's Manual) is the most comprehensive resource outlining model parameters and processes. Table 1 documents the process and modules used within the SWGM.

MODFLOW

Table 1: PRMS Modules used

Process	Module
Computation Order	*call_modules*
Basin Definition	*basin*
Cascading Flow	*cascade*
Common States and Fluxes	*climateflow*
Potential Solar Radiation	*soltab*
Parameter Setup	*setup_param*
Timestep Control	*prms_time*
Time Series Data	*obs*
Potential Evapotranspiration	*climate_hru*
Temperature Distribution	*temp_1sta*
Precipitation Distribution	*precip_1sta*
Solar Radiation Distribution	*ddsolrad*
Transpiration Distribution	*transp_tindex*
Canopy Interception	*intcp*
Snow Dynamics	*snowcomp*
Surface Runoff	*srunoff_smidx*
Soilzone Computations	*soilzone*
Groundwater	*gwflow*
Streamflow Routing Init	*routing*
Streamflow Routing	*muskingum*

MODFLOW is a finite difference groundwater model simulating spatial and temporal groundwater conditions in the watershed. The MODFLOW model simulates the spatially and temporal variable dynamics of groundwater fluxes and groundwater elevations which are sufficient to characterize a water budget for the Basin and determine whether there will be significant changes in water level that may impact groundwater users. Table 2 summarizes the MODFLOW packages used within SWGM.

Table 2: MODFLOW Pachages used to Calculate Groundwater Flows in the Basin

MODFLOW Package	Application
BAS6	Define Active Model Domain
DIS	Define Model Grid and Extent
LAK	Lake Shastina and Grass Lake
SFR	Shasta River, tributaries, and springs
UPW	Geologic model
GHB	Canals
UZF	Recharge and runoff
WEL	Groundwater pumping for irrigation needs
ZONE	Delineate hydrogeologic zones
PVAL	Parameters data
GAGE	Output from SFR and LAK packages
OC	Output control
NWT	Numerical solver
HOB	Head observation package

Hydrologic System

Climate

The Shasta Valley generally has a mixture of warm-summer Mediterranean and high desert environment climates with distinctive seasons of cooler, wetter winters and warm, dry summers. The orographic effect of the mountains to the west and south sides of the Valley creates a rain shadow in eastern areas of the Valley. The higher elevation areas to the west and south of the Valley historically receive greater annual precipitation (30–70 inches [in], or about 76–177 centimeters [cm]) in comparison to annual precipitation on the east side of the Valley (12–15 in). Annual mean precipitation ranges from a low of about 13 to 15 in (33–38 cm) at lower elevations to a high of about 67 in (170 cm) at Mount Shasta; see the summary statistics table for the (out of Watershed but close to the southern border) Mount Shasta rainfall gauge (station ID: 045983; SWRCB 2018). In the City of Yreka, annual precipitation averages range from 19 to 21 in (48–53 cm); see the attached plot of 1960–2005 Yreka annual precipitation (CDWR 2011) and the summary statistics table for the Yreka rainfall gauge (station ID: 049866; SWRCB 2018). Annual precipitation ranges from 25 to 29 in (64–74 cm) at853higher elevations of the Klamath Mountains to the west, and up to 33 in (84 cm) near China Mountain. To the east, higher elevations of the Cascade Range receive from 19 to 27 in (48–69 cm) of precipitation annually. The rainy season, which generally begins in October and lasts through April, accounts for about 80 percent of total annual rainfall. At elevations below 4,000 ft (~1,200 m) amsl, precipitation mostly occurs as rainfall, as is the case on the valley floor. Precipitation accumulates as snow in the surrounding mountains, with a rain-snow transition zone from 4,000 to 5,000 ft (~1,200–1,500 m) amsl. Accumulation of snowfall in the surrounding mountains results in runoff during spring snowmelt.

Surface Water

Elevation across the approximately 800 sq mi (~2,070 sq km) Watershed ranges from just over 2,000 ft (610 m) amsl near the confluence with the Klamath River to over 14,000 ft (4,300 m) near the peak of Mount Shasta. Several smaller watersheds encompassed by the Shasta River watershed; the two most notable being the Little Shasta River and Parks Creek. The Watershed is bounded to the west by the Scott River watershed, to the south by the Sacramento River watershed, to the east by the Butte Creek watershed, and by the Klamath River to the north. Shasta River is approximately 58 miles (93 km) long stretching from the peak of Mount Eddy at about 9,000 ft (2,750 m) amsl to the confluence with the Klamath River. The Little Shasta River drainage basin within the Watershed is bounded by Goosenest Mountain (8,260 ft; 2520 m amsl) to the south, Ball Mountain (7,792 ft; 2,375m amsl) to the east and Willow Creek Mountain (7,828 ft; 2386 m amsl) to the north. Little Shasta River is predominantly spring fed, sustained by a series of springs emerging from Quaternary and Tertiary High Cascade volcanic materials, discussed further in Section 2.2.1.3. Mount Shasta, snow-covered year-round, is the most conspicuous feature of the landscape, visible from all parts of the Valley. Several glaciers stretch along its upper slopes which are the primary source of recharge to the Basin. On its north slope, Whitney, Bolam, and Hotlum Glaciers descend to altitudes of about 10,000 ft (3,048 m) amsl. On the south slope, the Koiiwakiton Glacier descends to an altitude of 12,000 ft (3,658 m) amsl, and the Clear Creek and Winton Glaciers to about 11,000 ft (3,353 m) amsl. Regional climate models generally predict the loss of Mount Shasta's glacier volume over the next 50 years and total loss of the glacier by the year 2100, likely resulting in reduced recharge in the Basin (UCD 2010?).

The Shasta River has a complicated seasonal and longitudinal flow regime due to intricate surface water and groundwater interactions, coupled with extensive agricultural diversion and return flows (Vignola and Deas 2005; Nichols et al. 2010). The Watershed includes a small number of small-scale diversion dams and diversions of the Shasta River or major tributaries, with the two main sources of water being the Shasta River and Parks Creek with storage in Lake Shastina (Dwinnell Reservoir). A number of the small-scale diversion dams have been or are in the process of being removed or modified for fish passage. Water rights dictating usage throughout the Shasta Basin are a combination of riparian and appropriative water rights adjudicated as a part of the 1932 Decree (CDWR 1932). Buck (2013) constructed a groundwater model for a portion of the Watershed and summarized major balance components for the period 2008–2011. The upper Shasta River (i.e., upstream of Dwinnell Dam) originates on the eastern slope of Mt. Eddy and is characterized by a runoff-driven hydrograph derived from rainfall and snowmelt (Nichols et al. 2010). Inflows to Lake Shastina consist of the upper Shasta River, flows diverted from Parks Creek near Edgewood, and Carrick Creek originating from the northwest flank of Mount Shasta. In 1928, construction of Dwinnell Dam was completed, impounding Lake Shastina to primarily serve as a storage reservoir and diversion for agricultural irrigation water throughout the Valley. Lake Shastina is the largest single water source in the Watershed. Outflow from Lake Shastina to the lower Shasta River, regulated by Dwinnell Dam, has reduced mean annual discharge in the reaches immediately downstream of the reservoir by up to 90 percent (Jeffres et al. 2008; Nichols 2008; Nichols et al. 2010). Maximum reservoir storage capacity in Lake Shastina is rarely achieved because of the permeable underlying volcaniclastic rocks which allow impounded water to flow into the underlying aquifer (Vignola and Deas 2005). Mack (1960) reported that multiple springs along the base of the ridge forming the western embankment of Lake Shastina increased in flow following construction of the reservoir. Seepage losses from Lake Shastina have been estimated at 6,500 to 42,000 acre-feet (AF) (~8-52 million cubic meters (m^3)) annually, significant relative to the reservoir's 50,000 AF (~62 million m^3) storage capacity, representing a loss of 13 to 84 percent of storage capacity (Paulsen 1963, NCRWQCB 2006). Flows in the lower Shasta River (i.e., downstream of Dwinnell Dam) are composed of minimal releases from Lake Shastina, tributary creeks (e.g., Parks Creek, Willow Creek, Little Shasta River), multiple discrete groundwater springs (e.g., Big Springs, Little Springs, Clear Springs, Kettle Springs, Bridge Field Springs), and additional diffuse groundwater springs. The lower Shasta River is characterized by a spring-dominated hydrograph primarily sourced from Big Springs Creek, supplied by multiple groundwater springs in the Big Springs Complex vicinity (Jeffres et al. 2008, Nichols 2008, Nichols et al. 2010). Spring-fed baseflows from Big Springs Creek outside the irrigation season (i.e., November to March) are five times those of the lower Shasta River upstream of the Big Springs Creek confluence (including Parks Creek) for the same time period (Jeffres et al. 2009). Approximately 95 percent of baseflows during irrigation season (i.e., April to October) in the lower Shasta River originate from the Big Springs Complex. During irrigation season, Big Springs Creek baseflows are approximately 35 percent lower, caused by temporally variable irrigation diversions and unquantified groundwater pumping (Jeffres et al. 2009). Instream flows downstream of Big Springs Creek confluence quickly rebound to spring-fed baseflow conditions following irrigation season (Nichols et al. 2010). Dwinnell Dam (constructed in 1928) is the largest water storage structure in the Basin, with current1 capacity of 50,000 AF (~62 million m^3), upgraded from 36,000 AF (~44 million m^3) in 1965 (USFWS15422013). Water is delivered to users in Shasta Basin via canals, diversion facilities, pumps, and storage infrastructure (Willis et al. 2013). The largest storage and delivery systems in the Shasta Basin are maintained by water service agencies or private water users which operate in accordance with the Watermaster service requirements (Willis et al. 2013). Major diversions and smaller dams or weirs are located below Dwinnell Dam, along with numerous diversions on tributaries (CDFW15471997; Lestelle 2012; NOAA Fisheries 2014; CDFW 2016). Several diversions and return channels exist largely for agricultural purposes that primarily operate during the irrigation season (April 1-September 30), including the Grenada Irrigation District Ditch, the Shasta River Water Association, and Oregon Slough (Jeffres et al. 2010) (Figure 32). The City of Yreka obtains much of its water supply from Fall Creek (Figure 33), located outside the Watershed near Iron Gate Reservoir (Pace Engineering 2016). The City's treated wastewater, totaling 966 AF (1.2 million m^3) in 2015, is discharged to percolation fields near Yreka Creek (Pace Engineering 2016). Historical instream flow data were collected from the United States Geological Survey (USGS) and California Department of Water Resources (DWR) Water Data Library and California Data Exchange Center (CDEC). Two (2) USGS streamflow gauges (stations SRM and SRY) are present in the Watershed with observed data spanning water years 1958 to 1978, and 2002 to 2016. Five additional gauging stations are maintained by DWR and are associated with sporadic data collection in two to three-year periods. Gauge locations in the Watershed are shown in Figure (Figure33). Data were analyzed to assess quantity and quality of the observed record. Quantity was measured as percent of days with recorded flow data at each gauge, and quality was assessed as percent of days flagged by USGS as having been "edited or estimated by USGS personnel (USGS 2018)."Table (?; Table: Summary of streamflow data quantity and quality in the Shasta Valley Groundwater Basin) provides a summary of USGS data quantity and quality in the Watershed; a continuous flow record of reliable data (in terms of quantity and quality) is present throughout the watershed from 1957 to present. In 2005 and 2009, the Nature Conservancy acquired property in the Watershed, and at this time the University of California at Davis Center for Watershed Science, the Nature Conservancy, and Watercourse Engineering began monitoring streamflow in Big Springs Creek, the mainstem Shasta River, and Little Shasta River (Jeffres et al. 2008, 2009, 2010; Nichols et al. 2016, 2017; Null et al. 2010; Willis et al. 2012, 2013, 2017). Additional sources of flow data include gauges placed on the Shasta River and Parks Creek in 2001 and 2002 (Watercourse Engineering 2006); estimates of unimpaired flows (Deas et al. 2004); a 2016 water balance study (SVRCD 2016); summaries of discrete flow measurements for springs in the Watershed including Little Springs Creek (Deas et al. 2015) and Big Springs Creek (Appendix G of NCRWQCB15752006); measurements of springs, creeks, and diversions on the Shasta Springs Ranch (Chesney et al. 2009, Davids Engineering 2011); and a compilation of data for sites in the Little Shasta River drainage basin (CDFW 2016). Streamflow data from all available sources will be further assessed during hydrologic model development to identify important critical conditions. Data quantity and quality impact both selection of data to be used for calibration and interpretation of model performance during associated time periods. More weight will be given to locations and time periods with higher quantity and quality of data. Instream flows in the Watershed have been significantly affected by water resource management in the Basin. Seasonal low flow and drought conditions naturally occur in the watershed, but are becoming more common. Studies have been conducted to characterize hydrology and hydrologic habitat in the Watershed and to determine interim and minimum instream flow needs in the Watershed (McBain & Trush 2013, CDFW 2017). The Instream Flow Needs study documented historical and current sampling above and below Parks Creek confluence, in the center of the Watershed1588(McBain & Trush 2013). Historical data of unimpaired mean monthly flow in the Upper Shasta River and Parks Creek estimate a maximum of approximately 208 cubic feet per second (cfs) (~6 cubic meters per second (m^3/s)) and a minimum of 6 cfs (~0.2 m^3/s) during spring and summer months. Baseflows in spring and summer 2010 recorded a maximum of 36 cfs (~1 m^3/s) and a minimum of 5.6 cfs (0.16 m^3/s; see Figure: Historic stream flows at notable gauges along the Shasta River and Parks Creek). According to these studies, considerable inter-annual streamflow variability exists along with uniformity and predictability of streamflow between June and late October, consistent with other streams in the region.

Groundwater

The groundwater system is poorly understood in the Shasta Watershed. The complex geology is further discussed in Appendix 2-A In general groundwater flow is consistently towards the Shasta River in the middle of the watershed with an overall trend of flow to the north towards the Klamath River. The groundwater flow is further complicated by fracture flow within fractured basalt in the southeast area of the watershed. Groundwater is known to be connected in the majority of the Shasta River with groundwater daylighting at multiple springs near the Big Springs Complex.

Model Development

Climate Data

The following section provides an overview of the atmospheric time series inputs that drive the simulation of the energy and water balance of hydrologic response units (HRUs) within the PRMS model.

