Work Plan: Butte Creek Watershed Hydrology Model Development

SUBMITTED TO:

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ACRONYMS

3DEP	3D Elevation Program
ASCE-PM	American Society of Civil Engineers version of the Penman-Monteith equation
CA DWR	California Department of Water Resources
CAL FIRE	California Department of Forestry and Fire Protection
CDEC	California Data Exchange Center
CDFW	California Department of Fish and Wildlife
CDL	Cropland Data Layer
CDT	California Department of Technology
CIMIS	California Irrigation Management Information System
DEM	Digital Elevation Model
DWR	California Department of Water Resources
EOL	Earth Observing Laboratory
ESU	Evolutionary Significant Unit
ET	Evapotranspiration
eWRIMS	Electronic Water Rights Information Management System
FEMA	Federal Emergency Management Agency
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
HRU	Hydrologic Response Unit
HSG	Hydrologic Soil Group
HSPF	Hydrologic Simulation Program - Fortran
HUC	Hydrologic Unit Code
LCD	Local Climate Data
LSPC	Loading Simulation Program in C++
MODFLOW	USGS Modular Hydrologic Model
MRLC	Multi-Resolution Land Consortium
NCDC	National Climatic Data Center
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NLDAS	North American Land Data Assimilation System
NMFS	National Marine Fisheries Service
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutclife Model Efficiency Coefficent
PBIAS	Percent Bias
PEVT	Potential Evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Stations

SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
SWAT	Soil and Water Assessment Tool
SWRCB	State Water Resources Control Board
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
WBD	Watershed Boundary Dataset

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1. INTRODUCTION

1.1 Project Objectives

In April 2021, Governor Gavin Newsom issued a state of emergency proclamation for specific watersheds across California in response to exceptionally dry conditions throughout the state. The April 2021 proclamation, as well as subsequent proclamations, directed the State Water Resources Control Board (Water Board) to address these emergency conditions to ensure adequate, minimal water supplies for critical purposes. To support Water Board actions to address emergency conditions, hydrologic modeling and analysis tools are being developed to contribute to a comprehensive decision support system that assesses water supply and demand, and the flow needs for watersheds throughout California.

This work plan presents the available data and methodology that will be used to develop a hydrologic model of the Butte Creek watershed. This model will use historical records of precipitation, temperature, and evapotranspiration (ET) for simulation of processes associated with surface runoff, infiltration, interflow, and shallow groundwater flow. The final calibrated model will be used to evaluate scenarios including current hydrologic conditions, water allocation, changes in demand, and the impact of extreme events (e.g., droughts, atmospheric rivers, etc.).

1.2 Watershed Background

Butte Creek is one of the major tributaries of the Sacramento River. The non-estuarine Butte Creek watershed (HUC-8) area drains approximately 820 square miles and is made up of 17 HUC-12 subwatersheds (Figure 1-1). Butte Creek begins at around 7,000 feet of elevation in the forested Butte Meadows/Jonesville Basin (Sacramento River Watershed Program 2024) region almost 50 miles north of Chico, California, and flows 93 miles south-east through the Sacramento Valley amongst nearby volcanic plateaus, or "buttes", into a primarily agricultural region (Water Education Foundation 2023). Throughout its path, flows within the upper section of Butte Creek watershed is diverted at multiple locations for hydroelectric power generation, and the lower section of the watershed is utilized for irrigation and flood mitigation (Sacramento River Watershed Program 2024). The watershed has retained its rural nature with less than 6% of land cover being developed area, and the primary land cover being cultivated crops at 52% of the total watershed area (Dewitz 2023).

Butte Creek has a distinct wet and dry season with a mean annual precipitation ranging between 20 inches in the valley and 50 inches in the higher elevation headwaters (Sacramento River Watershed Program 2024). The watershed also acts as a habitat for the largest naturally spawning chinook salmon population in the Central Valley. However, there have been substantial declines in salmonid populations over time. The National Marine Fisheries Service (NMFS) lists 2 chinook salmon species as endangered, and 7 species as threatened under the federal Endangered Species Act (RWQCB North Coast Region 2000). Increased water temperature is a definite concern, as it negatively impacts the anadromous fish passage and survival. Sediment from surface erosion (roads, logging operations, etc.) is also a concern for the same reasons. Other fish are native to the creek as well, including Pacific Lamprey and Sacramento Pikeminnow.

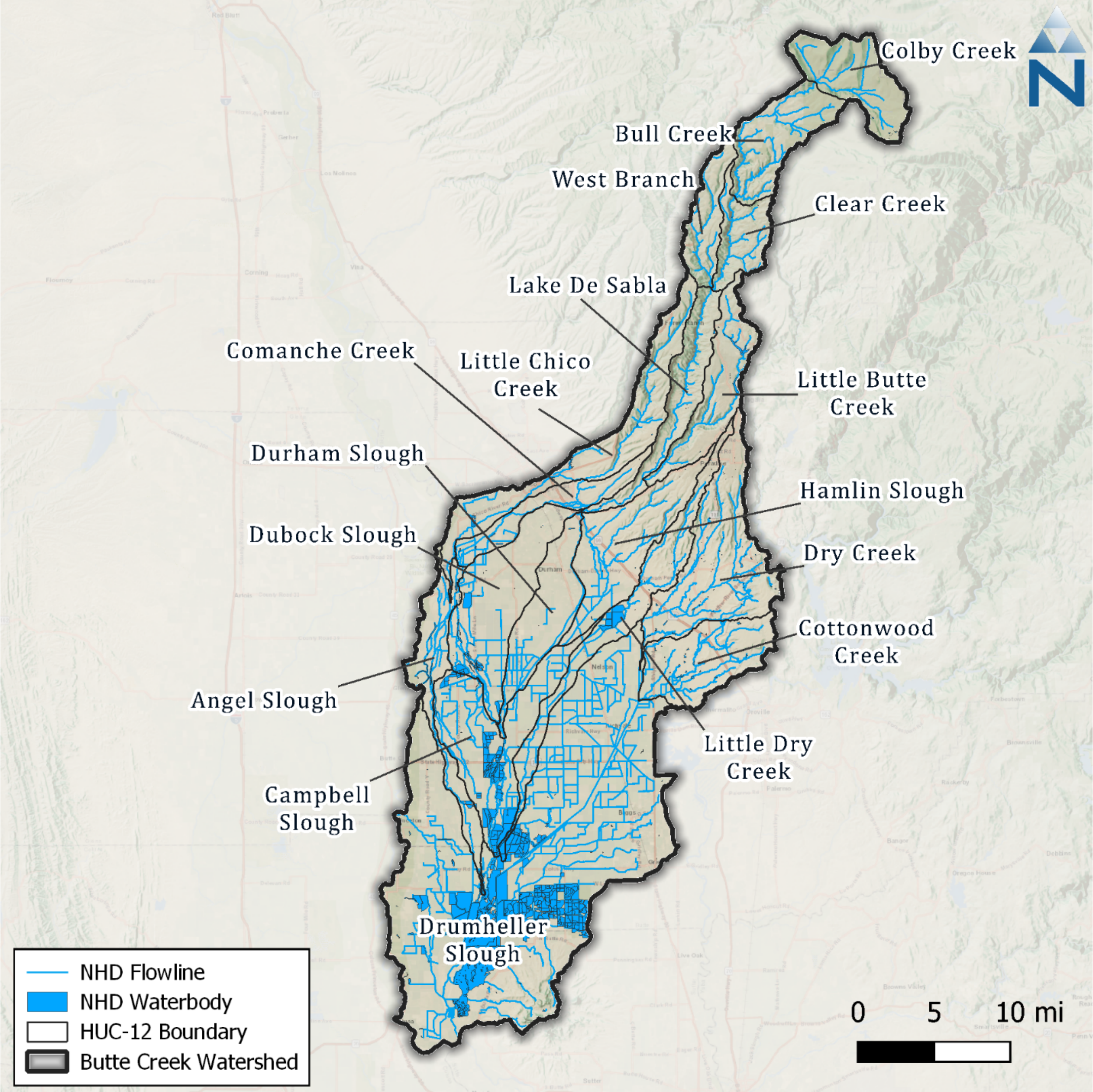

Figure 1-1. The Butte Creek watershed.

1.3 Model Approach

The primary goal of this work plan is to outline an approach with sufficient robustness to support an analytical assessment of the Butte Creek watershed. This is presented first through a comprehensive inventory of available hydrologic, meteorological, and geographic information system (GIS) data available for the Butte Creek watershed. The data compilation and assessment process is outlined below and aims to highlight any existing data gaps that create limitations for the analysis. Based on the available data, any data gaps are identified which may be filled through additional outreach, data collection efforts, or noted as points of uncertainty in the model documentation.

This hydrologic analysis is based on a model development process that has been a tested platform for gaining valuable information and insight about hydrologic systems. The model development process proposed is an iterative and adaptive cycle that improves understanding of the system over time as better information becomes available. Figure 1-2 is a conceptual schematic of the proposed model development cycle, which is represented as circular as opposed to linear. The cycle can be summarized in six interrelated steps:

1. **Assess Available Data**: Data for source characterization, trends analysis, and defining modeling objectives.
2. **Delineate Model Domain**: Model segmentation and discretization needed to simulate streamflow at temporal and reach scales appropriate for assessing supply and demand.
3. **Set Required Model Inputs**: Spatial and temporal model inputs defining the appropriate hydrologic inputs and outputs.
4. **Represent Processes (Calibration)**: Adjustment of model rates and constants to mimic observed physical processes of the natural system.
5. **Confirm Predictions (Validation)**: Model testing with data not included in the calibration to assess predictive ability and robustness.
6. **Assess Applicability for Scenarios**: Sometimes the nature of modeled responses can indicate the influence of unrepresented physical processes in the modeled system. Sometimes that can be resolved with minor parameter adjustments, while other times the assessment exposes larger data gaps. A well-designed model can be adapted for future applications as new information about the system becomes available. Depending on the study objectives, data gaps sometimes provide a sound basis for future data collection efforts to refine the model. New information may require minor parameter adjustments affecting the configuration or calibration.

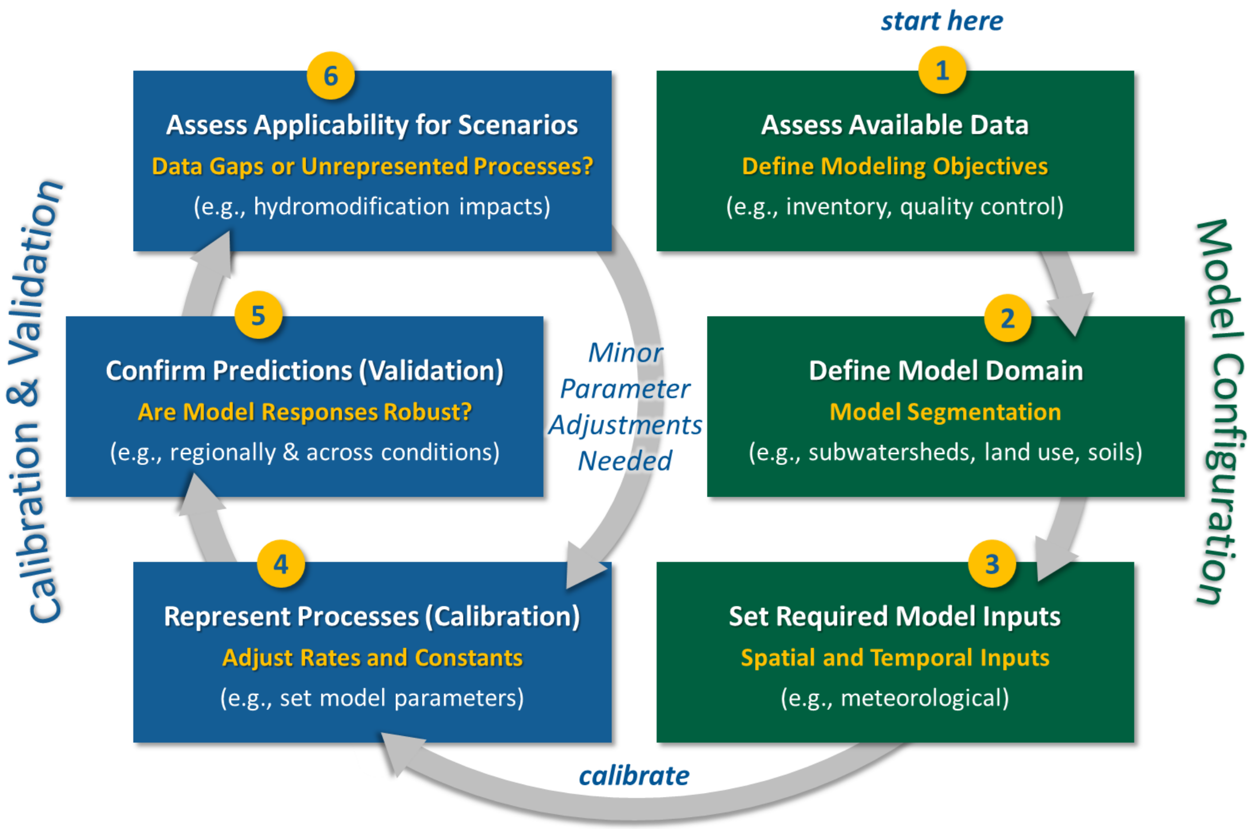

Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Butte Creek watershed.

1.4 Data Availability

Table 1-1 through Table 1-3 present an inventory of the initial data collected that will form the basis of this modeling workplan These datasets were compiled from readily available sources, primarily those publicly available and published online by state and federal agencies. The data in the tables are organized by data type including:

- **Meteorology Datasets**: Time series that represent water balance inputs and outputs to the watershed primarily from precipitation , evapotranspiration, temperature, solar radiation, dew point, and wind speed. These time series are often used as forcing functions for hydrologic models.
- **Surface & Groundwater Datasets**: Datasets describing Snow Water Equivalent (SWE), stream flow, groundwater, water use, and stream conditions for Butte Creek. Time series observations of instream responses for the Butte Creek are often used as calibration and validation datasets for hydrologic models.
- **Geospatial Datasets**: Spatial datasets describing the landscape of the Butte Creek watershed. These datasets include physical properties (e.g., soils, land cover, elevation).

