Work Plan: Putah Creek Watershed Hydrology Model Development

SUBMITTED TO:

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ACRONYMS

3DEP	3D Elevation Program
ALWU	Agricultural Land and Water Use Estimates
ASCE-PM	American Society of Civil Engineers version of the Penman-Monteith equation
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
CoCoRaHS	Community Collaborative Rain, Hail, and Snow Network
COOP	Cooperative Observer Program
DEM	Digital Elevation Model
DWR	California Department of Water Resources
EOL	Earth Observing Laboratory
ET	Evapotranspiration
ET_o	Reference evapotranspiration
eWRIMS	Electronic Water Rights Information Management System
GHCN	Global Historical Climatology Network
GIS	Geographic Information System
GSP	Groundwater Sustainability Plan
HRU	Hydrologic Response Unit
HSG	Hydrologic Soil Group
HSPF	Hydrologic Simulation Program - Fortran
HUC	Hydrologic Unit Code
KGE	Kling-Gupta Efficiency
LCD	Local Climatological Data
LSM	Land Surface Model
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
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutclife Model Efficiency Coefficient

PBIAS	Percent Bias
PEVT	Potential Evapotranspiration
POD	Point of Diversion
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Stations
RSR	Ratio of the root mean square error to the standard deviation of measured data
SGMA	Sustainable Groundwater Management Act
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 Putah 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 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 such as droughts or atmospheric rivers.

1.2 Watershed Background

Putah Creek is one of the major western tributaries to the San Pablo and San Francisco Bays. The Putah Creek watershed is part of the San Pablo Bay drainage area, which shares a boundary with the San Pablo Bay watershed to the south, the Upper Cache watershed to the north, and the Lower Sacramento watershed to the southeast. The upper watershed area drains approximately 654 square miles and is made up of 20 HUC-12 catchments: the Upper Eticuera Creek (HUC-12: 180201620101) and its major tributary, Pleasant Creek (HUC-12: 180201610302) (Figure 1-1) to name a few. Putah Creek originates from springs on the east side of Cobb Mountain in Lake County, it descends eastward to the town of Whispering Pines where it turns southeast parallel to State Route 175. The upper watershed tributaries include Dry Creek, Saint Helena Creek, Crazy Creek, and Big Canyon Creek, among others. Putah Creek enters Napa County at the confluence with Hunting Creek.

One of the key defining features of the watershed is Lake Berryessa, one of the largest reservoirs in California. The reservoir was created by the construction of Monticello Dam on Putah Creek in the 1950s. Spanning over 20,000 acres and storing 1.6 million acre-feet of water, the reservoir has been an important source of water and hydroelectricity to the north region of the San Francisco Bay Area (USBR 2024).

Another defining feature of the watershed is the Yolo Basin and Bypass, located in the eastern portions of the watershed. It once served as an 80,000-acre wetland for numerous species of birds, bats, and other Sacramento Valley wildlife. Recently, the lands within the Bypass have been converted to grazing and farmland. However, existing partnerships with the Yolo Basin Foundation, Caltrans, and the U.S Fish and Wildlife resulted in restoration projects re-storing permanent ponds and seasonal wetland areas for wintering waterfowl and other bird species (CDFW 2024).

The Putah Creek watershed ranges in elevation from near sea level to over 1,400 meters at the northwest most portion near Big Canyon and Dry Creek. It has a Mediterranean climate with distinct wet and dry seasons and an estimated mean annual precipitation total of 45 inches (USGS 2019). The valley floor of the watershed is dominated by grasslands and shrubland, which cover approximately

55% and 26% of the total area. Beyond the valley floor, the watershed is predominantly open water (4%), evergreen forest (4%), or cultivated crops (4%).

The Putah Creek watershed serves as a cold freshwater habitat and is home to a myriad of rare plants and endangered animals, including Western Pearlshell mussels. However, high mercury and aluminum levels and high water temperatures have impaired the streams (SWRCB 2024). Multiple programs have been launched to improve water quality across the Putah Creek watershed, including the Putah Creek Water Management Initiative and the Putah-Cache Riparian Restoration Program. Both programs seek cooperation with landowners in addition to restoration projects involving riparian ecosystems.