Climate Inputs

Precipitation Precipitation time series were manually processed by Paradigm Environmental using geographic information system (GIS) and software packages before being assigned to each

HRU within the Shasta PRMS model domain. Hourly modeled precipitation totals were extracted for the 29-year modeled period of record from the National Aeronautics and Space Administration (NASA) North American Land Data Assimilation System (NLDAS)[3]. NASA developed the NDLAS system to use the best available climatic land surface observations to construct a quality-controlled land surface model (LSM) for the U.S. NLDAS models conditions at a scale of 1.0 degree (approximately 84 kilometers longitude and 111 kilometers latitude) for data from 1979 to present and 0.25 degree (approximately 21 kilometers longitude and 27.75 miles latitude) from 2000 present.

Paradigm Environmental scaled hourly precipitation datasets for each NLDAS grid cell to align with monthly rainfall totals derived from the PRISM model[4], a high-resolution climate model developed and maintained by Oregon State University. PRISM applies a weighted regression scheme to model climatic conditions with a focus placed on complex regimes where factors such as orography (elevation driven), rain shadows, temperature inversions, slope aspect, and coastal proximity yield unique climates. The PRISM dataset is presented in “climatologies” at a scale of 30-arcsec (800 meters) and monthly data are available at 2.5 arcmin (4 km) resolution. NLDAS hourly data were used as relative hyetographs to distribute monthly PRISM totals. Hourly PRISM-scaled NLDAS totals were summed by day and manually assigned to PRMS HRUs corresponding to the centroid of each PRISM grid. The precip_1sta module was used to interpolate and distribute daily precipitation totals to HRUs between PRISM centroid grids using monthly correction factors to account for differences in altitude, spatial variation, topography, and measurement gage efficiency.

Temperature Hourly modeled temperature time series were extracted from NLDAS records and post-processed by Paradigm Environmental to represent maximum and minimum temperatures by day. These daily maximum and minimum temperature timeseries were manually assigned to PRMS HRUs corresponding to the centroid of each NLDAS grid. Daily maximum and minimum temperatures were adjusted based on temperature zones. The temp_1sta module was used to interpolate and distribute daily maximum and minimum temperatures to HRUs between NLDAS grid centroids using an estimated monthly lapse rate.

Potential Evapostranspiration Potential evaporation time series were manually processed by Paradigm Environmental using GIS and software packages. Hourly modeled evapotranspiration time series were extracted from NLDAS records, and manually assigned to PRMS HRUs corresponding to the centroid of each NLDAS grid. The climate_hru module was used to read daily evapotranspiration depths directly into PRMS by HRU.

Internal Climate

Solar Radiation Daily solar radiation was internally calculated based on the ddsolrad module within PRMS. The ddsolrad module distributes solar radiation to each HRU using a maximum temperature per degree-day relationship discussed extensively in the Solar-Radiation Distribution Modules section of the PRMS model documentation. Maximum assumed temperature within the PRMS model is used to establish a degree-day coefficient based on a relationship established by

[3] Additional information regarding the North American Land Data Assimilation System (NLDAS) can be found at: https://ldas.gsfc.nasa.gov/nldas]

[4] Additional information regarding PRISM model can be found at: https://prism.oregonstate.edu/

Leavesley and others in 1983. This degree-day coefficient is then used to translate potential short-wave solar radiation to assumed short wave solar radiation with the driving assumption being that higher temperatures correspond to summer months and longer days with higher solar radiation. Conversely, lower maximum temperatures correspond to winter periods with shorter days and lower short-wave solar radiation.

Snow Precipitation falling within the Shasta Watershed is partitioned in rain, snow, or a mix of rain and snow based on internal parameters established within PRMS. Precipitation occurring on a day where both the minimum and maximum daily temperature are above a threshold where all precipitation falling is assumed to be rainfall, parameter tmax_allrain, is simulated as only rainfall. Similarly, precipitation falling on days where both the minimum and maximum daily temperatures are below a threshold where all precipitation falling is assumed to be snow, parameter tmax_allsnow, is simulated as only snowfall.

When the assumed maximum daily air temperature falls between the tmax_allsnow and tmax_allrain thresholds and the minimum daily air temperature is less than or equal to the tmax_allsnow threshold, precipitation is modeled as a mixture of rain and snow. A comprehensive discussion of the simulation of precipitation as rain and snow can be found in the Precipitation-Distribution Modules section of the PRMS Users Manual.

The PRMS model simulates snowpack hydrology processes within the Snow module (snowcomp) including snow initiation, accumulation, and depletion by HRU. The Snow module simulates snowmelt as a function of the daily water and energy balance for each HRU including the accumulation, sublimation, and melt of snowpack. PRMS computes daily snowpack dynamics including snowpack depth, density, snow water equivalent (SWE), snowpack, temperature, albedo, and cover area to allow users to readily compare modeled representations to key on-site snowpack observations from snow pillows or snow courses as well as satellite-derived observations for factors such as snowpack albedo.

Watershed Parameters

PRMS requires users to translate the physical characteristics of a subject watershed and relevant dynamic temporal elements (e.g.; precipitation) into a representation that can be simulated using the quantitative relationships within the modeling platform. The process of translating physical characteristics such as elevation, land use or land cover, geology, and subwatersheds into a set of unique hydrologic units is often referred to as spatial discretization. The process of translating atmospheric conditions into time series that can drive a model is typically referred to as temporal discretization. Both of these processes are discussed below with each section providing an overview and referring readers to more comprehensive discussions in model documentation where available.

A key element of PRMS model development is the parameterization of a network of HRUs, stream segments or reaches, and lakes reflecting the understanding of the watershed model domain. HRUs are developed as a function of land use or land cover, soil, elevation, slope, aspect, and climate patterns and are assumed to be uniform in how they respond to atmospheric time series inputs. While PRMS is capable of integrating irregular or complex (non-rectangle) geometry HRUs, USGS strongly recommends that HRUs reflecting the discretization of the land surface align with the subsurface discretization represented in the coupled MODFLOW groundwater model discussed in Section 3.2.1.

The Shasta PRMS model is comprised of 42,586 18-acre HRUs arranged in 214 rows and 199 columns of a grid. Each HRU is assigned a unique set of land use/landcover and atmospheric inputs during spatial processing using an external GIS. The distribution of HRUs representing the discretized model domain for the Shasta PRMS model is presented in Figure 4.

Elevation and Runoff

A 10-meter resolution digital elevation model (DEM) was extracted from the USGS National Elevation Dataset (NED) to represent topography within the Shasta Watershed. This gridded representation of elevation was translated into mean elevation, slope, and aspect for each HRU and incorporated into the PRMS model.

Soils

The spatial distribution of soils within the Shasta Watershed were extracted from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) database (additional information regarding the SSURGO database can be found at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_053627). SSURGO presents soil characteristic and soil hydraulic summaries including percent sand, silt, clay, as well as available water holding capacity. Relevant hydraulic parameters were used to parameterize the soil-zone module and the soilzone process within PRMS. A comprehensive discussion of the simulation of precipitation as rain and snow can be found in the Soil Zone Module section of the PRMS Users Manual.

Vegetation

There are 5 types of vegetation cover within PRMS, bare soil, grasses, shrubs, trees, and coniferous correlating to 0 through 4, respectively. The vegetation types are generalized and interact with other variables to account for native vegetation water consumption and use. Distribution of vegetation type is shown on Figure 2.

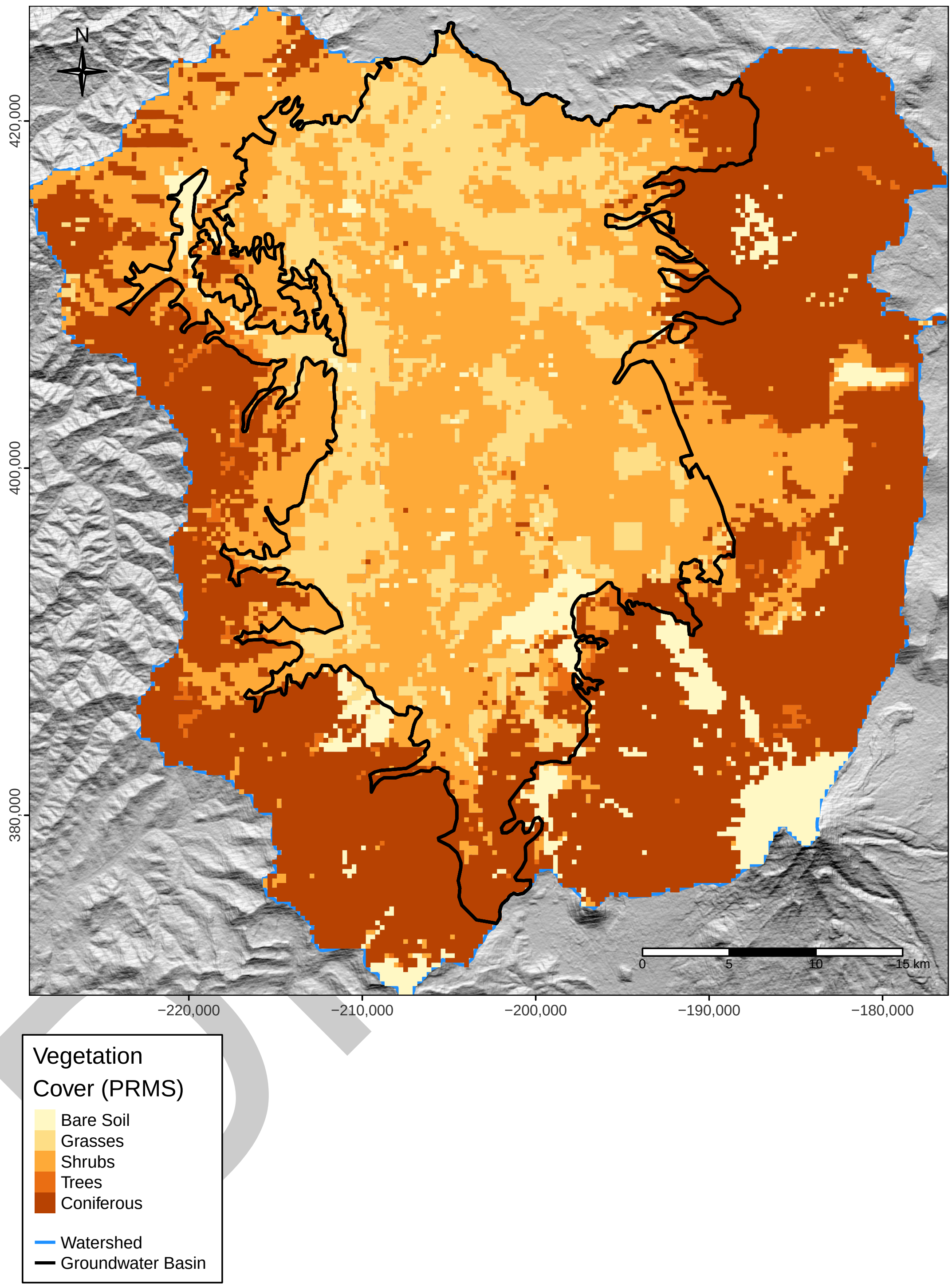

Figure 2: Vegetation type as simulated within PRMS.

Discretization

Spatial Discretization and Layering

The MODFLOW and PRMS models use the same grid consisting of 18 acre (270 meter x 270 meter) grid cells. The active portion of both surface water and groundwater is the HUC8 watershed boundary. Vertical discretization was carried out to keep layer thicknesses consistent throughout the model domain due to the amount of discontinuous volcanic geology. Layer 1 top is defined at land surface and extends 10 meters below land surface. Layers 2 through 4 are 40 meters, 100 meters, and 350 meters thick, respectively.

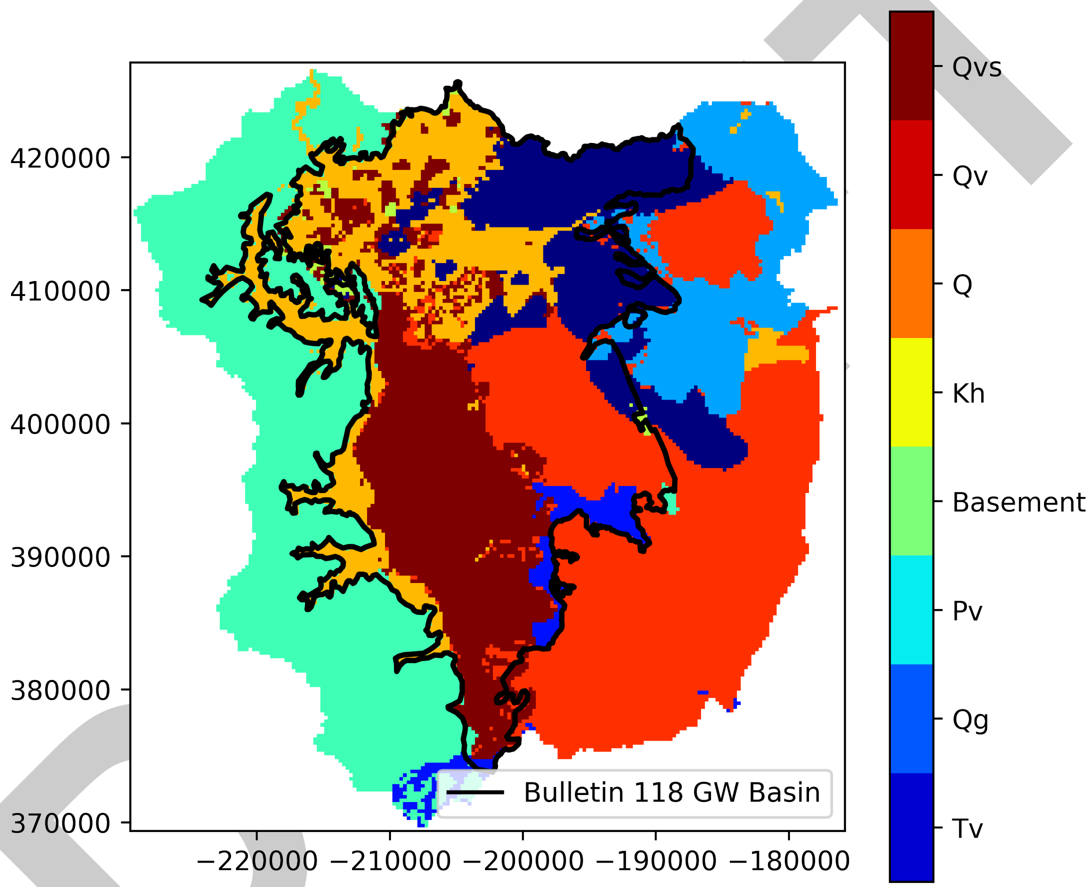

Figure 3: Shasta Valley Geology and model grid discretization

Temporal Discretization

The SWGM MODFLOW model has monthly stress periods with weekly time steps and runs from Water Year (WY) 1991-2018. Monthly stress periods are appropriate for the SWGM as the object of interest is the groundwater budget on the monthly and annual timescale at which groundwater is typically managed. The SWGM PRMS model uses daily time steps to account for the faster reaction time typically found in surface water systems.