Each of these types of datasets is described in the sections below.

Table 1-1. Inventory of meteorology datasets

Data Source	Data Set	Data Date	Description	Model Use
National Climatic Data Center (NCDC)	Global Historic Climate Network (GHCN)	--	Daily precipitation and temperature data (varied data quantity/quality).	Rainfall input boundary time series.
National Climatic Data Center (NCDC)	Local Climate Data (LCD)	--	Hourly precipitation, temperature, wind speed, dewpoint, cloud cover.	Rainfall input boundary time series.
Remote Automated Weather Stations (RAWS)	Hourly Climate Data	--	Meteorological records for Atlas Peak.	Climate data boundary time series.
California Data Exchange Center (CDEC)	Precipitation, Temperature, Snow	--	Meteorological records available for 12 stations.	Rainfall input boundary time series.
PRISM Climate Group	AN81m Monthly	1900- Present	4-km grid resolution time series of precipitation (1900 – present).	Rainfall time series QA; address rainfall data gaps.
North American Land Data Assimilation System (NLDAS)	NLDAS-2 Forcing Data	1979 - Present	1/8th-degree grid resolution hourly time series of precipitation and other surface parameters (e.g., temperature).	Rainfall hourly distributions; address rainfall data gaps.
Earth Observing Laboratory (EOL)	Daily/Hourly Gridded Precipitation	--	Various gridded precipitation time series; both daily and hourly time steps.	Rainfall hourly distributions; address rainfall data gaps.
California Irrigation Management Information System (CIMIS)	Reference Evapotranspiration	1990 – Present	Relative evapotranspiration spatial zones and monthly scaling factors. There is also a grid-based model data product.	Deriving PEVT input boundary time series.
Snow Telemetry (SNOTEL)	Daily Snow Water Equivalent	--	Daily snow water equivalent data (some stations also collect snow depth and other meteorological records)	Assessing the performance of model snow simulation module

Table 1-2. Inventory of surface water datasets

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Streamflow	Local	USGS	Stream Gage Discharge	1929 – Current	Observed streamflow at one active location and several inactive locations, using recent data to support calibration.	Hydrology calibration	LINK
Water Budget	State	CA DWR	Well Completion Reports	Current	Well-completion logs and reports.	Water budget.	LINK
			Interconnected Surface Water	2008	One (1) river flow CDEC station and two (2) rain CDEC stations identified as interconnected.		LINK
		SWRCB eWRIMS	Water Rights Points of Diversion	Current	Locations where water is being drawn from a surface water source such as a stream or river.		LINK
			Water Rights Overview Report	Current	This report will provide counts of various entities such as Applications, Registrations, Petitions etc. that will reflect the progress in processing such entities as of current date.		LINK
			Annual Water Use Report	1906 – 2023	Annual reports that provide monthly diversion data for various entities such as Applications, Registrations, Petitions, etc.		LINK
		CA DWR	Agricultural Land and Water Use Estimates	1998 – 2015	Water use estimates by various planning units.		LINK
		CDT	Water Districts	2022	Boundaries of all public water agencies in California.		LINK
			California Drinking Water System Locations	2023	Public California drinking water systems and state small drinking water system boundaries and information.		LINK

Table 1-3. Inventory of geospatial datasets

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Watershed Boundaries	National	USGS	Watershed Boundaries (WBD)	2023	Hydrologic unit boundaries to the 12-digit (6th level).	Model segmentation	LINK
Hydrology	National	USGS	National Hydrography Dataset (NHD) Plus High-Resolution National Release 1	2023	The NHDPlus HR combines the NHD, 3DEP DEMs, and WBD to create a stream network with linear referencing.		LINK
			National Hydrography Dataset (NHD) Best Resolution	2023	1:24,000; represents reaches and other network elements.		LINK
Soil	National	USDA NRCS	Grided Soil Survey Geographic Database (gSSURGO)	2022	State-wide, 10-meter raster grid approximating the SSURGO vector dataset.	Represent infiltration process within land segments.	LINK
Surficial Geology	National	USGS	The State Geologic Map Compilation (SGMC)	2017	1:1,000,000: Vector-based, state geologic map database.	As needed, hydrologic process with land segments.	LINK
Land Cover	National	MRLC	National Land Cover Dataset (NLCD) Land Cover	2021	Broad, 30 m grid-based land characterization. Differentiates developed land from coarse classifications of forest, cropland, wetlands, etc.	Land segment representation.	LINK
			National Land Cover Dataset (NLCD) Imperviousness All Years	2021	Broad, 30-meter grid-based land characterization. Represent percent impervious area within raster cells.		LINK
Land Use	State	CA DWR	Statewide Crop Mapping	2020	Polygons attributed with DWR crop categories.	Identify crop distributions; estimate irrigation demand.	LINK
	Local		Mendocino County Southwest Land Use	2010	DWR County land use survey.	Land segment representation.	LINK

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Vegetation	National	MRLC	Tree Canopy Cover	2021	Percent tree canopy estimates for each 30-meter pixel across all land covers and types.	Land segment representation.	LINK
	State	USFS	Existing Vegetation	2018	1:24,000 to 1:100,000: Existing vegetation mapping.	As necessary, additional vegetation types for model land segments.	LINK
Agriculture & Crop Cover	National	USDA	Cropland Data Layer	2022	30-meter grid-based crop-specific land cover data layer.	Identify crop distributions; estimate irrigation demand.	LINK
Timber Harvesting	National	USDA	Timber Harvests	1820 - Present	Area planned and accomplished acres treated as a part of the timber harvest program of work.	Representing changes in land cover due to timber harvest activities.	LINK
	State	CAL FIRE	CAL FIRE Nonindustrial Timber Management Plans TA83	1991 - Present	Timber management plans.		LINK
			CAL FIRE Notices of Timber Operations TA83	1991 - Present	Notice of Timber Operations accepted by CAL FIRE.		LINK
			CAL FIRE Working Forest Management Plans TA83	2019 - Present	Working forest management plans approved by CAL FIRE.		LINK
Fire Perimeters & Burn Areas	State	CAL FIRE	California Fire Perimeters	1950 - Present	Wildfire perimeters.	Representing changes in land cover due to forest fire activities.	LINK
			Prescribed Burns	1950 - Present	Prescribed burns perimeters.		LINK
Elevation	National	USGS	USGS one meter resolution digital elevation model (DEM)	2017	1-meter resolution digital elevation model (DEM) produced through the 3D Elevation Program (3DEP).	Land segment representation.	LINK

2 METEOROLOGY

Precipitation and evapotranspiration (ET) are key components of the water balance and critical inputs for developing a hydrologic model. The following subsections describe the primary data sources for precipitation and evapotranspiration.

2.1 Precipitation

The primary source of precipitation data for the Butte Creek watershed will be the observed data from land-based stations within and in vicinity of the watershed (Table 2-1). However, the gaps in observed data from the land-based stations will be filled with grid-based data. This is referred to as the "hybrid" approach, which has shown promising results by leveraging the strengths of both land-based and grid-based data. Use of a hybrid approach preserves locally sampled gauge data while increasing the spatial and temporal quantity and quality over the watershed. This approach has been applied for large watershed-scale modeling applications including the County-wide model for Los Angeles County (LACFCD 2020).

Land-based observed precipitation data are mainly acquired from the National Climatic Data Center (NCDC) climate networks including the Global Historic Climate Network (GHCN), the Cooperative Observer Program (COOP), and the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS). These networks provide quality-controlled hourly or daily observed precipitation and temperature data. There are 55 GHCN, Co-Op, CoCoRaHS, or other NOAA gages identified within and around the Butte Creek watershed. These gauges all have data with varied quantity and quality. The California Data Exchange Center (CDEC) reports precipitation at 11 locations within or near the watershed, Remote Automated Weather Stations (RAWS) networks report at 7 locations, and Local Climate Data (LCD) reports at 2 locations. Table 2-1 is an inventory of the precipitation stations near the Butte Creek watershed with available data after 2000 and generally with 90% completeness or better; Figure 2-1 shows the location of the stations proposed for model development in Table 2-1.

The primary source of the grid-based data for Butte Creek Watershed will be the Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM is developed and maintained by the PRISM Climate Group at Oregon State University and 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). Because of its spatial and temporal resolution and consistency across the lower 48 contiguous United States (4-km spatial resolution for the AN81d daily/monthly time series dataset and 800-m for the AN81m long term averages), PRISM is a commonly used and widely accepted source for meteorological data for hydrologic models (Behnke et al. 2016). The PRISM grid is shown in Figure 2-1.

Table 2-1. Summary of precipitation stations with observations available after 2000

Agency	Station ID[1]	Name	Start Date	End Date	Lat.	Long.	Elevation (meters)	Data Coverage (%)[2]
NOAA-LCD	WBAN:93203	CHICO ARMY FLYING SCHOOL, CA US	2/24/2005	11/25/2023	39.8	-121.85	82.9	100%
	WBAN:93210	OROVILLE MUNICIPAL AIRPORT, CA US	12/31/2004	11/25/2023	39.4943	-121.622	56.9	100%
NOAA-GHCN	GHCND:USC00041715	CHICO UNIVERSITY FARM, CA US	1/7/1906	3/27/2024	39.6911	-121.821	56.4	91%
	GHCND:USC00041948	COLUSA 2 SSW, CA US	9/30/1948	1/30/2024	39.1875	-122.027	15.2	97%
	GHCND:USW00093210	OROVILLE MUNICIPAL AIRPORT, CA US	6/12/1998	3/28/2024	39.4943	-121.622	56.9	99%
	GHCND:USC00046685	PARADISE, CA US	4/30/1957	8/28/2022	39.7538	-121.624	533.4	97%
NOAA-CoCoRaHS	GHCND:US1CABT0026	GRIDLEY 3.3 SE, CA US	12/6/2014	3/29/2024	39.33481	-121.646	28	98%
	GHCND:US1CABT0033	PALERMO 2.7 SE, CA US	11/17/2016	3/30/2024	39.4064	-121.5	84.1	100%
CDEC	DSB	DE SABLA (PG&E)	10/1/1989	9/30/2018	39.867	-121.617	2710	--
	HMB	HUMBUG	1/1/1984	Present	40.115	-121.368	6500	--
	JAR	JARBO GAP	8/27/2003	Present	39.736	-121.489	2700	--
	OPS	OPENSHAW	4/17/2014	Present	39.58983	-121.635	268	--
	PDE	PARADISE	1/13/2006	Present	39.7536	-121.625	1750	--
RAWS	CDEC1	CARPENTER RIDGE	7/1/2000	Present	40.06866	-121.584	4816	--
	CICC1	OPENSHAW	4/1/2014	Present	39.58983	-121.635	268	--
	CSTC1	COHASSET	5/1/1990	Present	39.87184	-121.769	1733	--
	JBGC1	JARBO GAP	4/1/2003	Present	39.73591	-121.489	2535	--
	NWRC1	SAC NWR	7/1/2001	Present	39.41722	-122.183	120	--
	CBXC1	COLBY MOUNTAIN	6/1/2015	Present	40.14564	-121.523	6004	--
	TR181	PNF23 PORTABLE	6/26/2001	3/29/2024	39.80008	-121.511	2367	--

1. Stations presented have at least 90% data coverage.

2. NCDC and NOAA data coverage as reported; CDEC and RAWS estimated based on data flagging and count of time steps. Data completeness will be further assessed under Task 3.2 and additional stations may be considered as required.

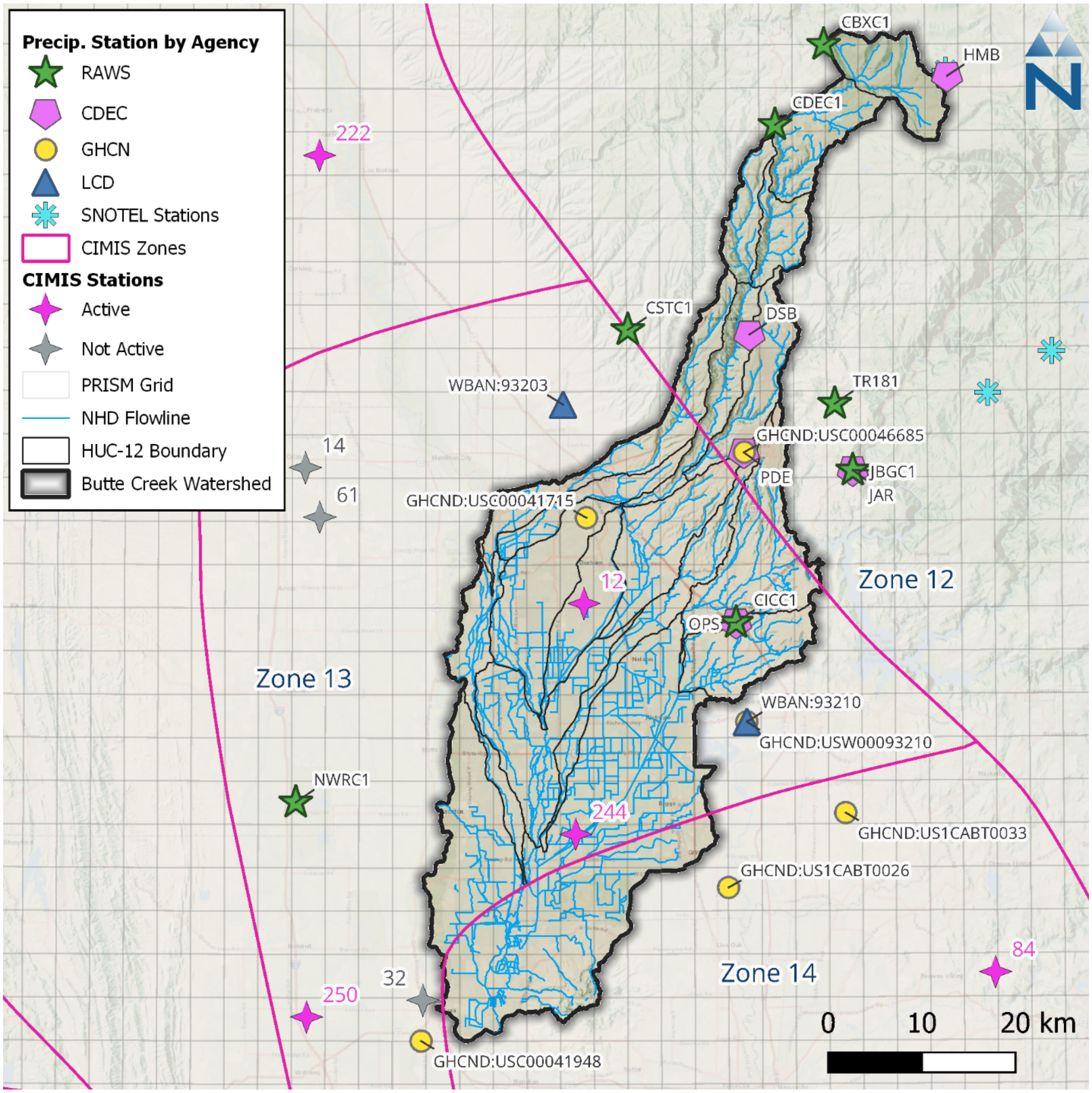

Figure 2-1. Identified rainfall gauges and CIMIS ET Zones near Butte Creek watershed.

