DRAFT

Shasta River Watershed Characterization and Model Study Plan

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ACRONYMS

AGWI	Active Groundwater Inflow
AGWO	Active Groundwater Outflow
ASOS	Automated Surface Observing System
BSID	Big Springs Irrigation District
CDEC	California Data Exchange Center
CDFG	California Department of Fish and Game
CDFW	California Department of Fish and Wildlife
cfs	Cubic Feet Per Second
CIMIS	California Irrigation Management Information System
DWR	California Department of Water Resources
EPA	United States Environmental Protection Agency
ET	Evapotranspiration
eWRIMS	Electronic Water Rights Information Management System
GHCN	Global Historical Climatology Network
GHCND	Global Historical Climatology Network-Daily
GIS	Geographic Information Systems
gpm	Gallons Per Minute
HRU	Hydrologic Response Units
HSPF	Hydrologic Simulation Program–FORTRAN
HUC	Hydrologic Unit Code
IGWI	Inactive Groundwater Inflow
LACDPW	Los Angeles County Department of Public Works
LSPC	Loading Simulation Program in C++
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MNW2	Multi-node Well package (of MODFLOW)
MWCD	Montague Water Conservation District
mya	Million Years Ago
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resource Conservation Service
PEVT	Potential Evapotranspiration
PEST	Parameter Estimation Tool
POI	Point of Interest
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Stations
RM	River Mile
SSURGO	Soil Survey Geographic Database
STAID	Station Identification
State Water Board	State Water Resources Control Board
STATSGO	State Soil Geographic Database
SWB	State Water Board

TAET	Total Actual Evapotranspiration
TMDL	Total Maximum Daily Load
TNC	The Nature Conservancy
UC	University of California
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WAP	Water Action Plan
WBD	Watershed Boundary Dataset
WY	Water Year

1. INTRODUCTION

1.1 Background

The California Natural Resources Agency, the California Environmental Protection Agency, and the California Department of Food and Agriculture developed the California Water Action Plan (WAP), released on January 22, 2014. The WAP has been developed to meet three (3) broad objectives:

1. More reliable water supplies;
2. The restoration of important species and habitat; and
3. A more resilient, sustainably managed water resources system (water supply, water quality, flood protection, and environment) that can better withstand inevitable and unforeseen pressures in the coming decades.

Action Four (4) of the WAP, to "Protect and Restore Important Ecosystems," contains the following sub-action:

"The State Water Resources Control Board and the Department of Fish and Wildlife will implement a suite of individual and coordinated administrative efforts to enhance flows statewide in at least five stream systems that support critical habitat for anadromous fish. These actions include developing defensible, cost-effective, and time-sensitive approaches to establish instream flows using sound science and a transparent public process. When developing and implementing this action, the State Water Resources Control Board and the Department of Fish and Wildlife will consider their public trust responsibility and existing statutory authorities such as maintaining fish in good condition."

Through a coordinated effort between the State Water Resources Control Board (State Water Board) and California Department of Fish and Wildlife (CDFW), the following five (5) priority stream systems have been identified as a starting point for the WAP effort:

1. Shasta River, tributary to the Klamath River, Siskiyou County
2. South Fork Eel River, tributary to the Eel River, Humboldt and Mendocino Counties
3. Mark West Creek, tributary to the Russian River, Sonoma County
4. Mill Creek, tributary to the Sacramento River, Shasta and Tehama Counties
5. Ventura River, Santa Barbara and Ventura Counties

The State Water Board and CDFW are currently working to identify potential actions that may be taken to enhance and establish instream flow for anadromous fish in these five (5) priority streams and other streams of importance to the WAP objectives. The development of hydrologic characterization models is one of the first efforts that the State Water Board will work on to better understand water supply, water demand, and instream flow in the priority watersheds.

This document specifically focuses on the Shasta River watershed, and provides:

1. An overview of the characteristics of the watershed that influence hydrology and can inform development of a hydrologic model.
2. A Study Plan that summarizes the proposed approach to development of a model that meets the study objectives.

1.2 Study Objectives

The objectives of this study and the characteristics of the watershed will influence hydrologic model selection and development. The State Water Board identified the following key study objectives to be addressed with the hydrologic model:

- Estimate existing instream flows[1] at multiple points of interest (POI) throughout the mainstem Shasta River and its tributaries.
- Predict unimpaired flow[2] at each POI that would occur with no water diversions, pumping, or storage.
- Depict how water use and other human activities affect the water balance and instream flows.
- Ensure the model simulation period is long enough to reasonably capture the variability of the full range of water year types from drought to flood years.
- Simulate groundwater pumping and surface-subsurface interactions to understand groundwater effects on instream flows.

In addition, the State Water Board identified other model capabilities that should be considered in the current study to support future studies and planning efforts. Although these capabilities may require future model refinements or linkages to other models, the base hydrologic modeling system will be developed in a manner that supports these potential future upgrades or linkages. Additional capabilities of interest include:

- Support assessments of habitat for important species.
- Represent the water rights priority system to evaluate water management scenarios.
- Simulate climate change and future water demand.
- Simulate water quality or the ability to link the surface water hydrology model to separate water quality models.

Section 2 provides a summary of the characteristics of the Shasta River watershed that influence hydrology and the selection of the modeling approach. Section 3 provides an overview of the Model Study Plan proposed for the project.

[1] For this model, "existing instream flows" are defined as the flows estimated by the model using the most recent and complete land use and water use data at the time of model development.

[2] Unimpaired flow is the flow that would have occurred had the natural flow regime remained unaltered in rivers instead of being stored in reservoirs, imported, exported, or diverted. Unimpaired flow is a modeled flow generally based on historical gage data with factors applied to primarily remove the effects of dams and diversion within the watersheds. Unimpaired flow differs from full natural flow in that the modeled unimpaired flow does not remove changes that have occurred such as channelization and levees, loss of floodplain and wetlands, deforestation, and urbanization. Where no diversion, storage, or consumptive use exists in the watershed, the historical gage data is often assumed to represent unimpaired flow.

2. WATERSHED CHARACTERIZATION

The Shasta River watershed, located in central Siskiyou County, has been deemed one of the most unique, complex, productive, and at times, controversial river systems in California (Jeffres et al 2009). The Shasta River originates as snowmelt from the southern portion of the Shasta River watershed and drains into the Klamath River. The center of the Shasta River watershed lies in the low gradient Shasta Valley, with the Siskiyou Range to the north, the Klamath Mountains to the west, the Cascade Range to the east, and Mt. Shasta and Mt. Eddy to the south. The watershed shares divides with the Scott River (west), Butte Valley (east), and the Trinity and Sacramento Rivers (south).

The Shasta River watershed, which has a population of about 16,000 people, is known historically for its large populations of coho salmon and steelhead trout (NCWQCB 2006). In recent years, anadromous salmonid populations have declined, spurring local restoration groups and stakeholders to identify potential sources of the decline. Factors likely contributing to declining salmonid populations include physical barriers (dams and weirs), flow alterations due to water withdrawals, degraded habitat, poor water quality (primarily due to temperature and dissolved oxygen levels), and loss of riparian vegetation (USFWS 2013, NOAA Fisheries 2014). The river was added to the U.S. Environmental Protection Agency's (EPA) 303d list of impaired waters in 1994, and in 1997, the National Fish and Wildlife Service listed the coho salmon as threatened under the Federal Endangered Species Act. A Total Maximum Daily Load (TMDL) was developed for temperature and dissolved oxygen (NCRWQCB 2006), and the Fish and Game Commission instituted a state-wide coho salmon recovery planning process.

The following sections discuss the Shasta River watershed in greater detail to provide a full characterization of major factors that influence hydrologic processes. The discussion outlines surface and groundwater resources, geology, land use, climate and precipitation, and soils.

2.1 Hydrology

The Shasta River watershed drains approximately 794 square miles of land in central Siskiyou County. The river originates as snowmelt from the southern part of the Shasta River watershed. The watershed shares divides with the Scott River (west), Butte Valley (east), and the Trinity and Sacramento Rivers (south).

The Shasta River watershed sits at the junction of two major geologic formations. The east side of the watershed, including Mount Shasta, contains relatively young, Cenozoic age, volcanic and intrusive rocks from the Cascade Range province. The mountainous western side of the watershed is comprised of older, Paleozoic-Mesozoic age, metamorphic rocks from the Klamath Mountains Province. The valley in the center is dominantly alluvium and contains a landslide deposit that covers about 180 square miles. The watershed contains two major types of topography: low-gradient floor and surrounding steep mountains. The Shasta River drops by about 220 feet in elevation in the valley (NCRWQCB 2006). The Shasta River flows north into the Klamath River, which begins in Oregon and meanders west to the Pacific Ocean in California (NCRWQCB 2006). The Shasta River is impounded by Dwinnell Dam at River Mile 40.6 (RM 40.6), and the primary tributaries are Parks Creek (RM 35), Big Springs Creek (RM 34), Willow Creek (RM 26), Little Shasta River (RM 16), and Yreka Creek (RM 8) (USFWS 2013).

Mt. Shasta has permanent glaciers that provide a constant source of spring water that, along with mountain precipitation, are the primary sources of flow in the Shasta River. The Shasta River watershed is predominantly a low rainfall, high desert environment characterized by cool winters and hot dry summers. Annual mean precipitation in the basin ranges widely from 8 to 125 inches, though average precipitation in the mountains can range from 45 or 85 inches to 125 inches (NCRWQCB 2006, PRISM Climate Group 2015). Figure 2-1 shows the Shasta River watershed and subwatersheds defined by the 10-digit Hydrologic Unit Code (HUC) Watershed Boundary Dataset (WBD) from the United States Geological Survey (USGS).

Water development and water diversions within the Shasta Basin are primarily used for agriculture, but also include municipal supply and recreation (NCRWQCB 2006). Water development dates to the beginning of agricultural development in the late 1800s during the gold rush when populations increased, as well as industrialization, agriculture, and over time, urbanization. Dwinnell Dam, along with other dams and diversions, was constructed to capture water during winter and early spring. Four irrigation districts make up the primary water rights holders in the Shasta Basin, with approximate irrigation season diversions totaling 227 cubic feet per second (cfs) (USFWS 2013).

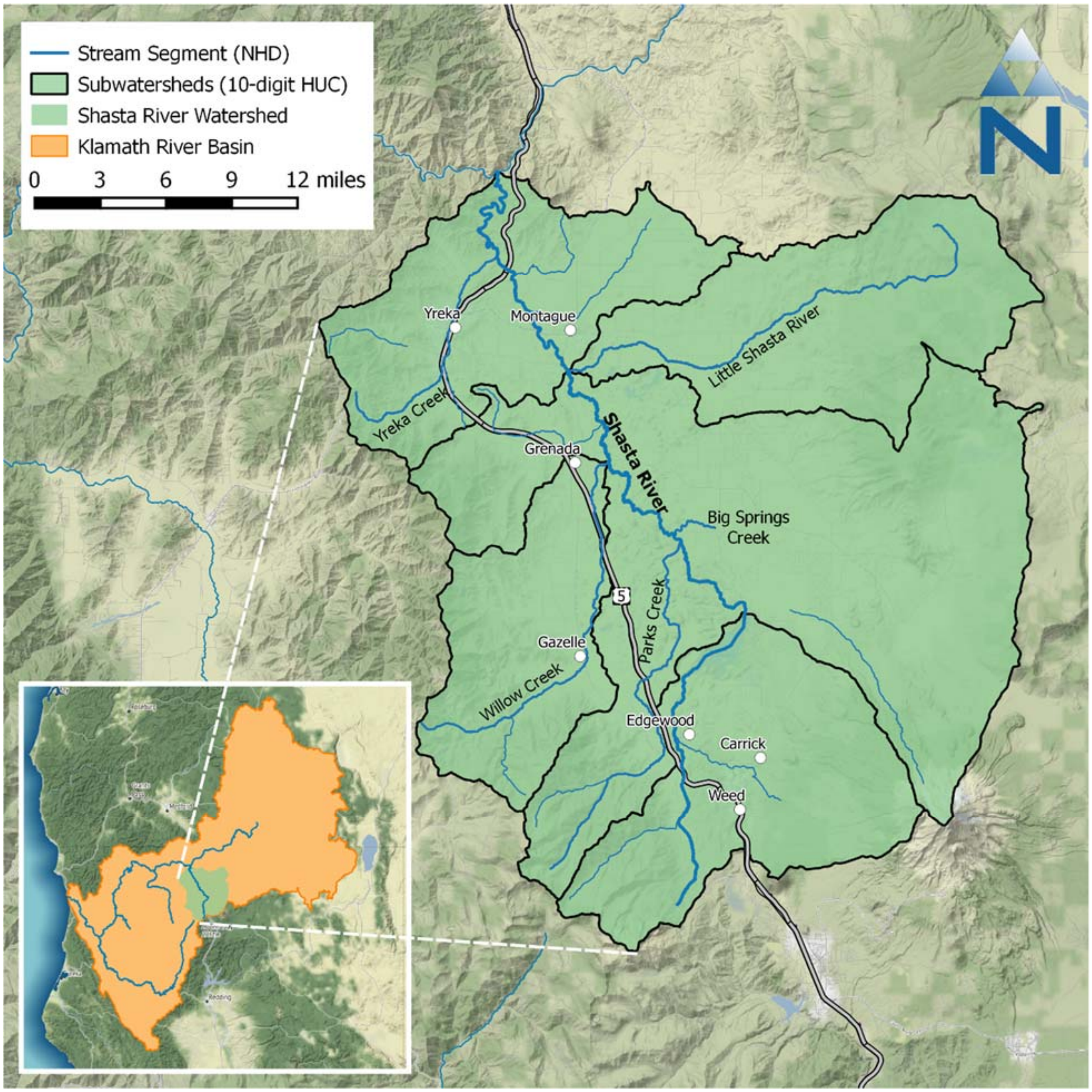


Figure 2-1. Shasta River watershed.

2.2 Land Characteristics

Shasta Nation tribes were the first known residents of the Shasta River watershed. European fur trappers entered the area in the late 1820s to trap beavers. Soon after, cattle drovers entered the watershed, bringing cattle from the Sacramento Valley to Oregon. Miners came to the watershed after the discovery of gold in 1851 in the town of Yreka (NCRWQCB 2006), taking possession of land and displacing indigenous inhabitants. Through the early to mid-1900s, farming, ranching, and timber harvest became dominant land uses in the basin as more people moved into Siskiyou County. Timber is still harvested on some US Forest Service and private lands, but that activity now occurs in a much smaller portion of the watershed than in past decades. The economy today is supported mainly by agriculture and ranching, as well as lumber mills and cow-calf operations that are supported by irrigated pasture and grazing lands. Recreation has also developed into a major land use, as Mt. Shasta provides popular downhill and cross-country skiing and hiking, and Lake Shastina and other lakes and streams are popular fishing destinations. There is also some urbanization in the City of Yreka, in the lower elevation areas along Interstate 5, and near Lake Shastina (NCRWQCB 2006).

Geographic Information System (GIS) layers of land use/land cover data, geology, and soils form the basis for characterizing surface hydrology. The primary source of land use/land cover for this effort was the 2011 National Land Cover Database (NLCD). Secondary datasets like the U.S. Department of Agriculture (USDA) CropScape coverage are also available for characterizing vegetative cover for estimating consumptive use, as further described in Section 2.5. Figure 2-2 shows NLCD land use coverage for the Shasta River watershed. Table 2-1 summarizes the composite land use distribution within the watershed. NLCD also provides a grid-based layer of percent impervious cover in the watershed, mapped at a 30-meter pixel resolution (Figure 2-3). Detail about geology and soils in the Shasta River watershed can be found in Section 2.4.1 and Section 2.4.3 respectively.

Table 2-1. National Land Cover Database land use summary.

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	1,688	0.3%
12	Perennial Ice/Snow	381	0.1%
21	Developed, Open Space[1]	10,000	2.0%
22	Developed, Low Intensity[1]	6,728	1.3%
23	Developed, Medium Intensity[1]	1,848	0.4%
24	Developed, High Intensity[1]	344	0.1%
31	Barren Land	17,134	3.4%
41	Deciduous Forest	1,491	0.3%
42	Evergreen Forest	180,217	35.5%
43	Mixed Forest	608	0.1%
52	Shrub/Scrub	119,451	23.5%
71	Grassland/Herbaceous	91,173	17.9%
81	Pasture/Hay	21,763	4.3%
82	Cultivated Crops	53,299	10.5%
90	Woody Wetlands	34	0.0%
95	Emergent Herbaceous Wetlands	1,393	0.3%
255	No Data (Added to Forest)	378	0.1%
Total:		**507,930**	**100.00%**

Data Source: 2011 National Land Cover Database

1: Imperviousness: Open Space (<20%); Low Intensity (20-49%); Medium Intensity (50-79%); High Intensity (≥80%).

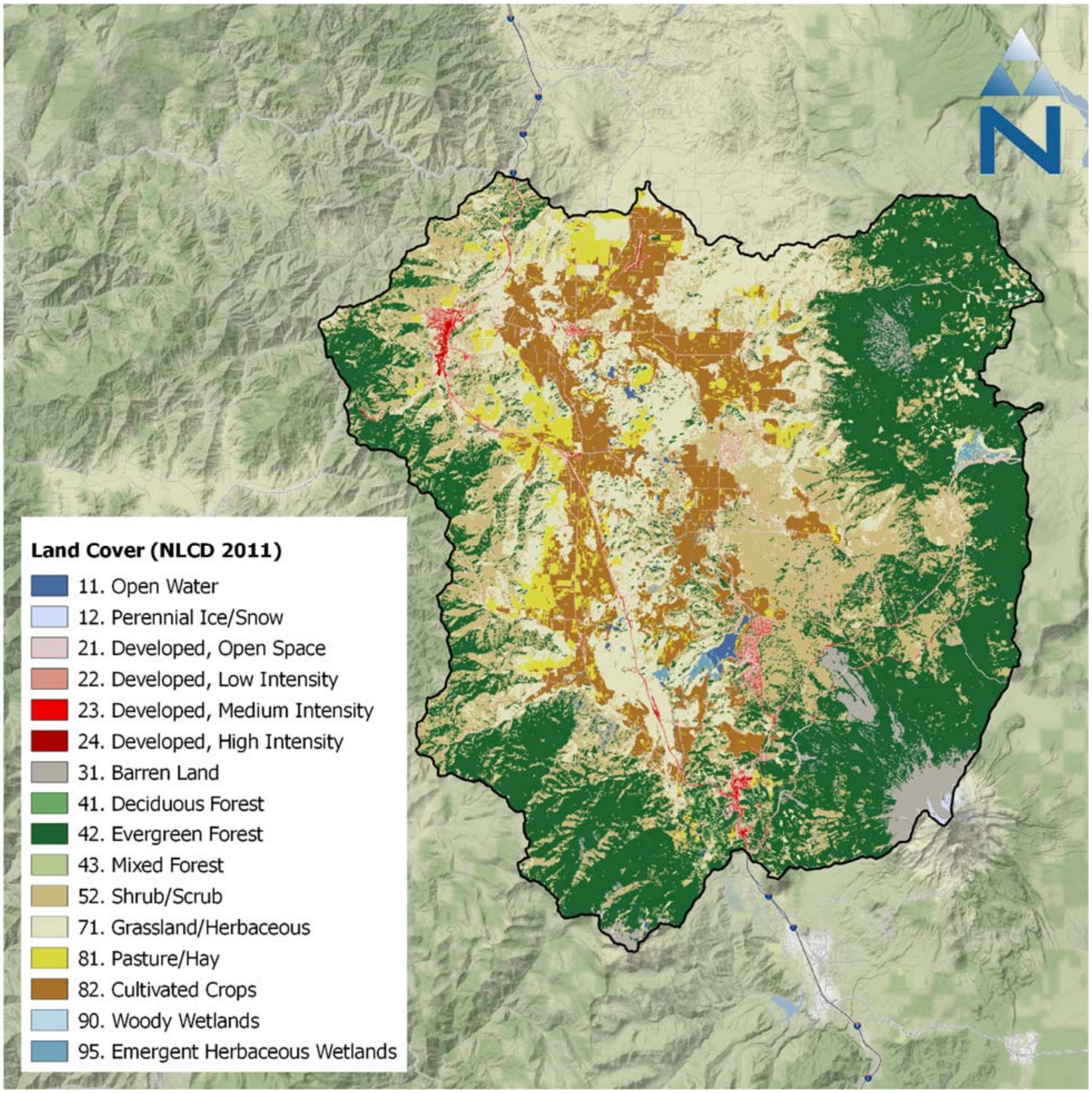


Figure 2-2. National Land Cover Database Land Cover in the Shasta River watershed.

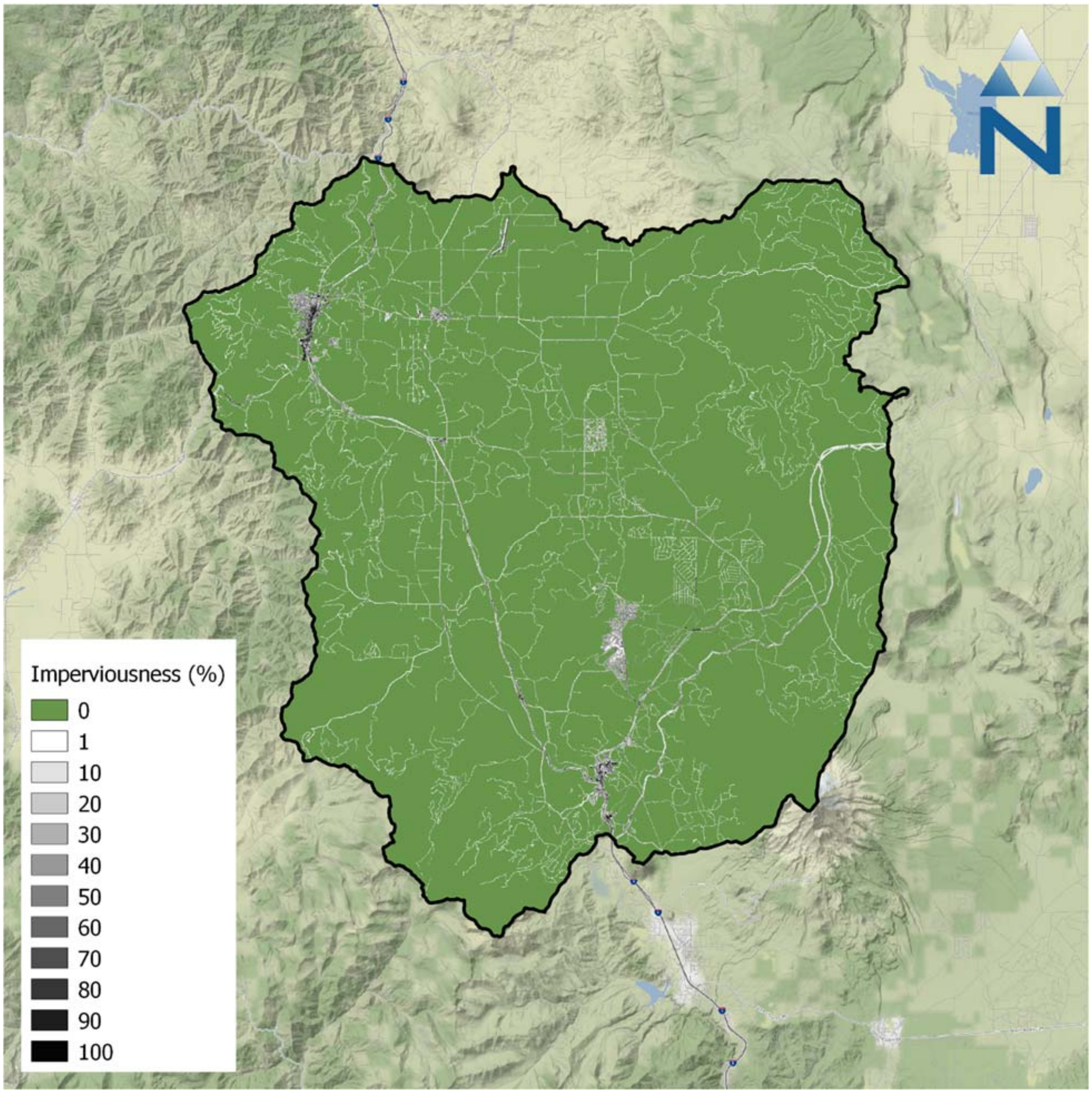


Figure 2-3. National Land Cover Database Percent Impervious Cover in the Shasta River watershed.

2.3 Climatic Characteristics

Climate in the Shasta River watershed is characterized by semi-arid conditions in the valley, and slightly wetter conditions in the upland portion near Mount Shasta. Rain dominates precipitation at lower elevations while snow typically accumulates at elevations greater than 5,000 feet (Van Kirk and Naman 2008). Due to the porous underlying geology, most of the precipitation that falls in the upland portion of the watershed infiltrates and flows underground through lava tubes, emerging as springs that feed the eastern tributaries such as Big Springs Creek. The rainy season, which generally begins in October and lasts through April, accounts for about 80 percent of total annual rainfall. The Mount Shasta rainfall gage is in the wettest area of the watershed; however, the Yreka gage is more representative of average conditions in the watershed. Table 2-2 presents summary statistics of monthly and annual precipitation at the Mount Shasta gage. Annual precipitation is about 42 inches at this location, with an annual average of 16 consecutive dry days between storms. The number of consecutive dry days between storms from May through October ranges from 16 to 27 days, but ranges between 9 to 12 days between November and April. In comparison, the Yreka gage (summarized in Table 2-3), averages about 19 inches of precipitation per year, with an annual average of 18 consecutive dry days between storms. Average dry days were derived by first calculating the number of antecedent dry days for each day and then averaging the number of dry days by month for the period of record. The Mount Shasta gage records more intense precipitation events than the Yreka gage, most of which is snowfall. Additional details on the meteorological characteristics and available data to support model development are presented in Section 3.4.