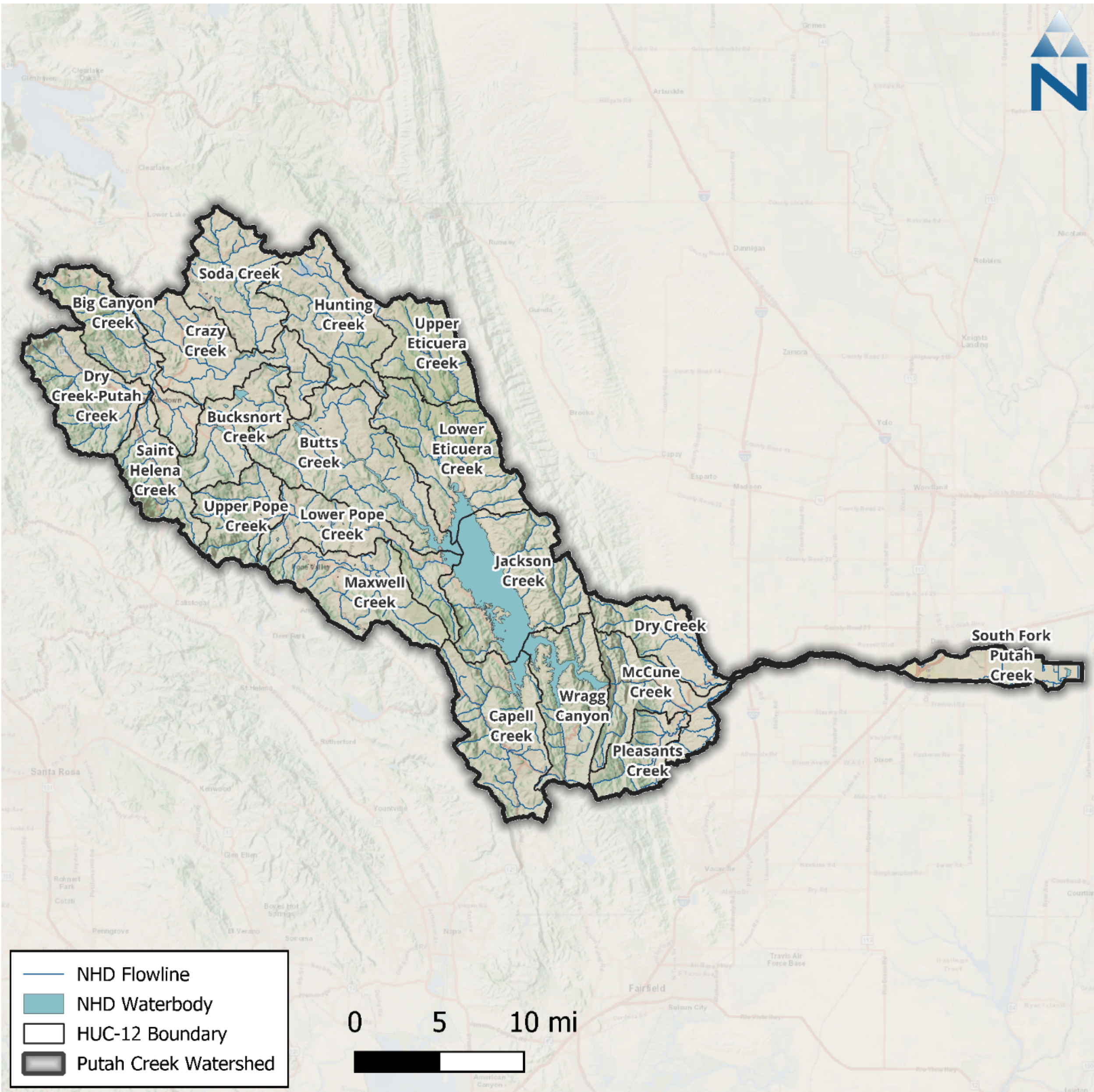

Figure 1-1. The Putah Creek watershed.

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 Putah Creek watershed. This is presented first through a comprehensive inventory of available hydrologic, meteorological, and geographic information system (GIS) data available for the Putah Creek watershed. The data compilation and assessment processes are outlined below and aim to highlight any existing data gaps that create limitations for the analysis. Based on the available data, any data gaps are identified that 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 is best summarized by the following 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.