The hybrid approach entails three main steps. First, impaired intervals (i.e., missing, or accumulated) at observed stations are patched with data from nearby gauges. Second, observed gages are mapped to the nearest PRISM grid cell and temporally complete hourly observed data distributions are used to downscale the monthly PRISM gridded data. The resulting set of gridded precipitation time series reflect monthly PRISM totals that have hourly distributions from the nearest observed gage If the number of sub-daily time series from observed data are limited, hourly data from North American Land Data Assimilation System (NLDAS) will be used to supplement observed distributions for downscaling the PRISM data. Third, the downscaled gridded meteorological data from the PRISM are used to fill spatial gaps in the observed station network as needed. It should be noted that while PRISM gridded data also provides estimates of precipitation on daily time step, using monthly PRISM totals for downscaling with hourly observed data, as opposed to daily PRISM totals, eliminates the need to estimate distributions for instances where an hourly distribution does not coincide with a daily total.

Figure 2-2 presents a summary of the hybrid approach to blend observed precipitation with gridded meteorological products. Observed data and gridded products are processed in parallel to: (1) create a temporally complete set of hourly distributions and (2) identify spatial gaps in coverage to be supplemented using downscaled gridded data. Assuming a 10-km buffer around observed gauges for this approach, the coverage shown in the lower right map in Figure 2-2 shows what a hybrid dataset of observed time series, supplemented by gridded products would look like.

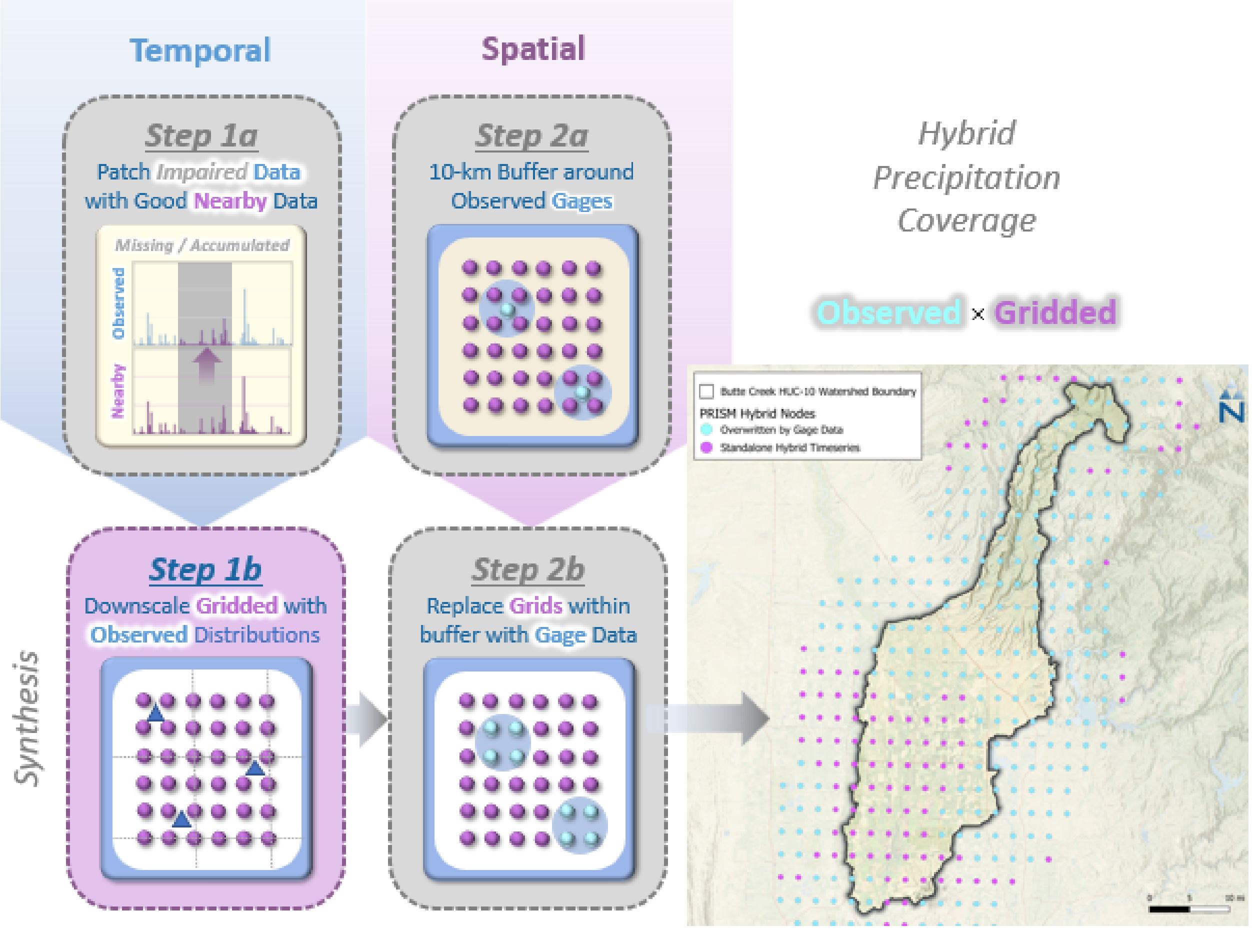

Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products.

2.2 Evapotranspiration

The primary evapotranspiration dataset identified for consideration is the California Irrigation Management Information System (CIMIS). CIMIS was developed in 1982 by the California Department of Water Resources (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, relative humidity, wind speed, and solar radiation are monitored and quality controlled. Observations are measured over standardized reference surfaces (e.g., well-watered grass or alfalfa) and are used to estimate reference evapotranspiration (ET_o) using versions of the Penman and Penman-Monteith equations. CIMIS has divided California into 18 zones based on long-term monthly average ET_o values calculated using data from CIMIS weather stations.

CIMIS operates four stations within 10 miles of the Butte Creek watershed, which include Durham (station 12), Biggs (244), Williams (250), and Colusa (32). The Colusa station, just west of the southern Butte Creek watershed border, is no longer operating, but its historical time series data covers the period from January 1983 through August 2016. There are also two other inactive stations, Orland (61), which was active from May 1987 through May 2010, and Orland (14), active from October 1982 through April 1987, that are just outside the 10-mile watershed buffer. The Durham gage is within the Butte Creek watershed and contains data from October 1982 through the present. The Biggs gage is also within the Butte Creek watershed and contains data from June 2015 through the present. The Williams gage is west of the southern end of the Butte Creek watershed border and contains data from August 2016 through the present (CIMIS 2024).

Representative potential ET time series can also be estimated for the Butte Creek watershed by first using data from RAWS meteorological data from the watershed area to calculate time series (e.g., using the Penman or Penman-Monteith equations), and then scaling those time series by monthly reference ET coefficients by ET zone obtained from the CIMIS dataset. As shown in Figure 2-1, the Butte Creek watershed intersects three CIMIS zones with 64% of the watershed area in Zone 12 (East Side Sacramento-San Joaquin Valley), 22% of the watershed area in Zone 13 (Northern Sierra Nevada), and 14% of the watershed area in Zone 14 (Mid-Central Valley, Southern Sierra Nevada, Tehachapi & High Desert Mountains). The northernmost end of the watershed falls into CIMIS zone 13, the middle watershed region falls into zone 12, and the southernmost watershed end falls into zone 14. These zones experience total annual reference evapotranspiration levels from 53.3 inches per year in Zone 12 to 57.0 inches per year in Zone 14 (CIMIS 2024).

CIMIS also has a newly derived gridded product, CIMIS Spatial, that expresses daily ET_o estimates calculated at a statewide 2-km spatial resolution using the American Society of Civil Engineers version of the Penman-Monteith equation (ASCE-PM). The ASCE-PM method calculates ET_o using solar radiation, air temperature, relative humidity, and wind speed at two meters height (California Department of Water Resources 2024). This product provides a consistent spatial estimate of ET_o that is California-specific, implicitly captures macro-scale spatial variability and orographic influences, is available from 2003 through Present, and is routinely updated within a couple of days.

In addition to precipitation, a unique potential evapotranspiration forcing input time series is assigned to each catchment. Those time series are consistently derived and provide a robust catchment-scale reference condition which, in the case of CIMIS, are derived using ASCM-PM and a suite of meteorological conditions. Within each catchment, actual ET is calculated for each Hydrologic Response Unit (HRU) during model simulation as a function of parameters representing differences in vegetation (type, height, and density) and soil conditions.

2.3 Other Meteorological Data

In addition to precipitation and evapotranspiration, LSPC also uses time series of air temperature, wind speed, solar radiation, and dew point temperature to simulate snow processes using an energy balance approach. Snow is important component of the water budget for the Butte Creek Watershed. The NLDAS gridded data provides continuous records of hourly data for those parameters, which will be used as input into the model. The NLDAS datasets are the result of collaboration between several groups, including NOAA and NASA. The NLDAS data were developed using a forcing dataset from a daily gage-based precipitation analysis (temporally disaggregated to hourly using Stage II radar data), and bias-corrected shortwave radiation. NLDAS is available at 1/8th degree (approximately 8.4 miles) spatial resolution on an hourly basis.

3 SURFACE HYDROLOGY

3.1 Watershed Segmentation

The United States Geological Survey (USGS) delineates watersheds nationwide based on surface hydrological features and organizes the drainage units into a nested hierarchy using hydrologic unit codes (HUC). These HUCs have a varying number of digits to denote scale ranging from 2-digit HUCs (larges) at the region scale to 12-digit HUCs (smallest) at the subwatershed scale. The Butte Creek watershed is defined by a HUC-8 watershed that comprises 17 HUC-12 subwatersheds.

For units smaller than HUC-12 subwatersheds, catchment and tributary boundaries, flow lines, outlet points and related attribute information will rely on the National Hydrography Dataset (NHD) hydrologic unit code (HUC) and catchment delineations. This analysis will primarily use readily available data to define the outer watershed boundary. Any available local data will be used to supplement and refine the understanding of tributary boundaries and reach geometry. NHD Plus High Resolution (NHDPlus) further discretizes the watershed into 1,052 catchments ranging in size between 0.0003 square miles to over 52 square miles. Table 3-1 presents summary statistics of NHDPlus catchment sizes by HUC-12 subwatershed. Figure 3-1 is a map of HUC-12 and NHDPlus catchments within the Butte Creek watershed (HUC-8).

Table 3-1. Summary of NHDPlus catchment sizes (acres) within the Butte Creek HUC-8

HUC-12 Name	Count of Catchments	Catchment Size (acres)			
		Minimum	Mean	Median	Maximum
Angel Slough	51	0.9	325.0	151.9	3,816.5
Bull Creek	21	22.0	917.1	868.0	2,453.5
Campbell Slough	101	0.4	323.9	82.1	2,688.8
Clear Creek	26	0.2	434.6	325.8	1,855.4
Colby Creek	17	11.1	1122.6	962.1	2,697.0
Comanche Creek	25	3.1	496.0	239.7	3,877.0
Cottonwood Creek	68	0.4	333.9	199.0	2,057.2
Drumheller Slough	328	0.2	541.5	78.8	33,410.1
Dry Creek	80	1.6	455.8	328.6	1,873.2
Dubock Slough	74	0.2	383.4	179.1	2,055.4
Durham Slough	42	0.2	458.1	213.2	3,942.8
Hamlin Slough	51	9.8	534.3	363.6	2,498.8
Lake De Sabla	24	0.2	684.3	190.6	3,682.9
Little Butte Creek	40	1.6	488.4	392.0	1,937.7
Little Chico Creek	57	0.8	540.6	378.1	3,786.8
Little Dry Creek	33	5.6	687.3	392.0	6,913.4
West Branch	14	75.5	787.1	603.4	1,895.1