Table 2-2. Rainfall summary statistics at the Mount Shasta rainfall gage (045983).

Month	Avg. Rainfall (in./month)	Avg. No. Consecutive Dry Days	Wettest Monthly Rainfall		Driest Monthly Rainfall		1-Day Maximum Rainfall		Avg. No. Rain Days with Rainfall ≥ Indicated Value (inches)			
			(in./month)	Water Year	(in./month)	Water Year	(in./day)	Date	≥0.01	≥0.10	≥0.50	≥1.00
Oct	2.3	21	7.7	2005	0.0	2003	3.8	10/19/2004	7	4	1	1
Nov	4.8	12	14.1	1982	0.4	2014	4.4	11/16/1981	11	7	3	1
Dec	7.5	11	25.9	2003	0.1	1990	4.9	12/14/2002	13	9	4	2
Jan	6.4	10	27.5	1995	0.2	1984	6.0	1/9/1995	13	9	4	2
Feb	6.9	10	21.8	1998	0.4	1988	4.9	2/6/2015	12	8	5	2
Mar	6.1	9	18.9	1995	0.4	1988	3.9	3/9/1989	14	9	4	2
Apr	2.8	11	9.1	2003	0.1	1985	2.1	4/12/2012	11	5	2	1
May	2.1	16	9.3	1990	--	1986	2.3	5/27/1990	8	4	1	0
Jun	1.2	19	3.8	2005	0.0	2008	1.8	6/17/2005	5	3	1	0
Jul	0.5	24	1.7	1985	--	2009	1.1	7/5/2000	3	1	0	0
Aug	0.4	27	1.3	1990	--	1995	1.2	8/20/1997	2	1	0	0
Sep	0.7	27	3.8	1986	--	2012	1.5	9/25/2001	4	2	0	0
Annual	**41.7**	**16**	**75.1**	**1998**	**16.0**	**2014**	**6.0**	**1/9/1995**	**103**	**62**	**25**	**12**

1: Data Source: Global Historical Climatology Network. Period of record: 10/1/1980 – 9/30/2015.
2: Average number of rainfall days with a rainfall total greater than or equal to the depth (inches) shown.
3: Relative Color Gradient: Rainfall depth/distribution and average consecutive dry days. Darker is higher.

Table 2-3. Rainfall summary statistics at the Yreka rainfall gage (049866).

Month	Avg. Rainfall (in./month)	Avg. No. Consecutive Dry Days	Wettest Monthly Rainfall		Driest Monthly Rainfall		1-Day Maximum Rainfall		Avg. No. Rain Days with Rainfall ≥ Indicated Value (inches)			
			(in./month)	Water Year	(in./month)	Water Year	(in./day)	Date	≥0.01	≥0.10	≥0.50	≥1.00
Oct	1.1	23	3.4	2008	0.0	2004	1.8	10/24/2010	5	3	1	0
Nov	2.7	12	8.2	1985	0.4	2001	2.4	11/23/1988	11	6	1	1
Dec	3.9	11	12.2	2006	0.3	2014	3.3	12/31/2005	12	7	2	1
Jan	2.9	12	7.4	1996	--	1985	2.6	1/8/1990	12	6	2	1
Feb	2.0	12	5.9	1999	--	1986	2.1	2/7/2015	9	5	1	0
Mar	1.9	11	5.4	2011	0.2	1994	1.3	3/3/1991	11	5	1	0
Apr	1.1	14	3.4	2000	--	1992	1.3	4/30/2002	8	3	0	0
May	1.3	18	4.1	2009	0.0	1982	2.8	5/3/2009	8	3	0	0
Jun	0.9	20	4.4	1982	--	1987	1.9	6/8/1998	5	2	0	0
Jul	0.5	25	2.1	1995	--	2008	1.3	7/27/2010	3	1	0	0
Aug	0.4	27	1.9	1983	--	1998	1.0	8/20/1997	3	1	0	0
Sep	0.5	27	2.2	1991	--	2012	2.2	9/7/1991	3	1	0	0
Annual	**19.0**	**18**	**33.4**	**1982**	**9.0**	**2001**	**3.3**	**12/31/2005**	**90**	**42**	**10**	**3**

1: Data Source: Global Historical Climatology Network. Period of record: 10/1/1980 – 9/30/2015.
2: Average number of rainfall days with a rainfall total greater than or equal to the depth (inches) shown.
3: Relative Color Gradient: Rainfall depth/distribution and average consecutive dry days. Darker is higher.

2.4 Geology

At approximately 794 mi^2, the Shasta River watershed is one of the most ecologically significant major tributaries to the Klamath River, and it encompasses a unique combination of geology and hydrology. With a mean discharge rate of approximately 180 cfs, or annual volume of 130,051 acre-feet (ac-ft.), the Shasta River is characterized by diverse flow regimes and complex surface water and groundwater interactions. The river flows for approximately 53 miles northward across the Shasta Valley and is divided into upper and lower rivers by Dwinnell Dam at river mile (RM) 40.6, which forms Lake Shastina.

2.4.1 Bedrock Geology

The Shasta River watershed is situated on the boundary between the Klamath Mountain and Cascade Range geomorphic provinces. The basin is bounded by the Scott Mountains to the west, the Siskiyou Mountains to the north, and the Cascade Range to the south and east (Figure 2-4). Geologic and hydrologic characteristics of the Shasta River watershed are highly variable and are delineated by the boundaries of the regional geomorphic provinces. Tributaries that drain the western and southwestern portions of the basin flow off the eastern slopes of the Scott Mountains and are underlain by the Paleozoic Eastern Klamath Belt terrane (Hotz 1977, Wagner and Saucedo 1987). Tributaries in the southeastern and eastern portions of the basin drain the western slope of the Cascade Range, which are underlain by the Cenozoic Western Cascade and High Cascade Volcanic subprovinces (Hotz 1977, Wagner and Saucedo 1987). The Shasta River flows through the Shasta Valley before entering the Shasta River Canyon, and eventually meeting the Klamath River. The Shasta Valley is primarily underlain by various volcanic and volcaniclastic units of the High Cascades subprovince and deposits of Quaternary alluvium in the Montague vicinity. The canyon reach of the Shasta River is incised into the Western Paleozoic and Triassic Belt terrane (Hotz 1977, Wagner and Saucedo 1987).

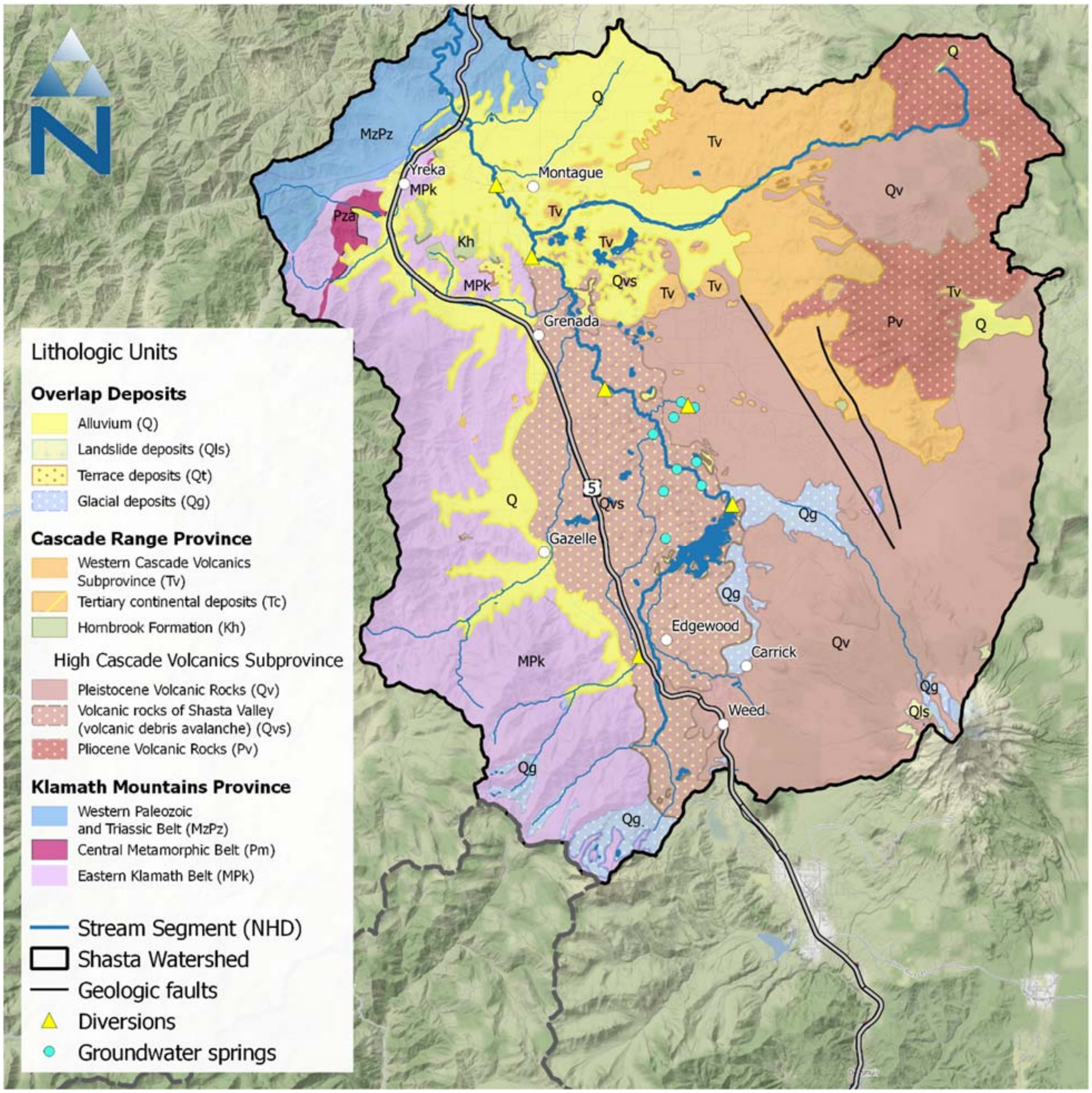


Figure 2-4. Simplified geologic map of the Shasta River watershed. Major groundwater springs and agricultural irrigation diversions are shown.

The Eastern Klamath Belt is the eastern-most terrane in the Klamath Mountains geomorphic province, which is interpreted as a structural sequence of east dipping thrust sheets, that decrease in age from east to west, formed by accretion of different oceanic and island-arc assemblages (Irwin 1981, Saleeby et al. 1982). Paleozoic rocks of the Eastern Klamath Belt terrane in the Shasta River watershed consist of partially serpentinized peridotite, gabbro, diorite, and marine meta-sedimentary units including sandstone, shale, phyllite, chert, conglomerate, and limestone (Mack 1960, Hotz 1977, Wagner and Saucedo 1987). These lithologic units compose the east face of the Scott Mountains and are dissected by a dendritic drainage pattern of Shasta River tributaries including Dale Creek, Eddy Creek, Parks Creek, Willow Creek, Julien Creek, and Yreka Creek (Figure 2-4). These stream channels flow roughly perpendicular to the northerly strike of the Eastern Klamath Belt. Hillslope mass wasting and valley bottom fluvial erosion are the dominant geomorphic processes in these tributary basins. Runoff response time is short during rainfall and snowmelt events in these areas of the Klamath Mountain terraces due to steep topography, high relief, shallow and well drained soils, and less permeable bedrock (McNab and Avers 1994).

The Miocene-aged (i.e., erupted 50 million to 5.3 million years ago [mya]) rocks of the Western Cascade subprovince in the Shasta River watershed are primarily andesitic flows but contain an assemblage of rhyolite domes, basalt intrusions and plugs, and breccia (Mack 1960, Hotz 1977, Wagner and Saucedo 1987). The Western Cascade subprovince dominates the hillslopes of the northeastern portion of the basin. These hillslopes have a moderately dissected drainage pattern and are largely devoid of perennial tributary channels, except for the Little Shasta River, which meets the Shasta River near Montague (McNab and Avers 1994).

Conformably overlying the Western Cascade Volcanics is the Pliocene to Holocene-aged (i.e., erupted 5.3 mya to present) High Cascade Volcanics geologic province. These rocks primarily consist of the andesite and basalt that compose the uplands, volcanoes, and cones (e.g., Miller Mountain, Goosenest Mountain, Willow Creek Mountain, Ball Mountain, Deer Mountain, The Whaleback, and Mt. Shasta) forming the southern and eastern portions of the Shasta River watershed (Mack 1960, Hotz 1977, Wagner and Saucedo 1987). The High Cascade Volcanics also includes more effuse basaltic flows (e.g., Pluto's Cave basalt) that dominate the eastern Shasta Valley, and the expansive pyroclastic (andesitic and volcaniclastic) deposits that cover much of the western Valley. These pyroclastic deposits represent a late Pleistocene debris avalanche originating from the northwest flank of Mount Shasta, and create the unique morphological assortment of conical hillocks, ridges, and depressions that dominate the Shasta Valley floor (Crandell et al. 1984, Crandell 1989). This volcanic debris avalanche, which occurred between 300,000 and 380,000 years ago, covers approximately 180 square miles of valley floor and consists of a block facies and a matrix facies. The block facies that composes the hillocks and ridges is made of individual andesite blocks (ranging in size from tens to hundreds of feet in maximum dimension) and intact stratigraphic sequences of volcaniclastic materials that were transported in the same relative positions are their original deposition (Crandell et al. 1984, Crandell 1989). The matrix facies consist of an unsorted and unstratified mixture of sediments derived from Mount Shasta and the Klamath Mountain terranes underlying the valley floor. The matrix facies embed the individual blocks and produced the lahar-like flow that transported the avalanche across the valley. Although both the block and matrix facies are considered water-bearing units, the block facies may be more permeable and transmit groundwater from both deep, confined aquifers as well as the younger, more permeable basalt flows (DWR 2011).

The highly permeable effuse basalt flows of the High Cascade subprovince allow rainfall and snowmelt to quickly infiltrate the porous groundwater aquifer, resulting in a poorly developed surficial drainage pattern (Mack 1960, Tague and Grant, 2004). Numerous groundwater springs are in these young permeable volcanic units and contribute significant flow to the Shasta River and tributary creeks. The abundance and high discharge of groundwater springs indicates a well-developed subsurface drainage network exists in the southern and central extents of the Shasta Valley (Figure 2-4) (Mack 1960, Jeffres et al. 2008, Nichols 2008, Nichols et al. 2010).

2.4.2 Surface Processes and Channel Geomorphology

The Shasta River exhibits distinct longitudinal variability in channel morphology primarily controlled by underlying geology and hydrologic regime. Stream channels in headwater areas of the Eastern Klamath Belt terrane are steep and cobble-dominated. Upon crossing the lithologic contact with the High Cascade subprovince, the drainage network transitions to predominantly gravel-bedded channels with moderate gradient. Meandering single-thread channel morphology in these reaches is interspersed with short multi-thread channel morphology containing active lateral, mid-channel, and point bars (Figure 2-4) (Nichols 2008). The presence of active gravel bars and trapezoidal channel cross-sectional morphology indicates a hydrologic regime dominated by precipitation (rain and snow) driven runoff (Nichols et al. 2010). Analysis of aerial photos and historical maps indicate channel morphology in these reaches has changed little since 1923 (Nichols 2008).

Channel gradient steadily decreases downstream of Dwinnell Dam as the Shasta River flows across the late Pleistocene debris avalanche described above (Crandell et al. 1984, Crandell 1989). These reaches have gravel- and sand-bedded, single-thread and meandering channel morphology without exposed point bars. Following closure of Dwinnell Dam in 1928, the Shasta River between Dwinnell Dam (RM 40.6) and the confluence of Big Springs Creek (RM 33.5) transitioned from a gravel-bedded meandering stream with exposed point bars to its present-day form without exposed bars (Figure 2-4) (Nichols 2008). Downstream of the Big Springs Creek confluence, the Shasta River takes on a more rectangular channel morphology with greater width-to-depth ratio that has changed little since 1923. The lack of change reflects less dynamic fluvial processes and a muted hydrologic response dominated by stable year-round baseflows controlled by groundwater inputs (Nichols 2008, Nichols et al. 2010). The Shasta River meanders at a near-constant low gradient throughout the central and northern portions of the Shasta Valley before steeply descending through the bedrock canyon near Yreka to the Klamath River (Figure 2-4).

2.4.3 Soils

The State Soil Geographic and Soil Survey Geographic Database (STATSGO/SSURGO) has four main hydrologic soil groups that characterize soil runoff potential. Group A generally has the lowest runoff potential with high infiltration rates and Group D has the highest runoff potential with very low infiltration rates. The soils database is composed of a GIS layer of polygon map units, and a linked database with multiple soil property tables. Soil characteristics of each hydrologic soil group are described in Table 2-4.

Table 2-5 and Figure 2-5 present the spatial distribution and a tabular summary of the STATSGO/SSURGO hydrologic soil groups for the Shasta River watershed. The dominant soil group in the watershed is Group D, containing poorly-drained clays, sandy and silty clays, clay loam, and silty clay loam, silt loams, and loams. Groups A and C are the next most common soil groups and each cover approximately 23 percent of the watershed. Group A contains very well drained sand, loamy sand, or sandy loam. Group C contains sandy clay loams that are moderately to poorly drained with low infiltration rates.

Table 2-4. NRCS Hydrologic soil group descriptions.

Hydrologic Soil Group	Description
A	Sand, Loamy Sand, or Sandy Loam
B	Silt, Silt Loam or Loam
C	Sandy Clay Loam
D	Clay Loam, Silty Clay Loam, Sandy Clay, Silty Clay, or Clay

Data Source: Natural Resource Conservation Service (NRCS), Technical Release 55 (TR-55)

Table 2-5. NRCS Hydrologic soil groups in the Shasta River watershed.

Hydrologic Soil Group	Area (acres)	Percent Area
A	128,405	25.3%
A/D	193	0.0%
B	46,374	9.1%
B/D	17,111	3.4%
C	142,858	28.1%
C/D	10,691	2.1%
D	161,060	31.7%
N/A	1,238	0.2%
Total	**507,930**	**100.0%**

Data Source: State Soil Geographic and Soil Survey Geographic Database (STATSGO/SSURGO)

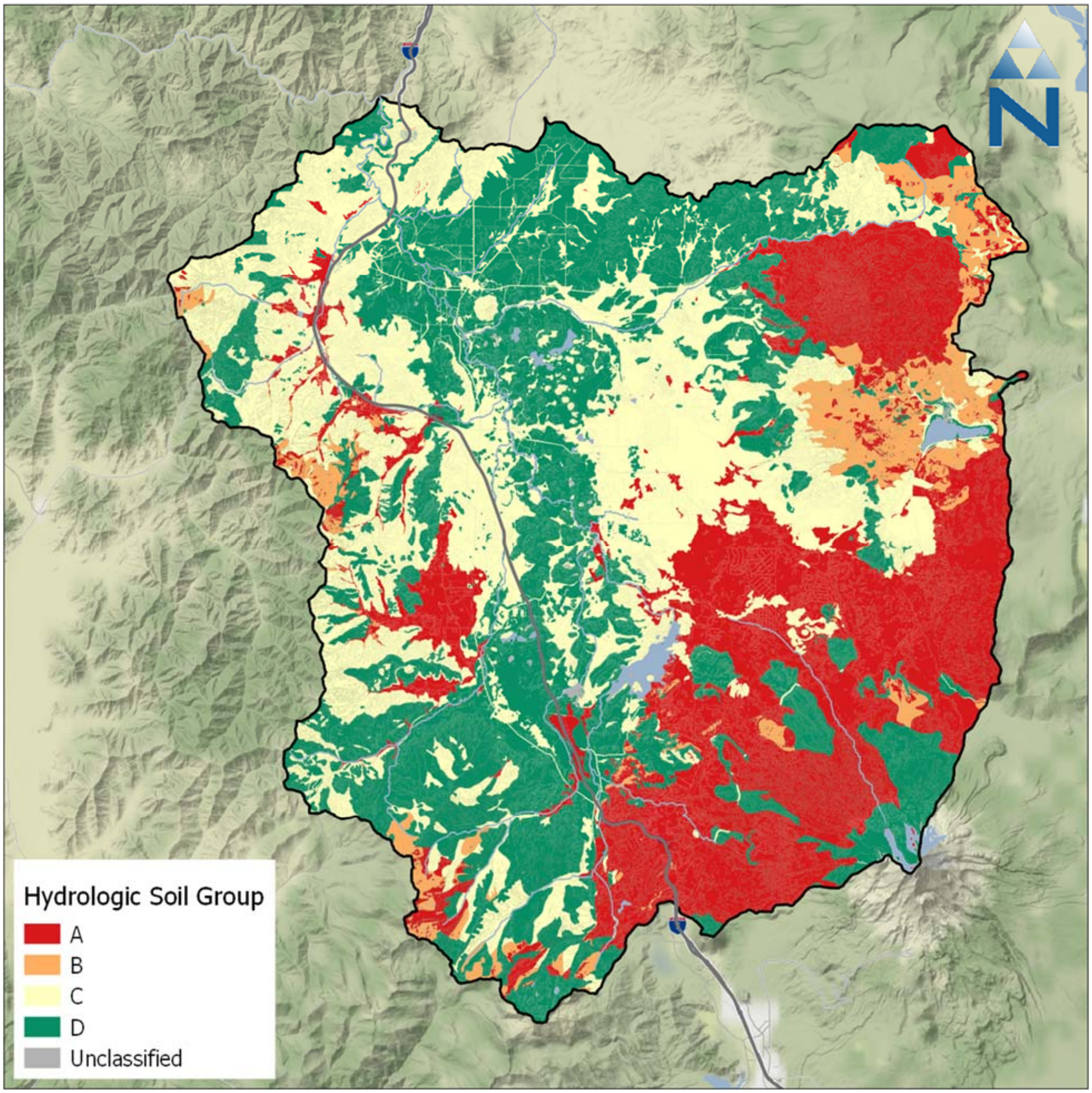


Figure 2-5. SSURGO Hydrologic Soil Groups in the Shasta River watershed.

2.4.4 Hydrogeology

2.4.4.1 Bedrock Aquifers

2.4.4.1.1 Klamath Mountains

The Klamath Mountain terranes forming the western boundary of the Shasta River watershed (Figure 2-4) generally consist of marine sediments and intrusive rocks that have experienced varying degrees of structural deformation and metamorphism during major tectonic (mountain building) episodes (approximately 500 mya to 65 mya). Extensive mineral recrystallization has reduced primary porosity in these units. Structural deformation has created secondary porosity in the form of fractures, joints, faults, and shear zones, however, these units are not important sources of groundwater within the watershed (DWR 2011).

2.4.4.1.2 Cascade Range

The diverse Tertiary Western Cascade volcanics can be highly fractured and weathered, although they tend to have reduced porosity and permeability due to secondary infilling of fine-grained sediments. These units have shallow subsurface flow paths yielding springs and seeps on basin hillslopes – an indication of impermeable horizons that preclude vertical transmission of groundwater through the aquifer (DWR 2011).

The younger High Cascade volcanics, which overlay the Western Cascade volcanics, are highly vesicular and fractured rocks that store and transmit large volumes of groundwater. Many springs discharge from the contact between the Western and High Cascade subprovinces due to the discontinuity in permeability (DWR 2011). The High Cascades volcanics includes the Holocene Pluto's Cave basalt, a highly vesicular and fractured unit that critically influences groundwater storage and recharge in the valley, contributing large volumes of water to wells and springs (DWR 2011). Wells in the Pluto's Cave basalt yield up to 4,000 gallons per minute (gpm), with an average of 1,300 gpm (Mack 1960, PGS 2001, DWR 2011). The unit ranges in thickness from approximately 800 feet in the south near its source, to 10 feet at its distal end in the northwest (Blodgett et al. 1988). The unit is composed of multiple individual flows providing permeable contact surfaces, as well as lava tubes (including Pluto's Cave) that facilitate groundwater flow. Recharge to the aquifer occurs from direct precipitation on the ground surface, streamflows that become subsurface upon reaching the unit (e.g., Whitney Creek), irrigation ditch loss, percolation from applied irrigation water, and groundwater flow from snowmelt in the Cascade peaks to the south and east (Mack 1960, DWR 2011).

The hydrogeologic characteristic of these volcanic units have been shown to play a dominant role on hydrologic patterns related to peak timing and magnitude of instream flows in other Cascade Range rivers (Tague et al. 2007). The timing and shape of hydrographs and irrigation season monthly average instream flows in valley streams are related to the percentage of High Cascade volcanic units in the contributing drainage area (Tague and Grant 2004).

2.4.4.1.3 Volcanic Debris Avalanche

The highly variable rock types within the volcanic debris avalanche, as well as the chaotic modes of transport and deposition during the event have resulted in a lack of coherent internal structure. Consequently, well yields from within the debris avalanche deposits are highly variable (DWR 2011). Although groundwater yields are variable, the avalanche deposit exerts control on regulating and redirecting groundwater flow through the valley and to the Shasta River. The debris avalanche occurred before the eruption of the Pluto's Cave basalt and acted as western boundary to the basalt flows. The less permeable avalanche deposits act as a barrier to groundwater flow through the more permeable Pluto's Cave basalt, resulting in multiple voluminous groundwater springs (including the Big Springs Complex) along the contact between the two formations (Mack 1960, DWR 2011).

2.4.4.2 Alluvial Aquifers

The Shasta Valley Groundwater Basin, as defined by the California Department of Water Resources (DWR), consists of the Quaternary-aged (approximately 2.6 mya to present) unconsolidated alluvium located along the western and northern portions of the Shasta Valley (Table 2-6, Figure 2-6) (DWR 2011). This aquifer unit includes stream and terrace deposits of Parks Creek, Willow Creek, Julien Creek, Yreka Creek, Shasta River, Little Shasta River, and Oregon Slu; as well as the alluvial fan deposits forming the sedimentary apron at the base of the Klamath Mountains (DWR 2011). Holocene alluvium is primarily silt and clay interbedded with sand and gravel. Calcium derived from mafic volcanic rocks in the Little Shasta Valley has cemented the subsoil into hardpan. The alluvial western valley margin extending south past Gazelle contains no hardpan (Mack 1960). The Holocene alluvium may be up to 150 feet thick in some locations, and well yields have previously been measured at 150 to 1,000 gpm (Mack 1960).