Agricultural Water Use

Agricultural water use is estimated through the RSRZ, see Appendix 2-I, in combination with land use maps developed by DWR with assistance by local stakeholders (Davids Engineering 2013).

Groundwater Use

Agricultural groundwater use was estimated through the RSRZ. Land irrigated by groundwater, see attached David's Engineering report, were intersected with the RSRZ polygons to create cell-by-cell estimates of groundwater pumping. Groundwater pumping data and pumping well locations were not sufficiently available to allocate groundwater pumping to individual wells, thus groundwater pumping for each node was assigned based on the *Applied Water* calculated by the RSRZ.

Surface Water Use

Surface water diversion are regulated through the Scott and Shasta Watermaster District (SSWD) and the State Water Resource Control Board (SWRCB). Review of historic SSWD reports was compiled by Davids Engineering.

The SSWD has seven service areas within the Shasta Watershed; Upper Shasta River, Boles Creek, Beaughan Creek, Carrick Creek, Parks Creek, Lower Shasta River, and Little Shasta River. Annual reports between WY 1991-2017 were considered for review, years with sufficient documentation were 1991-1994, 1996-2000, and 2013-2016. Total water rights by service area are shown in Table 3. Table 4 Shows estimated deliveries of water by service region and water year type. For water years with insufficient data, the mean deliveries for that region and water year type were used. The same methodology was used in climate projections when estimating surface water diversions.

Table 3: Total Water Rights by Service Region (shown in cubic feet per second).

Season	Upper Shasta	Lower Shasta	Little Shasta	Parks Creek	Boles Creek	Beaughan Creek	Carrick Creek	Jackson Creek
Irrigation	108.66	146.64	92.32	55.66	17.68	10.30	11.72	3.05
Winter	18.55	10.85	21.93	18.33	6.99	4.47	1.39	0.38

[a] Based on Davids Engineering water rights review.

Table 4: Estimates of water deliveries by service region and water year type.

Month	WY Type	Upper Shasta	Lower Shasta	Little Shasta	Parks Creek	Boles Creek	Beaughan Creek	Carrick Creek	Jackson Creek
April	Normal	100%	98%	70%	100%	100%	98%	100%	100%
April	Wet	100%	100%	98%	100%	100%	100%	100%	100%
April	Dry	58%	93%	27%	50%	100%	100%	100%	100%
August	Normal	28%	90%	31%	16%	100%	98%	92%	100%
August	Wet	59%	98%	41%	15%	97%	100%	100%	100%
August	Dry	16%	82%	26%	10%	78%	100%	94%	100%
July	Normal	50%	93%	37%	31%	100%	98%	97%	100%
July	Wet	91%	100%	47%	34%	100%	100%	100%	100%
July	Dry	42%	83%	29%	16%	91%	100%	97%	100%
June	Normal	84%	97%	47%	83%	100%	98%	100%	100%
June	Wet	100%	100%	67%	85%	100%	100%	100%	100%
June	Dry	43%	87%	41%	64%	100%	100%	100%	100%
March	Normal	100%	98%	71%	100%	100%	98%	100%	100%
March	Wet	100%	100%	100%	100%	100%	100%	100%	100%
March	Dry	99%	97%	28%	50%	100%	100%	100%	100%
May	Normal	100%	98%	66%	98%	100%	98%	100%	100%
May	Wet	100%	100%	91%	100%	100%	100%	100%	100%
May	Dry	73%	87%	55%	60%	100%	100%	100%	100%
October	Normal	6%	90%	33%	3%	97%	98%	88%	100%
October	Wet	13%	100%	39%	5%	90%	100%	100%	100%
October	Dry	15%	82%	26%	7%	74%	100%	94%	100%
September	Normal	7%	90%	33%	5%	97%	98%	90%	100%
September	Wet	15%	99%	39%	7%	90%	100%	100%	100%
September	Dry	15%	82%	26%	7%	74%	100%	94%	100%

[a] Based on Davids Engineering water rights review.

Aquifer Characteristics

Shasta Watershed Geology

A geologic model was developed to represent the complex geology of the Shasta Watershed. The geologic model was digitized and included the analysis of hundreds of DWR well logs along with regional surficial geology maps in Leapfrog[5]. There are 8 hydrogeologic units within the geologic model which are implemented in the MODFLOW model as listed in Table 4 in Chapter 2 Section 2.1.3. (Appendix 2-A Geologic Modeling Methodology). While there is evidence of faulting occurring within the watershed, there was insufficient geologic and hydrologic data to include them within the groundwater model geology. In addition, fracture flow is known to occur within Qv formation, but due to sparse information of the orientation, size, and connectivity of the fractures the Qv unit is modeled as equivalent porous media (Appendix 2-A Geologic Modeling Methodology). The hydraulic properties including horizontal hydraulic conductivity, horizontal anisotropy, vertical hydraulic conductivity, specific storage, and specific yield, are detailed in Hydraulic Parameters section. An example cross-section is shown in Figure 4.

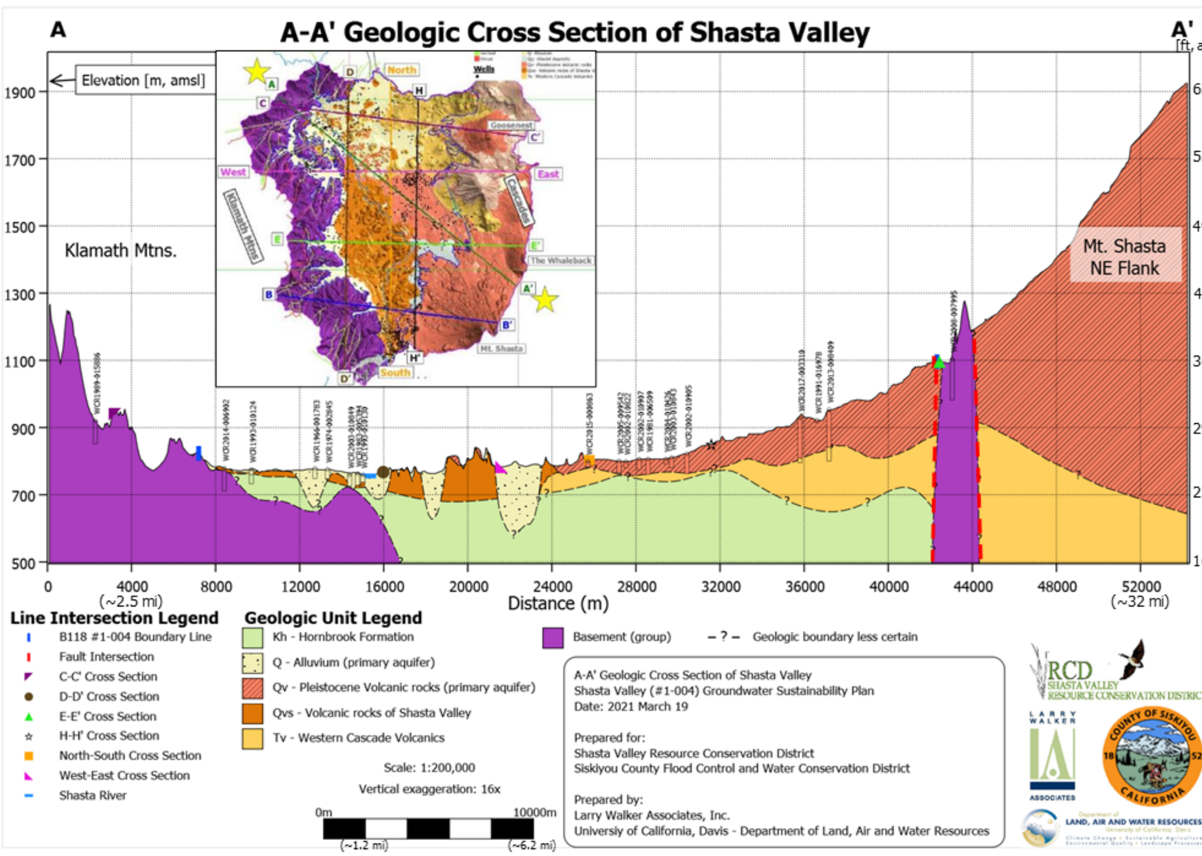

Figure 4: Geologic cross section A-A' from the Shasta Valley Watershed geologic model (inset includes the surface geologic overview map of the Shasta Valley Watershed geologic model.

[5]Sequent, Leapfrog Geo https://www.seequent.com/products-solutions/leapfrog-geo/

Hydraulic Properties

Initial Conditions

The SWGM is initiated with a steady-state model run. Recharge fluxes were estimated using the monthly recharge values before 1997 and averaged. Steady-state flows in the surface water system were estimated using the average flows in September before 1994. Agricultural pumping was estimated based on the first 9 years, from WY1991-WY1999. Steady-state fluxes were adjusted during model calibration.

Surface Water System

The mainstem of the Shasta River as well as major tributaries are modeled within PRMS and MODFLOW. PRMS uses the Muskingum package to route water and MODFLOW uses the Streamflow Routing Package (Niswonger and Prudic 2005). Reach and segment numbering were consistent between PRMS and MODFLOW. The stream network was developed using the same 10-meter resolution DEM from the NED used to establish the topographic setting to derive a representation of the stream system within the Watershed. Stakeholder input was requested to manually correct the DEM-derived stream network due to inaccuracies in elevation as well as the interaction of canal and stream networks.

Water conveyance in the Shasta Valley is typically carried out through a complex canal network. Figure 5 shows the entire mapped canal system and the mapped leaky ditches. Leaky ditch designation and locations were provided by the Shasta Valley Resource Conservation District (SVRCD).

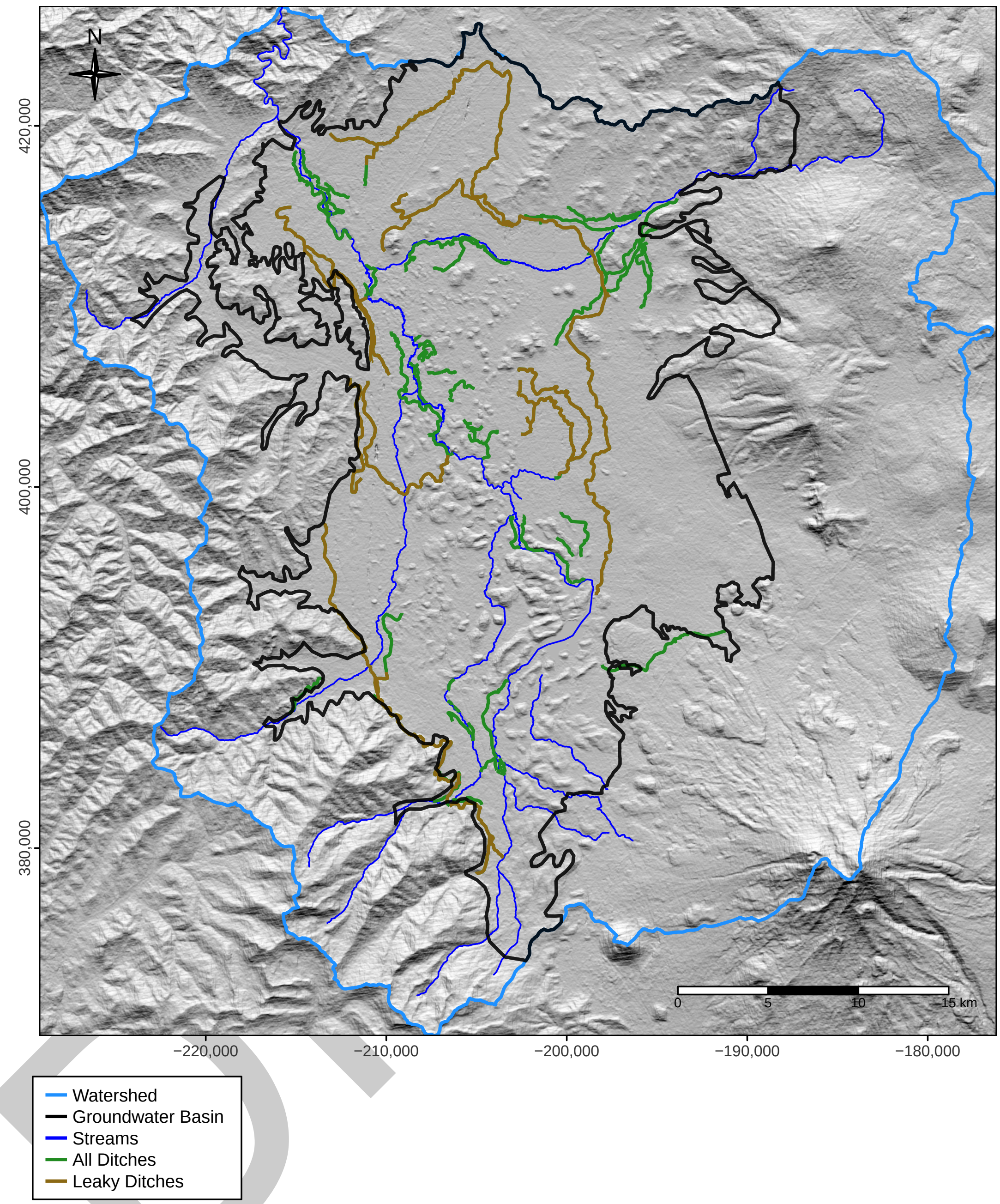

Figure 5: Complete ditch map of Shasta Valley with designation of leaky ditches, as mapped by the SVRCD.