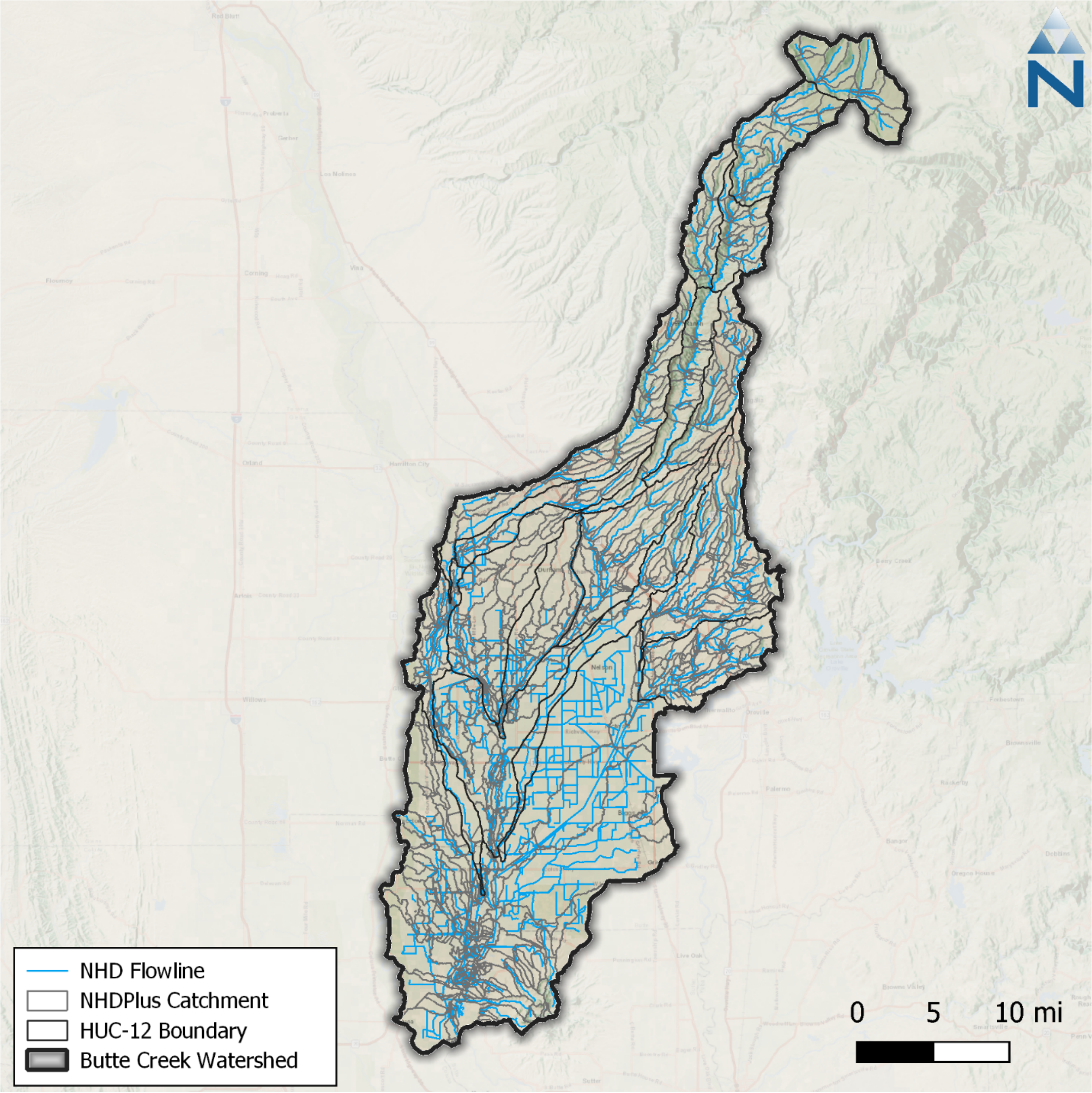

Figure 3-1. Initial catchment segmentation for the Butte Creek watershed.

The NHDPlus dataset provides a good foundation for model segmentation at a spatial scale suitable for modeling watershed streamflow for comparison at daily, seasonal, and annual temporal bases. While the proposed model segmentation is discussed further in Section 7, NHDPlus catchment boundaries will be aligned with the model boundaries and referenced against selected points of interest (e.g., flow monitoring sites) to allow for direct output of model results for comparison and analysis.

3.2 Streams and Channels

The hydrographic characteristics of the streams and rivers within the Butte Creek watershed (as shown in Figure 3-1) are primarily derived from NHDPlus. This dataset depicts flow paths based on a nation-wide 10-meter Digital Elevation Model (DEM) and includes additional attributes such as hydrologic sequence and flow line slope. Those characteristics will be important for creating representative reach segments within the hydrologic model.

3.3 Streamflow

The primary source of streamflow data is from the United States Geological Survey (USGS), which includes 16 gages throughout the Butte Creek watershed. Figure 3-2 shows the locations of these 16 USGS gages. Of the Butte Creek watershed gages, one long-term gage, Butte Creek near Chico CA (11390000), is currently active and has been operating and collecting streamflow data since October of 1930 just north of the watershed's center. The other 15 gages are no longer active but are scattered throughout the watershed and are useful in providing historical streamflow data as recent as 2022 which can still support model calibration. Table 3-2 presents a summary of the available daily streamflow data.

Table 3-2. Summary of USGS daily streamflow data

Gage Description	Station ID	Drainage Area (mi^2)	Start Date	End Date	Gage Active?
BUTTE C A BUTTE MEADOWS CA	11389700	44.4	8/1/1960	10/17/1974	No
BUTTE C BL DIV DAM NR STIRLING CITY	11389720	61.3	1/3/1986	9/30/2022	No
BUTTE C BL FKS OF BUTTE DIV DAM NR DE SABLA CA	11389740	96.4	4/1/1992	7/6/2021	No
FORKS OF BUTTE PP NR PARADISE CA	11389747	--	4/1/1992	9/29/2005	No
DE SABLA PH NR PARADISE CA	11389750	--	10/1/1979	9/30/2022	No
CENTERVILLE PH NR PARADISE CA	11389775	--	10/1/1979	9/30/2021	No
BUTTE C BL CENTERVILLE DIV DAM NR PARADISE CA	11389780	101	12/22/1985	9/30/2022	No
TOADTOWN CANAL AB BUTTE CANAL NR STIRLING CITY CA	11389800	--	10/1/1984	9/30/2022	No
LITTLE BUTTE C NR MAGALIA CA	11389950	11.4	10/1/1968	9/29/1985	No
BUTTE C NR CHICO CA	11390000	147	10/1/1930	Present	Yes
BUTTE C NR DURHAM CA	11390010	--	1/10/1959	4/4/1973	No
GOLD RUN TRIB NR NELSON CA	11390200	1.31	10/1/1960	3/31/1961	No
DRY CR N NELSON CA	11390210	62.9	9/1/1970	9/29/1974	No
WESTERN CN A INTAKE NR OROVILLE CA	11406880	--	11/1/1967	9/30/2022	No
RICHVALE CN A INTAKE NR OROVILLE CA	11406890	--	5/1/1968	9/30/2022	No
PGE LATERAL A INTAKE NR OROVILLE CA	11406900	--	5/1/1968	9/30/2022	No

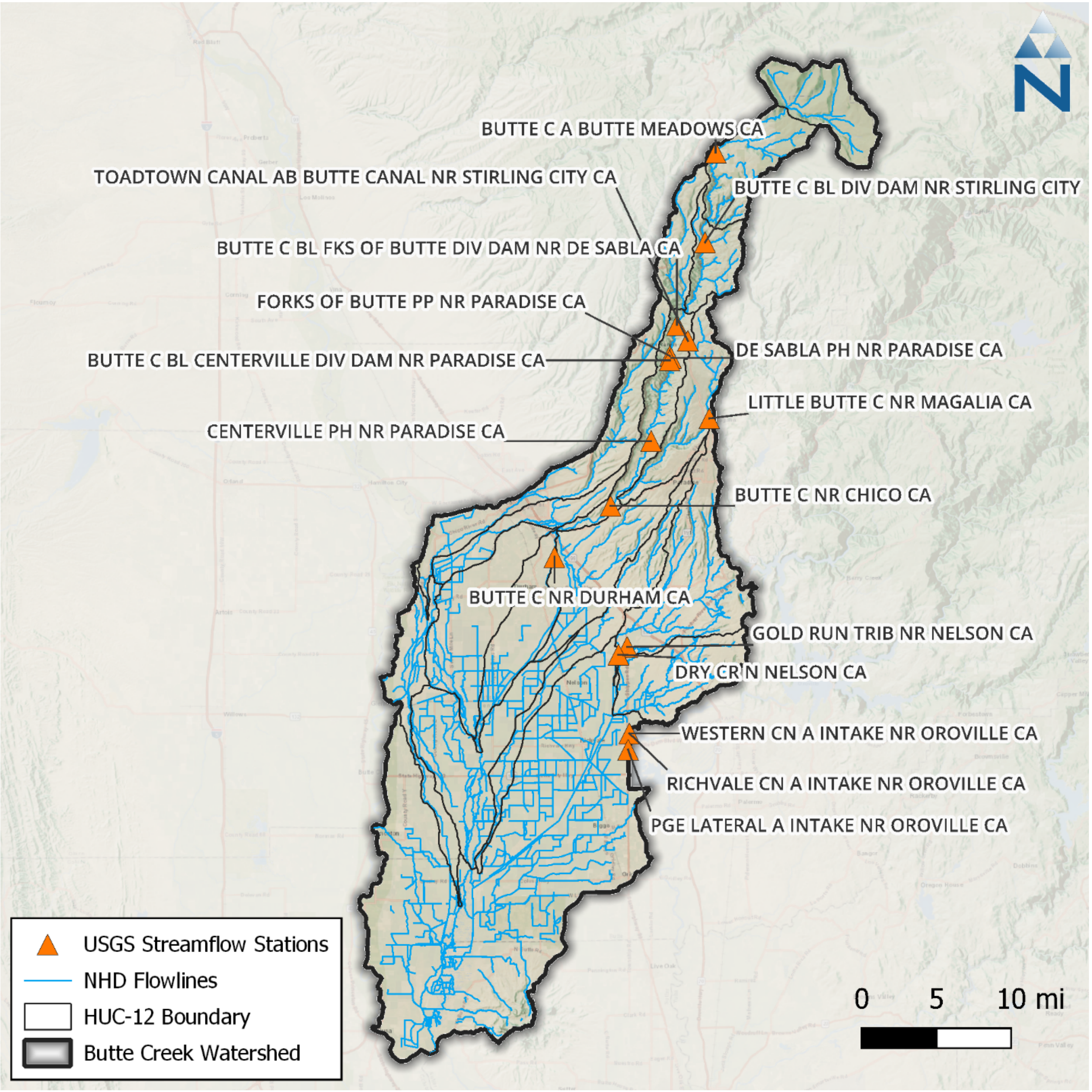

Figure 3-2. USGS streamflow stations in the Butte Creek watershed.

3.4 Surface Water Withdrawals

Initial datasets related to water rights, points of diversion, and irrigation use were identified through searches of the Water Board's eWRIMS database. These data can be used to represent diversions and withdrawals in the watershed model. The volumes quantified in those datasets can be compared to annual and seasonal water budget estimates in the Butte Creek watershed to assess the relative impacts based on observed precipitation and streamflow data. The impact of diversions or withdrawals may be localized along specific tributaries; however, the temporal resolution of the data determines the resolution of those impacts in the model. Additionally, water use to support the cultivation of crops has the potential to impact summer low flows. These areas will be mapped to the extent possible so that the estimated water demand can be represented.

Figure 3-3 provides an overview of water users in the watershed. Water systems and wells are primarily located along the central edges of the Butte Creek watershed and are also scattered throughout the edges of the Sacramento Valley Basin. There are 55 drinking water systems in the watershed serving over 100,000 individuals in residential, agricultural, commercial, and institutional areas. This includes a population of 88,000 in the urban center of Chico, CA in addition to other populations in smaller cities within the watershed like Biggs, Gridley, Paradise, and Durham (Sacramento River Watershed Program 2024). For 53 out of 55 drinking water systems, the water source is listed as groundwater, and the remaining two (2) have surface water listed as the source. Additionally, eWRIMS reports that there are 261 active surface water points of diversion in the watershed with active water rights statuses.

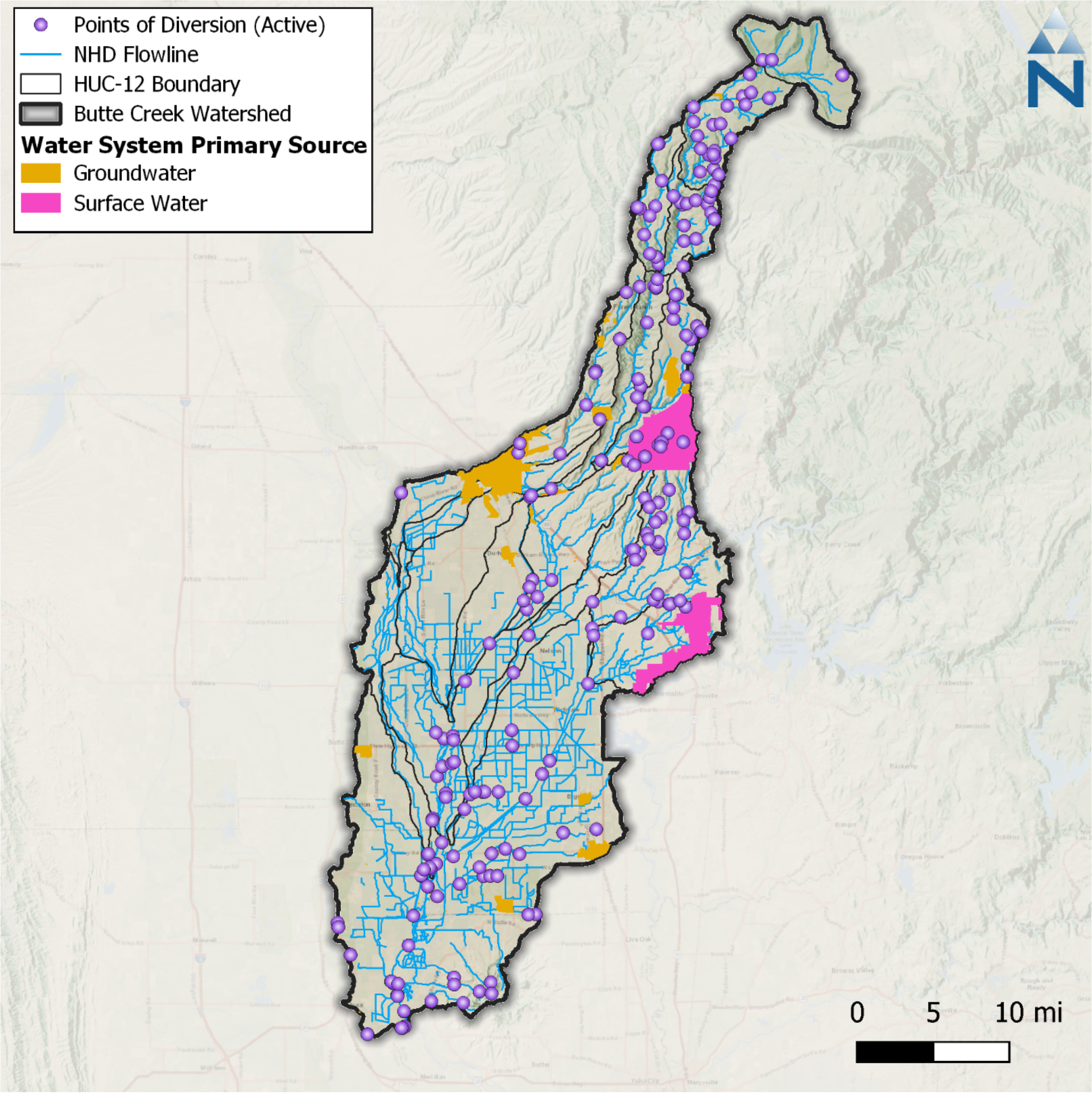

Figure 3-3. Water users in the Butte Creek watershed.