The portion of the Shasta Valley Groundwater Basin north of Montague is underlain by older Pleistocene alluvium up to 100 feet thick and contains gravels derived from the Klamath Mountains. This portion of the valley contains an iron-cemented hardpan just below the ground surface. Wells within Pleistocene alluvium have previously had sufficient yields to supply domestic and stock uses (Mack 1960).

Table 2-6. Shasta Valley Groundwater Basin.

Basin	Name	Area (acres)	Groundwater Budget Type[1]
1-4	Shasta Valley Groundwater Basin	52,480	B

[1] (B) use-based estimate of groundwater extraction for the basin (DWR 2003).

It is important to note, however, that the alluvial aquifer as defined by DWR is much less productive than the underlaying volcanic aquifer. Most large wells in the valley, including those in locations with quaternary alluvium, produce groundwater from the underlaying volcanic aquifer.

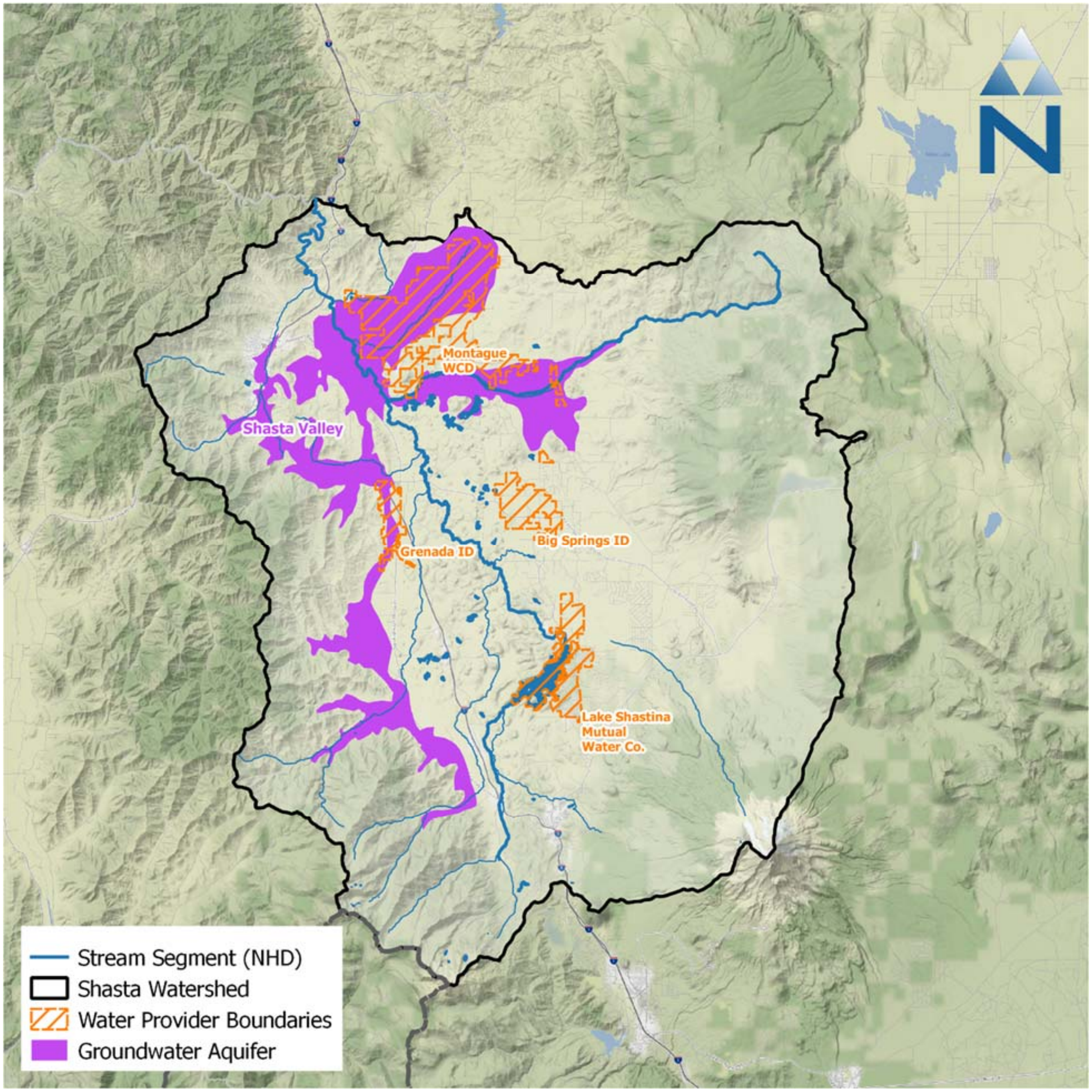


Figure 2-6. Alluvial aquifers recognized within the Shasta River watershed and water provider boundaries.

2.4.4.3 Surface Water–Groundwater Interactions

The Shasta River has a complicated seasonal and longitudinal flow regime due to complex surface water and groundwater interactions, coupled with extensive agricultural diversion and return flows (Vignola and Deas 2005, Nichols et al. 2010). The upper Shasta River (i.e., upstream of Dwinnell Dam) originates on the eastern slope of the Scott Mountains 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 Mt. Shasta. Lake Shastina primarily serves as a storage reservoir and diversion for agricultural irrigation water throughout the Shasta Valley. Outflow from Lake Shastina to the lower Shasta River is regulated by Dwinnell Dam, which has reduced mean annual discharge in the reaches immediately downstream of the reservoir by up to 90% (Jeffres et al. 2008, Nichols 2008, Nichols et al. 2010). Reservoir storage capacity in Lake Shastina is rarely achieved due to the permeable underlying volcaniclastic rocks (Vignola and Deas 2005). Mack (1960) reported that multiple springs along the western 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 per year, which is very high relative to the reservoir's 50,000 acre-feet 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 (Figure 2-7). The lower Shasta River currently has a spring-dominated hydrograph that is primarily sourced from Big Springs Creek (which is 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., October to April) are five times those of the lower Shasta River upstream of the Big Springs Creek confluence (which includes Parks Creek, see Figure 2-7) (Jeffres et al. 2009). During irrigation season (i.e., April to October), Big Springs Creek baseflows are reduced by approximately 35% from temporally variable irrigation diversion and unquantified groundwater pumping (Jeffres et al. 2009). Approximately 95% of baseflows during irrigation season in the lower Shasta River originate from the Big Springs Complex. Following cessation of the irrigation season, instream flows downstream of the Big Springs Creek confluence quickly rebound to spring-fed baseflow conditions (Nichols et al. 2010). Buck (2013) constructed a groundwater model for a portion of the Shasta River watershed and summarized major balance components for 2008-2011.

The City of Yreka obtains much of its water supply from Fall Creek (see Table 2-9), located outside Shasta River watershed near Iron Gate Reservoir (Pace Engineering 2016). The City's treated wastewater, totaling 966 acre-feet in 2015, is discharged to percolation fields near Yreka Creek (Pace Engineering 2016).

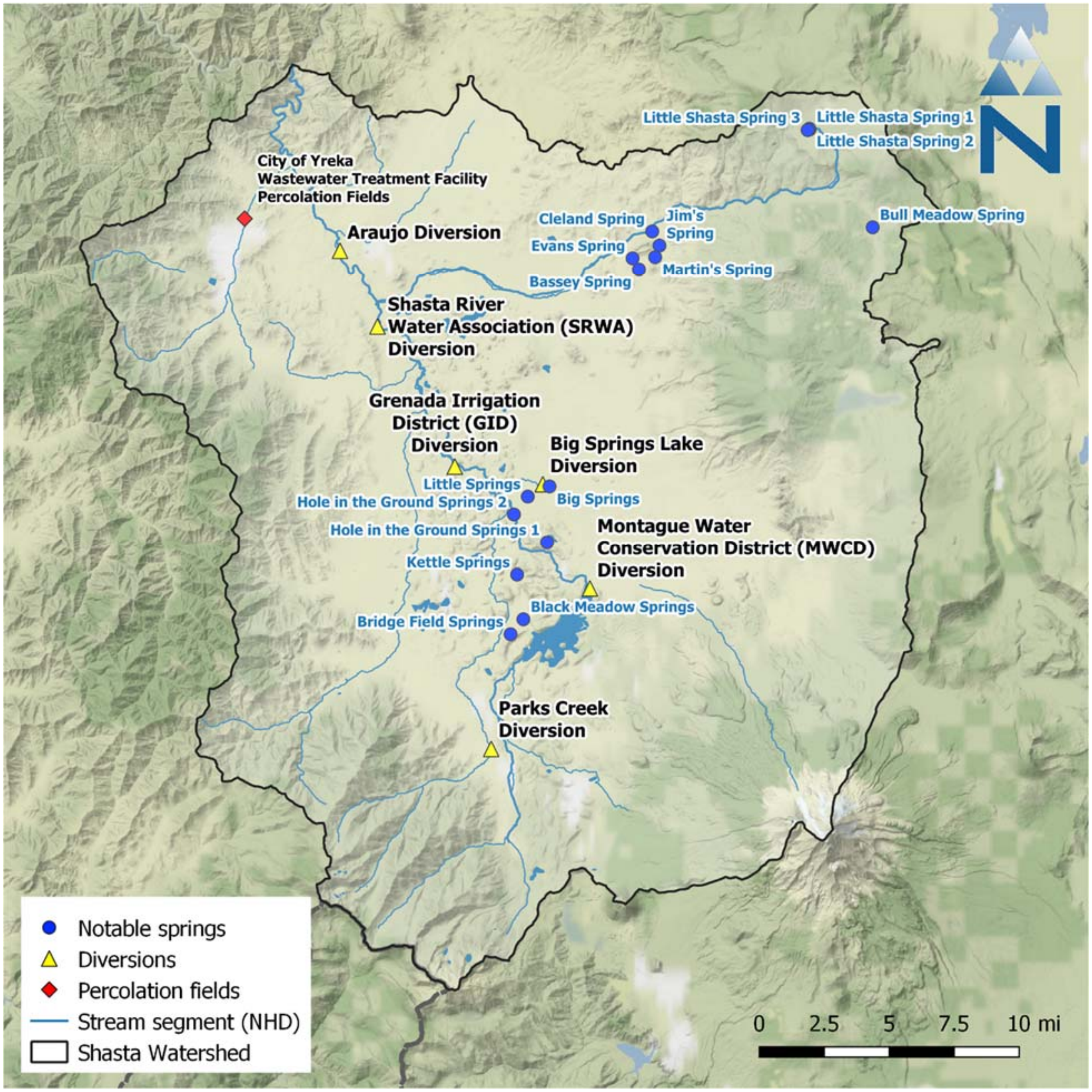


Figure 2-7. Notable groundwater springs, surface water diversions, and percolation fields in the Shasta Valley.

2.5 Consumptive Water Use

Water use in the Shasta Basin consists principally of agricultural supply for crop irrigation and stock watering, but municipal, industrial, recreation, fish and wildlife also play substantial roles in the overall water resources development and use (Willis 2013). The Shasta River watershed includes numerous dams, wells, 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 Dwinnell Dam. Water rights that dictate usage throughout the Shasta Basin are a mix of riparian and appropriative water rights that were adjudicated as a part of the 1932 Decree (DWR 1932), which are described below.

2.5.1 Water Use Impacts

Development of water resources in the Shasta River watershed has led to changes of the hydrologic behavior of the river (Jeffres et al. 2010), and to reductions in the quantity and quality of cold-water habitats required by rearing coho salmon throughout the Basin (Willis et al. 2013, Stenhouse et al. 2012). Water quality modeling conducted during development of the Shasta River TMDLs found depletion of streamflow to be a primary cause of high summer water temperatures in the Shasta River and its tributaries, and the TMDLs called for an additional 45 cfs of cool water to improve water temperature conditions (NCRWQCB 2006). In the recovery plan for Southern Oregon/Northern California Coast Coho Salmon, NOAA Fisheries ranked impaired water quality and altered hydrologic function as 'very high' key limiting stresses to juvenile coho salmon and ranked agricultural practices and dams/diversions as 'very high' key limiting threats (NOAA Fisheries 2014). Excess tailwater from flood irrigation can discharge hot water into the Shasta River and tributaries (NCRWQCB 2006, Aqua Terra Consulting 2011).

2.5.2 Water Sources and Development

Water is delivered to users in the Shasta Basin via canals, diversion facilities, pumps, and storage infrastructure (Willis et al. 2013). Dwinnell Dam (constructed in 1928) is the largest water storage structure within the Basin, with current capacity to 50,000 ac-ft. (upgraded from 36,000 ac-ft. in 1995) (USFWS 2013). The largest storage and delivery systems in the Shasta Basin are maintained by water service agencies or private water users which operate independently in accordance with the Watermaster service requirements (Willis et al. 2013). Major diversion dams and smaller dams or weirs are located below the Dwinnell Dam, along with numerous diversions on tributaries including Big Springs Creek, Little Shasta River, and Parks Creek (CDFG 1997, 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 2-7). Many of these structures are within the Montague Water Conservation District (MWCD), which contains approximately 60 miles of canals and laterals. There are approximately 1,825 domestic groundwater wells and 30 public/industrial groundwater wells within the Shasta Valley, with 170 wells for undetermined uses such as irrigation, stock watering, domestic supply and other uses (Willis et al. 2013). Several of the largest wells are operated by the MWCD and located near Big Springs Creek. While groundwater is not adjudicated in the Valley, MWCD is subject to pumping restrictions when Big Springs Lake drops low enough to limit gravity diversions to adjacent areas (Willis et al. 2013). The City of Yreka obtains much of its water supply from Fall Creek (see Table 2-9), located outside the Shasta River watershed near Iron Gate Reservoir (Pace Engineering 2016).

2.5.3 Municipal Water Use

Primary municipal water users in the Shasta River watershed include the communities of Yreka, Montague, and Weed along with several small hamlets with populations of less than 100 (e.g.

Edgewood and Gazelle). With a population of approximately 7,916 (2016), Yreka is the largest municipal water user in the Shasta River watershed. Yreka relies on several surface water sources for its water supply and does not use groundwater resources (Pace Engineering 2016). A water conduit from Fall Creek was constructed in 1968 to improve reliability of the water supply during drought conditions that allows diversion of up to 15 cfs. Yreka relies on six water rights, three of which are based on adjudicated claims before 1914, and three that were recorded more recently by the State Water Resources Control Board, listed in Table 2-7.

Table 2-7. City of Yreka reported water rights. Adapted from City of Yreka Urban Water Management Plan (2015), Table 6-2 p.35.

Reported Water Right	Year	Source	Quantity	Use	Area Served
State Water Board Permit 15379	1966	Fall Creek and an Unnamed Stream	6,300 ac-ft./yr.	Municipal, Domestic, & Industrial	City of Yreka Service Area Boundary
State Water Board License 6037	1955	Yreka Creek Underflow	1,214 ac-ft./yr.	Municipal & Industrial	City of Yreka Service Area Boundary
State Water Board License 9850	1958	Greenhorn Creek	285 ac-ft./yr.	Municipal, Industrial, & Recreational	City of Yreka Service Area Boundary
Adjudicated Right 501	1869		1.0 cfs/yr.	Domestic & Municipal	City of Yreka
Adjudicated Right 502	1870		1.0 cfs/yr.	Domestic, Municipal, & Irrigation	City of Yreka; Specified Ag. Lands
Adjudicated Right 503	1889	Yreka Creek	4.0 cfs/yr.	Domestic & Municipal	City of Yreka

In addition to irrigation supply via the MWCD, the Dwinnell reservoir provides water supply to the City of Montague via a pipeline that was completed in the summer of 2014[3,4]. The main water supply sources for the City of Weed are Beaughan Springs and Mazzei Well, which have a combined capacity of 2.1 Million Gallons Per Day (Pace Civil 2004).

2.5.4 Agriculture and Grazing

Agricultural water demands are met with direct diversion of surface water from the Shasta River and its tributaries, diversion of surface water stored in reservoirs (principally Lake Shastina), pumping from groundwater supplies, and re-use of applied irrigation water (Willis et al. 2013).

[3] https://ww2.kqed.org/science/2014/08/20/drought-stricken-california-town-struggles-to-keep-the-water-flowing/

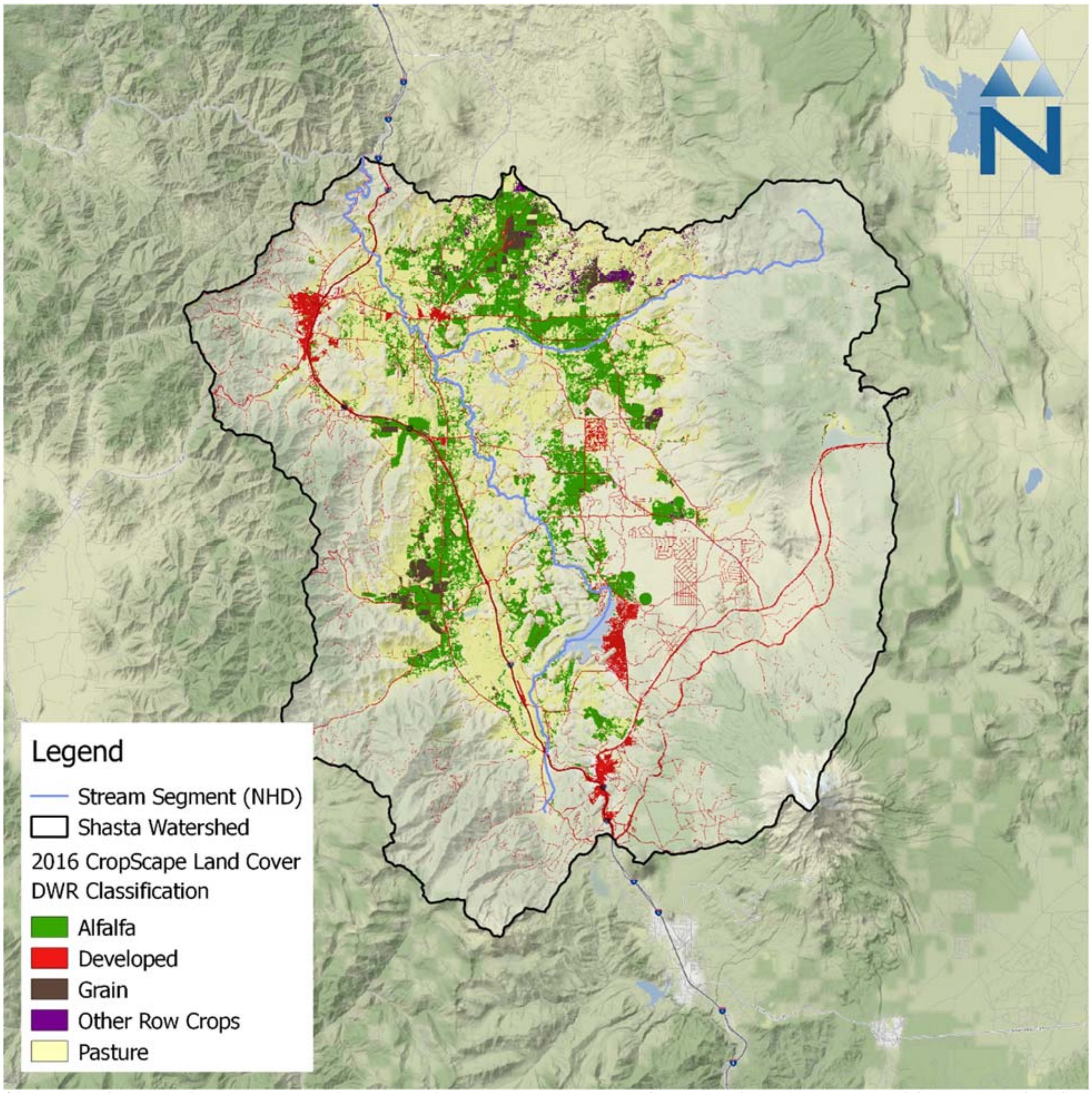
[4] https://www.waterboards.ca.gov/waterrights/water_issues/programs/water_quality_cert/docs/mwcd/mwcb_signed_cert.pdf

To quantify current irrigated lands and water use, land use data from the CropScape database (Han et al. 2014) were classified into categories that align with the DWR irrigated crops data to estimate agricultural consumptive uses across the Shasta Basin. Average water usage data (for each crop type) was available for 1998-2010 from DWR for the Shasta River watershed. The largest portion of the watershed is occupied by natural cover (forests, shrublands, grasslands, open space, wetlands), while about one quarter of the watershed is occupied by irrigated agriculture and urban development. Pasture is the most prevalent agricultural land use identified in both the DWR and CropScape data, but the irrigated pasture area in the DWR data is less than half the pasture area in the Cropscape data (Table 2-8). Alfalfa makes up the second most prevalent crop type identified in the CropScape and DWR data but similarly (Table 2-8), only a small portion of this area is listed as irrigated every year. The remaining crops include grain, onions and garlic, vine, corn, other row crops, and other deciduous crops, which when combined with pastures and alfalfa, total 51,810 acres of irrigated land in the basin (Table 2-8). The DWR irrigated area estimates were used to calculate the annual consumptive use from agricultural crops and grazing pastures, which totals 165,503 acre-feet/year for all crop types.

Table 2-8. Crop types and acreage.

Crop Type		Irrigated Area (ac) (DWR)	Water Usage Rate (ac-ft./ac/yr.)	Water Usage (ac-ft./yr.)
USDA CropScape	DWR			
Winter Wheat	Grain	3,910	1.69	6,607
Oats				
Triticale				
Barley				
Rye				
Spring Wheat				
Alfalfa	Alfalfa	7,770	3.08	23,931
Grass/Pasture	Pasture	39,050	3.39	132,379
Other Hay/Non-Alfalfa				
Other Crops	Onions, Garlic	380	2.71	1,029
-	Row Crops	670	2.06	1,380
Fallow/Idle Cropland	-	-	-	-
Walnuts	Other Deciduous	20	2.12	42
Grapes	Vine	10	1.35	135
Corn	Corn	-	-	-
Totals		**51,810**	**N/A**	**165,503**

*Crop types are listed for both USDA CropScape data (Han et al. 2014), https://nassgeodata.gmu.edu/CropScape/ and DWR along with irrigated acreage from DWR (DWR Land and Water Use Estimates http://www.water.ca.gov/landwateruse/anlwuest.cfm , accessed May 2017) and water usage for each DWR crop type. Dashes indicate no data. Data accessed May 2017.



*(Han, et al. 2014) (https://nassgeodata.gmu.edu/CropScape/). Note that crops have been grouped into categories that correspond with DWR water use estimates.

Figure 2-8. Grazing pasture, crops, and developed areas from the CropScape database.

The DWR irrigated acreage estimates listed above correspond with previous reports of roughly 53,000 acres of irrigated land in the Shasta Valley (DWR 2008). The total water use estimates from the DWR and CropScape data (165,503 ac-ft./yr.) approximately correspond with previous estimates made by the DWR of approximately 175,000 total applied water (DWR 2011). DWR (2011) estimated that from this total withdrawal, roughly 152,000 acre-feet (87%) comes from surface water, while 23,000 acre-feet (13%) is sourced from groundwater.

2.5.5 Small Private Water Users

Small private surface water users account for a considerable portion of water use. More than 200 private water users have been reported to be active in the Shasta Basin (Clements 2006). Private water users typically pump water directly from the Shasta River and its tributaries, shallow wells, or maintain small dams and weirs for seasonal gravitational or off-channel pumping through interconnected ditches and pipes (Willis et al. 2013).

2.6 Historic Instream Flows

Historic instream flow data were collected from USGS, the DWR water data library, and the DWR California Data Exchange Center (CDEC). There are three USGS streamflow gages in the Shasta River watershed with observed data between water years 1958 – 1978, and 2002 - 2016. There are five other stations from DWR that have sporadic data that have been collected in 2 to 3-year periods. The data were analyzed to assess the quantity and quality of the observed record. Quantity was measured as percent of days with recorded flow data at each gage, while quality was measured as percent of days flagged by USGS as having been "edited or estimated by USGS personnel (USGS 2018)." Table 2-9 provides a summary of USGS data quantity and quality in the Shasta River watershed. As seen in Table 2-9, there is a continuous flow record of good data (in terms of quantity and quality) throughout the watershed from 1957 to present. Gage locations in the Shasta River watershed are shown in Figure 2-9. Since the Nature Conservancy's property acquisitions in the Shasta River watershed, the University of California at Davis Center for Watershed Science, the Nature Conservancy, and Watercourse Engineering have been monitoring streamflow in Big Springs Creek, the mainstem Shasta River, and Little Shasta River (Jeffres et al. 2008, 2009, 2010; Null et al. 2010; Willis et al. 2012, 2013, 2017, Nichols et al. 2016, 2017). Additional sources of flow data include gages 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 Shasta River watershed including Little Springs Creek (Deas et al. 2015) and Big Springs Creek (Appendix G of NCRWQCB 2006); 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 watershed (CDFW 2016). During model development, streamflow data from all available sources will be further assessed to identify important critical conditions. Data quantity and quality will impact both the selection of data to be used for calibration as well as the 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 Shasta River watershed have been significantly affected by water resource management in the basin. Seasonal low-flow and drought conditions are natural in the watershed but are becoming more common. There have been a few studies performed on hydrology and hydrologic habitat in the Shasta River watershed as well as one study to determine interim and minimum instream flow needs in the watershed (McBain & Trush 2013, CDFW 2017). The Instream Flow Needs study, by McBain & Trush, documented historical and current sampling above and below the Parks Creek confluence, in the center of the Shasta River watershed. Historical data of unimpaired mean monthly flow in the Upper Shasta River and Parks Creek estimate a maximum of approximately 208 cfs and a minimum of 6 cfs during spring/summer months. Baseflows in spring/summer 2010, comparatively, ranged from a maximum of 36 cfs to a minimum of 5.6 cfs (see Figure 2-10). According to these studies, there is considerable inter-annual streamflow variability, but, at the same time, there is uniformity and therefore predictability of streamflow between June and late October. This seasonal variability is consistent with other streams in the region.