Two lakes are modeled in the SWGM, Dwinnell Reservoir and Grass Lake. Dwinnell Reservoir is a managed reservoir with a total capacity of 50,000 acre-feet of water. Inflows to the reservoir are difficult to measure due to the lack of monitoring upstream of the reservoir. The reservoir is fed by the upper Shasta River and various spring fed tributaries. Releases from Dwinnell Reservoir include instream flow to the Shasta River, prior rights in the Shasta River, and agricultural water demand to the MWCD Canal. Seepage under the dam is also measured and accounted for by MWCD. Releases into the Canal are estimated based on total monthly water deliveries, as submitted to the SWRCB.

The complete surface water system as modeled within MODFLOW is shown in Figure 6.

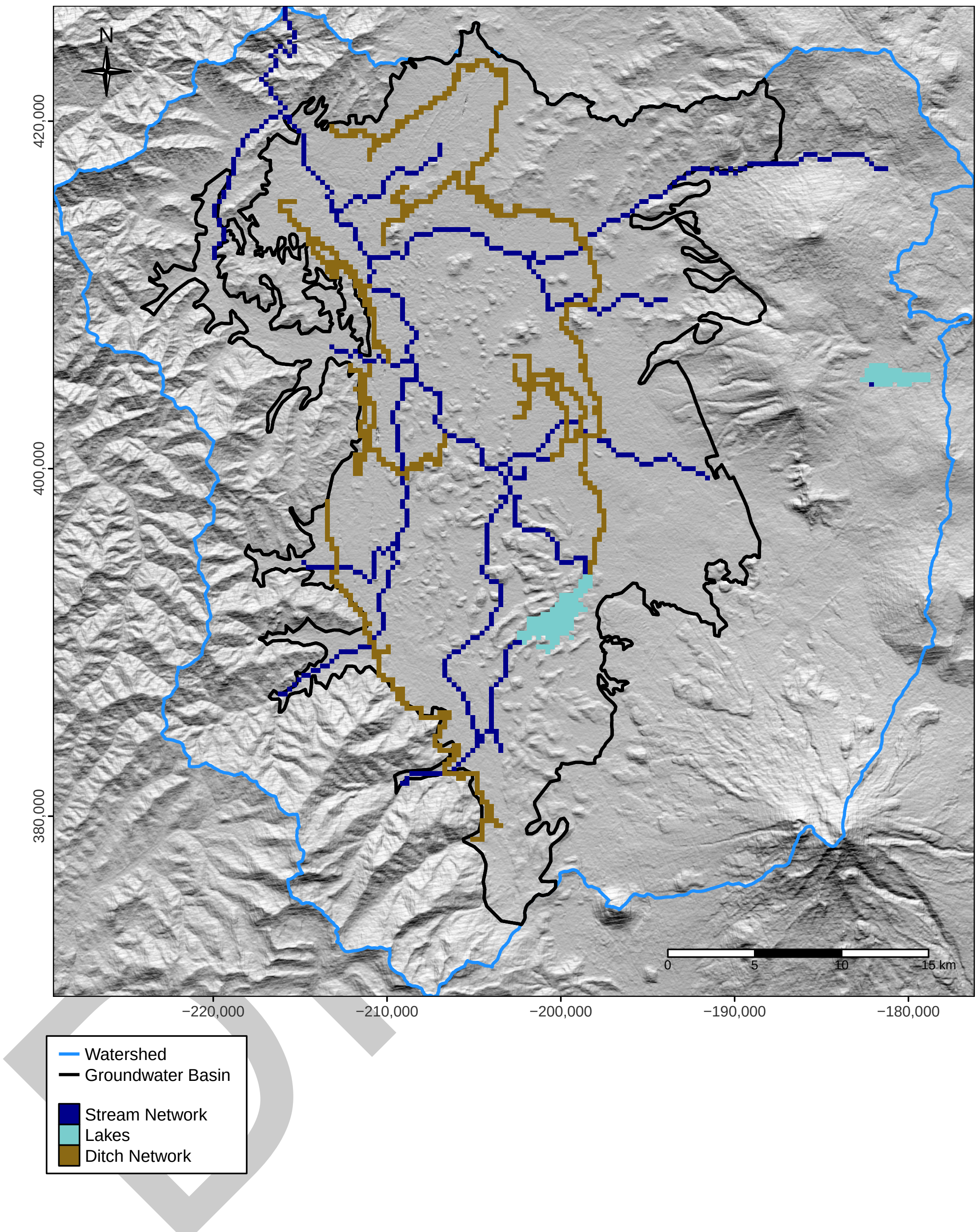

Figure 6: Surface water as modeled within MODFLOW.

Model Calibration and Sensitivity

The SWGM transient model which ran from WY1991-2018 was calibrated with the groundwater elevation and streamflow targets described in this section. The sensitivity analysis and calibration software UCODE2014[6] was applied to the SWGM. UCODE2014 uses the sum of square weighted residuals as the objective function for determining the models ability to match observations. Preliminary calibration was conducted on the groundwater flow system but due to data scarcity additional calibrations will be done for SWGM v1.1. Ongoing recommendations and collaboratoin with the SWRCB is aiding in constraining the calibration.

Observations Used in Model Calibration

Groundwater Observations

The California Statewide Groundwater Elevation Monitoring (CASGEM) database was filtered and cleaned for the Shasta Valley area and modeled time period to create a database of groundwater observations that were corrected with respect to the model top elevations. In addition to the periodic groundwater level measurements, The Nature Conservatory (TNC) has collected groundwater level data more recently that were included. The groundwater level observations were weighted using an acceptable standard deviation of 0.1 for observation data from CASGEM and 0.15 for observation data from TNC. Each well was given a unique name to identify it within the modeling framework as shown in Table 5. Figures Figure 7, Figure 8, and Figure 9 show the locations of groundwater elevation wells used in calibration of the SWGM.

Table 5: Overview of Groundwater Elevation Observations

MODFLOW ID	ROW	COL	Start Date	End Date	No. of Obs
c_10	151	95	1990-10-01	2018-03-01	54
c_11	148	121	1990-10-01	2008-10-01	34
c_12	139	70	1990-10-01	2018-03-01	55
c_13	139	90	1990-10-01	2017-10-01	55
c_14	120	65	2013-04-01	2018-03-01	10
c_15	115	86	2005-10-01	2018-03-01	26
c_16	101	113	1990-10-01	2017-10-01	54
c_17	95	111	1990-10-01	2018-03-01	53
c_18	43	50	1990-10-01	1992-10-01	5
c_19	127	118	1990-10-01	2007-03-01	31
c_20	124	62	1990-10-01	2018-03-01	56
c_21	113	72	1990-10-01	2018-03-01	51
c_22	108	68	1990-10-01	2018-03-01	55
c_23	108	88	1990-10-01	2011-10-01	40
c_24	105	96	1990-10-01	1997-10-01	14
c_25	104	122	1990-10-01	2005-10-01	29
c_26	91	109	1990-10-01	2018-03-01	52

[6] https://igwmc.mines.edu/wp-content/uploads/sites/117/2018/11/UCODE_2014_User_Manual-version02.pdf

Table 5: Overview of Groundwater Elevation Observations *(continued)*

MODFLOW ID	ROW	COL	Start Date	End Date	No. of Obs
c_27	89	93	1990-10-01	2018-03-01	53
c_28	81	71	1990-10-01	2018-03-01	56
c_29	80	103	1991-03-01	2017-10-01	52
c_30	74	110	1990-10-01	2018-03-01	53
c_31	66	69	1990-10-01	2018-03-01	56
c_32	47	50	1990-10-01	2018-03-01	55
c_34	47	96	1990-10-01	2002-03-01	22
c_35	46	69	1990-10-01	2018-03-01	48
c_36	45	51	2000-09-01	2008-10-01	18
c_37	31	93	1990-10-01	2018-03-01	53
c_38	30	85	1990-10-01	2018-03-01	50
c_39	28	76	1990-10-01	2018-03-01	45
c_40	20	104	1990-10-01	2018-03-01	53
c_41	18	89	1990-10-01	2018-03-01	54
c_42	24	88	2013-04-01	2018-03-01	9
c_43	104	89	2010-04-01	2015-04-01	12
c_44	74	53	2004-10-01	2018-03-01	23
c_45	53	65	2013-04-01	2018-03-01	11
c_46	46	76	2004-09-01	2018-03-01	28
TNC_01	101	98	2010-01-01	2017-10-01	54
TNC_02	104	89	2010-09-01	2017-10-01	86
TNC_03	89	93	2010-03-01	2016-03-01	73
TNC_04	89	93	2010-01-01	2017-12-01	95
TNC_05	92	103	2010-03-01	2013-03-01	37
TNC_06	92	103	2010-01-01	2014-02-01	50
TNC_07	93	103	2010-01-01	2017-09-01	93
TNC_08	92	102	2012-04-01	2013-03-01	12
TNC_09	102	101	2010-04-01	2016-03-01	72
TNC_10	91	99	2014-02-01	2017-09-01	44

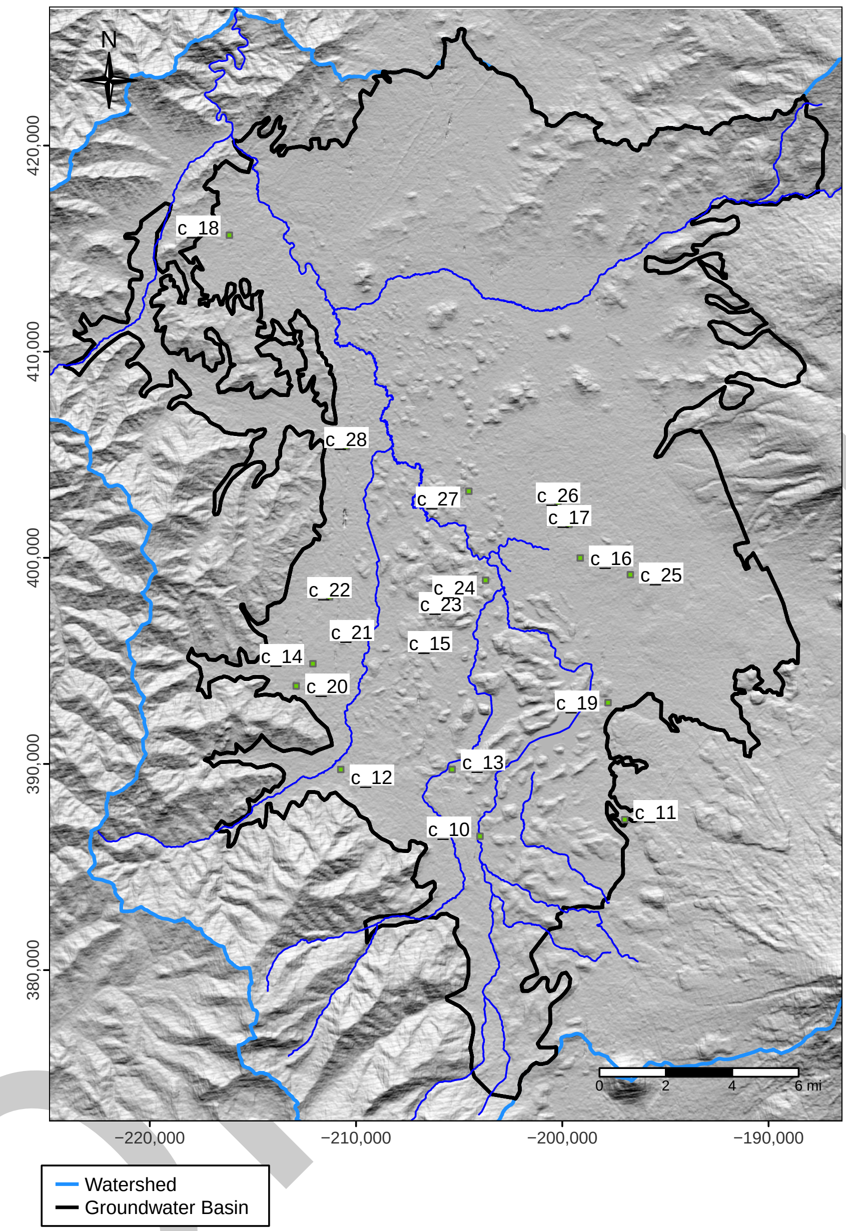

Figure 7: Groundwater Elevation wells used in model calibration, Wells c_10 through c_28.

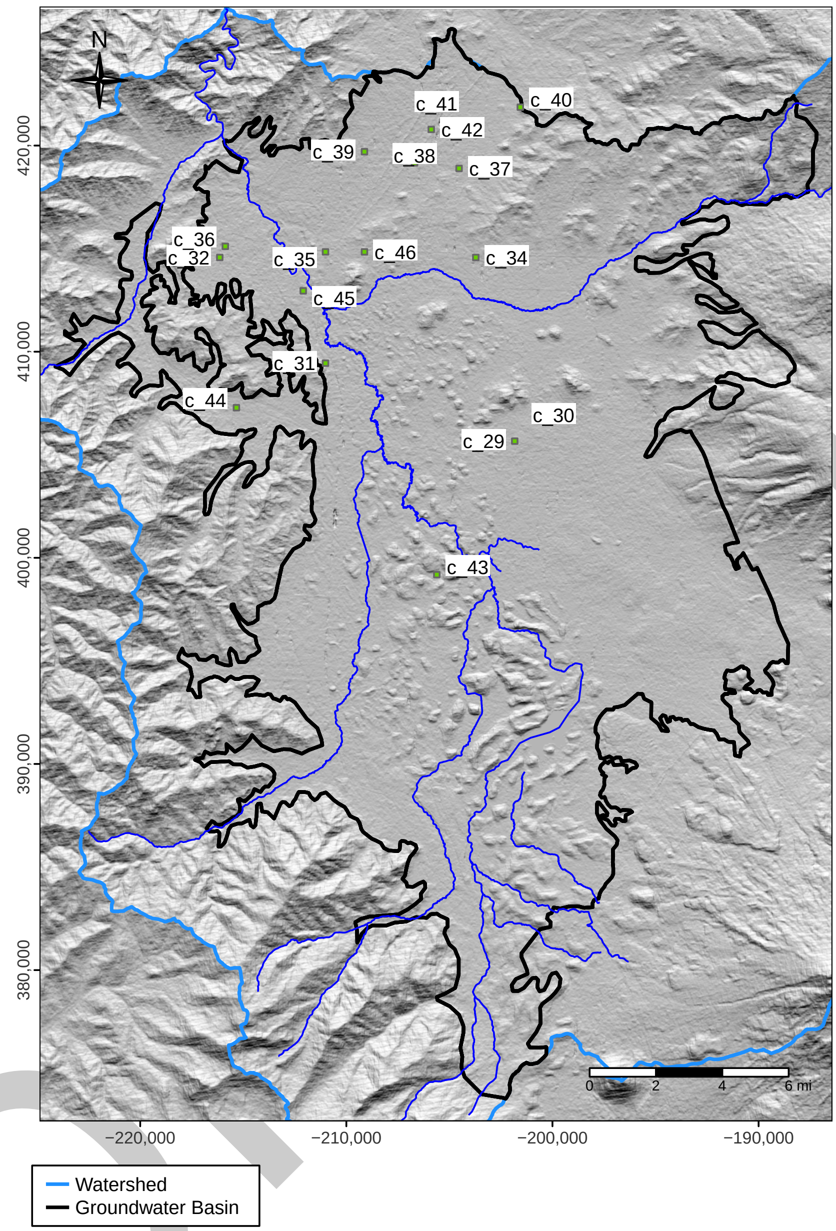

Figure 8: Groundwater Elevation wells used in model calibration, Wells c_29 through c_46.