4 SUBSURFACE HYDROLOGY

The Butte Creek watershed is partially located within the Sacramento Valley Basin (Basin number 5-021) and overlaps with several Subbasins as delineated by Bulletin 118 (DWR 2020a). These groundwater basins primarily include the Butte Subbasin (number 5-021.70), which is largely encompassed within the Butte Creek watershed delineation with a small portion extending beyond the watershed boundary in the southeast, and the Vina Subbasin (number 5-021.57), half of which approximately overlaps with the Butte Creek watershed. Very small portions of Sutter Subbasin (number 5-021.62), Wyandotte Creek Subbasin (number 5-021.69), and Colusa Subbasin (number 5-021.52) overlap with the Butte Creek watershed. Approximately 69% of the Butte Creek watershed area falls within the alluvial groundwater basins delineated by Bulletin 118, and the remaining 31% is in the upstream reaches underlain by bedrock in the northeast. Figure 4-1 shows the extents of the Butte Creek watershed boundary and the overlapping subbasins within the Sacramento Valley Basin.

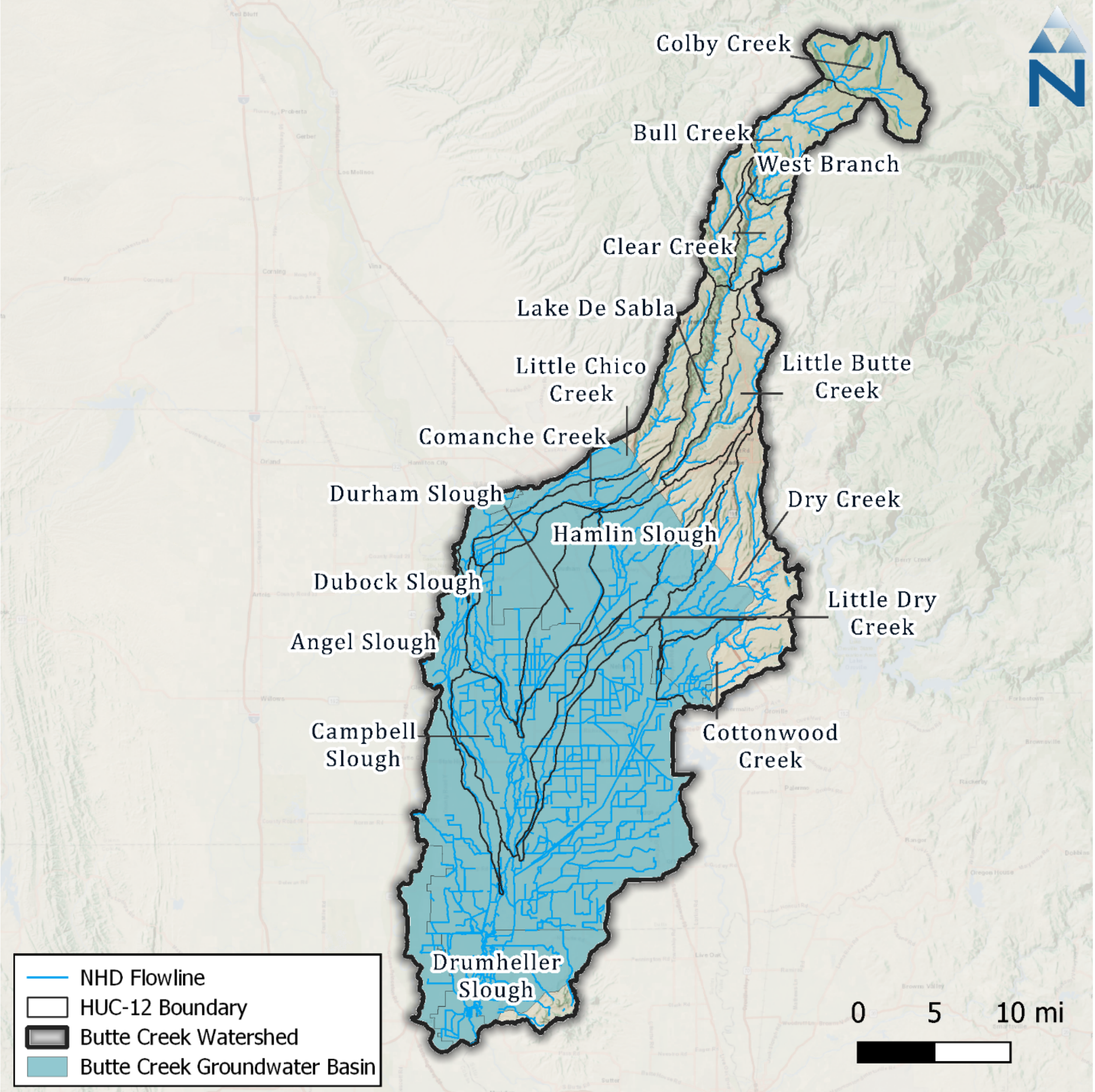

Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118.

As per the respective basin priority details (Sustainable Groundwater Management Act (SGMA) Basin Prioritization Dashboard), the Vina Subbasin is a high priority subbasin as designated by SGMA's basin prioritization and is heavily reliant on groundwater supply with 98% of water supply provided by groundwater. The Butte Subbasin is a medium priority subbasin in which 26% of water supply is provided by groundwater based on the 2020 report. The Vina Groundwater Sustainability Agency (GSA) and several GSAs within the Butte Subbasin overlap with the Butte Creek watershed in the alluvial basins. Groundwater level declines have been reported, indicating that groundwater depletion has played an important role in the water budgets of the Butte Creek watershed, and therefore, considering groundwater flow in the current study is imperative (GSAS, 2023).

The groundwater basins within the Sacramento Valley Basin delineated as per Bulletin 118 are comprised of alluvial basins formed by quaternary deposits located along stream and river channels, and alluvial fan deposits. The Bulletin 118 delineations do not account for any potential sources of 'non-basin' water within weathered bedrock formations, fractures, or other void spaces outside or underneath the designated basins. C2VSim-CG, C2VSim-FG, and SVSim provide approximate estimates of surface and groundwater inflow occurring from the bedrock underneath small watersheds upgradient of the alluvial fan deposits, which will be utilized during model development and calibration. The interaction between surface water and groundwater is expected to be minimal within the bedrock, however, any available information relevant to groundwater use within the bedrock will be included in the model.

4.1 Water Budget Components

There are multiple sources of water budget estimates within the alluvial basin that underlies the Butte Creek watershed boundary. These sources include several groundwater models that overlap within the alluvial formation: the coarse and fine grid versions of the central valley model, C2VSim-CG (Brush et al. 2013) and C2VSim-FG (DWR 2020b), respectively, developed by the Department of Water Resources (DWR), the Sacramento Valley Simulation Model, SVSim (Bedekar et al. 2021), also developed by DWR, the Central Valley Hydrologic Model, CVHM2 (Faunt 2022), developed by USGS, and the Butte Basin Groundwater Model (BBGM), developed by Butte County Department of Water and Resource Conservation (BCDWRC) (BCDWRC 2021). The models provide hydrologic data, hydrogeologic configuration, and water budget estimates that will be utilized as a guide during the model development and calibration process in this study. All model data and files other than the BBGM model files are publicly available.

5 LANDSCAPE CHARACTERIZATION

Landscape characterization describes the physical characteristics of the landscape including the types of soils and geology, topography, land cover, land use, and other physical properties that can be represented within the hydrologic model. HRUs are the core landscape unit in a watershed model. Each HRU represents areas of similar physical characteristics attributable to certain hydrologic processes. Spatial or geological characteristics such as land cover, soils, geology, and slopes are typically used to define HRUs. The areal combinations of those various characteristics ultimately determine the number of meaningful HRU categories considered for the model. The following sections describe the component layers available to derive HRUs for the Butte Creek watershed.

5.1 Elevation & Slope

The USGS publishes DEMs expressing landscape elevation through a raster grid data product with 30-meter resolution. The Butte Creek watershed ranges in elevation from just above sea level (9 meters) in Verona, CA at the mouth of the Feather River in the southern part of the watershed to over 2,100 meters at Humboldt Peak in the northern most portion of the watershed. As a geoprocessing input, the DEM can be used to derive both slope and aspect as data inputs to a model. Figure 5-1 shows the change in elevation across the Butte Creek watershed.

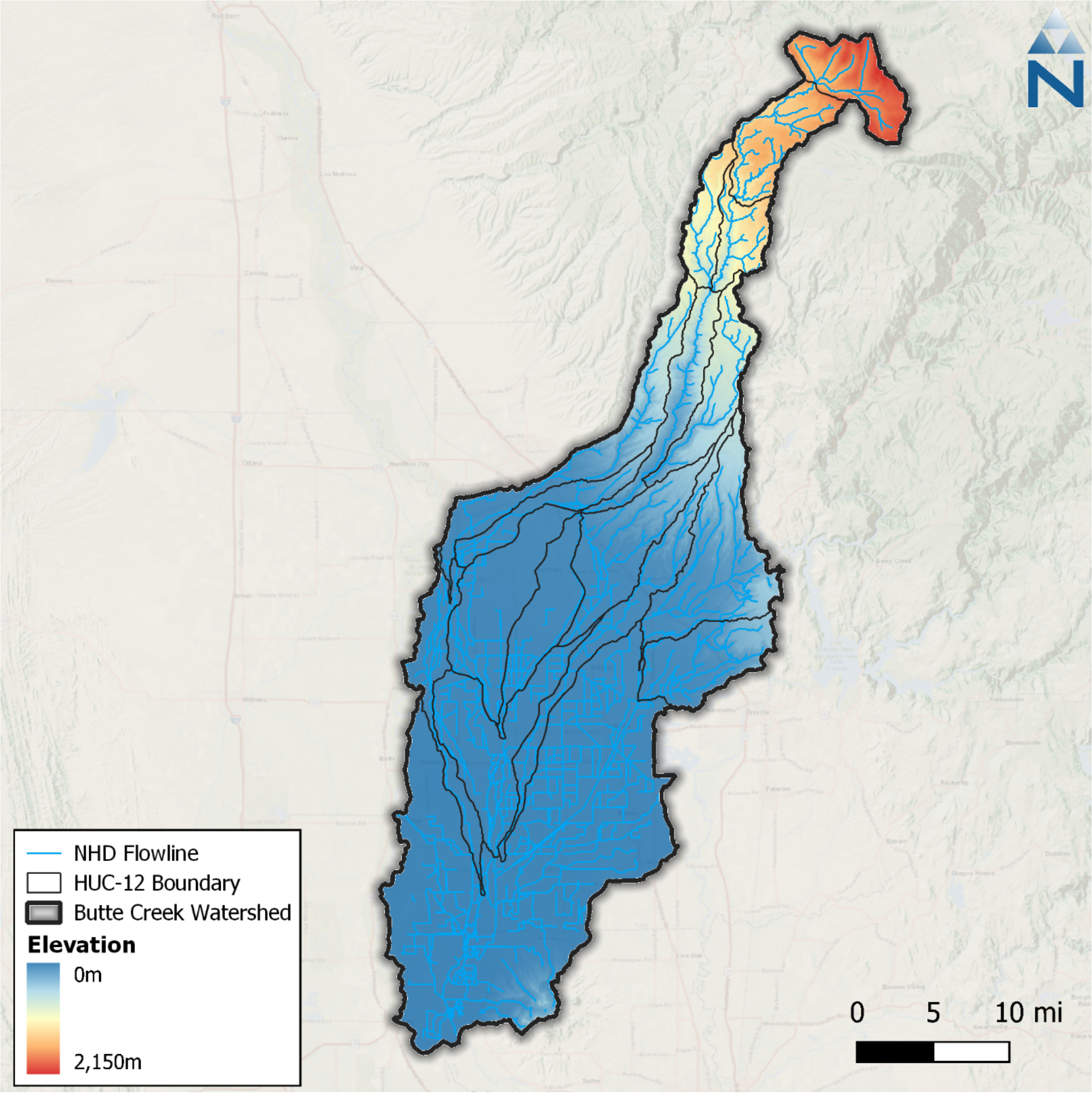

Figure 5-1. Digital elevation model of the Butte Creek watershed.

5.2 Soils & Geology

Soils data for the Butte Creek watershed were obtained from the Soil Survey Geographic Database (SSURGO) and State Soil Geographic Database (STATSGO) both published by the Natural Resource Conservation Service (NRCS). There are four primary hydrologic soil groups (HSG) used to characterize soil runoff potential. Group A generally has the lowest runoff potential whereas Group D has the highest runoff potential. Both SSURGO and STATSGO soils databases are composed of a GIS polygon layer of map units and a linked database with multiple layers of soil property. Soil characteristics of each hydrologic soil group are described in Table 5-1.

Table 5-1. 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

Source: Natural Resource Conservation Service (NRCS), Technical Release 55 (TR-55) (USDA 1986).

Table 5-2 presents a tabular summary and Figure 5-2 shows the spatial distribution of the SSURGO hydrologic soil groups for the Butte Creek watershed. The dominant soil group in the watershed is Group D (47%), with the lowest infiltration rates, containing clay loam, silty clay loam, sandy and silty clay, and clay. Group C (31%) is the next most common soil group in the watershed, containing sandy clay loam that typically have low infiltration rates. Group B, containing moderately well to well-drained silt loams and loams, makes up 12% of the total watershed area. Group A, containing well-draining sand, loamy sand, and sandy loam, makes up 6%. Less than 4% of the watershed areas have mixed soils. For modeling purposes, mixed soils will be grouped with the nearest primary group as follows: A/D → B, B/D → C, and C/D → D. Finally, approximately 1% of the watershed HSG area is classified as unknown in the SSURGO database. For those areas, the corresponding HSG from the STATSGO dataset can be used to supplement the data gaps; however, many of these unknown soil areas may correspond to waterbodies.