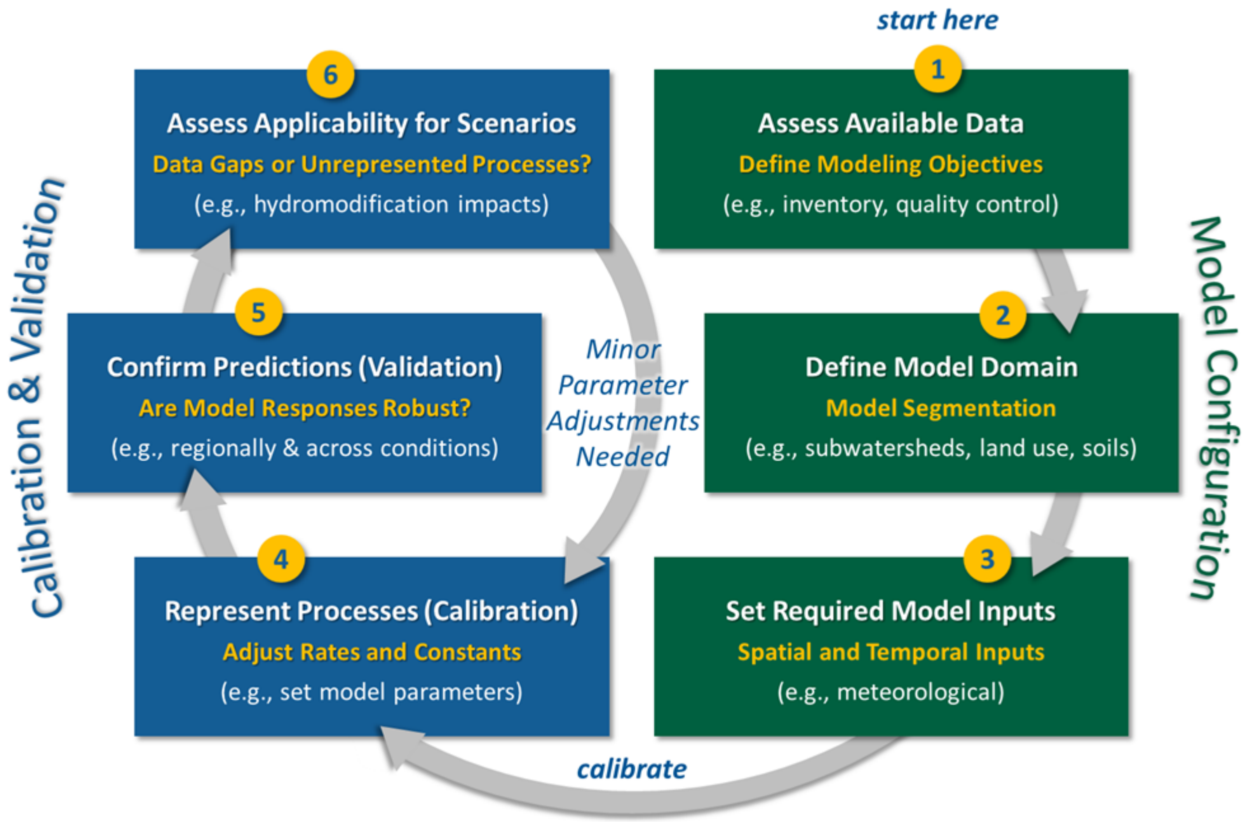

Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Putah Creek watershed.

1.4 Data Availability

Table 1-1 through Table 1-4 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 is organized by data type including:

- **Meteorology Datasets**: Time series that represent water balance inputs and outputs to the watershed primarily from precipitation and evapotranspiration. These time series are often used as forcing functions for hydrologic models.
- **Surface & Groundwater Datasets**: Datasets describing stream flow, groundwater, water use, and stream conditions for Putah Creek. Time series observations of instream responses for the Putah Creek are often used as calibration and validation datasets for hydrologic models.
- **Geospatial Datasets**: Spatial datasets describing the landscape of the Putah 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 available for 3 stations.	Climate data boundary time series.
California Data Exchange Center (CDEC)	Precipitation, Temperature	--	Meteorological records available for 2 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., potential evapotranspiration, and solar radiation).	Rainfall hourly distributions; address rainfall data gaps. Daily potential evapotranspiration totals × hourly solar radiation distributions.
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 forcing time series; estimation of irrigation demand.
OpenET	OpenET CONUS Ensemble Monthly Evapotranspiration	2016 - 2024	Satellite-based estimates (30-m res) of observed monthly evapotranspiration for the CONUS; data is bias corrected against observational weather station networks.	Parameterization & evaluation of ET; estimation of irrigation demand.

Table 1-2. Inventory of surface water datasets

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Streamflow	Local	USGS	Stream Gauge Discharge	1904 – Current	Observed Streamflow at four active locations in the watershed	Hydrology calibration.	LINK
Water Budget	State	DWR	Well Completion Reports	Current	Well completion logs and reports.	Water budget.	LINK
			Interconnected Surface Water	2008	Two (2) river flow CDEC stations near the Putah Creek watershed.		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
		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 Area Boundaries	2024	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	DWR	Statewide Crop Mapping	2020	Polygons attributed with DWR crop categories.	Identify crop distributions; estimate irrigation demand.	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