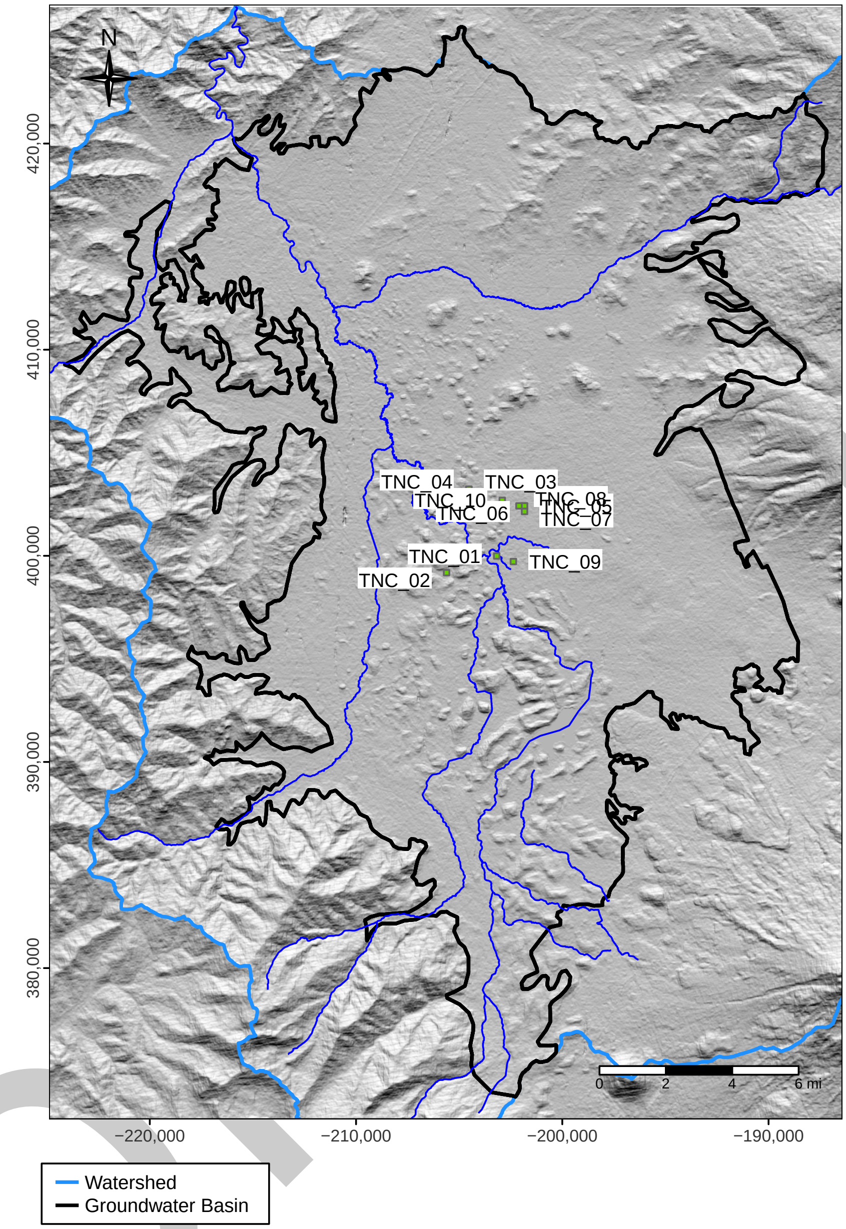

Figure 9: Groundwater Elevation wells used in model calibration, Wells TNC_01 through TNC_10

Surface Water Flow Observations

Several USGS stream gages exist on the Shasta River and its tributaries which were applied to both the PRMS and MODFLOW models to calibrate stream and watershed related parameters. Streamflows measured throughout the upper watershed and Shasta Valley were included as flow observations with a coefficient of variation of 10% as a weighting parameter.

Additional Observations

Precipitation gages were used to manually calibrate rainfall distribution within the PRMS model framework. Remotely sensed snowfall estimations (Bair et al. 2016) were used to examine total snow pack and the relative distribution of snow within the Shasta Watershed.

Model Parameters

Hydraulic Parameters

There are 41 hydraulic parameters in the SWGM. Table 6 shows the the name of the parameters as used within the modeling framework in addition to final values used. These parameters are used exclusively within MODFLOW and control the storage and movement of water through the subsystem.

Table 6: Hydraulic properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
an1	HANI	1.0000000	Anisotropy multiplier for Unit 1
an2	HANI	1.0000000	Anisotropy multiplier for Unit 2
an3	HANI	1.0000000	Anisotropy multiplier for Unit 3
an4	HANI	1.0000000	Anisotropy multiplier for Unit 4
an5	HANI	1.0000000	Anisotropy multiplier for Unit 5
an6	HANI	1.0000000	Anisotropy multiplier for Unit 6
an7	HANI	1.0000000	Anisotropy multiplier for Unit 7
an8	HANI	1.0000000	Anisotropy multiplier for Unit 8
DRE_leak	LAK	5.3900000	Lakebed leakance (BDLKNC) for Dwinnell Reservoir
kx1	HK	0.0362000	Horizontal hydraulic conductivity for Unit 1
kx2	HK	1.0920000	Horizontal hydraulic conductivity for Unit 2
kx3	HK	0.0111000	Horizontal hydraulic conductivity for Unit 3
kx4	HK	2.4260000	Horizontal hydraulic conductivity for Unit 4
kx5	HK	0.0063900	Horizontal hydraulic conductivity for Unit 5
kx6	HK	12.8910000	Horizontal hydraulic conductivity for Unit 6

Table 6: Hydraulic properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
kx7	HK	17.1500000	Horizontal hydraulic conductivity for Unit 7
kx8	HK	0.0006650	Horizontal hydraulic conductivity for Unit 8
kz1	VK	16.2800000	Vertical hydraulic conductivity for Unit 1
kz2	VK	44.2900000	Vertical hydraulic conductivity for Unit 2
kz3	VK	5.9460000	Vertical hydraulic conductivity for Unit 3
kz4	VK	0.0294000	Vertical hydraulic conductivity for Unit 4
kz5	VK	0.5002000	Vertical hydraulic conductivity for Unit 5
kz6	VK	16.2900000	Vertical hydraulic conductivity for Unit 6
kz7	VK	66.1400000	Vertical hydraulic conductivity for Unit 7
kz8	VK	0.5590000	Vertical hydraulic conductivity for Unit 8
ss1	SS	0.0003520	Specific storage for Unit 1
ss2	SS	0.0004320	Specific storage for Unit 2
ss3	SS	0.0004140	Specific storage for Unit 3
ss4	SS	0.0001670	Specific storage for Unit 4
ss5	SS	0.0004270	Specific storage for Unit 5
ss6	SS	0.0016300	Specific storage for Unit 6
ss7	SS	0.0000374	Specific storage for Unit 7
ss8	SS	0.0000986	Specific storage for Unit 8
sy1	SY	0.7138000	Specific yield for Unit 1
sy2	SY	0.2500000	Specific yield for Unit 2
sy3	SY	0.2500000	Specific yield for Unit 3
sy4	SY	0.1632000	Specific yield for Unit 4
sy5	SY	0.2510000	Specific yield for Unit 5
sy6	SY	0.0115000	Specific yield for Unit 6
sy7	SY	0.5847000	Specific yield for Unit 7
sy8	SY	0.2731000	Specific yield for Unit 8

Soil Parameters

There are 16 soil parameters in the SWGM. Table 7 shows the the name of the parameters as used within the modeling framework in addition to final values used. The soil parameters are spatially variable and are based on SSURGO data. Soil modle parameters are generally multipliers to scale the entire basin values. This was done to maintain the spatial distribution of soil properties. These parameters are used within PRMS.

Table 7: Soil properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
carea_max	carea	1.000000	Multiplier for maximum possible area contributing to surface runoff expressed as a portion of the HRU area
fastcoef_lin	Soil_Zone	0.001000	Linear preferential flow routing coefficient

Table 7: Soil properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
fastcoef_sq	Soil_Zone	0.549791	Non linear preferential flow routing coefficient
pref_flow_den	Soil_Zone	0.040000	Fraction of the gravity reservoir in which preferential flow occurs for each HRU
sat_threshold	Soil_Zone	4.560000	Multiplier for water holding capacity of the gravity and preferential flow reservoirs
slowcoef_lin	Soil_Zone	6.380000	Multiplier for linear coefficient in equation to route gravity reservoir storage
slowcoef_sq	Soil_Zone	11.020543	Multiplier for nonlinear coefficient in equation to route gravity reservoir storage downslope
smidx_coef	Sroff	0.100000	Coefficient in nonlinear contributing area algorithm
smidx_exp	Sroff	0.100000	Exponent in nonlinear contributing area algorithm
soil_moist_max	Soil_Zone	2.795000	Multiplier for maximum available water holding capacity of capillary reservoir from land surface to rooting depth
soil_rechr_max	Soil_Zone	1.000000	Multiplier for maximum storage for soil recharge zone
soil2gw_max	Soil_Zone	0.001000	Maximum amount of the capillary reservoir excess that is routed directly to the GWR
srain_intcp	Intcp	1.000000	Multiplier for summer rain interception storage capacity for the major vegetation type
ssr2gw_exp	Soil_Zone	2.400000	Multiplier for nonlinear coefficient in equation used to route water from the gravity reservoirs to the GWR
ssr2gw_rate	Soil_Zone	1.000000	Linear coefficient in equation used to route water from the gravity reservoir to the GWR
wrain_intcp	Intcp	3.259831	Multiplier for winter rain interception storage capacity for the major vegetation type

Climate Parameters

There are 103 soil parameters in the SWGM. Table 8 shows the the name of the parameters as used within the modeling framework in addition to final values used. These parameters are used within PRMS.

Table 8: Climate properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
adj_rain_apr	adjmix_rain	1.0000000	Multiplier for rain in April
adj_rain_aug	adjmix_rain	1.0000000	Multiplier for rain in August
adj_rain_dec	adjmix_rain	1.2000000	Multiplier for rain in December
adj_rain_feb	adjmix_rain	1.0000000	Multiplier for rain in February
adj_rain_jan	adjmix_rain	1.0000000	Multiplier for rain in January
adj_rain_jul	adjmix_rain	1.0000000	Multiplier for rain in July
adj_rain_jun	adjmix_rain	1.2000000	Multiplier for rain in June
adj_rain_mar	adjmix_rain	1.0000000	Multiplier for rain in March
adj_rain_may	adjmix_rain	1.0000000	Multiplier for rain in May
adj_rain_nov	adjmix_rain	1.0000000	Multiplier for rain in November
adj_rain_oct	adjmix_rain	1.1000000	Multiplier for rain in October
adj_rain_sep	adjmix_rain	1.0000000	Multiplier for rain in September
dday_in_apr	dday_intcp	-7.5759444	Intercept in degree day equation for PRMS solar radiation in April
dday_in_aug	dday_intcp	-34.0000000	Intercept in degree day equation for PRMS solar radiation in August
dday_in_dec	dday_intcp	-8.0000000	Intercept in degree day equation for PRMS solar radiation in December
dday_in_feb	dday_intcp	-7.0000000	Intercept in degree day equation for PRMS solar radiation in February
dday_in_jan	dday_intcp	-12.8721115	Intercept in degree day equation for PRMS solar radiation in January
dday_in_jul	dday_intcp	-37.5030524	Intercept in degree day equation for PRMS solar radiation in July
dday_in_jun	dday_intcp	-13.5515332	Intercept in degree day equation for PRMS solar radiation in June
dday_in_mar	dday_intcp	-7.0000000	Intercept in degree day equation for PRMS solar radiation in March
dday_in_may	dday_intcp	-14.6390135	Intercept in degree day equation for PRMS solar radiation in May
dday_in_nov	dday_intcp	-26.4071231	Intercept in degree day equation for PRMS solar radiation in November
dday_in_oct	dday_intcp	-13.0000000	Intercept in degree day equation for PRMS solar radiation in October
dday_in_sep	dday_intcp	-13.0000000	Intercept in degree day equation for PRMS solar radiation in September
dday_sl_apr	dday_slope	0.1960800	Slope in degree day equation for PRMS solar radiation in April
dday_sl_aug	dday_slope	0.6500000	Slope in degree day equation for PRMS solar radiation in August
dday_sl_dec	dday_slope	0.3100000	Slope in degree day equation for PRMS solar radiation in December
dday_sl_feb	dday_slope	0.1001000	Slope in degree day equation for PRMS solar radiation in February
dday_sl_jan	dday_slope	0.3100000	Slope in degree day equation for PRMS solar radiation in January
dday_sl_jul	dday_slope	0.6989744	Slope in degree day equation for PRMS solar radiation in July