Table 5-2. NRCS Hydrologic soil groups in the Butte Creek watershed.

Hydrologic Soil Group	Area (acres)	Percent Area
A	28,914.52	5.5%
A/D	204.47	<0.1%
B	64,427.39	12.3%
B/D	321.30	<0.1%
C	160,097.14	30.6%
C/D	18,631.98	3.6%
D	244,286.83	46.6%
N/A	7,106.43	1.4%
Total	**523,990.06**	**100.0%**

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

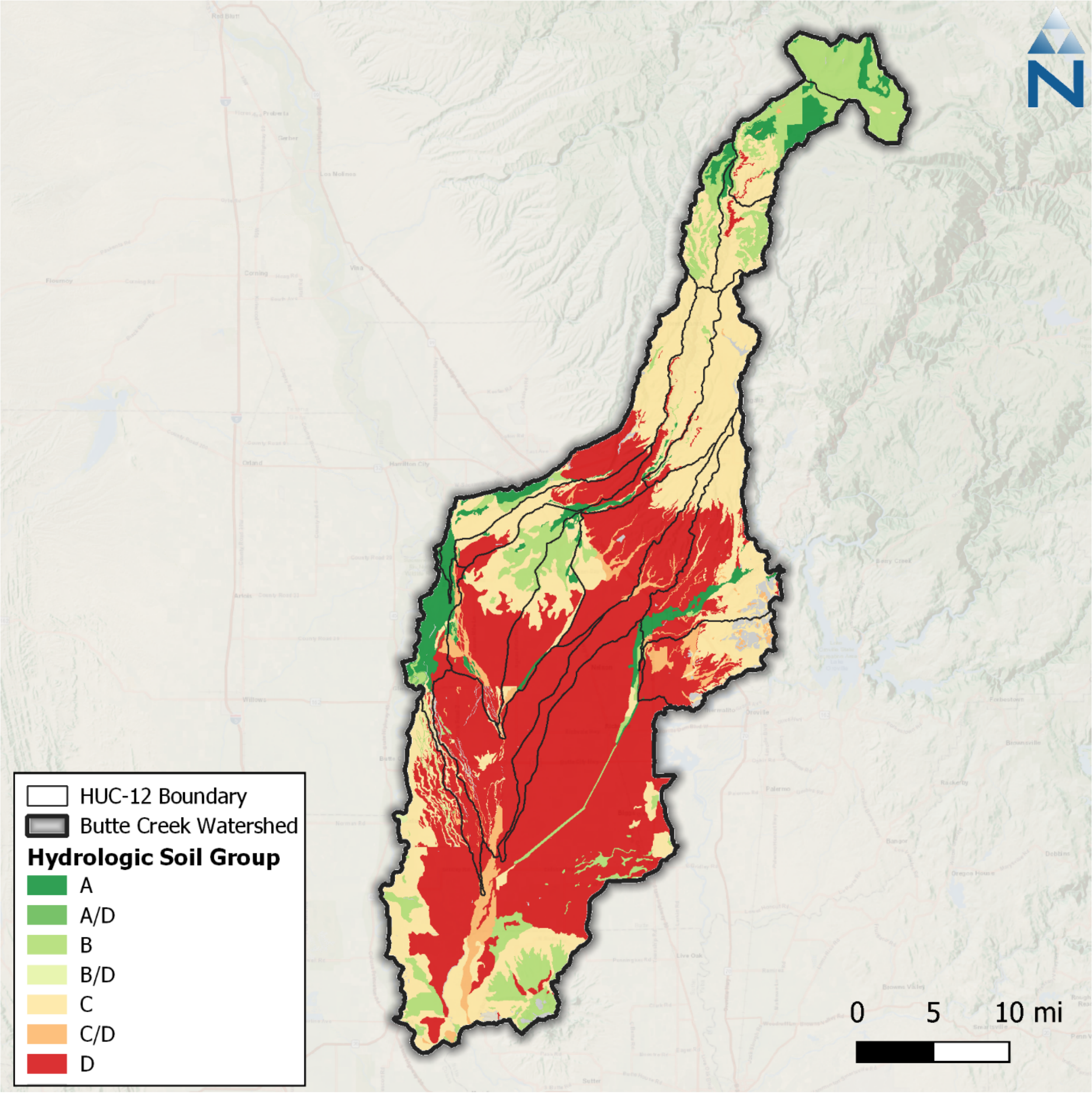

Figure 5-2. SSURGO hydrologic soil groups within the Butte Creek watershed.

5.3 Land Cover

Land cover data are the primary basis layers for HRUs. The primary source of land cover data identified for this effort is the 2021 National Land Cover Database (NLCD) maintained by the Multi-Resolution Land Consortium (MRLC), a joint effort between multiple federal agencies. The primary objective of the MRLC NLCD is to provide a current data product in the public-domain with a consistent characterization of land cover across the United States. The first iteration of the NLCD dataset was in 1992. Since the 2001 NLCD version, a consistent 16-class land cover classification scheme has been adopted nationwide. The 2021 NLCD adopted this 16-class scheme at a 30-meter grid resolution.

Table 5-3 summarizes the composite land cover distribution for the Butte Creek watershed. Figure 5-3 shows the NLCD 2021 land cover for the Butte Creek watershed. Cultivated crops are the dominant land cover classification covering approximately 52% of the watershed area. True cultivated area is potentially underestimated by this percentage, as many individual cultivated areas in the watershed may be smaller than the NCLD's 2.7-acre minimum mapping unit. When combined, evergreen forest, the undeveloped categories of deciduous forest, mixed forest, shrub/scrub, and grassland/herbaceous account for approximately 38% of the total watershed area. Developed land cover makes up less than 6% of the total watershed area and is classified mostly as "Developed, Open Space," which suggests that much of the developed area is dispersed.

Table 5-3. National Land Cover Database 2021 land cover summary in the Butte Creek watershed.

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	729.90	0.14%
21	Developed, Open Space[1]	14,310.90	2.70%
22	Developed, Low Intensity[1]	9,015.30	1.70%
23	Developed, Medium Intensity[1]	5,818.05	1.10%
24	Developed, High Intensity[1]	1,797.75	0.34%
31	Barren Land (Rock/Sand/Clay)	627.30	0.12%
41	Deciduous Forest	2,302.65	0.43%
42	Evergreen Forest	79,976.48	15.07%
43	Mixed Forest	1,332.68	0.25%
52	Shrub/Scrub	42,458.18	8.00%
71	Grassland/Herbaceous	73,174.50	13.79%
81	Pasture/Hay	412.65	0.08%
82	Cultivated Crops	275,041.13	51.82%
90	Woody Wetlands	2,972.25	0.56%
95	Emergent Herbaceous Wetlands	20,750.85	3.91%
	TOTAL	**530,720.55**	**100%**

Source: 2021 National Land Cover Database

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

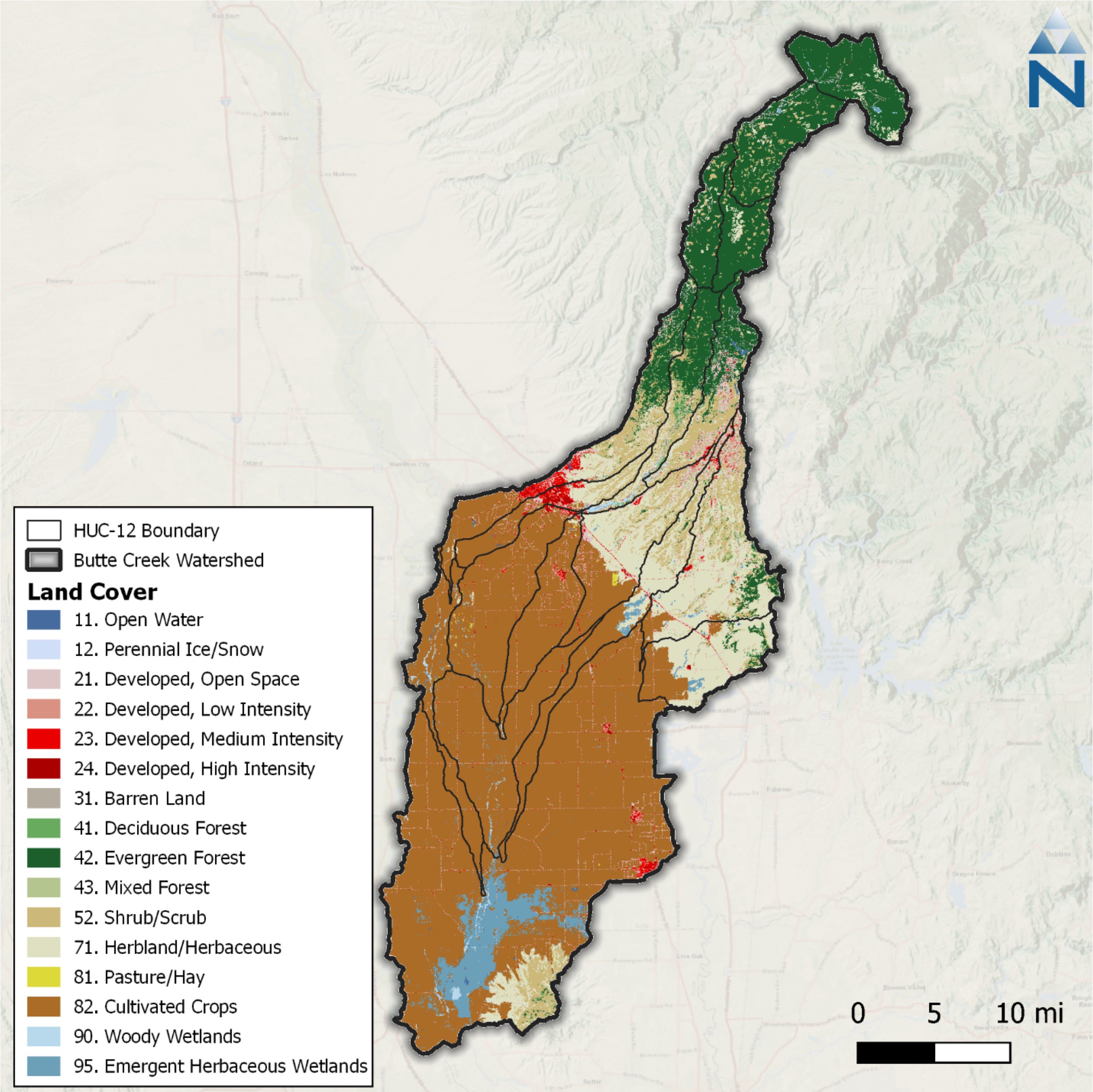

Figure 5-3. NLCD 2021 land cover within the Butte Creek watershed.

MRLC publishes a developed impervious cover dataset as a companion to the NLCD land cover. This dataset is also provided as a raster with a 30-meter grid resolution. Impervious cover is expressed in each raster pixel as a percentage of total area ranging from 0 to 100 percent. Because this dataset provides impervious cover estimates for areas classified as *developed,* non-zero values closely align with developed areas (NLCD classification codes 21 through 24). Review of the Butte Creek watershed using this dataset shows that less than 6% of the area is developed, or impervious. The developed area is classified further into open space, and low, medium, and high intensity of development. Of those subcategories, open space and low intensity development make up most of the total developed area. Therefore, the total watershed area is largely undeveloped, and the areas that are developed are mostly developed to a small degree.

Because land cover can vary significantly over time due to anthropogenic changes (e.g., development, timber harvest) or naturally occurring events (e.g., forest fires, landslides), it may be necessary to also time-vary land cover through the model simulation or, at a minimum, align the dataset used to represent land cover with the same time period as streamflow data used for model calibration. The NLCD 1992, 2001, 2006, 2011, and 2021 snapshots are all available for representing land cover changes within the model depending on the period, or multiple periods, or time selected for model calibration and validation. Land use change in the Butte Creek watershed will be assessed as part of the model development and a decision will be made based on the results as to whether land use change is represented explicitly, or a single land use snapshot is used.

Furthermore, the California Department of Forestry and Fire Protection (CAL FIRE) maintains databases of timber harvest plans and fire perimeters (see Table 1-2) which may be used in conjunction with the basic NLCD land cover snapshots to vary the land cover representing dynamic processes like timber harvests or episodic fire-related activities. The CAL FIRE timber harvest database contains approved timber harvest plans (THPs) of harvests for commercial purposes on non-federal lands from the past 15-years.

5.4 Tree Canopy Cover

MRLC publishes a tree canopy dataset as a companion to the NLCD land cover dataset that estimates the percentage of tree canopy cover spatially. The underlying data model was developed by the United States Forest Service (USFS) and is available through their partnership with the MRLC. This dataset is also provided as a raster with a 30-meter grid resolution. Like the impervious cover dataset, each raster pixel expresses the percent of the total area covered by tree canopy with values ranging from 0 to 100 percent. The percent tree canopy cover layer was produced by the USFS using a Random Forests regression algorithm (trademarked by Leo Breiman and Adele Cutler). Tree canopy cover data can be used to estimate model parameters like interception storage and lower-zone evapotranspiration rates.

5.5 Agriculture & Crops

Analysis of the NLCD land cover distribution (see Section 5.3) shows that approximately 52% of the Butte Creek watershed area is classified as Pasture/Hay (class 81) and Cultivated Crops (class 82). Additionally, NLCD classifies 22% of the watershed area as Shrub/Scrub (class 52) or Grassland/Herbaceous (class 71). Some portions of these shrub or grassland areas may include areas of cultivated crops that were not automatically recognized through processing of the remote sensing data or include cultivated crops on a rotating schedule. To reflect these situations, supplemental information published by the United States Department of Agriculture (USDA) can be used. The USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) is an annual raster, geo-referenced, crop-specific land cover data layer. The dataset is available at a 30-meter resolution and can be combined with tabular metadata with information on crop types which can be aggregated to a possible 85 standardized categories for display purposes, with the emphasis being agricultural land cover. The purpose of the CDL dataset is to provide an annual supplemental of acreage estimates for major crop commodities. Additionally, large-scale crop and land use identification published by DWR in March 2023, for the year 2020, is available to supplement this analysis as needed. DWR developed a crop mapping dataset through remote sensing land use surveys performed at a field scale to quantify crop acreage statewide.