Table 2-9. Summary of USGS and DWR streamflow data quantity and quality in the Shasta River watershed.

Period	Station ID	Water Years (October 1, 1956 – September 30, 1976)																			
		1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
1957-1976	11516900		●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	11517000																				
	11517500	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	F21300																				●
	F21370																				
	F21675																				
	F21700					●	●	●	●	●	●	●									
	F21940																				

Period	Station ID	Water Years (October 1, 1976 – September 30, 1996)																			
		1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996
1977 - 1996	11516900	●	●																		
	11517000																				
	11517500	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	F21300	●	●																		
	F21370																				
	F21675																				
	F21700			●	●	●	●	●	●	●	●	●	●	●	●	●					
	F21940																				

Period	Station ID	Water Years (October 1, 1996 – September 30, 2016)																			
		1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
1997 - 2016	11516900																				
	11517000						●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	11517500	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	F21300																				
	F21370									●											
	F21675									●											
	F21700																				
	F21940									●	◕							●	●	●	

Legend:

Data Quantity (Percent Complete):

0%	25%	50%	75%	100%

Data Quality (Percent Estimated):

	○	◔	◑	◕	●
No Data	90-100%	65-90%	35-65%	10-35%	0-10%

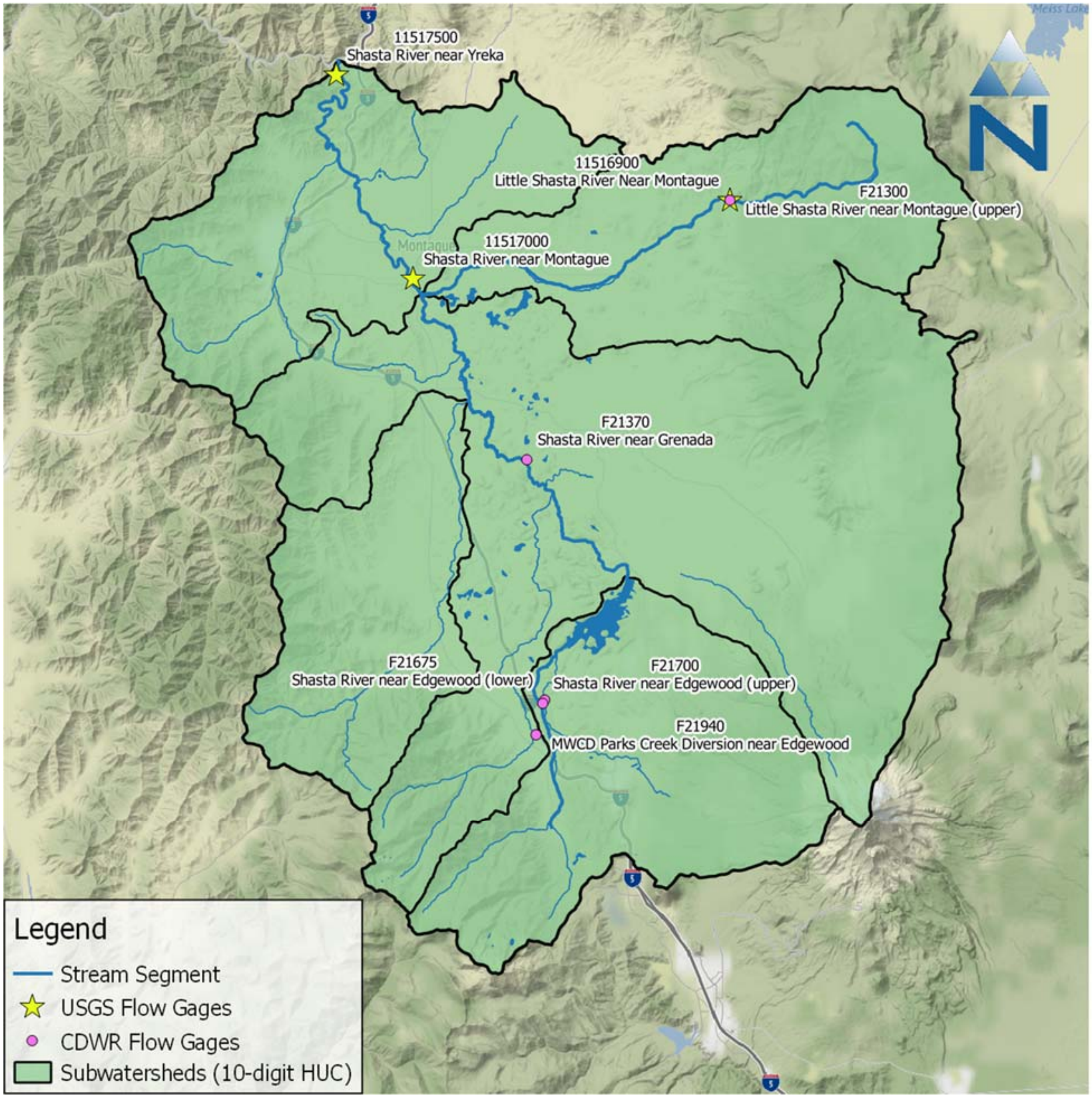


Figure 2-9. Flow gages in the Shasta River watershed.

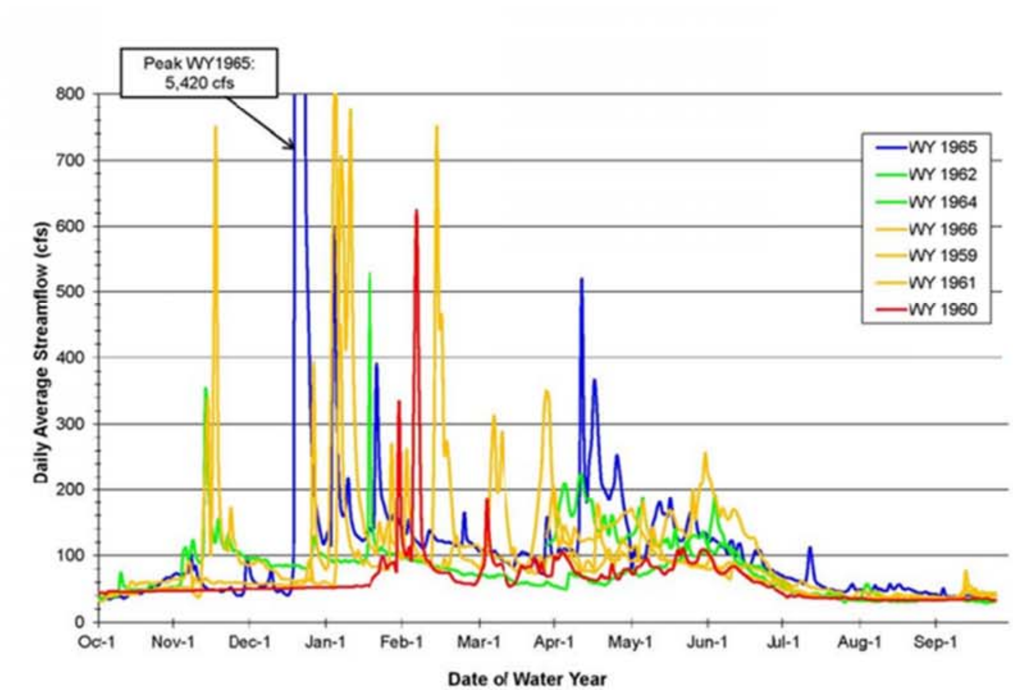


Figure 6. Estimated unimpaired annual hydrographs, for the Shasta River immediately downstrea of the Parks Creek confluence in Reach No.3.

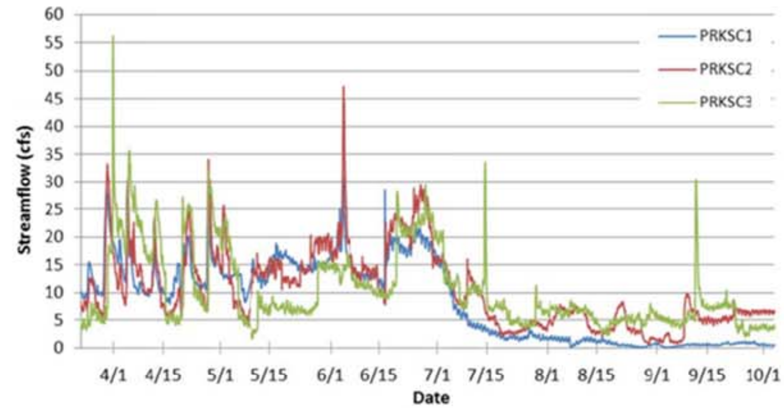


Figure 9. Observed streamflows for April 1 – October 1 2010, in Parks Creek.

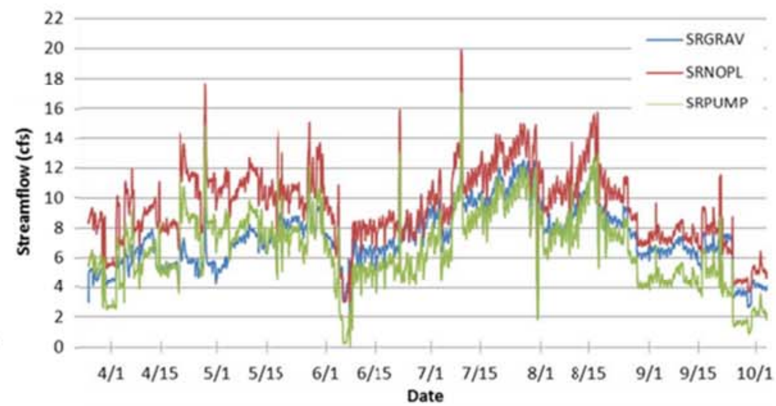


Figure 12. Observed streamflows for April 1 – October 1 2010, in the Shasta River above Parks Creek.

Figure 2-10. Historic streamflow trends (WY 1960 – 1965) compared with more recent trends (WY 2010) (adapted from McBain and Trush 2013).

3. MODEL STUDY PLAN

Based on the study objectives identified in Section 1.2 and the preliminary characterization of the watershed presented in Section 2, a Model Study Plan was prepared. The model selection process considered the available data compiled to date, ongoing or future data collection efforts, and past and parallel modeling efforts within the watershed. The primary goal of the Study Plan is to outline a modeling approach with sufficient robustness to address the study objectives, while considering available data to base modeling assumptions on and to support model calibration. The Model Study Plan also considers flexibility of the model to address future planning needs. The following sections outline considerations and recommendations for the Model Study Plan.

3.1 The Model Development Cycle

The model development process can be a good platform for gaining valuable information and insight about a watershed. If well-designed, the model development process is an iterative and adaptive cycle that improves understanding of a watershed over time as better information becomes available. Ultimately a watershed model can inform future data acquisition efforts and management decisions by highlighting factors that have the most impact on the subject watershed. Figure 3-1 is a conceptual schematic of a model development cycle, which is represented as circular as opposed to linear. That cycle can be summarized in six interrelated steps:

1. **Assess Available Data**: these data are used for source characterization, trends analysis, and defining modeling objectives
2. **Delineate Project Extent**: which refers to model segmentation and discretization
3. **Set Boundary Conditions**: including quality-controlled spatial and temporal model inputs
4. **Represent Processes:** refers to calibration of model rates and constants to mimic observed physical processes of the natural system
5. **Confirm Responses:** refers to validation of model processes over space and time to assess if the model is a robust predictive tool.
6. **Assess Data Gaps:** Sometimes the rigidity of modeled responses can highlight unrepresented physical processes in the natural system. Those data gaps sometimes provide a sound basis for further data collection efforts to refine the model, which cycles back to Step 1.

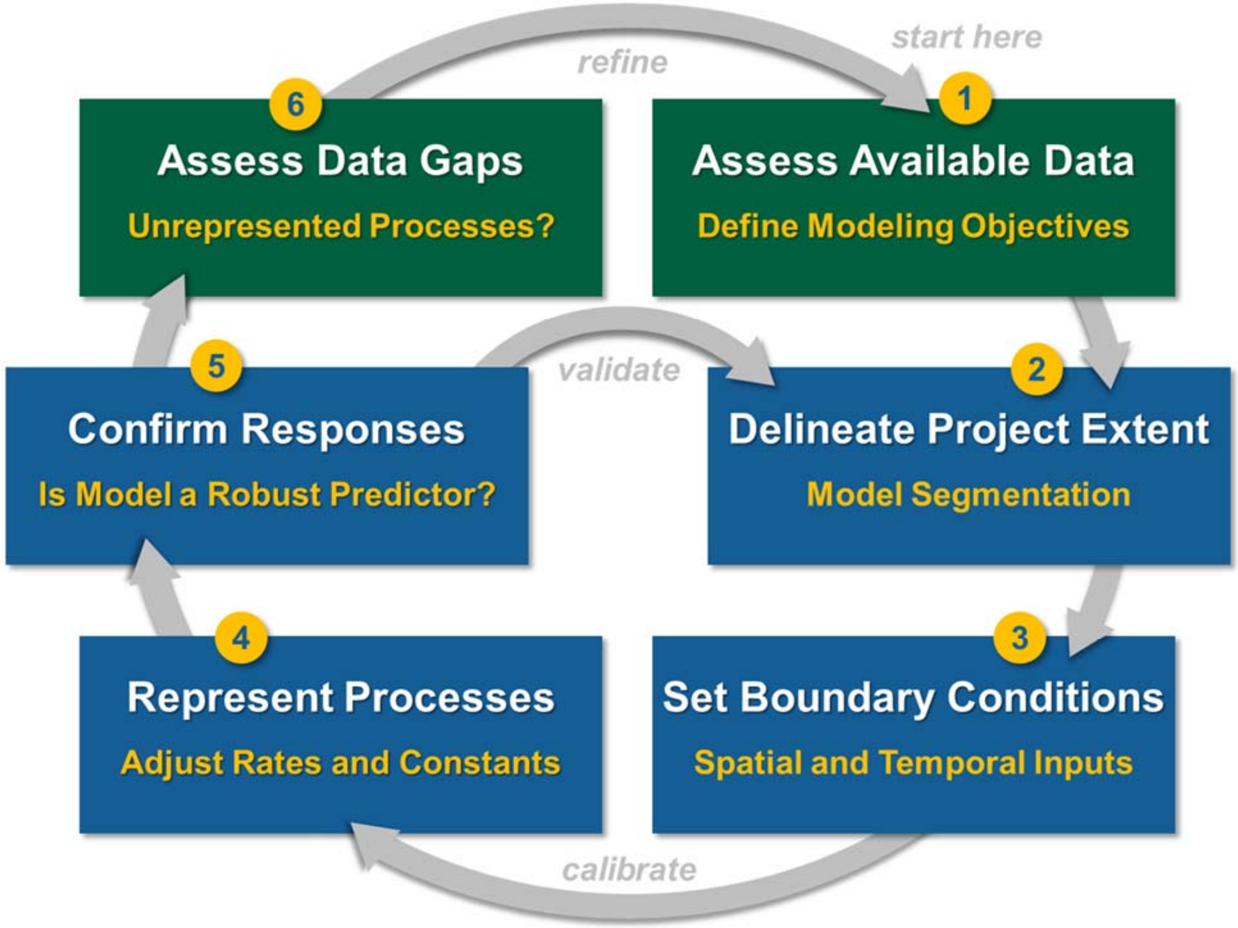


Figure 3-1. Conceptual schematic of a model development cycle.

3.2 Overview of Proposed Modeling System

A modeling approach selection process was undertaken that considered multiple important study factors, including: (1) simulation of seasonally-variable hydrologic conditions, (2) sub-daily (e.g., hourly) model time step for representing instream flows, (3) groundwater influence on surface water quantity, and (4) use of non-proprietary public-domain software to facilitate peer and public review and use. In addition to simulating instream flows, the model should also be flexible and adaptable to support future investigations such as water quality and temperature modeling. Spatial variability of land cover and vegetation, and its influence on hydrology, is also an important factor that should be considered when parameterizing hydrologic responses for the model. The selected platform should be flexible and adaptable for representing hydrologic impacts of changes in the watershed. Watershed models such as Hydrologic Simulation Program–FORTRAN (HSPF) (Bicknell et al. 1997; EPA 2000) and Loading Simulation Program in C++ (LSPC) (EPA 2018) address many of the analytical considerations for model selection. Where groundwater influences are especially important, these models can be coupled to a groundwater model to extend its analytical ability to represent those effects.

The hydrologic model proposed for this study is the Loading Simulation Program in C++ (LSPC), which is a watershed modeling system that includes Hydrologic Simulation Program–FORTRAN (HSPF) algorithms for simulating watershed hydrology, temperature, erosion, water quality processes, and in-stream fate and transport processes. Groundwater interactions are an important element of this study; therefore, the Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW) will be coupled with LSPC to represent groundwater influence on instream flow. Section 3.5.2.3 provides more detail about a conceptual approach for coupling LSPC with MODFLOW.

LSPC integrates GIS outputs, comprehensive data storage and management capabilities, the original HSPF algorithms, and a data analysis/post-processing system into a convenient PC-based Windows environment. The algorithms of LSPC are identical to a subset of those in the HSPF model with selected additions, such as algorithms to address land use change over time. LSPC is a public domain watershed model originally made available through EPA's Office of Research and Development in Athens, Georgia as a component of EPA's National TMDL Toolbox. Some of the most recent advancements and applications of LSPC are in the Los Angeles, CA area (http://dpw.lacounty.gov/wmd/wmms/) (LACDPW 2010). Figure 3-2 is a generalized schematic of the underlying hydrology model (Stanford Watershed Model) used in HSPF and LSPC. The schematic represents land-based processes for a single land unit in the model. A complete description of proposed land units is provided in Section 3.5.1. Meteorological data are the driver for the modeled hydrologic processes. As shown in the schematic, precipitation is the primary input, while total actual evapotranspiration (TAET) and streamflow are the primary outputs in the water budget. Potential evapotranspiration (PEVT; not explicitly shown in the schematic) is another key meteorological boundary condition for the model. The interaction of model parameters shown in Figure 3-2 will ultimately determine how much PEVT becomes TAET. There are several pathways that water can take as it makes its way through the network. For each land unit, process-based parameters that reflect differences in geology, soils, vegetation, and land cover will govern the rates and volumes of water at each stage throughout the schematic.

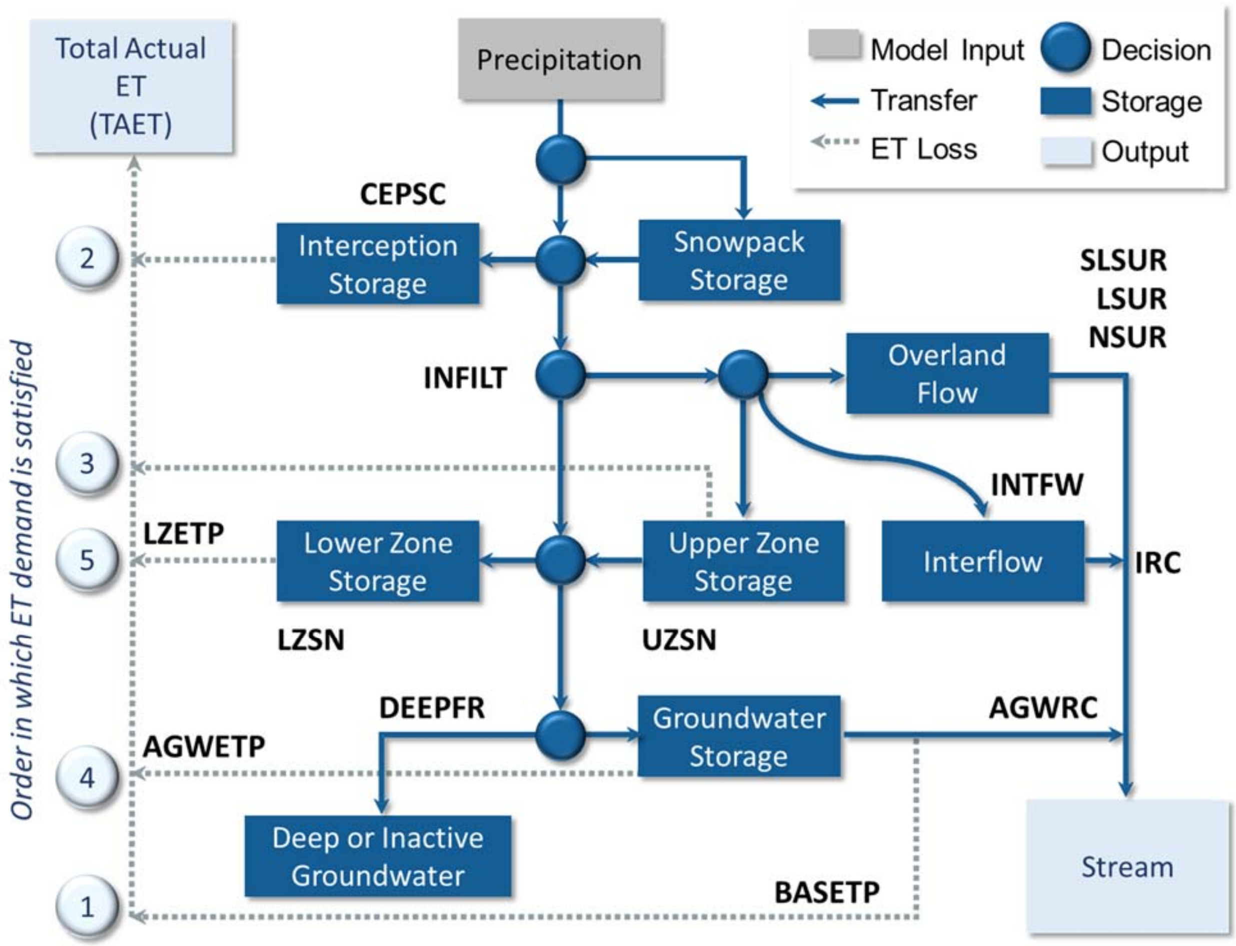


Figure 3-2. Hydrology model schematic (based on Stanford Watershed Model).

3.3 Model Segmentation

The USGS WBD provides a good starting point for delineation of the project extent, however, finer resolution subwatershed delineations are required to provide sufficient model segmentation to address the characteristics of the watershed and the study objectives. For each subwatershed represented in the LSPC model, continuous estimates of instream flows can be output from the model. Therefore, careful consideration will be made in the delineation of subwatersheds to correspond with POIs or other instream assessment points potentially considered for future investigations. Subwatersheds will also be delineated to correspond to locations of instream monitoring gage locations, allowing direct comparison of model-predicted flows with observed flows for model calibration and measurement of model accuracy.

A preliminary analysis was performed to delineate subwatersheds of the Shasta River watershed at a finer spatial resolution. This process provided a validation of HUC watershed boundaries, while considering physical characteristics and locations for model segmentation to support the study objectives and model calibration. Subwatersheds were delineated based on known physical, biological, and geologic parameters. Primary characteristics that drive boundary investigation are elevation (Figure 3-3), topography, reach connectivity, and locations of instream monitoring gages (Section 2.6). Secondary characteristics include underlying geology, dominant climatic patterns, and dominant land cover or vegetation. Figure 3-4 presents the subwatershed delineations with some of the high-level spatial considerations (USFWS 2013). Figure 3-5 shows the location of Dwinnell Dam and Lake Shastina. Detailed descriptions and analyses of these specific watershed characteristics are found in Section 2.2 (Land Characteristics), Section 2.3 (Climatic Characteristics), Section 2.4.4 (Hydrogeology), Section 2.5 (Consumptive Water Use), and Section 2.6 (Historic Instream Flows).

Following approval of the Model Study Plan and during model development, the subwatershed delineations will continue to be refined based on additional information and considerations, including such factors as:

- POIs for instream flow studies.
- Subwatershed boundaries that correspond to additional instream flow gage locations (e.g. DWR gages).
- Jurisdictional boundaries to make it possible to summarize information or represent management activities that are associated with specific jurisdictions.
- Improved representation of complex stream connectivity, locations of impoundments, diversions, or refinement of areas with large or sudden changes in elevation, topography, or other influential spatial attributes.