Table 8: Climate properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
dday_sl_jun	dday_slope	0.5508728	Slope in degree day equation for PRMS solar radiation in June
dday_sl_mar	dday_slope	0.3900000	Slope in degree day equation for PRMS solar radiation in March
dday_sl_may	dday_slope	0.9583546	Slope in degree day equation for PRMS solar radiation in May
dday_sl_nov	dday_slope	0.6350482	Slope in degree day equation for PRMS solar radiation in November
dday_sl_oct	dday_slope	0.3400000	Slope in degree day equation for PRMS solar radiation in October
dday_sl_sep	dday_slope	0.4000000	Slope in degree day equation for PRMS solar radiation in September
freeh2o_cap	snow	0.0521899	Free water holding capacity of snowpack
pet_adj_apr	Pot_ET	1.1000000	Potential ET adjustment in April
pet_adj_aug	Pot_ET	0.8271625	Potential ET adjustment in August
pet_adj_dec	Pot_ET	1.1252488	Potential ET adjustment in December
pet_adj_feb	Pot_ET	0.9410774	Potential ET adjustment in February
pet_adj_jan	Pot_ET	1.1000000	Potential ET adjustment in January
pet_adj_jul	Pot_ET	0.9000000	Potential ET adjustment in July
pet_adj_jun	Pot_ET	1.1000000	Potential ET adjustment in June
pet_adj_mar	Pot_ET	1.0932620	Potential ET adjustment in March
pet_adj_may	Pot_ET	1.3110423	Potential ET adjustment in May
pet_adj_nov	Pot_ET	0.8000000	Potential ET adjustment in November
pet_adj_oct	Pot_ET	1.2000000	Potential ET adjustment in October
pet_adj_sep	Pot_ET	1.2000000	Potential ET adjustment in September
pet_juniper	Pot_ET	1.3000000	Potential ET adjustment in areas with juniper cover
pet_other	Pot_ET	1.1000000	Potential ET adjustment in areas without juniper cover
ppt_radj_apr	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in April
ppt_radj_aug	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in August
ppt_radj_dec	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in December
ppt_radj_feb	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in February
ppt_radj_jan	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in January
ppt_radj_jul	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in July
ppt_radj_jun	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in June
ppt_radj_mar	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in March
ppt_radj_may	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in May
ppt_radj_nov	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in November
ppt_radj_oct	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in October
ppt_radj_sep	ppt_rad_adj	0.0200000	PRMS ppt_rad_adj factor in September
radj_sppt	Sol_Rad	0.3444511	Adjustment factor for computed solar radiation for summer day with greater than ppt_rad_adj inches of precipitation
radj_wppt	Sol_Rad	0.1277979	Adjustment factor for computed solar radiation for winter day with greater than ppt_rad_adj inches of precipitation

Table 8: Climate properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
radmax	Sol_Rad	0.8000000	Maximum fraction of the potential solar radiation that may reach the ground due to haze, dust, smog, and so forth
tmax_in_apr	tmax_index	57.4738530	Index temperature used to determine precipitation adjustments to solar radiation in April
tmax_in_aug	tmax_index	84.3901690	Index temperature used to determine precipitation adjustments to solar radiation in August
tmax_in_dec	tmax_index	42.1902520	Index temperature used to determine precipitation adjustments to solar radiation in December
tmax_in_feb	tmax_index	47.0413480	Index temperature used to determine precipitation adjustments to solar radiation in February
tmax_in_jan	tmax_index	47.5186048	Index temperature used to determine precipitation adjustments to solar radiation in January
tmax_in_jul	tmax_index	85.0927650	Index temperature used to determine precipitation adjustments to solar radiation in July
tmax_in_jun	tmax_index	75.1458640	Index temperature used to determine precipitation adjustments to solar radiation in June
tmax_in_mar	tmax_index	52.1053100	Index temperature used to determine precipitation adjustments to solar radiation in March
tmax_in_may	tmax_index	66.2615090	Index temperature used to determine precipitation adjustments to solar radiation in May
tmax_in_nov	tmax_index	49.2785800	Index temperature used to determine precipitation adjustments to solar radiation in November
tmax_in_oct	tmax_index	64.7301510	Index temperature used to determine precipitation adjustments to solar radiation in October
tmax_in_sep	tmax_index	77.1708690	Index temperature used to determine precipitation adjustments to solar radiation in September
tmax_lap_apr	tmax_lap	11.2936403	Change in maximum air temperature per 1,000 feet elevation change (°F) in April
tmax_lap_aug	tmax_lap	7.0000000	Change in maximum air temperature per 1,000 feet elevation change (°F) in August
tmax_lap_dec	tmax_lap	12.0000000	Change in maximum air temperature per 1,000 feet elevation change (°F) in December

Table 8: Climate properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
tmax_lap_feb	tmax_lap	12.0000000	Change in maximum air temperature per 1,000 feet elevation change (°F) in February
tmax_lap_jan	tmax_lap	9.4700610	Change in maximum air temperature per 1,000 feet elevation change (°F) in January
tmax_lap_jul	tmax_lap	7.5693981	Change in maximum air temperature per 1,000 feet elevation change (°F) in July
tmax_lap_jun	tmax_lap	5.6314665	Change in maximum air temperature per 1,000 feet elevation change (°F) in June
tmax_lap_mar	tmax_lap	12.7798857	Change in maximum air temperature per 1,000 feet elevation change (°F) in March
tmax_lap_may	tmax_lap	11.0000000	Change in maximum air temperature per 1,000 feet elevation change (°F) in May
tmax_lap_nov	tmax_lap	13.1165216	Change in maximum air temperature per 1,000 feet elevation change (°F) in November
tmax_lap_oct	tmax_lap	9.6706430	Change in maximum air temperature per 1,000 feet elevation change (°F) in October
tmax_lap_sep	tmax_lap	9.0000000	Change in maximum air temperature per 1,000 feet elevation change (°F) in September
tmax_snow	tmax_snow	32.0000000	Maximum temperature snow can form (°F)
tmin_lap_apr	tmin_lap	7.3058421	Change in minimum air temperature per 1,000 feet elevation change (°F) in April
tmin_lap_aug	tmin_lap	7.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in August
tmin_lap_dec	tmin_lap	11.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in December
tmin_lap_feb	tmin_lap	11.7491194	Change in minimum air temperature per 1,000 feet elevation change (°F) in February
tmin_lap_jan	tmin_lap	13.2407952	Change in minimum air temperature per 1,000 feet elevation change (°F) in January
tmin_lap_jul	tmin_lap	7.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in July
tmin_lap_jun	tmin_lap	8.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in June
tmin_lap_mar	tmin_lap	12.9059633	Change in minimum air temperature per 1,000 feet elevation change (°F) in March
tmin_lap_may	tmin_lap	15.5359526	Change in minimum air temperature per 1,000 feet elevation change (°F) in May

Table 8: Climate properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
tmin_lap_nov	tmin_lap	2.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in November
tmin_lap_oct	tmin_lap	10.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in October
tmin_lap_sep	tmin_lap	9.0000000	Change in minimum air temperature per 1,000 feet elevation change (°F) in September

Streamflow Parameters

There are 4 streamflow parameters in the SWGM. Table 9 shows the the name of the parameters as used within the modeling framework in addition to final values used. These parameters are used within the SFR package of MODFLOW.

Table 9: Streamflow properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
sfr_hc	SFR	1.2620	Multiplier for streambed hydraulic conductivity
sfr_rough	SFR	0.5721	Multiplier for Manning's roughness coefficient
sfr_thick	SFR	0.9254	Multiplier for streambed thickness
sfr_width	SFR	1.0000	Multiplier for streambed width

Pumping Parameters

There are 13 pumping parameters in the SWGM. Table 10 shows the the name of the parameters as used within the modeling framework in addition to final values used. These are adjustment factors to pumping volumes for the entire watershed. They are used within the WEL package of MODFLOW.

Table 10: Pumping properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
WEL_apr	WEL	1.0	Multiplier for all pumping in April
WEL_aug	WEL	1.0	Multiplier for all pumping in August
WEL_dec	WEL	1.0	Multiplier for all pumping in December
WEL_feb	WEL	1.0	Multiplier for all pumping in February
WEL_jan	WEL	1.0	Multiplier for all pumping in January
WEL_jul	WEL	1.0	Multiplier for all pumping in July
WEL_jun	WEL	1.0	Multiplier for all pumping in June
WEL_mar	WEL	1.0	Multiplier for all pumping in March

Table 10: Pumping properites descriptions and values used in the SWGM. *(continued)*

Parameter Name	Group Name	Value	Description
WEL_may	WEL	1.0	Multiplier for all pumping in May
WEL_nov	WEL	1.0	Multiplier for all pumping in November
WEL_oct	WEL	1.0	Multiplier for all pumping in October
WEL_par	WEL	1.1	Multiplier for all pumping in all months
WEL_sep	WEL	1.0	Multiplier for all pumping in September

Recharge Parameters

There are 14 recharge parameters in the SWGM. Table 11 shows the the name of the parameters as used within the modeling framework in addition to final values used. These parameters are adjustment factors to recharge after PRMS and the RSRZ are calculated.

Table 11: Recharge properites descriptions and values used in the SWGM.

Parameter Name	Group Name	Value	Description
RCH_apr	UZF	1.0000	Recharge multiplier for April
RCH_aug	UZF	1.0000	Recharge multiplier for August
RCH_dec	UZF	1.0000	Recharge multiplier for December
RCH_feb	UZF	1.0000	Recharge multiplier for February
RCH_jan	UZF	1.0000	Recharge multiplier for January
RCH_jul	UZF	1.0000	Recharge multiplier for July
RCH_jun	UZF	1.0000	Recharge multiplier for June
RCH_mar	UZF	1.0000	Recharge multiplier for March
RCH_may	UZF	1.0000	Recharge multiplier for May
RCH_nov	UZF	1.0000	Recharge multiplier for November
RCH_oct	UZF	1.0000	Recharge multiplier for October
RCH_sep	UZF	1.0000	Recharge multiplier for September
VKS	UZF	100.0000	Saturated vertical hydraulic conductivity, used for rejected infiltratrion only
strt_rch	UZF	0.5579	Starting recharge multiplier for the steady state stress period

Calibration Results

The hydrographs below present the observed groundwater hydrographs versus the simulated heads (after calibration). The map below shows the location of each observation well in the model domain using the MODFLOW node as the naming convention for observations. This is a preliminary calibration run. Additional work on including additional observations and changing parameterization is currently underway in collaboration with the SWRCB.

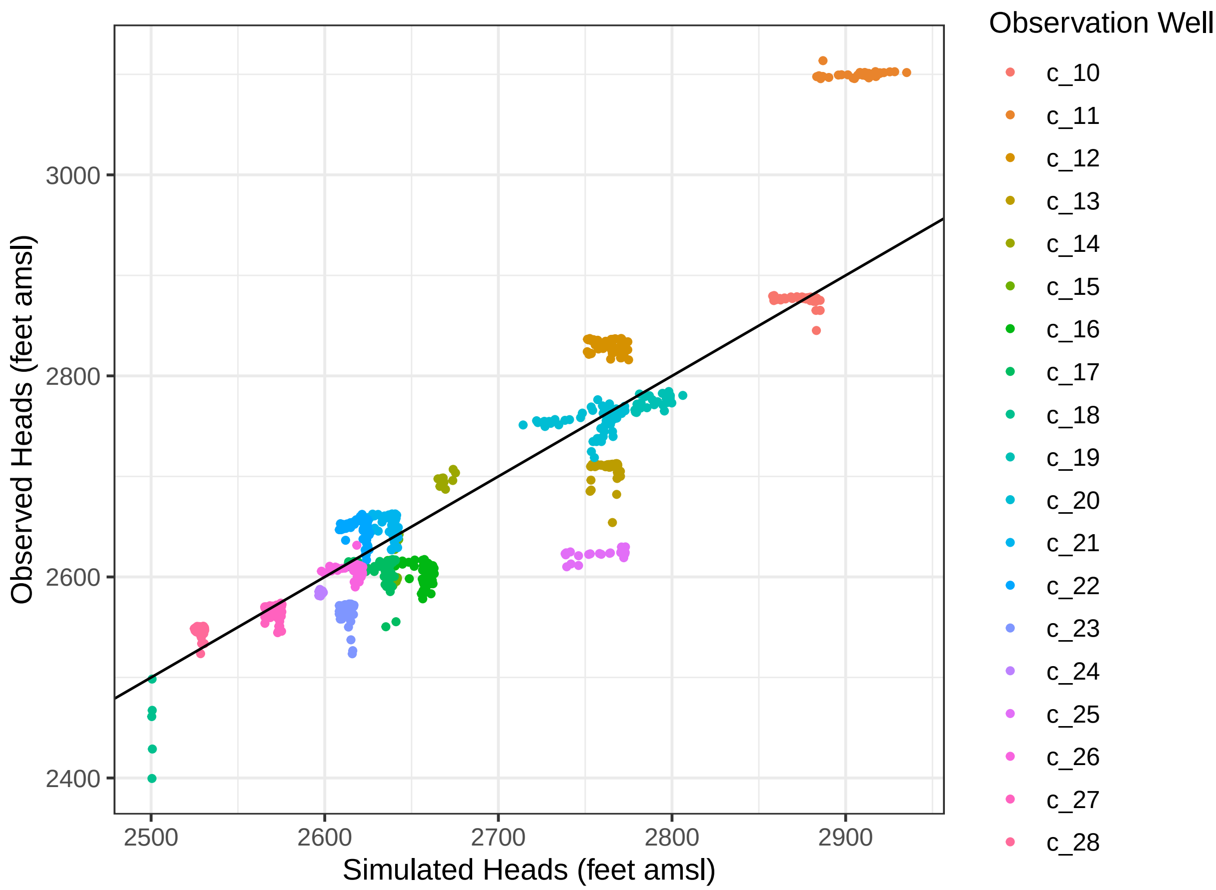

Figure 10: Observed vs. Simulated groundwater elevations in CASGEM Wells (1 of 2).