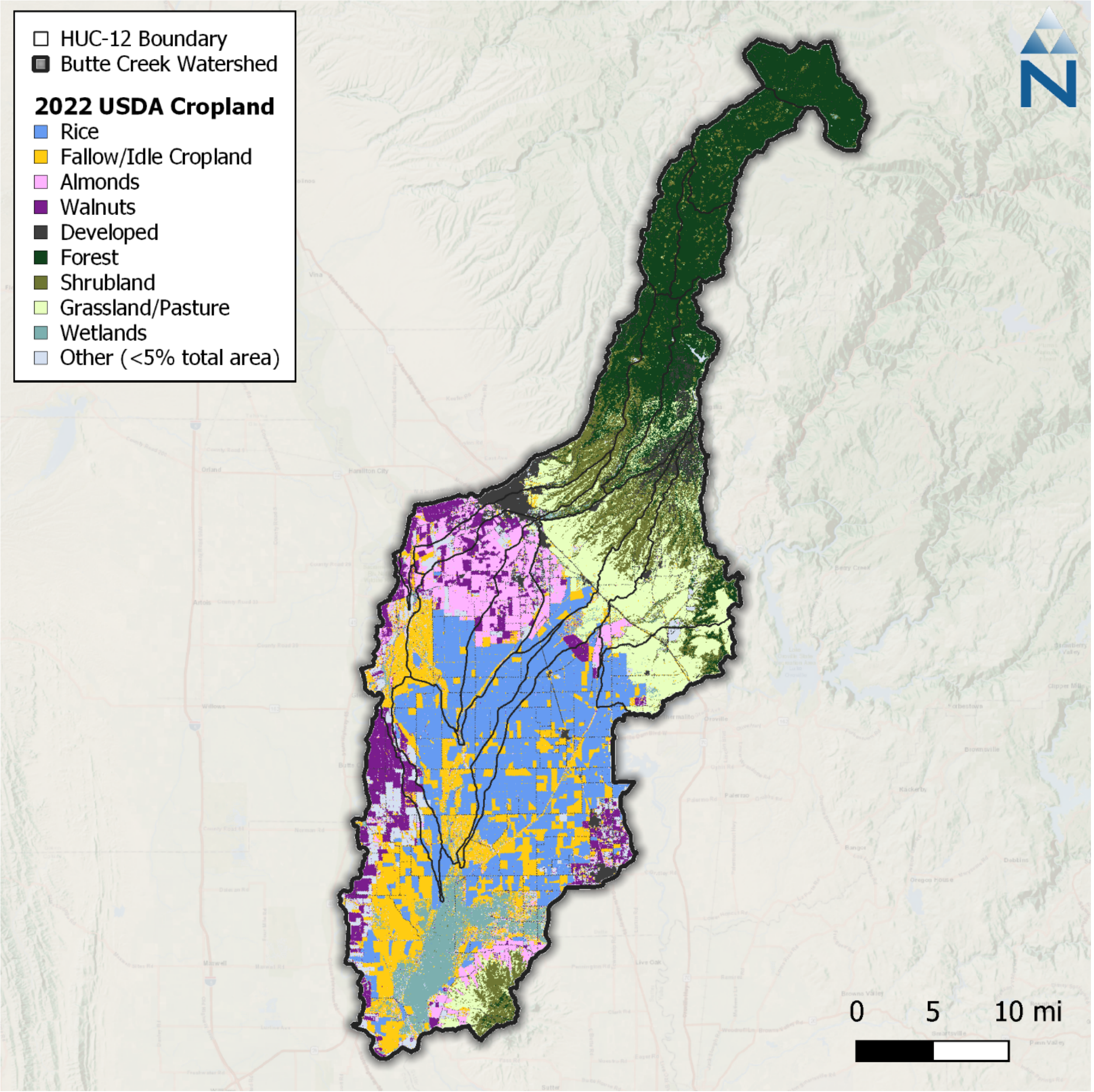

Figure 5-4. USDA 2022 Cropland Data within the Butte Creek watershed.

Table 5-4. USDA 2022 Cropland Data summary within the Butte Creek watershed, sorted by percent of area

Crop Type	Area (ac)	Area (%)
Rice	105,345.70	19.85%
Forest	92,551.10	17.44%
Fallow/Idle Cropland	71,379.50	13.45%
Grassland/Pasture	60,197.90	11.34%
Shrubland	46,884.80	8.83%
Almonds	35,599.10	6.71%
Walnuts	35,328.20	6.66%
Developed	29,353.90	5.53%
Other (<5% Total Area)	54,112.80	10.20%
TOTAL	**530,753.00**	**100.00%**

6 DATA GAPS AND LIMITATIONS

Based on review of the hydrology dataset presented in Table 1-2, one potential limitation is the spatial extent of available daily streamflow data to support a model calibration. USGS only operates one active gauge, Butte Creek near Chico CA (USGS 11390000), with long-term daily data for the period 10/1/1930 through Present. Ten other streamflow gauges provide more recent data that is still useful to support model calibration; however, many of these gauges do not have reported drainage area estimates from USGS, suggesting the contributing drainage area is not well known. This suggests there may be complicating factors when comparing observed and simulated time series. Therefore, model calibration to observed data will be focused at minimum on matching predicted discharges at active or recent gauge locations with well-understood drainage areas. Calibration at locations without well-understood contributing drainage areas will be subject to some uncertainty.

Another potential limitation is the availability, quality, and temporal resolution of data for surface water diversions and irrigation within the watershed. The eWRIMS database was used to initially identify major surface water diversions that are likely to have data to integrate into the model; however, other surface water diversions, such as other agricultural operations may not be mapped or have available data. These diversions may need to be mapped and assumptions could be needed to represent water demand in the model if these demands are needed for model calibration purposes.

Finally, inter-basin transfer (inflow) of water is known to exist on the West Branch Feather River from the PG&E DeSabla-Centerville hydroelectric facility as well as three intake points near Oroville. While some of these inflows are available through USGS flow gages (see Table 3-2), it's possible other inflows could be discovered through interpretation of model outputs which were not known during workplan development; however, these flow data will need to be obtained or otherwise estimated to represent the source in the model.

7 MODEL CONFIGURATION (WATERSHED MODEL)

7.1 Model Selection

The objectives of this modeling study influence both hydrologic model selection and technical approach development. The available data presented in Section 2 through Section 5 for characterizing the watershed also influence model selection. The key study objectives to be addressed with the selected hydrologic model are summarized below:

- Representation of unimpaired flows and baseline flows (e.g., water use and other human activities that impact instream flows and how they affect the water balance)
- Capability for potential pairing with a groundwater model (e.g., MODFLOW) for more detailed representation of groundwater processes and surface-groundwater interactions.
- Application of a representative simulation period to capture the variability of the full range of hydrologic conditions including high flows, baseflows, dry and wet year flows, environmental flows, drought curtailment, etc.

To simulate streamflow, the model must be able to represent seasonal variability on the landscape and be responsive to both natural changes (e.g., meteorological conditions, vegetation cycles) and anthropogenic/hydromodification impacts (e.g., stream diversions, impoundments, groundwater pumping, timber harvest). An ideal platform should also be adaptable for simulating (1) spatial changes like those associated with representing pre-developed/unimpaired land cover states, (2) temporal changes like those associated with modeling climate change impacts, or (3) catastrophic impacts like those associated with extreme events such as 100-year storms and wildfires.

Public-domain models that can address those study objectives include the Hydrologic Simulation Program – Fortran (HSPF), Loading Simulation Program in C++ (LSPC) (USEPA 2009), the Precipitation-Runoff Modeling System (PRMS), and Soil and Water Assessment Tool (SWAT). LSPC has been used extensively throughout California to model the unique hydrologic characteristics of the State's watersheds and to inform regulatory decisions (i.e., development of Total Maximum Daily Loads and associated amendments to Water Quality Control Plans), watershed management, or climate change analyses. Watersheds in California where LSPC modeling has been conducted include those in the San Francisco Bay region (SCVURPPP 2019; SMCWPPP 2020; Zi et al. 2021 and 2022), the Clear Lake watershed in the Central Valley Region (CVRWQCB 2006), the Lake Tahoe watershed in the Lahontan Region (LRWQCB and NDEP 2010; Riverson et al. 2013), all coastal watersheds of Los Angeles County (LACFCD 2020; LARWQCB 2010, 2012, 2013b, 2013a, and 2015; LARWQCB and USEPA 2005a, 2005b, 2006, and 2011; Tariq et al. 2017), the San Jacinto River watershed in the Santa Ana Region (SAWPA 2003 and 2004), and most coastal watersheds of the San Diego Region (City of San Diego and Caltrans 2016; City of Vista 2008; Los Peñasquitos Responsible Agencies 2015; San Diego Bay Responsible Parties 2016; SDRWQCB 2008, 2010, and 2012). These efforts have included comprehensive peer review processes and public comment, requiring demonstration of model accuracy based on standard practices for quantifying and documenting model performance. All the modeling documentation and reports cited here have withstood peer review and have supported amendments to Water Quality Control Plans or the approval of watershed plans submitted to the Water Board or Regional Water Quality Control Boards to demonstrate regulatory compliance. Additionally, the Water Board recently utilized LSPC to perform analyses of hydrology within the South Fork Eel River and Shasta River watersheds.

LSPC is a modernized version of the HSPF platform now organized around a Microsoft Access relational database, but otherwise the LSPC model is functionally identical to the HSPF model. The relational database provides efficient data management, model maintenance, and development of alternative scenarios. The LSPC model runs using hourly input boundary conditions and can be sufficiently configured using the meteorological datasets discussed in Section 2. LSPC also has features to vary land use over time for explicitly representing dynamic processes such as timber harvests and wildfires. Additionally, LSPC is the selected modeling platform for two other Water Board studies performed for the South Fork Eel River and Shasta River watersheds. Those two watershed models utilize data from many of the same sources compiled in this study plan for the Butte Creek watershed. Based on the extensive history of successful LSPC model applications and its strengths and flexibility for potential coupling with a groundwater model (e.g., MODFLOW), LSPC is recommended as the watershed model for this study.

7.2 Model Configuration

An LSPC model will be configured using the datasets presented in Section 2 through Section 5. A hydrologic analysis shall be developed with the primary goal of simulating instream flow time series for a minimum of 20 years through Water Year 2023 (10/1/2003 – 9/30/2023) and capable of representing both current/managed flow conditions and natural (pre-development) conditions. While the LSPC model is not a grid-based model by default, the flexibility of the model for subcatchment segmentation and HRU development provides the opportunity for a grid-based setup for a more detailed representation of hydrological processes and forcing inputs (i.e., weather data) as well as a potential linkage with a groundwater model (e.g., MODFLOW) if needed.

For this effort, a gridded boundary layer (e.g., 200-meter resolution mesh) will be used to segment the watershed into "subcatchments grids". Each grid will have a distribution of HRUs, which are derived at a finer grid resolution than the subcatchment grids. Figure 7-1 shows how those LSPC model configurations are organized. Because LSPC assigns attributes such as weather data and average elevation by subcatchment, using a gridded layer can improve the performance of processes such as snow simulation in areas with large elevation changes over short distances. For surface routing, LSPC allows multiple subcatchment grids to be routed to a modeled stream routing segment by turning off routing in grids without stream segments and pointing them directly to one with a modeled stream segment. Finally, if a linkage to a groundwater model is needed, having subcatchment grids can streamline the spatial linkage to the groundwater model.

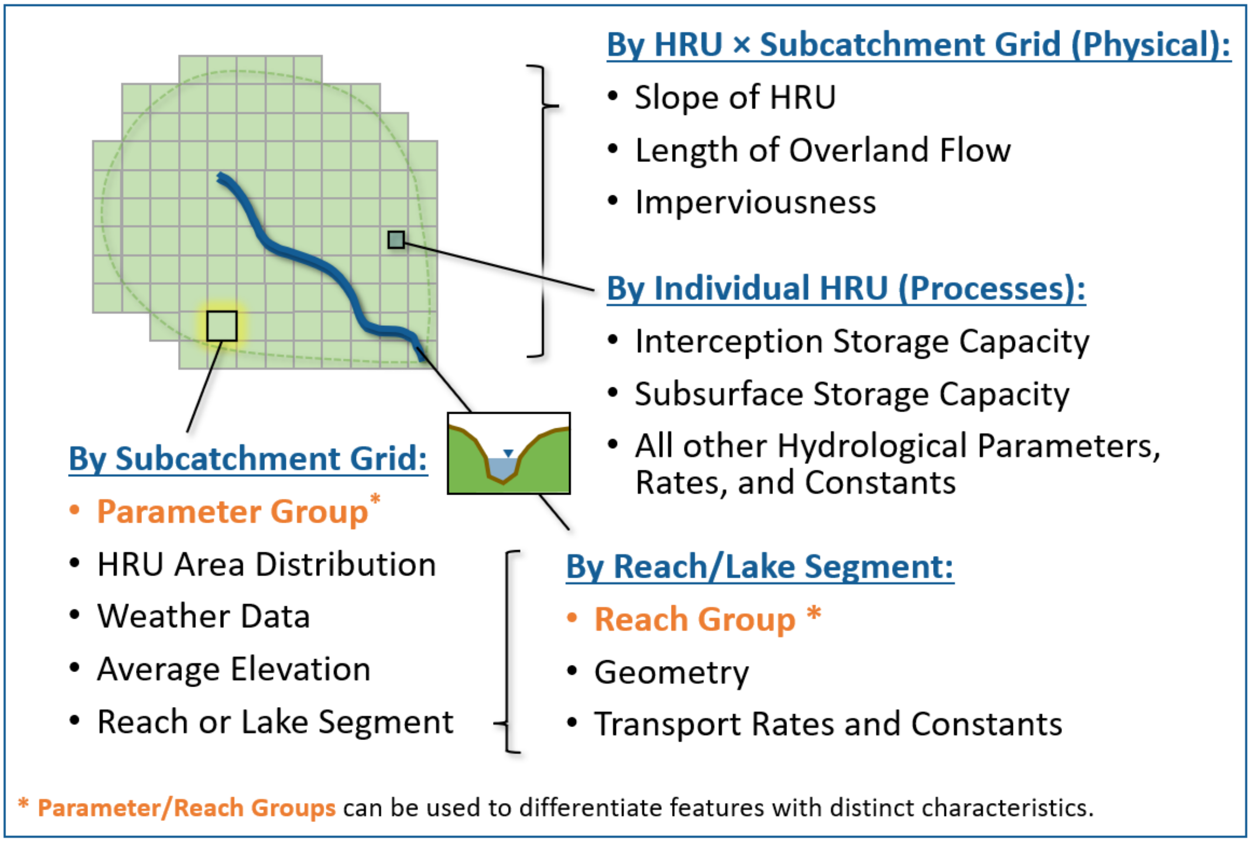

Figure 7-1. Organization of LSPC model configuration components.