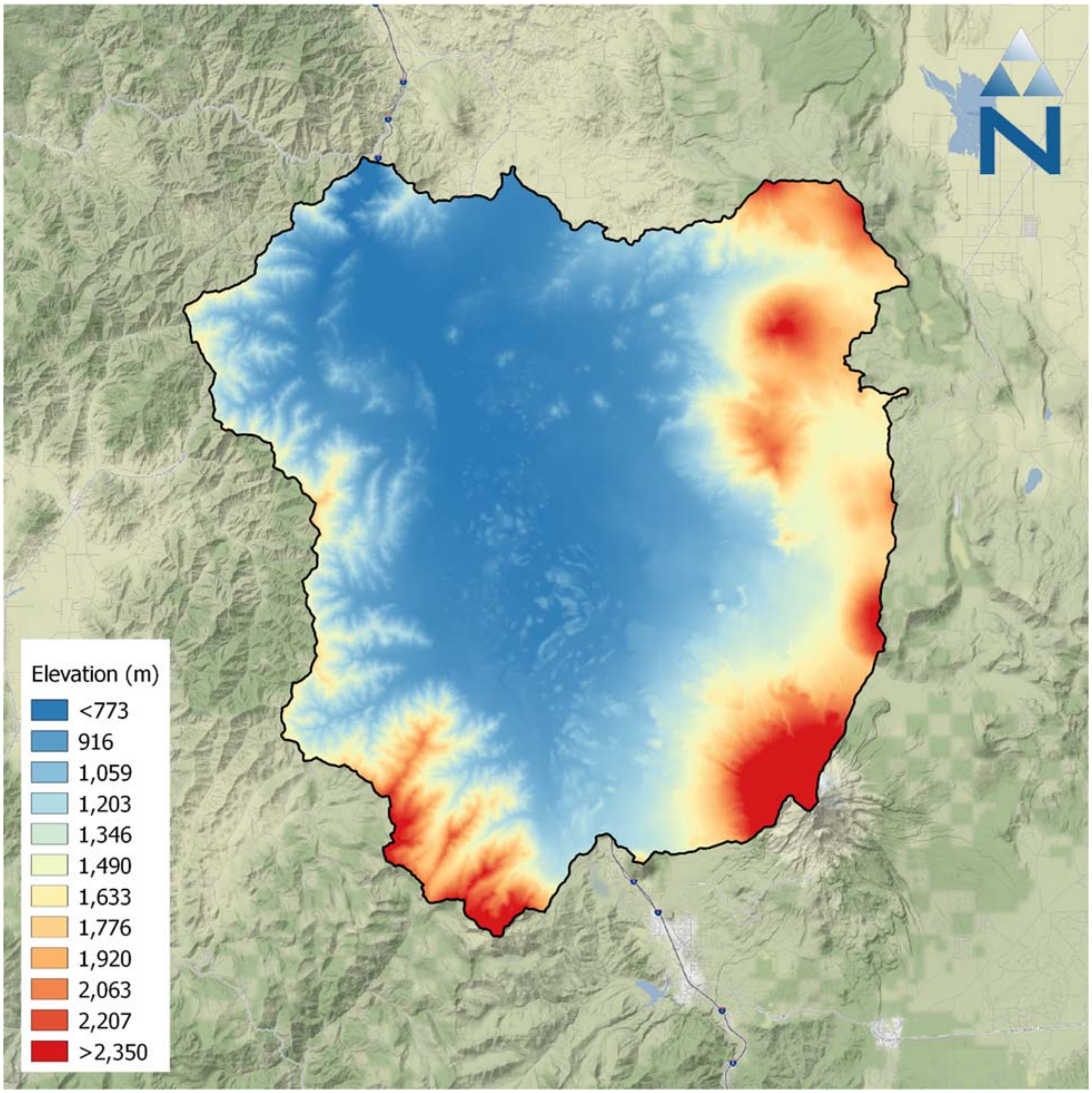
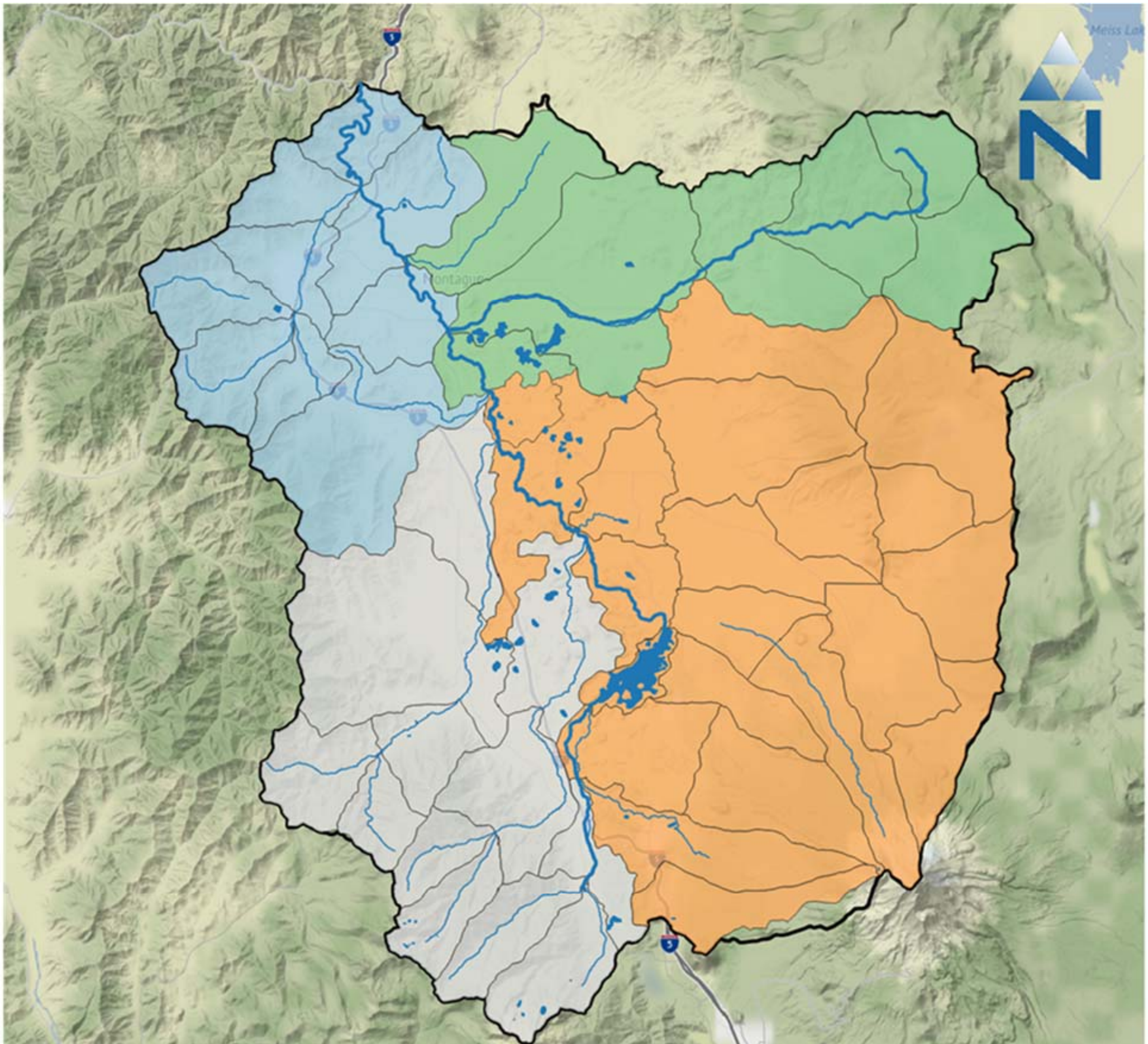


Figure 3-3. Elevation of the Shasta River watershed.



Attribute	Zone 1	Zone 2	Zone 3	Zone 4
Square Miles	182	335	146	128
% of Basin	23%	42.5%	18.5%	16%
Mainstem Miles	5	21	27	13
Dominant Hydrology	Rainfall and Snowmelt	Springs	Springs and Snowmelt	Rainfall
Dominant Vegetation	Evergreen Forest	Evergreen Forest	Evergreen Forest	Shrub and Scrub

Source: Study Plan to Assess Shasta River Salmon and Steelhead Recovery Needs, 2013

Figure 3-4. Spatial considerations for subwatershed delineation (from USFWS 2013).

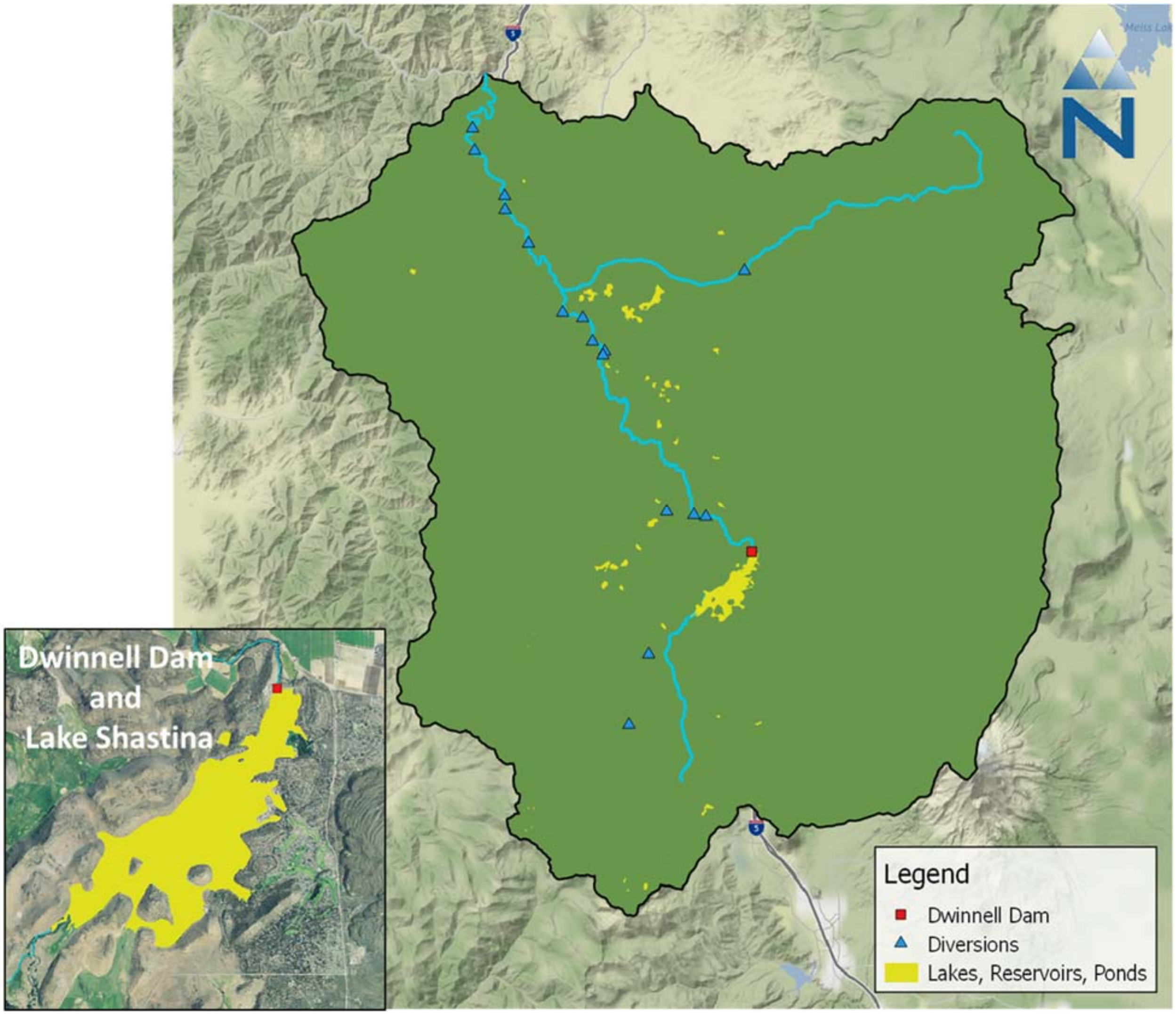


Figure 3-5. Location of Lake Shastina and Dwinnell Dam.

3.4 Meteorological Boundary Conditions

Meteorological data such as precipitation, evapotranspiration, temperature, and other climate time series are the primary forcing functions of the model. Several primary and secondary meteorological data products were compiled and reviewed for this effort. Three such datasets described in further detail in the following sections include precipitation data from the Global Historical Climatology Network (GHCN), precipitation and air temperature data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM), and potential evapotranspiration estimates from the California Irrigation Management Information System (CIMIS). There are additional precipitation and air temperature data available from the California Data Exchange Center (CDEC), Remote Automated Weather Stations (RAWS), National Weather Service's Automated Surface Observing System (ASOS), and The Nature Conservancy (TNC) that have not yet been evaluated or compiled.

3.4.1 Primary Precipitation (GHCND)

Previous experience has shown that the National Climate Data Center (NCDC) daily precipitation dataset tends to be more reliable, (in terms of total reported volumes), than the hourly dataset; however, depending on model requirements, gages with finer-resolution time steps may be used to disaggregate daily rainfall. Many of the Global Historical Climatology Network Daily (GHCND) rainfall stations contain intervals of missing, deleted, or accumulated data. Missing or deleted intervals are periods during which either the gage malfunctioned, or the data records were lost. Accumulated intervals contain cumulative precipitation reported over several hours or days, but the exact temporal distribution of the data is unknown due to a gage malfunction.

Two commonly-used estimation techniques for patching missing rainfall data are the Normal Ratio Method (Dunne and Leopold 1978) and the Distance Power Method. The Normal Ratio Method corrects for orographic variability through normalization; however, the Distance Power Method does not consider orographic variability. A hybrid approach was used to quality-controlling the Shasta Basin data for watershed characterization. First, candidate stations were selected from among the gages using nearest distance to gage (a minimum of 3 nearby stations). The search radius was incrementally widened to add stations until at least one good nearby candidate station was available for each impaired month in the historical record for the station. The approach used is a hybrid because stations were preferentially selected, but not weighted, by distance. Second, the Normal Ratio Method was used to patch each station with its respective set of nearby stations. Patching of missing and deleted data intervals was performed on a daily time step, but may be disaggregated to a finer resolution depending on the needs of the selected modeling approach. The Normal Ratio Method estimates missing daily rainfall using a weighted average from surrounding stations with similar rainfall patterns per the relationship:

$$P_A = \frac{1}{n}\left(\sum_{i=1}^{n} \frac{N_A}{N_i} \times P_i\right)$$

where P_A is the missing precipitation value at station A, n is the number of surrounding stations with valid data for the same day, N_A is the long-term average monthly precipitation at station A, N_i is the long-term average monthly precipitation at nearby station i, and P_i is the observed daily precipitation at nearby station i. For months where data were either zero or heavily-impaired (i.e. more than 50% missing), the long-term average *annual* precipitation value was used for N_A and N_i instead of the impaired monthly values. For each missing day at station *A*, *n* consists of only the surrounding stations with valid data; therefore, for each day, *n* can vary from 1 to the maximum number of surrounding stations. When no precipitation is available at the surrounding stations from the same island, zero precipitation is also assumed at station *A*. In general, gages located at airports or in relatively high population/traffic locations tend to be better maintained and have better data quality than those located in more remote locations.

A few of the gages contained long time intervals with no rainfall and no missing flags; however, sometimes rainfall occurred at nearby stations during those un-flagged missing intervals. Some intervals were as short as one month, while others extended beyond a year. The longer the period, the less likely that there was truly no rainfall occurring during that interval. Two gages within the watershed, Mount Shasta (045983) and Yreka (049866), were among the best-quality observed GHCND rainfall gages. Data between 10/1/1980 and 9/30/2015 were analyzed to assess the average number of dry days occurring between rainfall events by month (Figure 3-6). The summer months of August and September were the driest months with an average of 48 dry days between rainfall events at Yreka and about 26 on Mount Shasta; however, the wetter months had fewer dry days between rainfall events. The number of dry days during the wet months were similar between the two locations. The Yreka gage is more representative of more of the watershed. Based on that finding, a threshold of 50 days was selected so that any unflagged "dry" intervals greater than 50 days in the original GHCND time series would be flagged as "missing," thereby providing the opportunity to be patched as needed if there was rainfall observed at nearby gages. If no rainfall occurred at any of the nearby stations, the missing intervals were left as dry days.

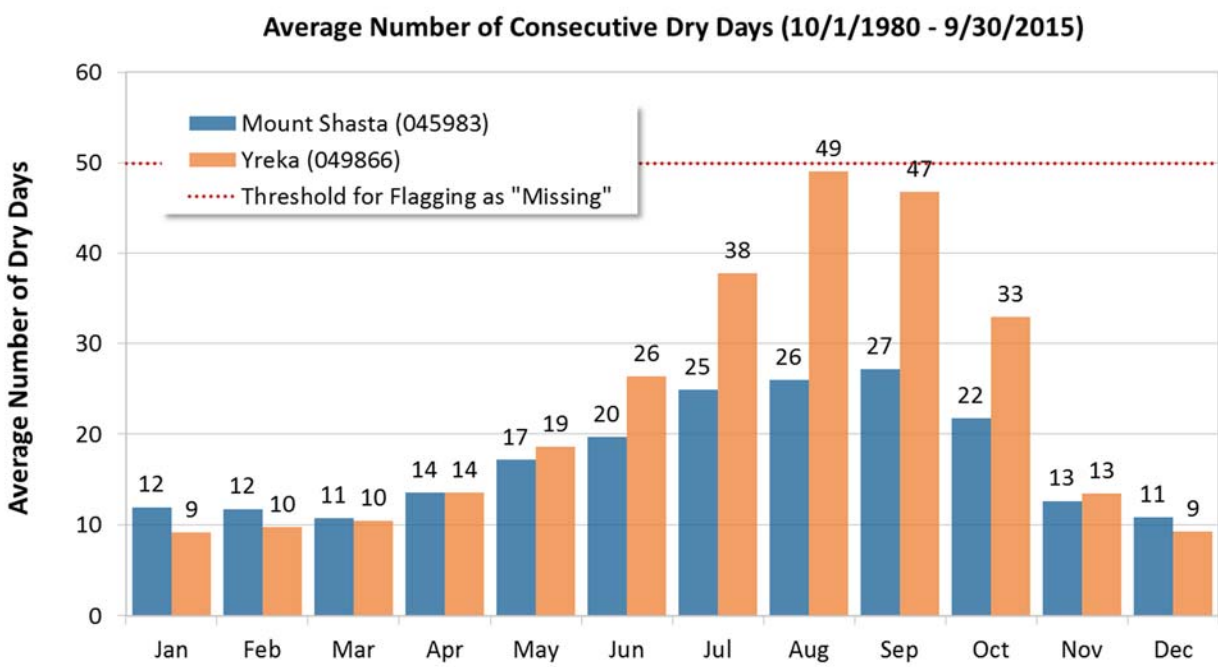
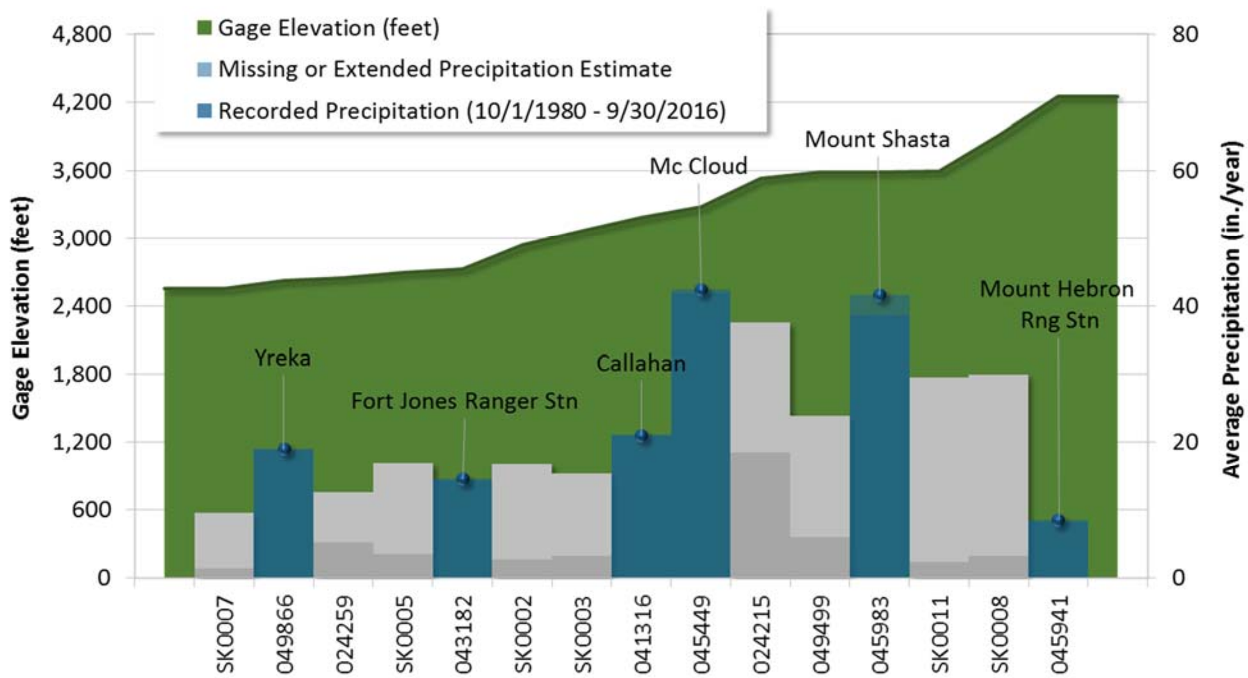


Figure 3-6. Average number of consecutive dry days by month at two Shasta River watershed rainfall stations.

Figure 3-7 shows a summary of precipitation data near the Shasta River watershed that have been analyzed to fill in missing records. Table 3-1 is a tabular summary of observed vs. quality-controlled GHCND rainfall in the Shasta River watershed. The blue-highlighted and labeled columns in Figure 3-7 are the selected gages with the best quality time series. The darker-tone portion of each station/column represents the recorded portion of annual average rainfall, while the lighter-tone portion represents the missing or extended portion of the rainfall record. The differences highlight some of the spatial and temporal quantity and quality deficiencies commonly found in observed rainfall data. The rainfall totals were also plotted against gage elevation to highlight macroscale orographic influences on rainfall totals. This two-dimensional profile does not consider the spatial locations of gages. For this reason, microscale orographic influences like aspect and rain-shadow are reflected as fluctuations in totals among gages at or near the same elevation. The Shasta rainfall gages show orographic influence on rainfall magnitude across the study area.



Blue: Selected high-quality gages; Gray: nearby gages with lower percent coverage

Figure 3-7. GHCND precipitation gage data before and after patching missing data for the Shasta River watershed.

Table 3-1. Summary of GHCND precipitation gage data before and after patching missing data for the Shasta River watershed.

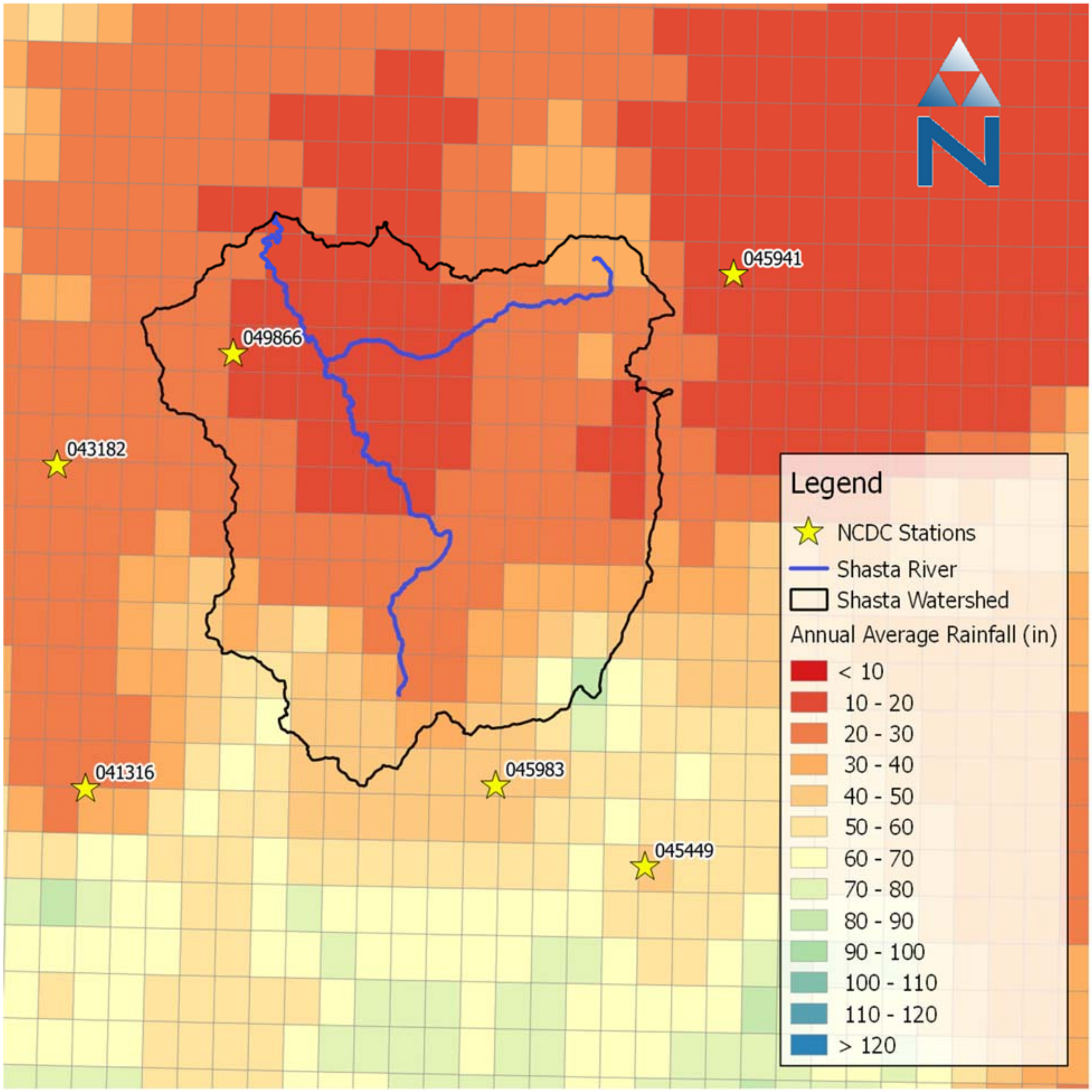
Quality Rank	Station Name	Station ID	Elevation (ft.)	Evaluation Period		Percent Missing		Rainfall (inches/year)	
				Start	End	Reported	Adjusted	Reported	Adjusted
1	CALLAHAN	041316	3,185	1/1/1980	1/22/2017	0%	8%	20.99	21.05
2	YREKA	049866	2,625	1/1/1980	3/8/2017	0%	10%	18.88	19.00
3	MOUNT HEBRON RNG STN	045941	4,250	1/9/1980	3/9/2017	0%	14%	8.21	8.53
4	FORT JONES RANGER STN	043182	2,725	1/2/1980	3/9/2017	0%	15%	14.33	14.60
5	MOUNT SHASTA	045983	3,590	1/5/1980	3/6/2017	0%	15%	38.58	41.70
6	MC CLOUD	045449	3,280	1/1/1980	3/9/2017	0%	16%	41.92	42.38
7	MOUNT SHASTA, CA US	024215	3,535	4/2/1998	3/6/2017	49%	54%	18.45	37.52
8	MONTAGUE SISKIYOU AIRPORT, CA US	024259	2,651	1/3/2001	3/8/2017	56%	62%	5.26	12.60
9	WEED FIRE DEPT	049499	3,589	1/5/1980	5/29/1989	76%	79%	5.99	23.91
10	WEED 5.4 N, CA US	SK0003	3,064	10/31/2008	3/10/2017	78%	80%	3.31	15.39
11	YREKA 0.9 WNW, CA US	SK0005	2,692	12/13/2008	3/9/2017	78%	81%	3.51	16.89
12	YREKA 4.5 S, CA US	SK0002	2,937	10/31/2008	11/1/2014	83%	85%	2.76	16.78
13	MONTAGUE 1.6 ESE, CA US	SK0007	2,556	12/2/2010	2/21/2017	84%	86%	1.42	9.56
14	MOUNT SHASTA 5.1 NW, CA US	SK0008	3,911	5/18/2012	3/8/2017	88%	90%	3.25	30.00
15	MOUNT SHASTA 1.7 SSE, CA US	SK0011	3,593	4/7/2013	3/10/2017	90%	93%	2.33	29.53

3.4.2 Secondary Precipitation (PRISM)

Secondary datasets are available to help overcome deficiencies commonly found in primary observed datasets. Behnke et al. (2016) published a first-of-its-kind study that comprehensively evaluated many of the available secondary datasets on a large geographical scale. Four key findings from their study were: (1) temperature was represented more accurately than precipitation, (2) climate *averages* were more consistently predicted across datasets than weather extremes, (3) datasets with the best agreement to observed data varied geographically, and (4) accuracy did not depend on spatial resolution. Behnke et al. ultimately concluded that no single secondary dataset was "best" everywhere for all variables, highlighting the need to spatially validate selected dataset against observed data to assess if it is adequately representative for the goals of the study.