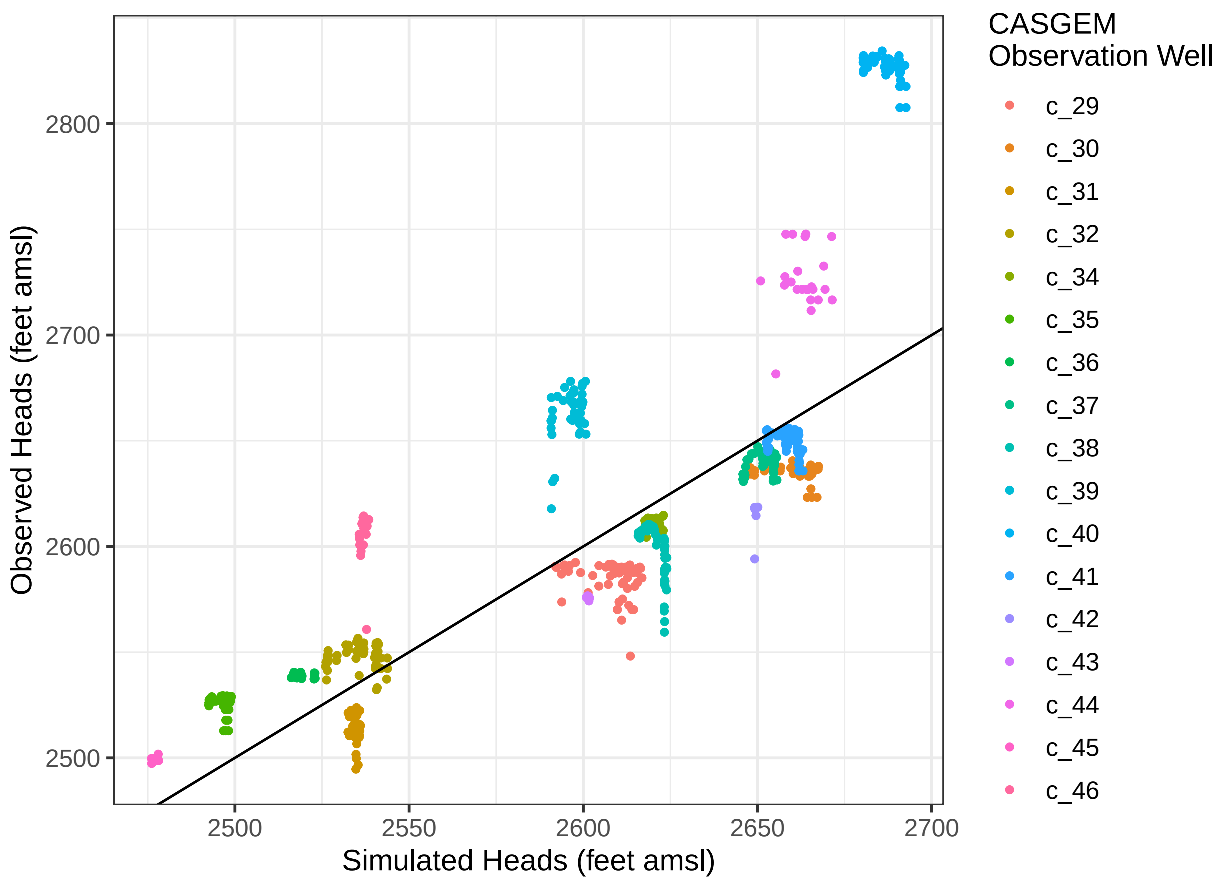

Figure 11: Observed vs. Simulated groundwater elevations in CASGEM Wells (2 of 2).

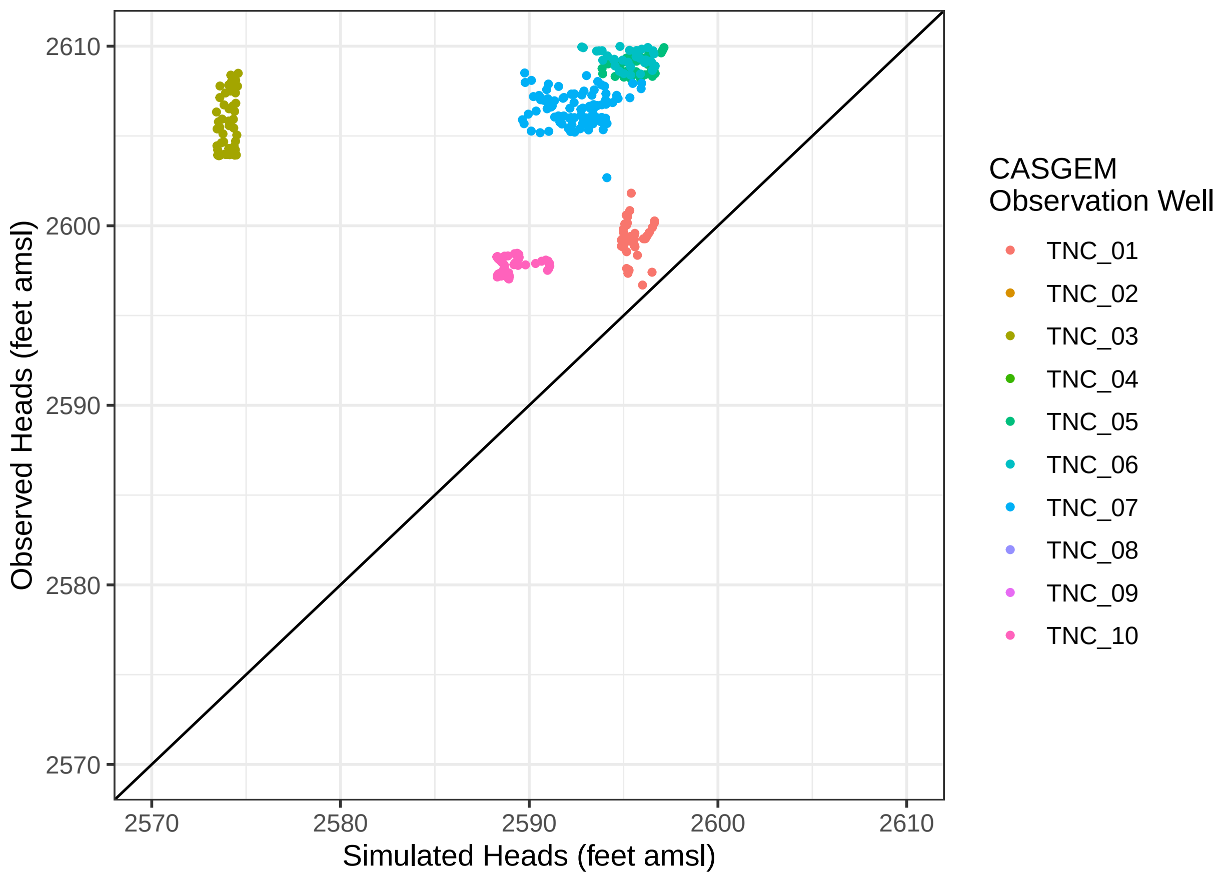

Figure 12: Observed vs. Simulated groundwater elevations in TNC wells near Big Springs.

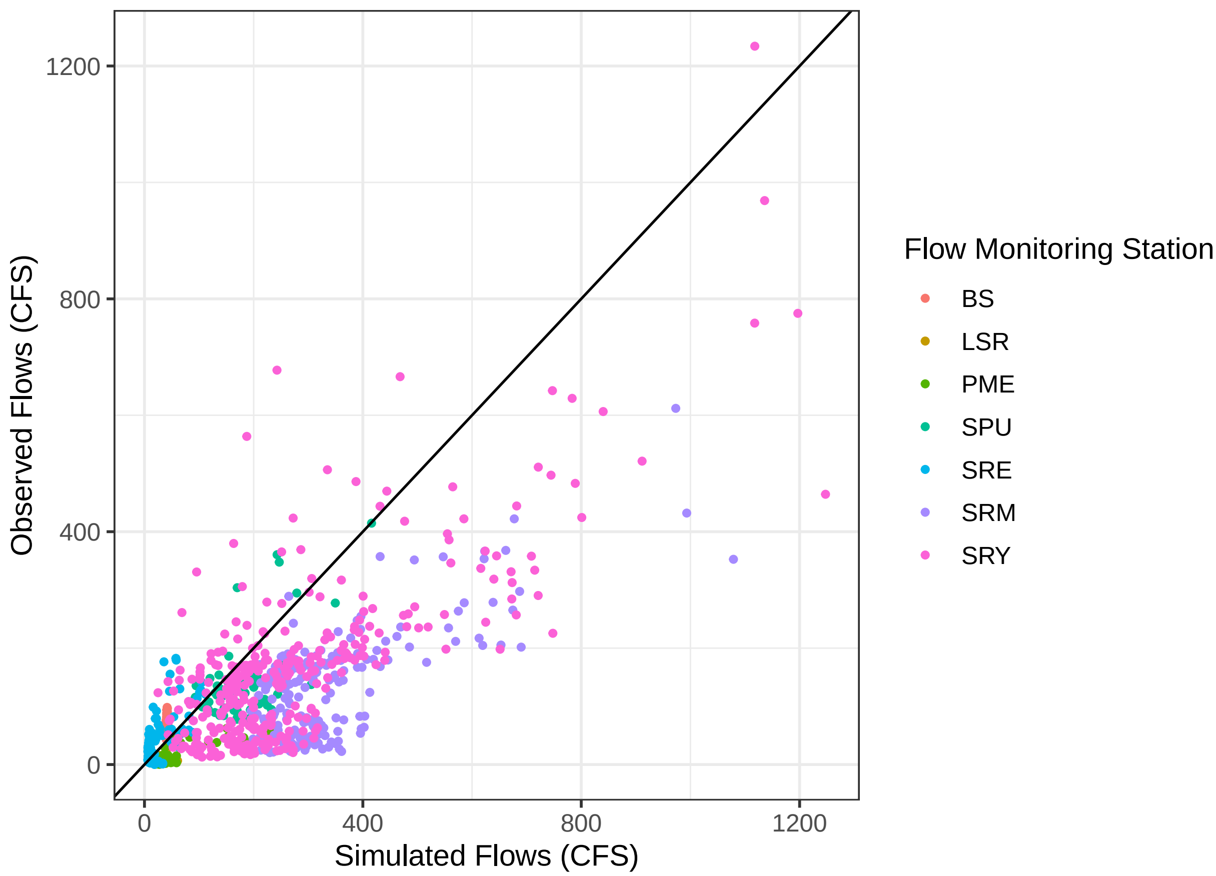

Figure 13: Observed vs. Simulated river flows within Shasta Watershed

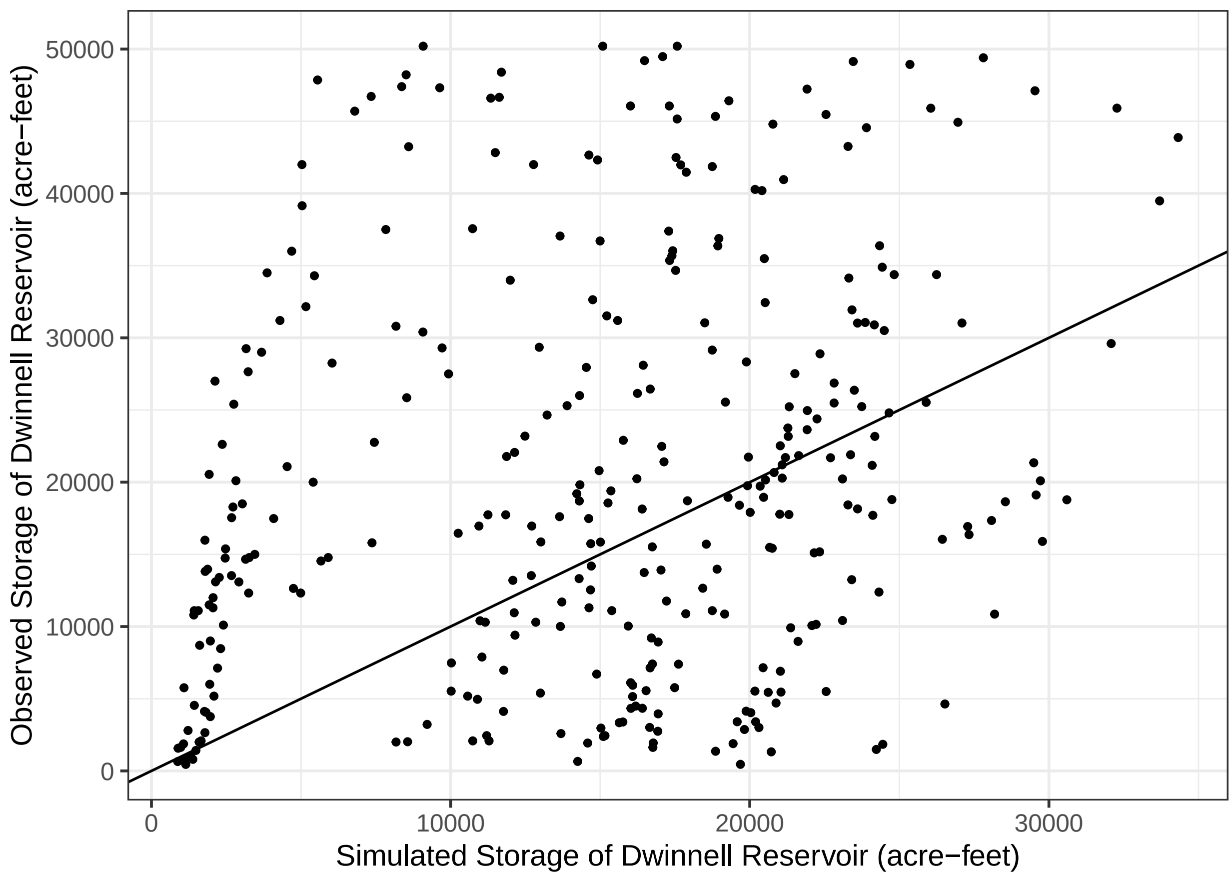

Figure 14: Observed vs. Simulated total storage in Dwinnell Reservoir.

Sensitivity and Uncertainty Analysis

A complete sensitivity and uncertainty analysis will be published in the SWGM v1.1 documentation.

Hydrologic Budget and Flow

Climate Budget

Climatic water budgets are summarized from PRMS modeled output.