The following describes how major elements of the model will be constructed using the available data sets. Further details about each process and underlying assumptions will be documented in a modeling report:

- **Climate Boundaries:** Climate boundary inputs to the model will include both precipitation and ET. To create a dataset with the highest coverage, and spatial and temporal resolution, a hybrid land-based/grid-based approach will be used as explained in section 2. To prepare the precipitation input data, the land-based data from NOAA (LCD, GHCN, and CoCoRaHS), RAWS, and CDEC gauges identified in Section 2 will be used as a base. The 4-km gridded PRISM monthly precipitation data will also be collected and downscaled to hourly using land-based hourly data and/or NLDAS. The gaps in land-based data will be filled with the downscaled hourly PRISM data. Due to high variations in elevation across the Butte Creek watershed, capturing the dynamics of snowpack accumulation and melting is critical. The data from the SNOwpack TELemetry Network (SNOTEL) will be leveraged to assess the performance of the model in capturing the snow processes. SNOTEL is an automated system of snowpack and related climate sensors operated by the Natural Resources Conservation Service (NRCS). SNOTEL data are regularly used to forecast annual water supplies, predict floods, and conduct general climate research. Evapotranspiration will be represented using the CIMIS daily reference evapotranspiration 2-km gridded dataset and downscaled to hourly based on the distribution of clear sky solar radiation.
- **Model Segmentation**: The subcatchment delineation will entail generating a regular grid mesh, initially anticipated at 200-meter resolution, or consistent with the mesh used for a linked groundwater model if deemed necessary. This mesh will be overlayed with the HUC-12 NHDPlus catchment boundaries described in Section 3.1 to determine the routing scheme for the grids. Since the maximum resolution provided by NHDPlus is at HUC-12 level, depending on the resolution of the grid mesh and availability of a high-resolution LiDAR dataset, a detailed flow accumulation raster will also be generated to assist with determining grid routing if needed. Each grid will represent an LSPC subcatchment, with multiple grids associated with NHDPlus stream segments. Figure 7-2 illustrates the relationship between the regular grid segmentation, HUC-12 boundaries, stream segments, and HRUs. This approach will create a consistent spatial representation of hydrologic processes to ensure a seamless linkage between LSPC and a possible groundwater model. One primary reach segment will be represented per subcatchment and will use a cross-section calculated using trapezoidal geometry as a function of the cumulative upstream drainage area. If additional cross-sectional information is available, these geometries can be updated based on better available data.

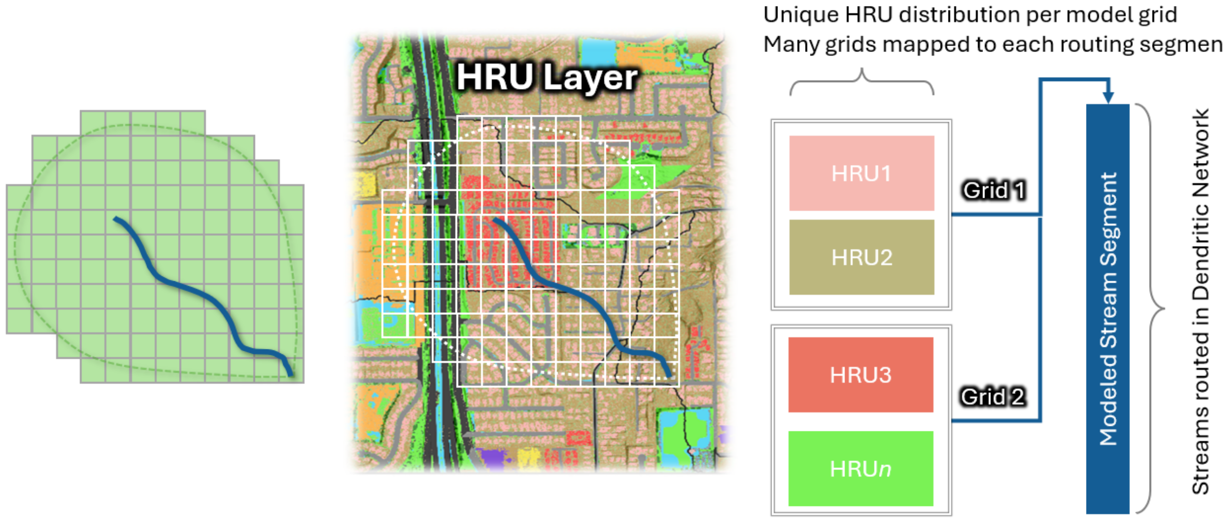

Figure 7-2. Schematic grid-based setup for LSPC model for potential linkage with MODFLOW.

- **Hydrologic Response Units**: HRUs represent unique combinations of landscape characteristics derived by overlaying GIS datasets describing land cover, hydrologic soil group, and slope. The unique combinations of these three elements will form a set of HRUs that will be configured within the LSPC model. When crop type is known, this will be used to override the land cover data. For Butte Creek watershed, due to extensive agricultural operations, the 2023 USDA NASS Cropland Data—the most recent version at the time of this effort—will be leveraged for HRU definition to represent the hydrologic effects of agricultural operations (e.g., irrigation). In the final model configuration, some HRUs may be reclassified and grouped when appropriate for model parameterization (e.g., multiple forest types may be grouped into a single "forest" HRU category unless there is reason to represent different responses in the model for each type).
- **Water Use and Inflows**: To the extent that major sources of water use (e.g., groundwater pumping, surface diversions) or inter-basin transfers are known, these volumes will be included as withdrawals or inputs to the model. Assumptions may need to be made and documented for some of these sources/sinks, and others may need to be excluded entirely if the impact(s) on the model prediction raises questions about the accuracy of the data. Priority will be given to representing these features when they influence points where the model is being compared to observed data for calibration purposes. A known inflow from the PG&E DeSabla-Centerville hydroelectric facility occurs on the West Branch Feather River which is an imported water source from outside the basin. Records of these flow data will need to be obtained or estimated to represent them in the model.

8 MODEL CALIBRATION

A combination of visual assessments and computed numerical evaluation metrics will be used to assess model performance during calibration. Model performance will be assessed using graphical comparisons or modeled vs. observed data (e.g., time-series plots, flow duration curves, etc.) quantitative metrics and qualitative thresholds recommended by Moriasi et al. (2015) and Duda et al (2012), which are considered highly conservative. Moriasi et al. (2007 and 2015) assign narrative grades for hydrology and water quality modeling to the percent bias (PBIAS), the ratio of the root mean square error to the standard deviation of measured data (RSR), and the Nash-Sutcliffe model efficiency (NSE). These metrics are defined as follows:

- The percent bias (PBIAS) quantifies systematic overprediction or underprediction of observations. A bias towards underestimation is reflected in positive values of PBIAS while a bias towards overestimation is reflected in negative values. Low magnitude values of PBIAS indicate better fit, with a value of 0 being optimal.
- The ratio of the root mean square error to the standard deviation of measured data (RSR) provides a measure of error based on the root mean square error (RMSE), which indicates error results in the same units as the modeled and observed data but normalized based on the standard deviation of observed data. Values for RSR can be greater than or equal to 0, with a value of 0 indicating perfect fit. Moriasi et al. (2007) provides narrative grades for RSR.
- The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe 1970). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values for NSE can range between -∞ and 1, with NSE = 1 indicating a perfect fit.

Other metrics can also be computed and used to assess calibrated model performance, including the Kling-Gupta Efficiency (KGE). This metric can provide additional or complementary information on model performance to the three metrics listed above and is defined as follows:

- The Kling-Gupta Efficiency (KGE) metric is based on the Euclidean Distance between an idealized reference point and a sample's bias, standard deviation, and correlation within a three-dimensional space (Gupta et al. 2009). KGE attempts to address documented shortcomings of NSE, but the two metrics are not directly comparable. A KGE value of 1 indicates perfect fit, with agreement becoming worse for values less than 1. Knoben et al. (2019) have suggested a KGE value > - 0.41 as a benchmark that indicates a model has more predictive skill than using the mean observed flow.

Both modeled time series and observed data will be binned into subsets of time to highlight seasonal performance and different flow conditions. Those bins include annual average streamflow, highest 10% of flows (to isolate model performance during high flows), lowest 50% of flows (to isolate model performance during low flows). Hydrograph separation will also be performed to assess stormwater runoff vs. baseflow periods. Table 8-1 is a summary of performance metrics that will be used to evaluate hydrology calibration. As shown in the table, "All Conditions" (i.e., annual interval) for RSR and NSE is the primary condition typically evaluated during model calibration. For sub-annual intervals, the pattern established in the literature for PBIAS/RME when going from "All Conditions" to sub-annual intervals is to shift the qualitative assessment by one category (e.g., use the "good" range for "very good," "satisfactory" for "good," and so on). This pattern will also be followed for RSR and NSE qualitative assessments of sub-annual intervals.

An important aspect of the calibration effort for the Butte Creek watershed study is attaining a reasonable representation of the snow processes, as they play an important role in the overall hydrologic regime for this watershed. For this purpose, the model simulated outputs related to snow processes (e.g., snow vs. rain volume, snowpack depth, and snow water yield) will be compared against observed data (e.g., SNOTEL) where available to ensure the sound performance of the model for capturing the snow processes. If local snow data are lacking, the performance of the model snow simulation module will be checked against observed data from nearby watersheds with available observed data and/or literature data for watersheds with similar characteristics.

The LSPC calibration performance in the Butte Creek watershed will be assessed to see if linkage of the LSPC model with a groundwater model (e.g., MODFLOW) could improve performance and process interactions. This could be manifested through a significant mismatch between the simulated and observed baseflow during dry periods. Other indicators include the mismatch between the simulated and observed hydrograph shape, demonstrating significant flow timing and magnitude differences. The presence of substantial agricultural operations in the watershed, which alters the overall hydrologic budgets through groundwater pumping, stream flow diversions, and return flows, could also necessitate the linkage of the LSPC model with a groundwater model.

Table 8-1. Summary of qualitative thresholds for performance metrics used to evaluate hydrology calibration.

Performance Metric	Hydrological Condition	Performance Threshold for Hydrology Simulation			
		Very Good	Good	Fair	Poor
Percent Bias (PBIAS)	All Conditions [1]	<5%	5% - 10%	10% - 15%	>15%
	Seasonal Flows [2]	<10%	10% - 15%	15% - 25%	>25%
	Highest 10% of Daily Flow Rates [3]				
	Lowest 50% of Daily Flow Rates [4]				
	Days Categorized as Storm Flow [5]				
	Days Categorized as Baseflow [5]				
	Highest 10% of Daily Flow Rates [3]				
	Lowest 50% of Daily Flow Rates [4]				
	Days Categorized as Storm Flow [5]				
	Days Categorized as Baseflow [5]				
RMSE – Std Dev Ratio (RSR)	All Conditions [1]	≤0.50	0.50 - 0.60	0.60 - 0.70	>0.70
	Seasonal Flows [2]	≤0.40	0.40 - 0.50	0.50 - 0.60	>0.60
Nash-Sutcliffe Efficiency (NSE)	All Conditions [1]	>0.80	0.70 - 0.80	0.50 - 0.70	≤0.50
	Seasonal Flows [2]	>0.70	0.50 - 0.70	0.40 - 0.50	≤0.40

1. All Flows considers all daily time steps in the model time series.
2. Seasonal Flows considers daily flows during a predefined, six-month seasonal period (e.g., Wet Season and Dry Season). The Wet Season includes the months of November through April. The Dry Season includes the months of May through October.
3. Highest 10% of Flows considers the top 10% of daily flows by magnitude as determined from the flow duration curve.
4. Lowest 50% of Flows considers the bottom 50% of daily flows by magnitude as determined from the flow duration curve.

Baseflows and Storm flows were determined from analyzing the daily model time series by applying the USGS hydrograph separation approach (Sloto et al. 1996)

9 SUMMARY & NEXT STEPS

This work plan presented the available data and proposed methods for developing a hydrologic model of the Butte Creek watershed. Once this work plan is finalized, the data sets described in this memo will be used to develop an LSPC model with a configuration as described in Section 7. After finalizing the work plan, the first step of that process will be to present and finalize watershed boundaries and subcatchment delineations that capture key points of interest in the watershed (e.g., tributary confluences, gage locations, etc.). Once built, this model will be calibrated using the metrics presented in Section 8 and documented in a model development report. Table 9-1 presents a summary of the deliverables planned for the Butte Creek watershed.

Table 9-1. Proposed schedule and summary of deliverables

Task	Subtask	Deliverable	Due Date
2	2.1	Data Compilation Inventory in Excel Format	--
	2.2	Draft Work Plan	--
	2.3	Final Work Plan	Two (2) weeks after receiving comments
3	3.1	Subbasin delineation and stream GIS files	Two (2) weeks after completing Task 2.3
	3.2	LSPC database, model inputs, and GIS files[1]	Twelve (12) weeks after completing Task 3.1
4	4.1	Draft Calibration Slide Deck	Six (6) weeks after completing Task 3.2
		Final Calibration Slide Deck	Four (4) weeks after receiving comments on Draft Calibration Slide Deck
5	5.1	Partial Draft Model Development Report[1]	Twelve (12) weeks after completing Task 3.1
		Draft Model Development Report	Six (6) weeks after completing Task 3.2
	5.2	Final Model Development Report	Four (4) Weeks after receiving comments on Task 5.1 Draft MDR
	5.3	Final LSPC Model Code & Software	Two (2) Weeks after Task 5.2
	5.4	Final Model Files including LSPC executable, LSPC database, LSPC model inputs, final GIS files	Two (2) Weeks after Task 5.2

1. Partial Draft Model Development Report under Task 5.1 will be delivered in conjunction with Task 3.2 to document the model configuration.

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