Parameter-elevation Regressions on Independent Slopes Model (PRISM) was among the datasets reviewed by Behnke et al. (2016). PRISM provides a spatially-refined climatological coverage for the lower 48 contiguous United States at a 4-km spatial resolution for the AN81d daily dataset and both 4-km and 800-m for the AN81m monthly dataset. The notation "AN81" refers to the data product as inclusive of input data from "all networks" and covering the period starting in 1981. The appended "d" and "m" character refers to daily and monthly data, respectively (PRISM 2013). Developed and maintained by the PRISM Climate Group at Oregon State University (http://prism.oregonstate.edu), PRISM provides gridded estimates of event-based climate parameters including precipitation, temperature, and dew point. The algorithm uses observed point data, a digital elevation model, and other spatial datasets to capture influences such as high mountains, rain shadows, temperature inversions, coastal regions, and other complex climatic regimes (Gibson et al., 2002). Climate station networks near the Shasta River watershed that are used by PRISM for generating daily and monthly time series include GHCND, California Irrigation Management Information System (CIMIS, see section 3.4.3), Remote Automated Weather Stations (RAWS), and Automated Surface Observing System (ASOS). PRISM only uses California Data Exchange Center (CDEC) data for calculating normals (not for generating daily time series).

Monthly PRISM time series data were downloaded and summarized for the 36-year period between 10/1/1980 and 9/30/2016. Figure 3-8 shows annual average 4-km gridded PRISM rainfall coverage near the Shasta River watershed. The selected NCDC stations from Table 3-1 (and labeled on Figure 3-7) were also plotted against data from the nearest PRISM centroid to validate the temporal representation of PRISM (seasonally and monthly). Figure 3-9 and Figure 3-10 are validation plots that show a close match between PRISM and observed GHCND rainfall at Yreka (049866) and Mount Shasta (045983), respectively. The Mount Shasta gage showed more variability in seasonal and month-to-month comparisons than the Yreka gage, but showed a reasonable prediction of long-term average rainfall. The upland portions of the watershed near Mount Shasta generally do not contribute runoff to the Shasta River; therefore, the month-to-month variability in precipitation volume are less important for model prediction than the long-term average rainfall. The Yreka gage, which is representative of the runoff-contributing portions of the Shasta River watershed showed a tight correlation between GHCND and PRISM. These observations corroborate the findings of others (Oswald and Dupigny-Giroux 2015; Daly et al. 2008) that PRISM can be a robust predictor of observed rainfall variability. Additional comparisons between PRISM and observed rainfall at gages within other monitoring networks (e.g. CDEC, RAWS, ASOS, TNC) will be performed to further validate the PRISM predictions and applicability as a model input.



PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 30 Mar 2017

Figure 3-8. PRISM rainfall coverage for the Shasta River watershed vs. selected GHCND gages. [5]

[5] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 30 Mar 2017

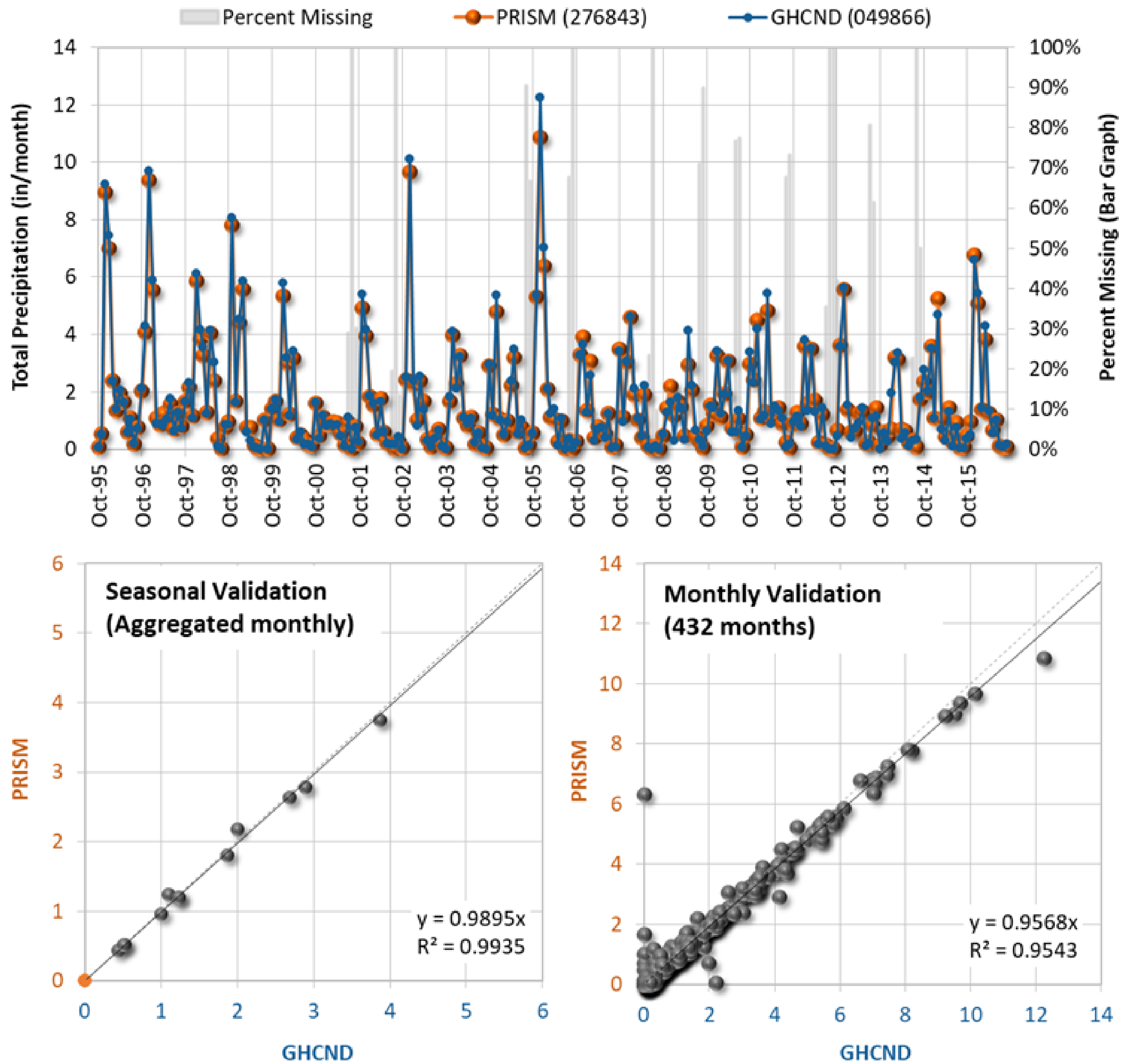


Figure 3-9. Validation of observed GHCND (049866) vs. PRISM (276843) monthly rainfall totals. [6]

[6] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 30 Mar 2017

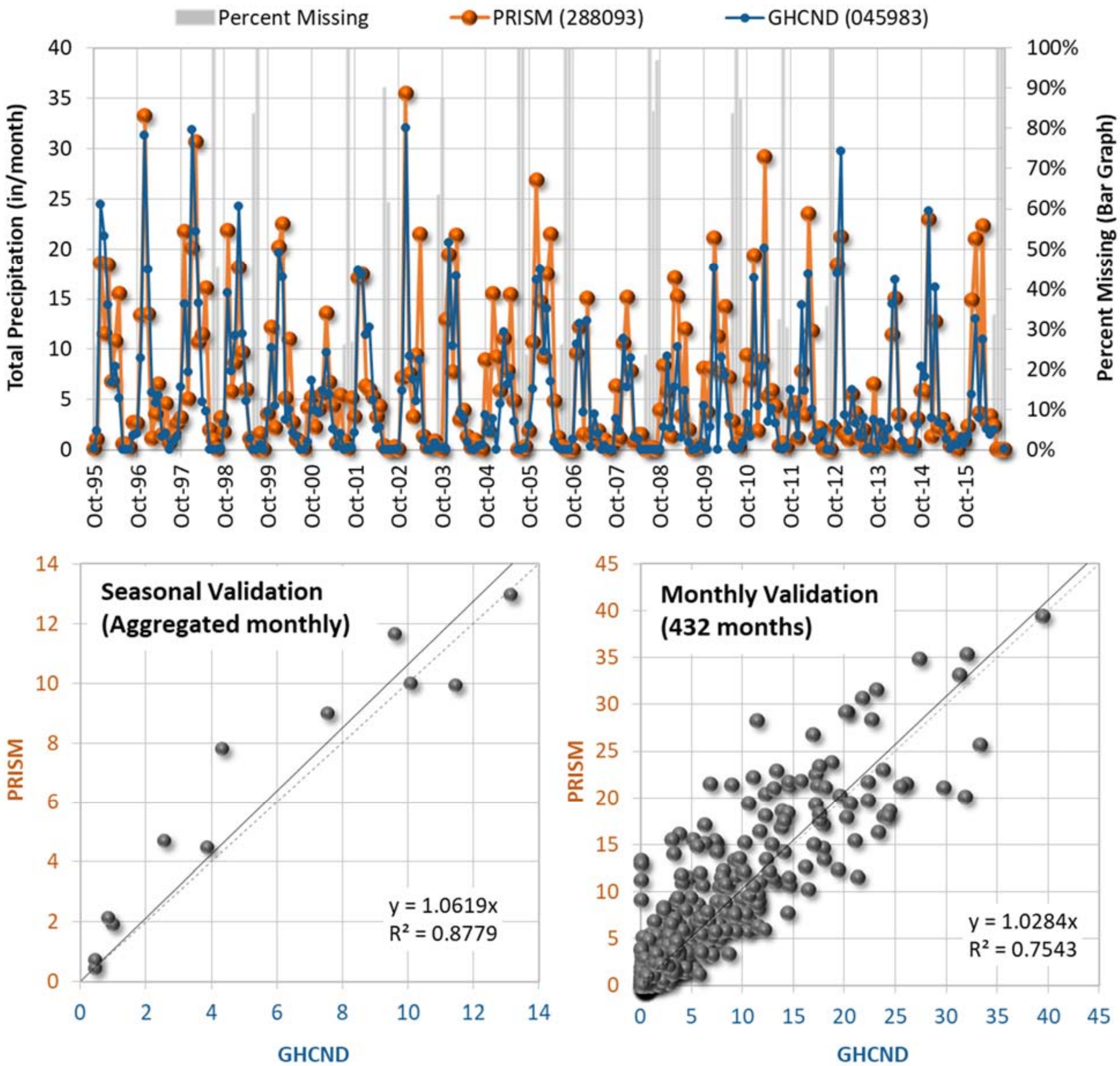


Figure 3-10. Validation of observed GHCND (045983) vs. PRISM (288093) monthly rainfall totals. [7]

[7] PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created 30 Mar 2017

3.4.3 Evapotranspiration (CIMIS)

Evapotranspiration (ET), the combined loss of water to the atmosphere from soil evaporation, plant surfaces, and plant transpiration, accounts for a large portion of a hydrologic water budget. Actual ET varies depending on vegetative cover (type, density, height) and soil conditions, making it virtually impossible to measure precisely for all environmental conditions. Nevertheless, having approximate estimates for ET is beneficial for efficient management of irrigation, which saves water, energy, and money.

The California Irrigation Management Information System (CIMIS) was established to help irrigators efficiently manage water resources. CIMIS was developed in 1982 by DWR and the University of California, Davis. The network is composed of over 145 automated weather stations throughout California where primary weather data including temperature, precipitation, relative humidity, wind speed, and solar radiation are monitored and quality-controlled. Those data are measured over standardized reference surfaces (e.g. well-watered grass or alfalfa) and are used to estimate reference evapotranspiration (ETo) using the customized Penman and Penman-Monteith equations. CIMIS has divided California into 18 zones based on long-term monthly average ETo values calculated using data from CIMIS weather stations. Figure 3-11 is a map of CIMIS zones for the Shasta River watershed with a plot of monthly average ETo for the mapped zones.

The western portion of the Shasta River watershed falls within CIMIS Zone 13, Northern Sierra Nevada Zone, overlapping 12% of the watershed area. The eastern portion of the watershed falls within CIMIS Zone 7, Northeastern Plains, overlapping <1% of the watershed area. The remaining 88% of the Shasta River watershed falls within CIMIS Zone 10, the North Central Plateau & Central Coast Range. As shown in Figure 3-11, average reference ET is uniform across the watershed. CIMIS also provides a spatial model which estimates a daily 2003–present time series of ETo statewide at a 2-km spatial resolution by combining meteorological variables measured at CIMIS stations, satellite-based estimates of solar radiation, and spatial interpolation (Hart et al. 2009).

CIMIS provides relative macro-scale differences in potential ET that will be applied to model timeseries boundary conditions; however actual ET varies in magnitude as a function of vegetative cover. Local practitioners in the watershed have observed regional changes to instream flows due to changes in agriculture and irrigation demand. For water budget calculations, ET coefficients are applied to pan evaporation estimates as a function of land cover to get PEVT that reflect stratification of vegetative impacts. Example ET coefficients are shown in Table 3-2. This approach adds spatial resolution by allowing ET to vary as a function of land cover, which also varies by subwatershed. Stratification by land cover, using coefficients like those presented in Table 3-2, adds more texture and spatial variability when calculating the ET component of the water balance.

Table 3-2. Examples of estimated stratification of modeled ET by land cover type.

Cover Type	Land Cover	Evapotranspiration Multiplier	Rationale [1]
Urban	Impervious	1.2	Above average ET (warm exposed surfaces)
	Pervious	0.9	Grass or shrub vegetation
	Construction	1.0	No vegetation, use standard ET rate
Rural [2]	Agriculture	0.9	Grass or shrub vegetation
	Barren	0.9	Grass or shrub vegetation
	Forest/Wetland	0.85	Light wind, high relative humidity
	Grass-Shrub	0.9	Grass or shrub vegetation
Water	Water	1.0	Use evaporation rate for open water

1 Reference: Bedient and Huber, 2002. Table 1.2, Page 47.
2 Rural Land Cover categories and ET coefficients will be further refined to account for irrigation activity.

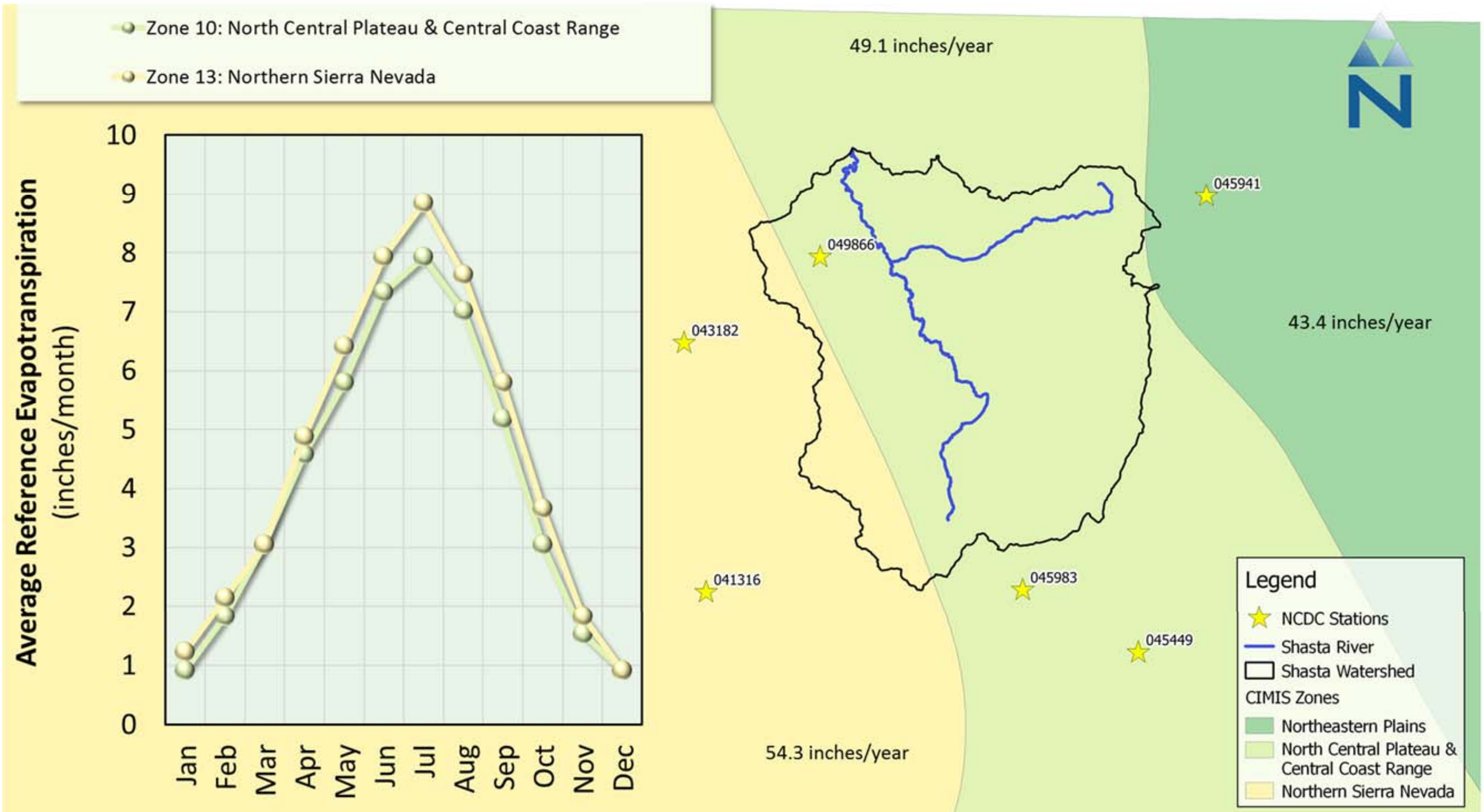


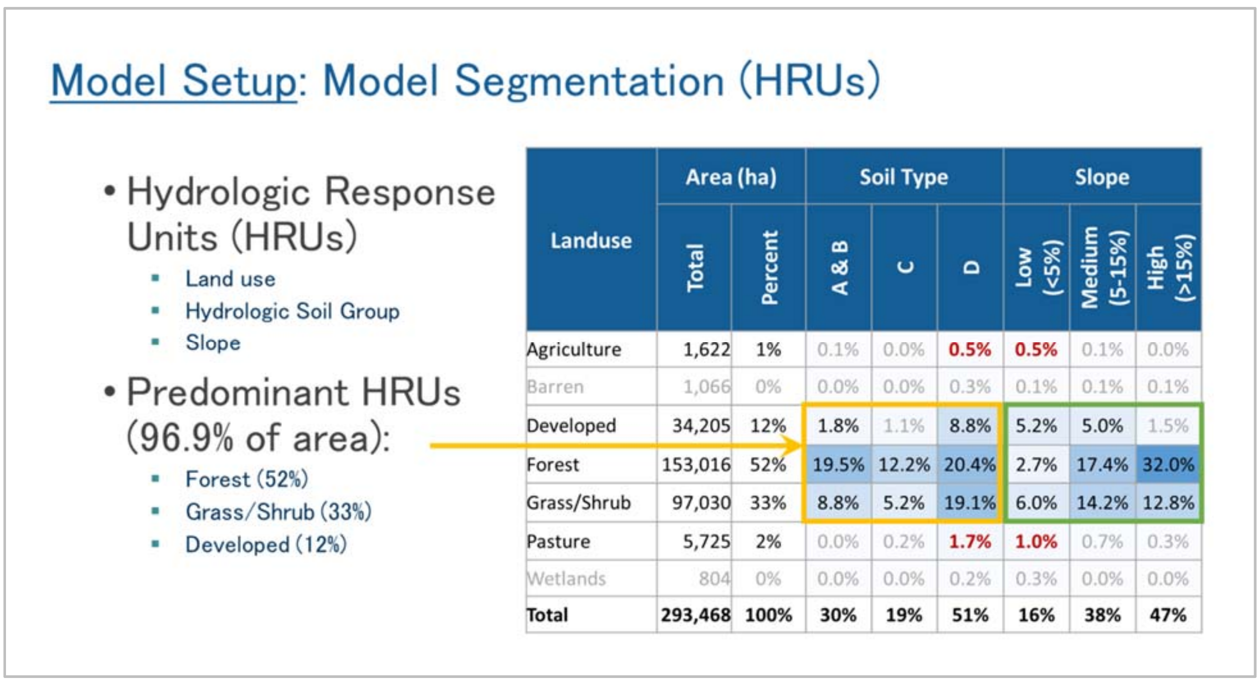
Figure 3-11. Average monthly reference evaporation for CIMIS zones in the Shasta River watershed.

3.5 Other Considerations for Model Configuration

The organizational framework for LSPC is a relational database. By their very nature, both GIS and time series elements of watershed data are organized in a relational database structure (i.e. spatial objects with tabular attributes). In the organizational hierarchy, certain watershed attributes are logically associated with subwatersheds, while other associations are better expressed at a finer spatial scale. It may be suitable to assign climate time series to individual subwatersheds; however, process-based parameters like those illustrated in Figure 3-1 are more readily-associated with individual land segments. Irrigation application is one example of activities that are logically associated at the land-segment level. An important part of the model development process is determining the acceptable level of resolution to express different parameters. Processes associated with smaller spatial elements of the model provide more degrees of freedom for expressing the spatial resolution of its hydrologic impact; however, more resolution increases computational time. Therefore, model configuration involves finding a representative balance between spatial resolution and model complexity.

3.5.1 Hydrologic Response Units

One such area where a representative balance is needed is in the development of hydrologic response units (HRUs). HRUs, which represent the core hydrologic modeling units in the model, are a convenient way to capture combined hydrologic influences. Three common layers that are intersected to derive HRUs are land cover, soil type, and slope. In the example shown in Figure 3-12, the summary table shows that most of the area (96.9%) falls within 1 of 18 different combinations of land use, soil type, and slope. This analysis is helpful for identifying predominant HRU combinations for characterizing hydrologic responses.



Landuse	Area (ha) Total	Area (ha) Percent	Soil Type A & B	Soil Type C	Soil Type D	Slope Low (<5%)	Slope Medium (5-15%)	Slope High (>15%)
Agriculture	1,622	1%	0.1%	0.0%	0.5%	0.5%	0.1%	0.0%
Barren	1,066	0%	0.0%	0.0%	0.3%	0.1%	0.1%	0.1%
Developed	34,205	12%	1.8%	1.1%	8.8%	5.2%	5.0%	1.5%
Forest	153,016	52%	19.5%	12.2%	20.4%	2.7%	17.4%	32.0%
Grass/Shrub	97,030	33%	8.8%	5.2%	19.1%	6.0%	14.2%	12.8%
Pasture	5,725	2%	0.0%	0.2%	1.7%	1.0%	0.7%	0.3%
Wetlands	804	0%	0.0%	0.0%	0.2%	0.3%	0.0%	0.0%
Total	**293,468**	**100%**	**30%**	**19%**	**51%**	**16%**	**38%**	**47%**

Figure 3-12. Example summary table (not based on Shasta Basin) showing the intersect of HRU components.

3.5.2 Groundwater Interactions

Groundwater pumping is one of the activities in the watershed that has a direct impact on instream flows. Groundwater storage in LSPC (as shown in Figure 3-2 and Figure 3-13**Error! Reference source not found.**) is represented as a series of independent land use-associated compartments. Recharge from the surface layers becomes either active-groundwater inflow (AGWI) or inactive groundwater inflow (IGWI), which is the volume of water that is lost to an inactive groundwater layer. The groundwater storage layer of HSPF provides a compartment to attenuate and release a portion of recharge back to the streams as active groundwater outflow (AGWO). Furthermore, there is no physical connection between groundwater storage compartments of adjacent land segments. To provide a more robust representation of groundwater and surface-subsurface interactions, the surface water model will be dynamically coupled to a dedicated groundwater model.