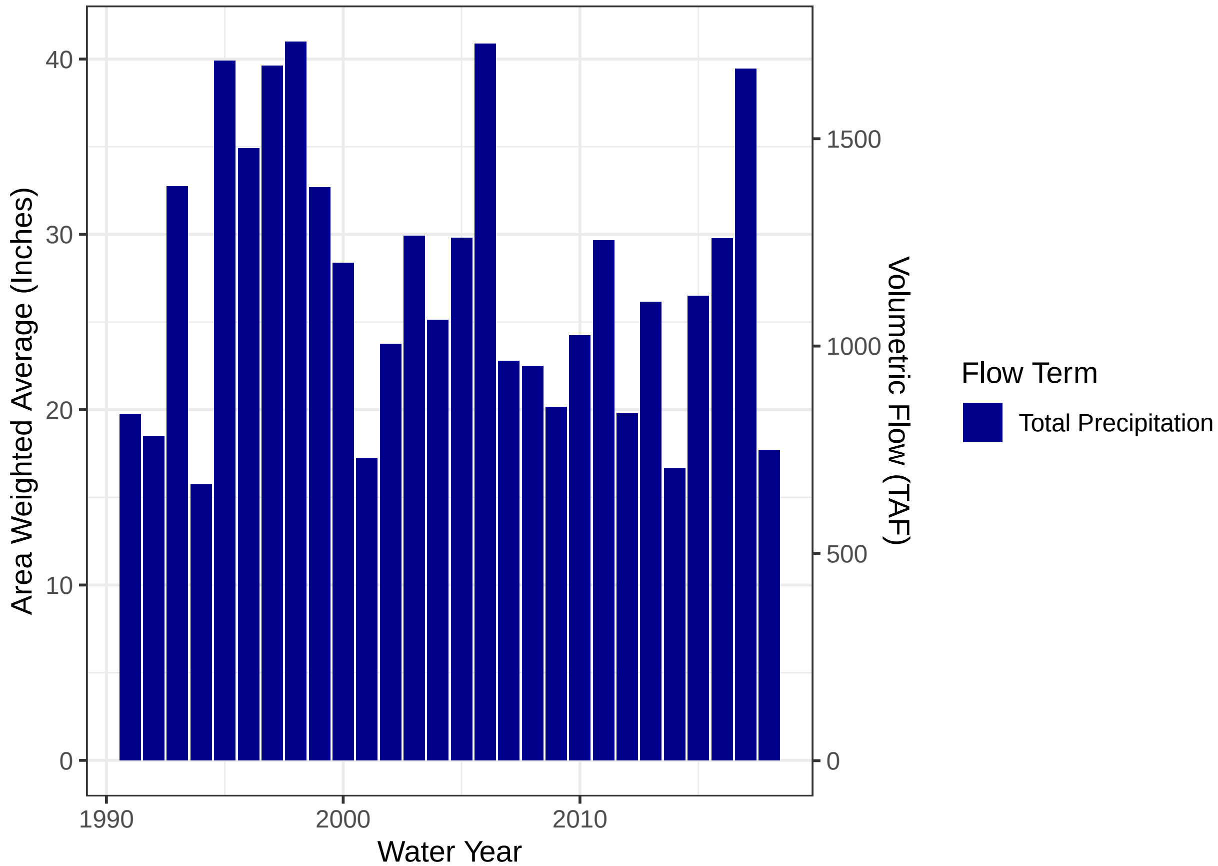

Figure 15: Yearly precipitation within the Shasta Watershed.

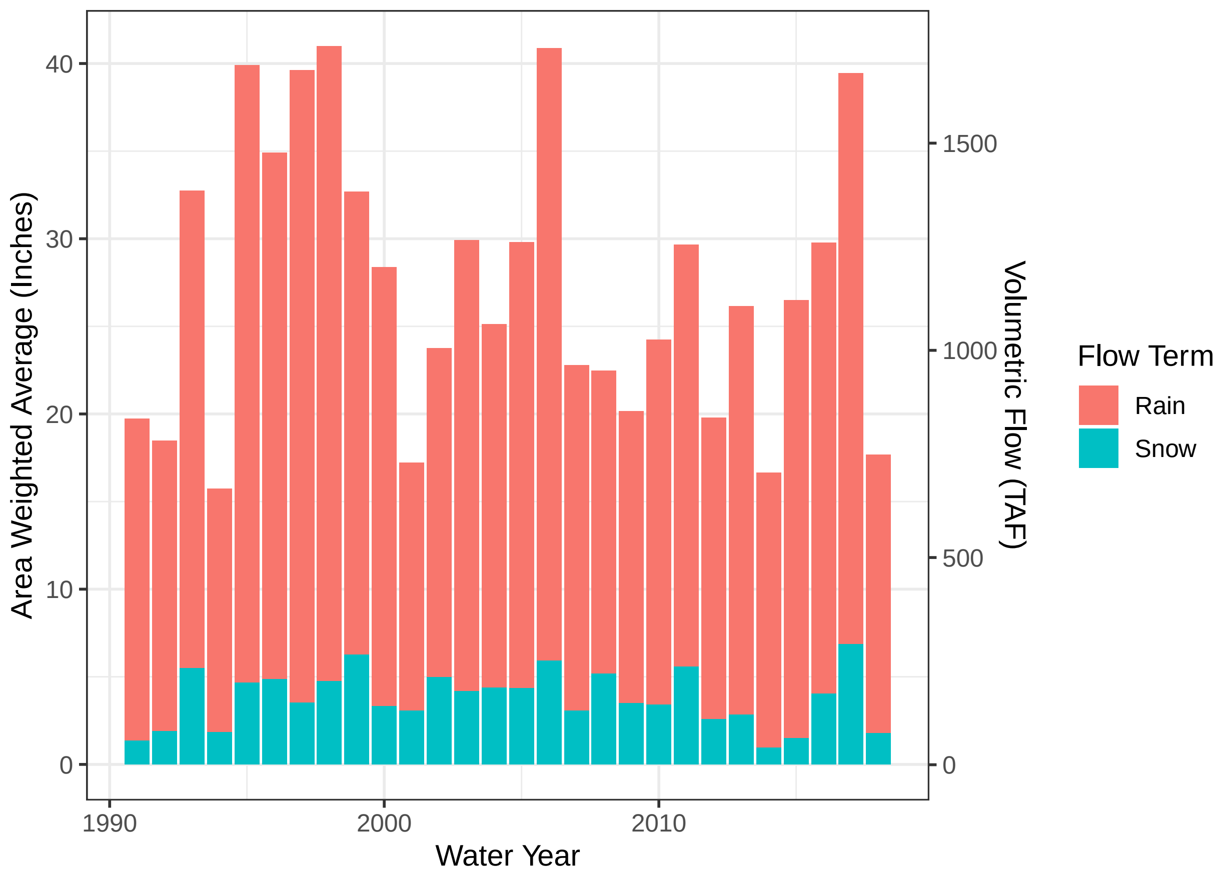

Figure 16: Yearly rain and snowfall within the Shasta Watershed.

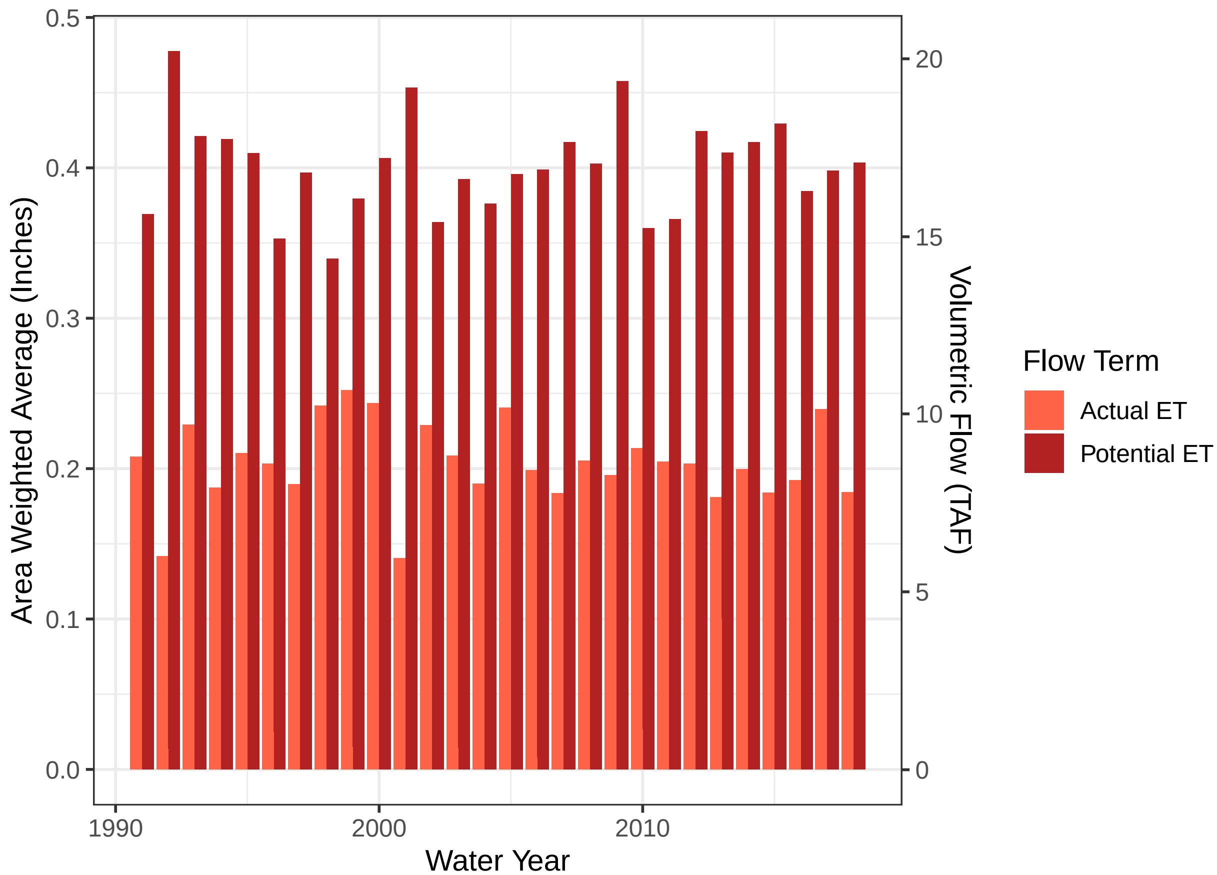

Figure 17: Yearly rain and snowfall within the Shasta Watershed.

Groundwater Budget

Groundwater budgets can be reviewed in Chapter 2 of the Shasta GSP. Updates to the groundwater budget will be presented in the SWGM v1.1 updatted documentation.

Climate Projections

Modeled water balances reflecting a series of climate projections was evaluated with the calibrated SWGM. Water years were selected from the historic time period (WY1991-WY2018) and repeated as needed to make a 50-year climate period. The 50-year climate period is recorded as WY2022-2071. Table 12 shows the sequence of historic climate used to create the projected baseline.

Table 12: Projected climate referenced to historic climate reference years with water year type, as described by DWR, for historic climate.

Projected Climate	Historic Climate	Water Year Type
2022	1994	Dry
2023	1995	Wet

Table 12: Projected climate referenced to historic climate reference years with water year type, as described by DWR, for historic climate. *(continued)*

Projected Climate	Historic Climate	Water Year Type
2024	1996	Wet
2025	1997	Wet
2026	1998	Wet
2027	1999	Wet
2028	2000	Above Normal
2029	2001	Critical
2030	2002	Dry
2031	2003	Above Normal
2032	2004	Above Normal
2033	2010	Below Normal
2034	2006	Wet
2035	2007	Below Normal
2036	2008	Dry
2037	2009	Dry
2038	2011	Above Normal
2039	1991	Critical
2040	1992	Critical
2041	1993	Above Normal
2042	1994	Dry
2043	1995	Wet
2044	1996	Wet
2045	1997	Wet
2046	1998	Wet
2047	1999	Wet
2048	2000	Above Normal
2049	2001	Critical
2050	2002	Dry
2051	2003	Above Normal
2052	2004	Above Normal
2053	2010	Below Normal
2054	2006	Wet
2055	2007	Below Normal
2056	2008	Dry
2057	2009	Dry
2058	2011	Above Normal
2059	1991	Critical
2060	1992	Critical
2061	1993	Above Normal
2062	1994	Dry
2063	1995	Wet
2064	1996	Wet
2065	1997	Wet
2066	1998	Wet
2067	1999	Wet
2068	2000	Above Normal
2069	2001	Critical

Table 12: Projected climate referenced to historic climate reference years with water year type, as described by DWR, for historic climate. *(continued)*

Projected Climate	Historic Climate	Water Year Type
2070	2002	Dry
2071	2003	Above Normal

Four climate scenarios were created using the projected baseline climate data, these four scenarios are labeled as “Far,” “Near,” “Dry,” and “Wet,” corresponding to DWR future scenarios “2030”, “2070”, “2070DEW”, and “2070WMW”, respectively. Model differencing was used to examine trends in different climate scenarios using the baseline projected data as the differencing base.

DWR’s Climate Change Data and Guidance for Use During GSP[7] development contains a dataset of “change factors” which each GSA can use to convert local historical weather data into 4 different climate change scenarios (DWR 2018). Change factors are geographically and temporally explicit. Geographically, a grid of 1/16-degree resolution cells covers the extent of California; for each of these cells, one change factors applies to each month, 1911-2011.

Under their SGMA climate change guidance, DWR provided a dataset of “change factors” which each GSA can use to convert local historical weather data into 4 different climate change scenarios (DWR 2018). Change factors are geographically and temporally explicit. Geographically, a grid of 1/16-degree resolution cells covers the extent of California; for each of these cells, one change factors applies to each month, 1911-2011.

The 2030 (Near) and 2070 central tendency (Far) scenarios predict similar rainfall conditions to the Base case, while the 2070 DEW (Dry) and 2070 WMW (Wet) scenarios show less and more cumulative rain, respectively. Conversely, all scenarios predict higher future ET than the Base case.

Additional information, water budgets, and further discussion on the climate scenario water budgets will be presented in SWGM v1.1.

Model Limitations and Future Improvements

Potential Improvements

SWGM v1.0 should be considered a preliminary effort to characterize the Shasta Watershed. Data from continuous groundwater sensors, increased number of stream gages, and agricultural water usage will provide updates to the calibrated values of the system. There are a number of updates that are under consideration for the base model:

- Updates to glacier melt and snow dynamics on Mount Shasta. Updates to the PRMS code, v 5.2, include a more robust characterization of glacier dynamics. Increased data collection on precipitation, solar radiation, air temperature, and other climate variables should also be included in PRMS updates.

[7] https://groundwaterexchange.org/wp-content/uploads/2020/09/Resource-Guide-Climate-Change-Guidance_v8_ay_19.pdf

- Geologic updates to include fracture flow within basalt geology.
- Hydrogeologic updates to refine anisotropy, storage, and model layer thicknesses.
- Agricultural demands should be internally calculated within the code. Both Ag package within GSFLOW and FMP package with OWHM are possible codes that can be used.
- Update to stream morphology using LiDAR data from SWRCB.
- Representation of the canal network using SFR.
- Update the model simulation period through 2021 to include new continuous groundwater level data collected as part of the GSP.
- Surface water diversions can be dynamically linked with priorities to the SFR package to meet surface water demand.

Model Archiving

The SWGM will be released to the public after the public comment period and after consulting DWR about best management practices for model release.

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