3.5.2.1 Groundwater Model

MODFLOW (MODFLOW-2005: Harbaugh 2005; Harbaugh et al. 2017; MODFLOW-USG: Panday et al. 2015), a widely used and accepted finite-difference flow simulator developed by USGS, will be used for developing the groundwater model. The groundwater model will adopt an integrated approach based on available data and various assumptions as described below. The LSPC model will provide the AGWI to the model. The groundwater model will be used to evaluate baseflow response in stream segments resulting from changes in well-pumping. That model will be used to provide the AGWO term as a function of AGWI and groundwater pumping. These functions will then replace the existing groundwater components of LSPC, as shown in Figure 3-13.

The first step for groundwater model development is the delineation of groundwater basins. Groundwater basin delineation will be based on geologic analysis of the extent, depth, and connectivity of alluvial and fractured bedrock aquifers. The final delineation of sub-watershed boundaries will be reviewed and approved by State Water Boards staff.

The proposed groundwater model will have multiple layers encompassing the hydrologic boundaries of the Shasta River watershed as shown in Figure 3-4. The watershed boundary will constitute the active model domain. Lateral boundaries of the groundwater model will be no-flow conditions where the groundwater basin boundary coincides with the watershed boundary, or general head boundary conditions to allow for lateral flow to/from adjacent groundwater basins as needed. The model will be spatially partitioned into 4 zones: 1 zone representing alluvial aquifers in the valley as listed in Section 2.4.4, and 3 zones representing the fractured bedrock aquifer formations. Multiple layers allow for greater precision in the assignment of groundwater pumping to appropriate hydrostratigraphic units. Stratigraphic layering will be developed to provide the appropriate depths and thicknesses for the hydrogeologic units being modeled. Spatially distributed aquifer thickness information for the groundwater basin will need to be determined or estimated. A uniform model cell spacing of a quarter of a mile will be used initially and will be updated or refined as necessary. Spatial zonation of aquifers shall be refined to better represent horizontal and vertical spatially-varying hydrogeologic properties. Existing local aquifer test results will also be incorporated into the model, as well as other data required for the evaluation of hydrogeologic properties of aquifer units. A transient model will be simulated to match the duration of the LSPC model. The model calibration objective for the groundwater model will be to match historical baseflow and stream depletion records as a function of recharge and pumping inputs from the watershed model.

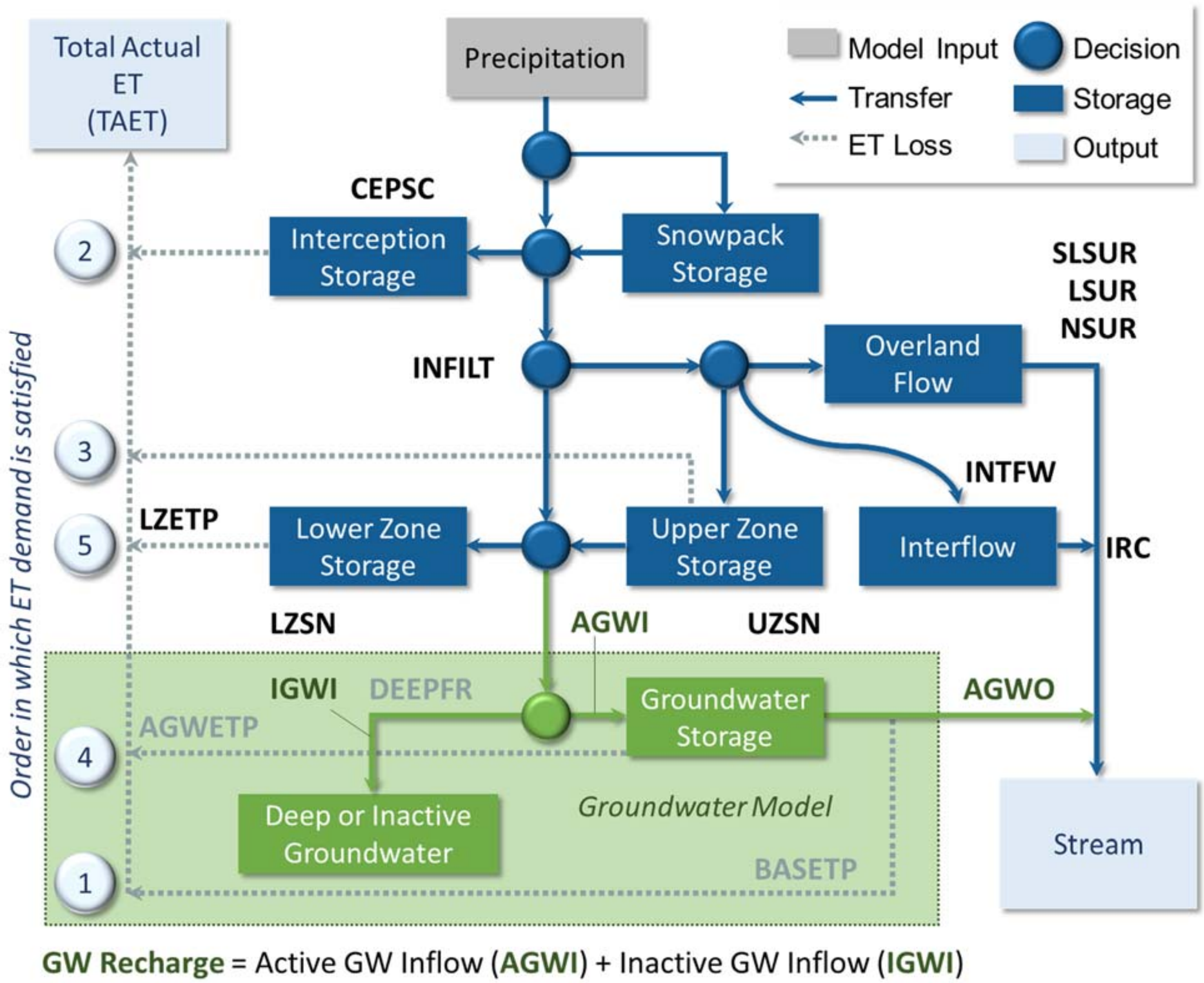


Figure 3-13. Conceptual linkage of a coupled groundwater model with HSPF.

Hydraulic conductivity and storage coefficients will be spatially varied based on the four groundwater zones as specified above. These two parameters will be estimated initially based on available descriptions of the aquifers and well-log data. The hydraulic conductivity and storage coefficients will then be subject to parameter estimation to appropriately capture: (1) gaining or losing stream reaches; (2) dry gaps; and (3) estimated baseflow rates. These stream conditions will be provided by measured data, site information, and the LSPC model. PEST (Doherty 2008) will be used for parameter estimation. The "confined" option of MODFLOW-2005 will be implemented to accelerate model computations; this option is reasonable when aquifer thicknesses are large in comparison to the drawdowns.

Net groundwater recharge will be implemented in the groundwater flow model. Net groundwater recharge for this work is represented by the term AGWI in Figure 3-13**Error! Reference source not found.**. Transient groundwater recharge will be provided by the LSPC model which will be aggregated into longer stress periods (seasonal or monthly) as is appropriate for groundwater flow conditions. Streams in the groundwater model will be represented using the river or "RIV" package of MODFLOW. The LSPC model will provide the stream locations, streambed conductance, and water levels in streams for the various groundwater stress periods that will be simulated.

Numerous groundwater springs are in the alluvial valley of the Shasta River watershed, which are a source of streamflow to the Shasta River. Spring flows will be simulated as a boundary condition in the model using the drain or "DRN" package of MODFLOW. Available spring discharge measurements/estimates will be used for calibration.

Groundwater pumping will be implemented in the model using the multi-node-well (MNW2) package of MODFLOW. The feature of assigning well efficiency to wells of the MNW2 package will be used to assign the representative pumping from a deeper aquifer to the groundwater model. The MNW2 package is further advantageous in that it allows for multiple groundwater wells to be represented within a single aquifer grid-block.

3.5.2.2 Groundwater Pumping

Approximate locations are available for a total of 240 wells in Siskiyou County by tract number, with location accuracy that places these within approximately one-eighth of a mile accuracy (DWR 2017). Figure 3-14 shows grid locations in which one or more wells have been identified. Pumping rates for wells will be estimated based on their designated use and either the population that the well serves or irrigation usage, and will be consistent between the groundwater model and the LSPC model. Pumping rate estimates will ultimately be aggregated by subwatershed as a function of consumptive uses associated with groundwater sources.

Historical records will be evaluated to determine a representative steady-state starting period for the model. The model will then be run in transient mode through water year 2017 in accordance with the period simulated by the LSPC model. Stress periods will be used to vary recharge and pumping. Recharge output from the LSPC model as well as pumping estimates will be aggregated into seasonal or monthly periods for input to the groundwater model. The steady-state model will be calibrated to baseflow estimates for various stream reaches, including gaining or losing conditions and estimates of dry gap locations. The transient model will be calibrated to the general changes in these conditions resulting from changes in groundwater recharge and pumping.

The approach discussed above will provide an assessment of groundwater pumping on instream flows. The model may be applied to evaluate the impact of reduced recharge to the groundwater domain or increased pumping from groundwater wells on baseflow to streams. The proposed system of models is well suited for supporting the current study objectives and also provide flexibility for other future investigations in the Shasta River watershed.

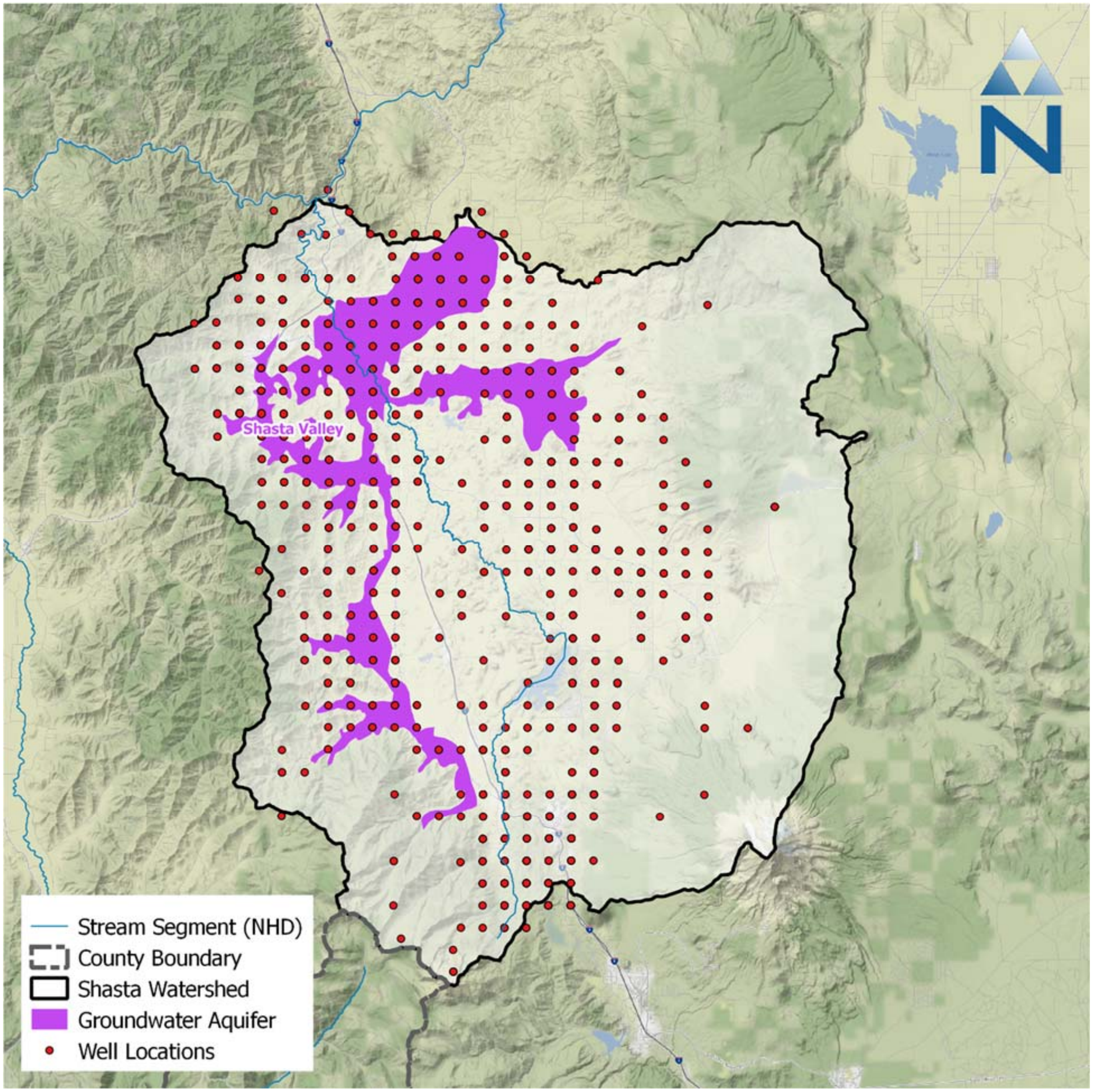


Figure 3-14. Estimated groundwater well locations in the Shasta River Watershed (1/8-mile location accuracy). Some red dots represent multiple wells within that area.

3.5.2.3 Coupled Surface–Groundwater Model

The AGWO component of LSPC has an attenuated and delayed response compared to the surface runoff (SURO) and interflow outflow (IFWO) components. Coupling LSPC to a groundwater model involves some spatial and temporal aggregation. Because groundwater interactions have a longer temporal response period (i.e. monthly or seasonal) compared to surface interactions, it is reasonable to aggregate recharge inputs to a monthly time step at the subwatershed scale. Using best available information to characterize the groundwater basin, the groundwater model will be calibrated to match observed trends in stream depletion. As illustrated in Figure 3-15, the goal of this effort is to develop a coupled groundwater model that is capable of predicting changes in AGWO as a function of AGWI and groundwater pumping rates. Outputs from the groundwater model will be translated back to an hourly temporal scale when linking to the LSPC model. The resulting outputs will be applied in the same way as the original LSPC model prior to coupling.

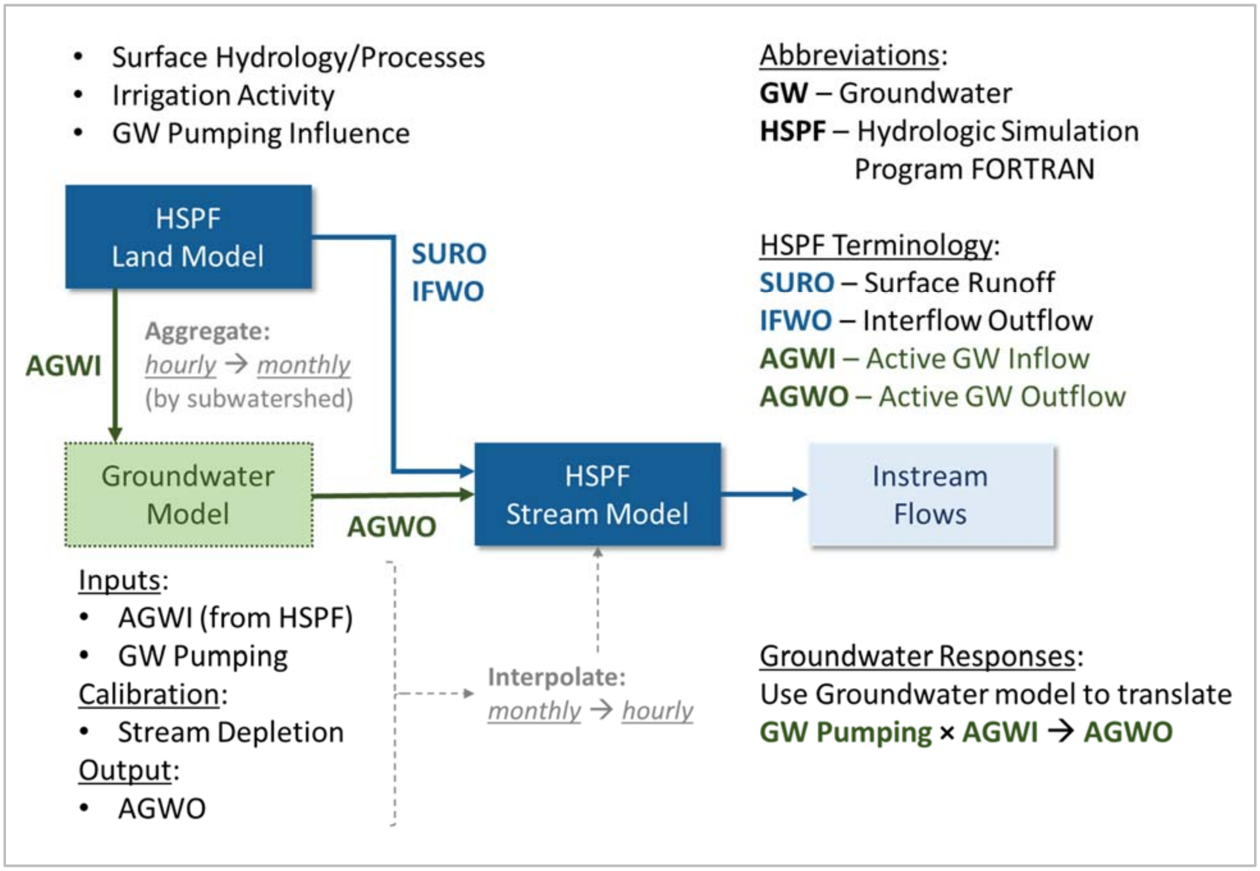


Figure 3-15. Development of groundwater response functions for LSPC using a groundwater model.

3.6 Process for Model Calibration and Validation

The modeling approach is designed to follow internationally-recognized modeling protocols and conventions. For example, the EPA (2002) guidance for Quality Assurance Project Plans for modeling refers to calibration as the configuration and refinement of the analytical instruments that will be used to generate analytical data. The "instrument" is the predictive tool (i.e. the model) that is to be developed and/or applied. Figure 3-16 is a schematic describing a process for model calibration that aims to minimize the propagation of uncertainty. This process builds upon the model development cycle and elements of data quality control previously shown in Figure 3-1. Through development of the Model Study Plan, the analysis of weather data was initiated and discussed in Section 3.4. The calibration process discussed below follows the snow, land hydrology, and stream transport components of Figure 3-16.

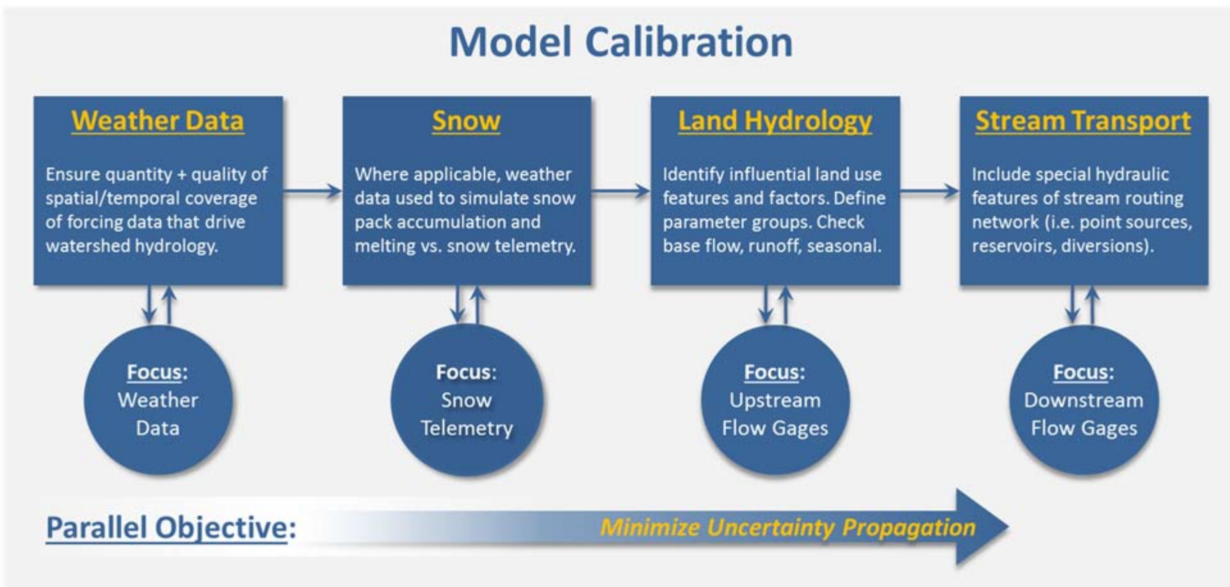


Figure 3-16. Process for model calibration to minimize propagation of uncertainty.

3.6.1 Snow Calibration

For the higher-elevation subwatersheds in the Shasta River watershed, snowfall and snowmelt may influence the water balance. From the model's point of view, the snowpack acts like a reservoir that sometimes stores water based on a set of temperature-based rules that govern when precipitation arrives as snowfall, and releases water based on another set of climate-based rules that govern when snowmelt occurs. The Natural Resources Conservation Service maintains a network of snowfall telemetry gages (SNOTEL) that report valuable information for informing and calibrating snow in watershed models. Daily snow water equivalent data (SWE) track water content in the snowpack. SWE can be used directly as observed snowpack data for calibrating the LSPC SNOW module. Daily minimum and maximum temperatures are also reported at each site. When disaggregated to an hourly basis, those data improve the precision of temperature for informing the model as to when to consider precipitation as snowfall.

There are no primary SNOTEL gages in the Shasta River watershed; however, there are some cooperator snow sensors nearby with some recorded data that can be used for model calibration. Data from other SNOTEL sites in the Klamath River watershed can be used to calibrate snowfall/snowmelt processes. SNOTEL gages report precipitation, temperature, and snow-water equivalent (SWE) snowpack volume. The model uses precipitation and temperature to simulate snow accumulation, and solar radiation to simulate snowmelt. Those processes are influenced by elevation, aspect, shading, and the like. The snow module is calibrated to predict SWE at the higher-elevation SNOTEL gages; however, modeled SWE is adjusted spatially as a function of precipitation, temperature, and elevation. The same parameters that produce more snow at cooler/wetter/higher elevations produce less snow at warmer/drier/lower elevations.

The modeled temperature lapse rate, which is the rate at which temperature decreases with increasing elevation, influences snowfall prediction when extrapolating snow behavior to subwatersheds without gages. Analyzing the SNOTEL dataset against elevation can reveal inherent trends in the data, which can help to inform/refine the modeled temperature lapse rate assumptions. LSPC adjusts the temperature for each subwatershed during model simulation according to the mean difference between the gage elevation and the average subwatershed elevation.

3.6.2 Land Hydrology

The demonstration of model calibration is key to the model development process, as it forms the basis for establishing the degree of uncertainty in model predictions and the reliability of the model in making management decisions. Models will be deemed acceptable when they can simulate field data within predetermined statistical measures. In evaluating a given calibration, it will be useful to look at several parameters. After weather data and meteorological boundary conditions are well established, a top-down weight of evidence approach will progress as follows: (1) calibrate background conditions, (2) add intermediate mixed land use areas, and (3) aggregate all sources via routing to a downstream location for comparison with co-located flow data. Figure 3-17 is a schematic showing the parameterization and calibration sequence for land hydrology. Unit-area results from this step will be summarized and compared relative to each other and against representative published literature values. This step will provide an early opportunity to identify possible errors, anomalies, or other unrepresentative behavior prior to aggregation, instream routing, and transport.

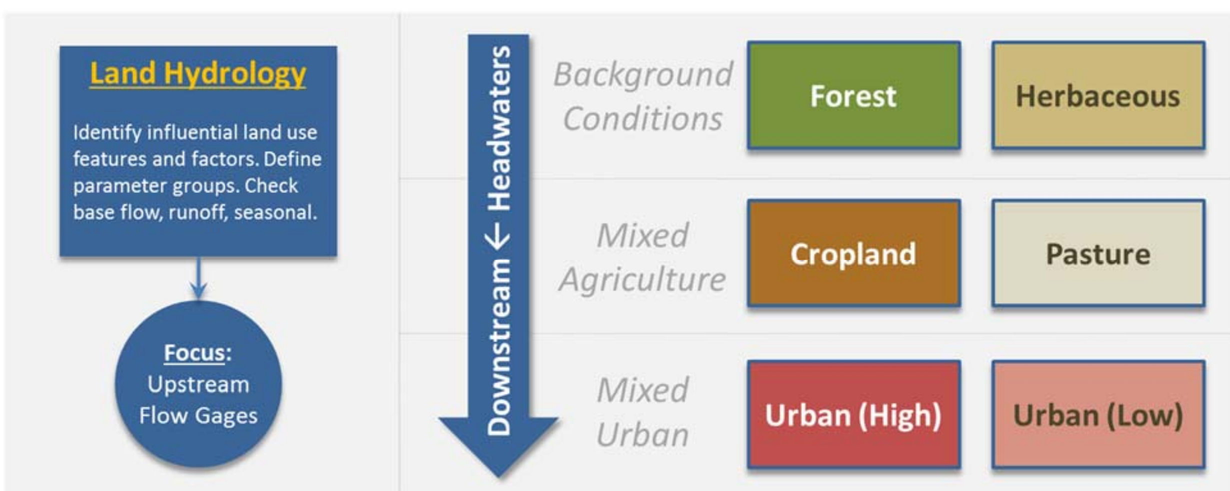


Figure 3-17. Model parameterization and calibration sequence for land hydrology.

3.6.3 Stream Transport

Figure 3-18 is a schematic of stream transport model parameterization and calibration sequence. Outputs from land hydrology will be aggregated and routed to the stream transport model, where other features such as impoundments, diversions, withdrawals, and point sources may influence the water balance. Using the most representative spatial and temporal data inputs to characterize elements at this stage will further minimize propagation of uncertainty through the model.

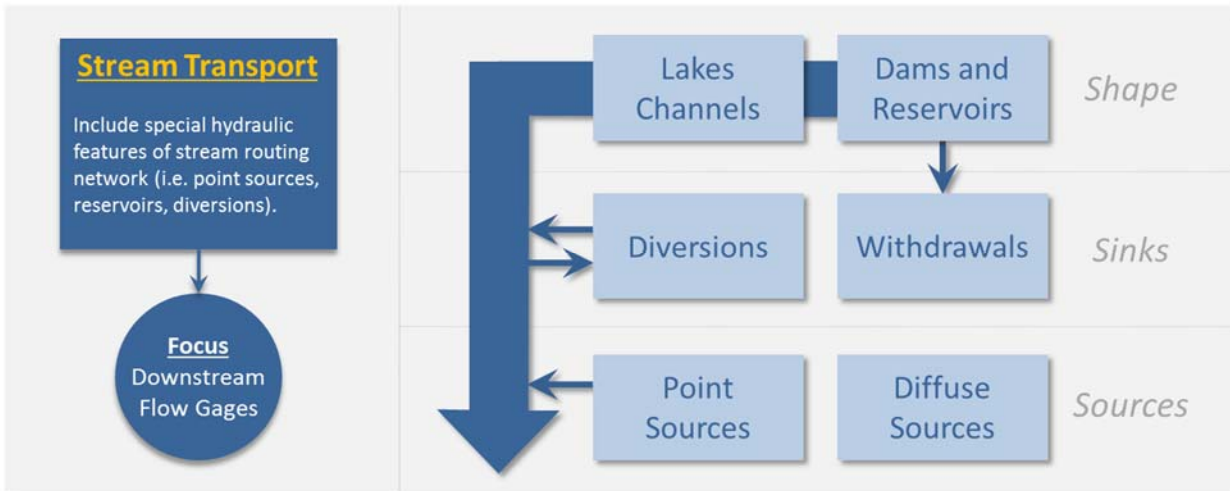


Figure 3-18. Model parameterization and calibration sequence for waterbodies and stream transport.

A two-phase weight-of-evidence approach is proposed to guide LSPC's calibration. In the first phase, the model will be set up with typical parameter values, such as those suggested in BASINS Technical Note 6: *Estimating Hydrology and Hydraulic Runoff Parameters* (EPA 2000). Land-level hydrology will be calibrated to best reflect the central tendency of land use runoff using supporting information such as geology, soil type, canopy cover, and surface cover conditions. After the model is calibrated to reflect overall trends and reasonable process dynamics, the second phase involves fine tuning the parameters and calculating various error statistics to find a most appropriate calibration within the range of acceptable parameter values to characterize instream transport routing processes in conjunction with other natural or anthropogenic activities, as applicable.

For hydrologic calibration of HSPF, performance targets have been specified in various literature sources, including Donigian et al. (1984), Lumb et al. (1994), and Donigian (2000). The LSPC model is functionally identical to the HSPF model. Based on those literature sources, performance targets for simulation of the water balance components are summarized in Table 3-3. The relative error is the ratio of the absolute mean error to the mean of the observations and is expressed as a percent. Model performance will be deemed fully acceptable where a performance evaluation of "Very Good" is attained. Nevertheless, every calibration outcome will be explained, with some insights and rationale provided for both "Very Good" to "Poor" calibration metrics in light of the top-down weight-of-evidence approach described above. If these levels are not attained, an analysis of sources of uncertainty and implications for model usability will be conducted.

Table 3-3. Performance targets for HSPF hydrology simulation (modeled vs. observed)

Model Component	Very Good	Good	Fair	Poor
Error in Total Volume	<5%	5-10%	10-15%	>15%
Error in 50% Lowest Flow Volumes	<10%	10-15%	15-25%	>25%
Error in 10% Highest Flow Volumes	<10%	10-15%	15-25%	>25%
Error in Storm Volumes	<10%	10-15%	15-25%	>25%
Winter Volume Error	<15%	15-30%	30-50%	>50%
Spring Volume Error	<15%	15-30%	30-50%	>50%
Summer Volume Error	<15%	15-30%	30-50%	>50%
Fall Volume Error	<15%	15-30%	30-50%	>50%
R^2 Daily	≥0.80	≥0.70	≥0.60	<0.60
R^2 Monthly	≥0.85	≥0.75	≥0.65	<0.65

Sources: Donigian et al. (1984), Lumb et al. (1994), and Donigian (2000)

3.6.4 Example Summaries of Model Outputs

The top-down weight-of-evidence based approach for model calibration will use a variety of graphical and statistical points of comparison. Figure 3-19 shows an example summary of a modeled long-term water balance. Figure 3-20 shows example calibrated surface runoff and evapotranspiration summaries by land use category. Some sample time series plots of corresponding modeled versus observed streamflow time series are also shown in Figure 3-21 and Figure 3-22. This series of graphs illustrates how an example flow time series from a watershed can be aggregated and presented in different ways to highlight various aspects of hydrology and instream flows as part of a top-down weight-of-evidence-based modeling approach.

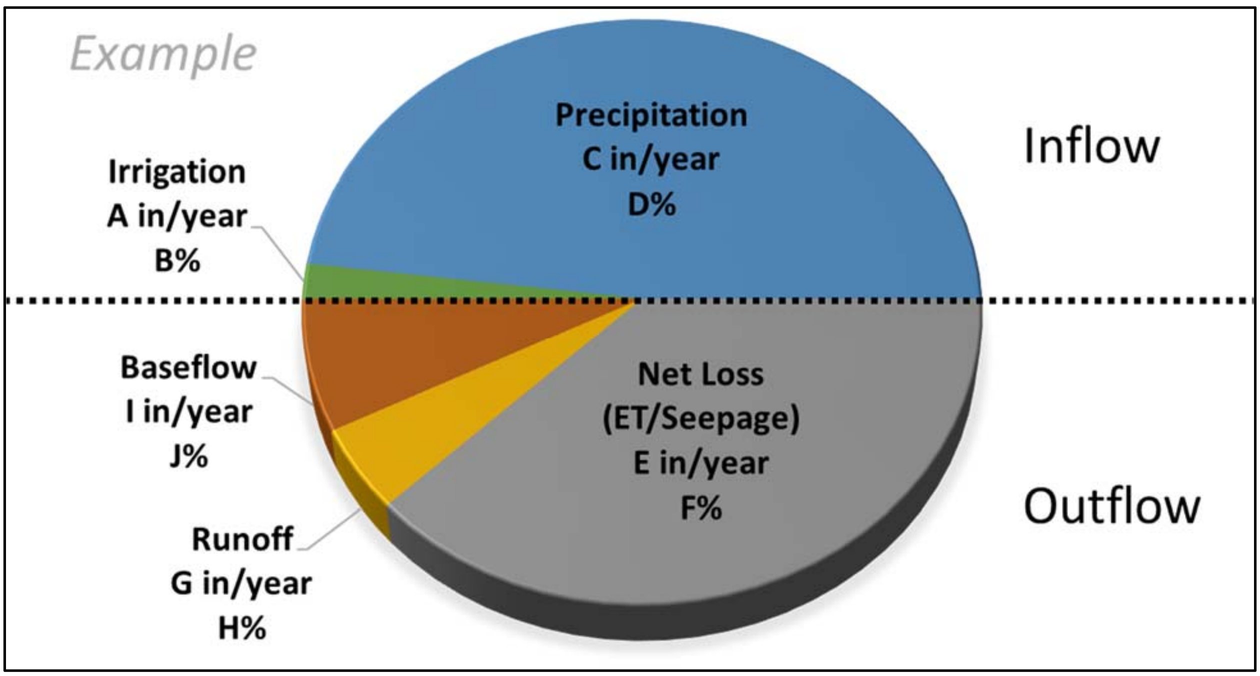


Figure 3-19. Example calibrated water balance for modeled watershed (not based on the Shasta Basin).

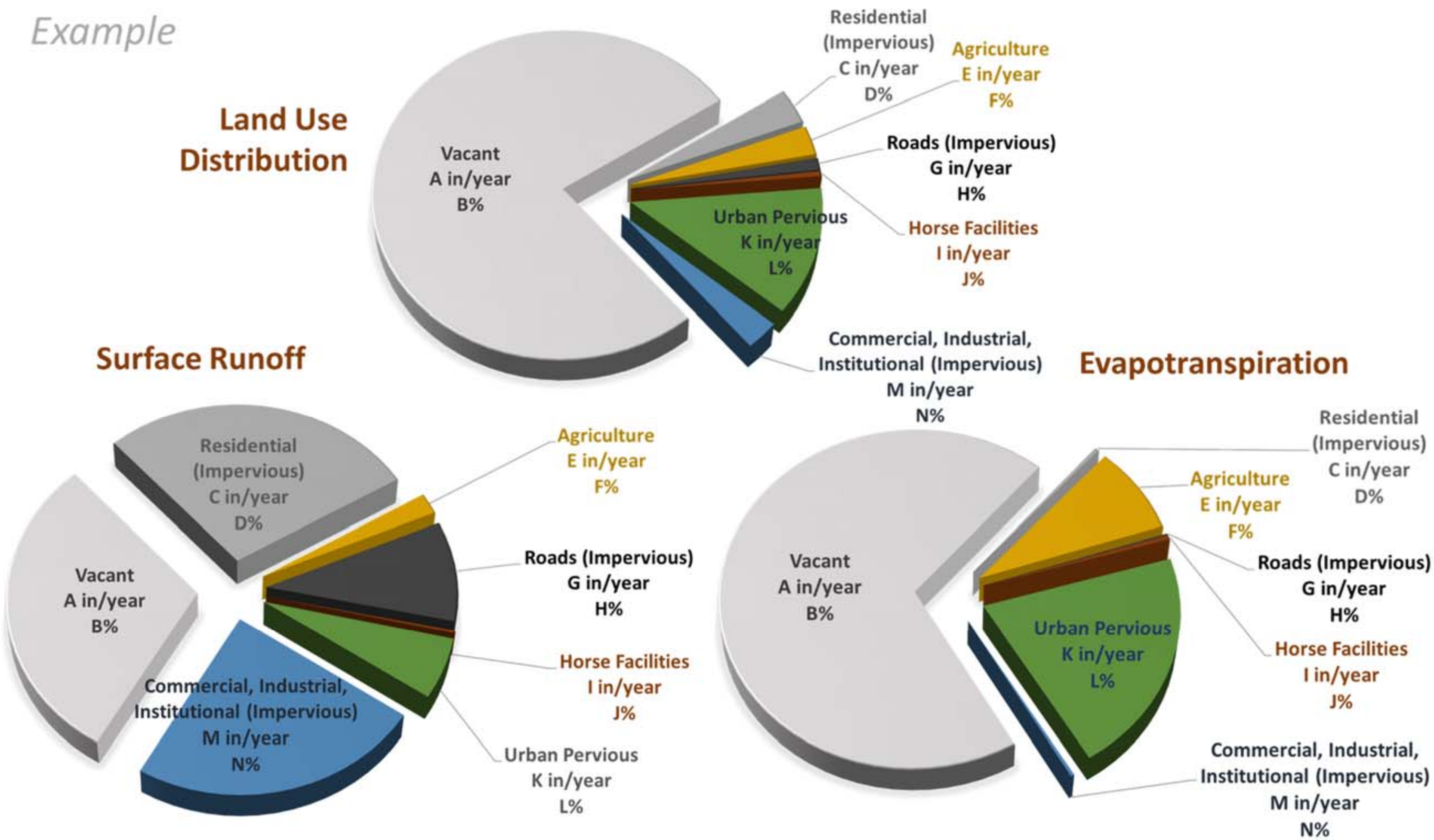


Figure 3-20. Example surface runoff and evapotranspiration summaries by land use category (not based on the Shasta Basin).

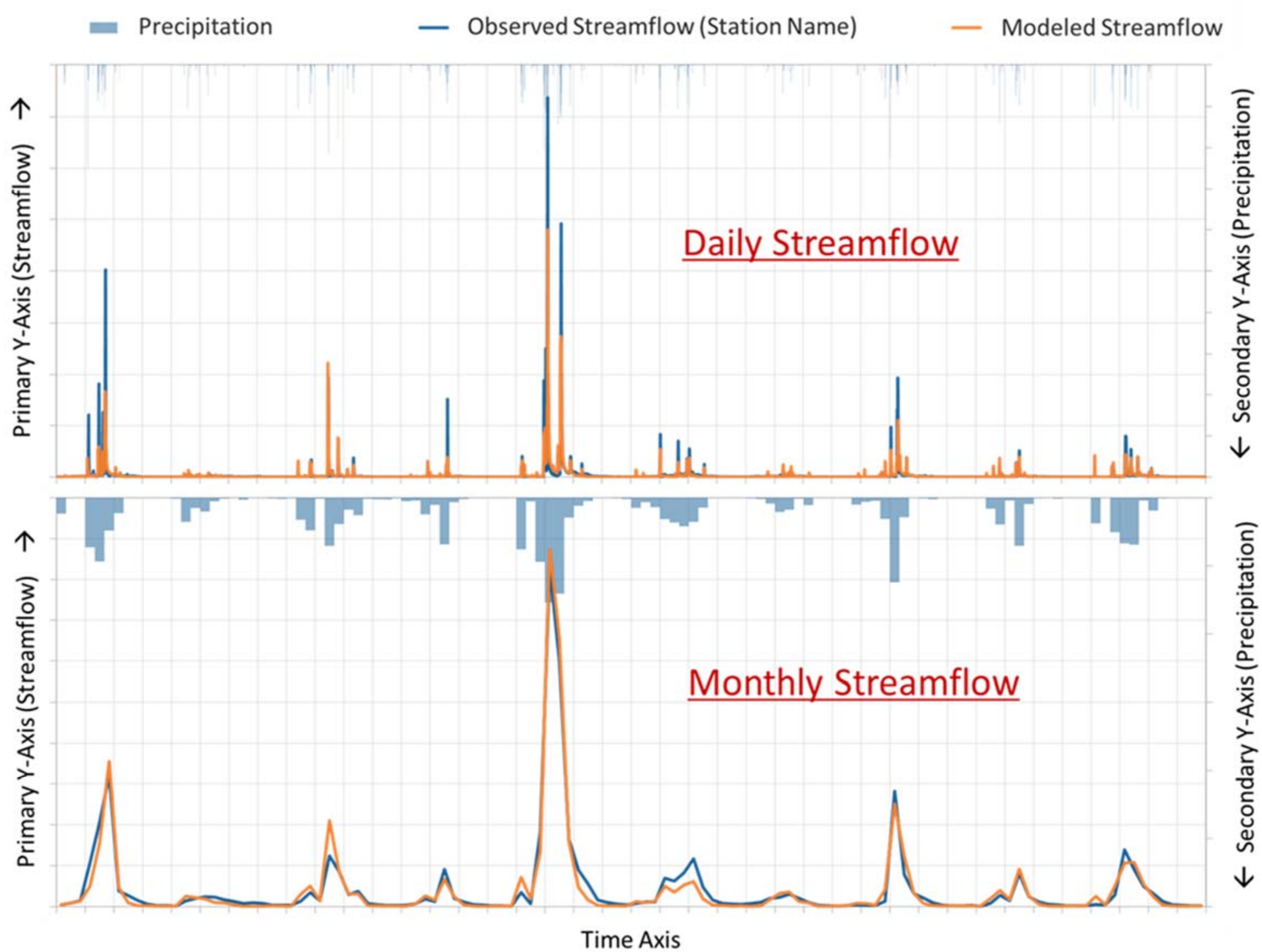


Figure 3-21. Examples of daily and monthly modeled versus observed streamflow (not based on the Shasta basin).

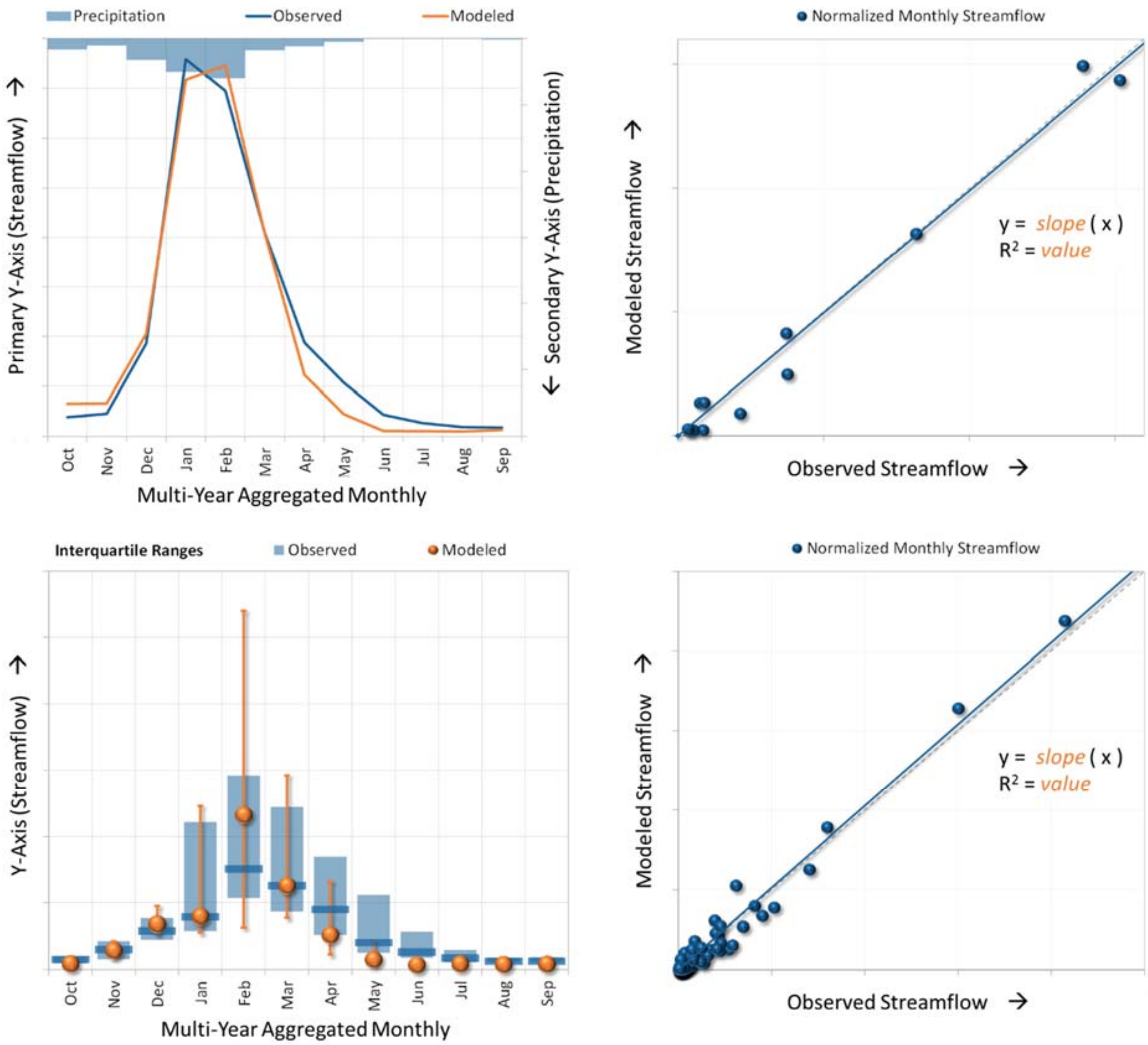


Figure 3-22. Example seasonal average and interquartile modeled versus observed streamflow (not based on the Shasta Basin).

3.6.5 Model Validation

Validation is defined as testing the model through application to a set of data not used to develop the calibration. Model validation is an extension of the calibration process. Its purpose is to test the predictive ability of the calibrated model, identify aspects of the calibration that might need further refinement, and provide information on prediction uncertainty.

Although several approaches can be used to validate a model, perhaps the most effective way is to use only a portion of the available observed values for calibration and use the rest for validation. Once final calibration parameters are developed, simulation will be performed for the remaining period of observed values and the goodness-of-fit between recorded and simulated values will be reassessed. Such a split-sample calibration and validation procedure is commonly used for evaluating model robustness. Figure 3-23 presents an overview of the model validation process which begins with testing the locked down model response for alternative points in space and time. As illustrated in Figure 3-1, the model calibration/validation process concludes with an assessment of possible data gaps or limitations in model process simulation, and recommendations for future data collection or model refinement.

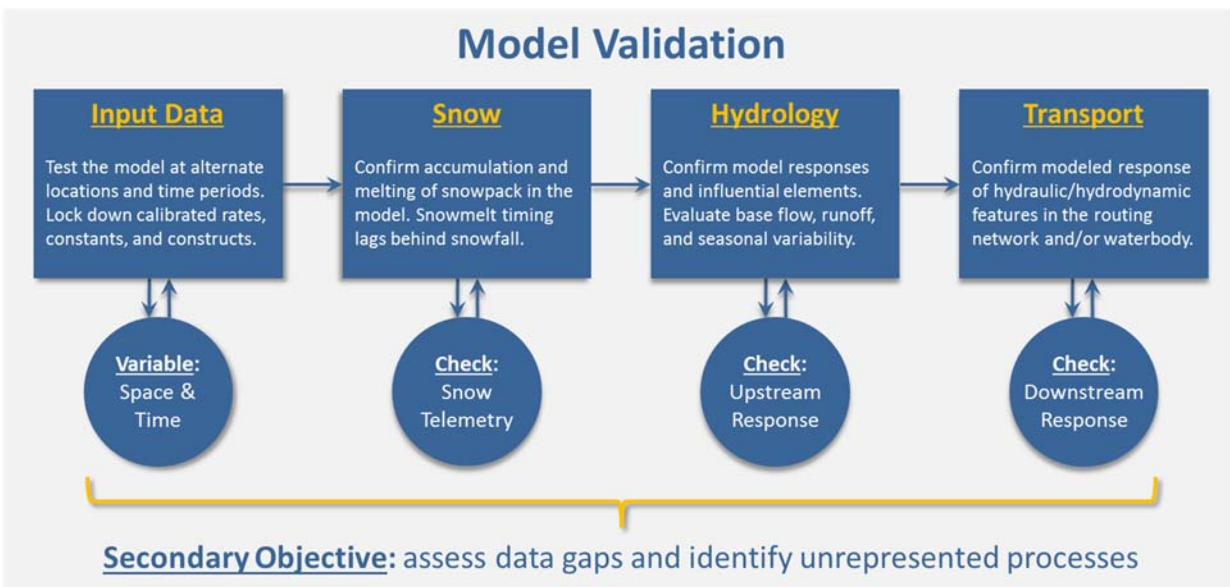


Figure 3-23. Process for model validation and identification of data gaps.

3.7 Model Scenarios to Investigate Study Objectives

Based on the calibrated model, analyses will be performed for modeled streamflow at various locations and POIs throughout the watershed to address the study objectives. Assessment will be performed for various flow regimes, including historic peak flows, low flows, annual volumes during various periods, and unimpaired flows. The analysis will support the generation of flow "return periods," or the statistical likelihood that high and low percentile flows occur within varying stream and tributary reaches of each watershed.

Figure 3-24 presents an example flow-duration curve analysis to define a critical condition flow rate during dry weather, with a focus on summer conditions. A representative watershed model can provide mechanistically-derived estimates of hydrological conditions where there are gaps in spatial or temporal resolution.

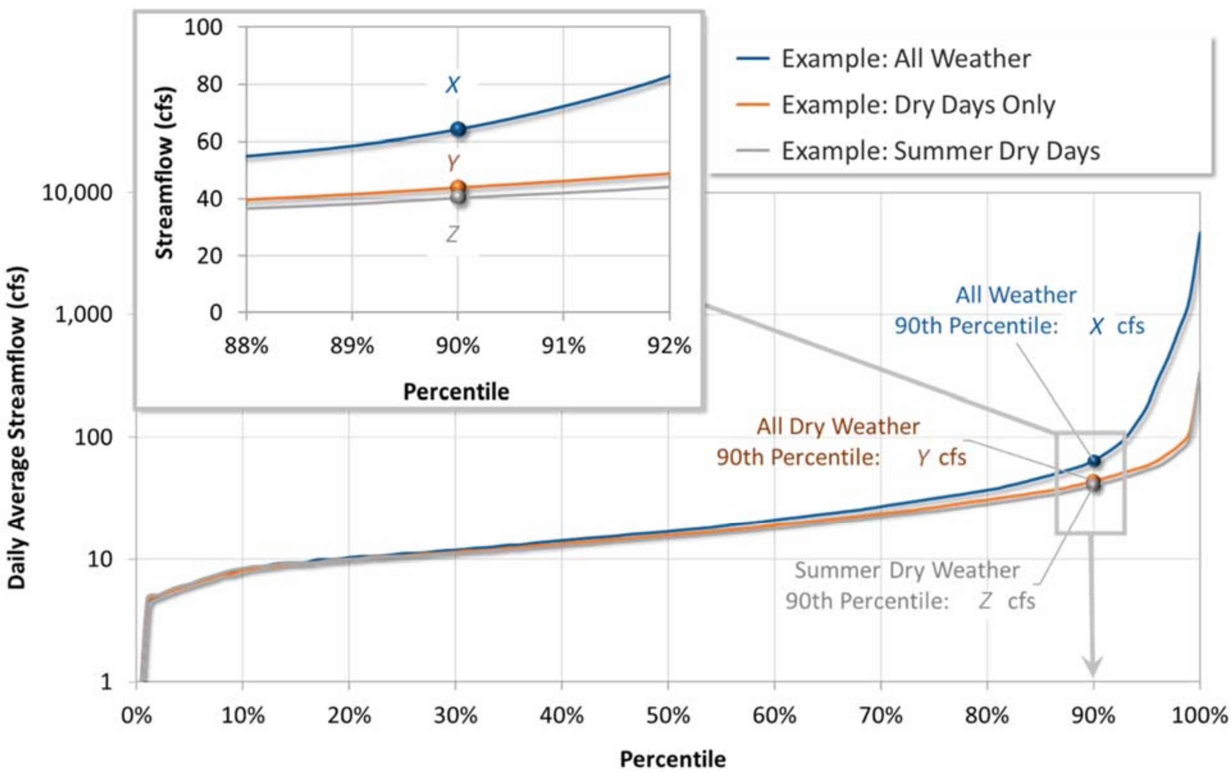


Figure 3-24. Example flow-duration curve analysis to define summer low-flow critical conditions (not based on the Shasta Basin).

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