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	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 ten-meter resolution digital elevation model (DEM)	2020	10-meter resolution digital elevation model (DEM) produced through the 3D Elevation Program (3DEP).	Land segment representation.	LINK

Table 1-4. Inventory of groundwater datasets

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Groundwater Basin Boundaries	State	DWR	DWR's Bulletin 118	2020	Groundwater basin boundaries represent alluvial basins delineated by DWR.	Groundwater domain.	LINK
Groundwater levels	State	DWR	Periodic Groundwater Level Measurements	2023	Groundwater levels	Model calibration.	LINK
Geologic information	State	DWR	Well Completion Reports (OSWCR)	2023	Geologic information	Groundwater stratigraphy and properties.	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 Putah Creek watershed will be the observed data from land-based stations within and in the vicinity of the watershed (Table 2-1). However, any 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), which maintains 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 12 GHCN gauges identified within 10 miles of the Putah Creek watershed. These gauges all have data with varied quantity and quality. In addition to the daily precipitation gauges, NCDC also maintains the Local Climatological Data (LCD) network. There are three LCD stations with hourly observations located within 10 miles of the Putah Creek watershed. The California Data Exchange Center (CDEC) and Remote Automated Weather Stations (RAWS) networks also report hourly precipitation within the watershed. CDEC reports at two locations and RAWS reports at three locations. Table 2-1 is an inventory of the precipitation stations near the Putah Creek watershed with available data after 2000 and around 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 Putah Creek watershed will be the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 2008; Daly, Neilson, and Phillips 1994; Gibson et al. 2002). 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 subset of the PRISM grid that covers the current study area is shown in Figure 2-1. To downscale the PRISM data to hourly, the North American Land Data Assimilation System (NLDAS) is used. NLDAS is a quality-controlled land surface model (LSM) dataset of meteorological data designed specifically to support continuous simulation modeling activities (Cosgrove et al. 2003; Mitchell et al. 2004). NLDAS provides real-time hourly predictions of meteorological data required for LSPC at a 1/8th degree spatial resolution (about 8.625-mile intervals) for North America, with retrospective simulations beginning in January 1979. NLDAS has undergone rounds of refinement, extensive peer review, and performance validation through case study applications, all of which have demonstrated it to be a more robust predictor of variable meteorological conditions for continuous simulation modeling than using individual gauges (Xia et al. 2012).

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:23232	SACRAMENTO AIRPORT ASOS, CA US	6/30/1947	Present	38.50659	-121.496	5.9	100%
	WBAN:00174	UNIVERSITY AIRPORT, CA US	1/1/2009	Present	38.533	-121.783	21	100%
NOAA-GHCN	GHCND:USC00040212	ANGWIN PACIFIC UNION COLLEGE, CA US	12/31/1939	Present	38.573	-122.441	522.7	92%
	GHCND:USC00042294	DAVIS 2 WSW EXPERIMENTAL FARM, CA US	12/31/1892	Present	38.5349	-121.776	18.3	92%
	GHCND:USC00044673	LAKE BERRYESSA, CA US	5/31/2005	7/31/2008	38.57944	-122.25	138.7	100%
	GHCND:USC00044712	LAKE SOLANO, CA US	7/31/1975	Present	38.492	-122.004	57	99%
	GHCND:USC00045360	MARKLEY COVE, CA US	2/28/1970	Present	38.4916	-122.124	146.3	99%
	GHCND:USW00023271	SACRAMENTO 5 ESE, CA US	8/01/1877	8/1/2024	38.5552	-121.418	11.6	100%
	GHCND:USW00023232	SACRAMENTO AIRPORT ASOS, CA US	11/9/1941	Present	38.50659	-121.496	5.9	96%
	GHCND:US1CANP0003	CALISTOGA 0.4 SSE, CA US	2/10/2009	Present	38.5764	-122.578	106.1	94%
	GHCND:US1CALK0018	HIDDEN VALLEY LAKE 2.7 W, CA US	3/17/2021	Present	38.81363	-122.568	355.7	99%
CDEC	ATL	ATLAS PEAK	1/1/1987	Present	38.42833	-122.248	1660	--
	WSP	WHISPERING PINES	1/1/1987	Present	38.80583	-122.708	2700	--
RAWS	ATLC1	ATLAS PEAK	1/20/2011	Present	38.47485	-122.265	1934	--
	KNO	KNOXVILLE CREEK CALIFORNIA, CA US	5/23/1985	Present	38.86	-122.42	2200	--
	BRO	BROOKS CALIFORNIA, CA US	5/2/1990	Present	38.74	-122.14	354	--
	KON	KONOCTI CALIFORNIA, CA US	3/20/1995	Present	38.91	-122.7	2163	--

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.

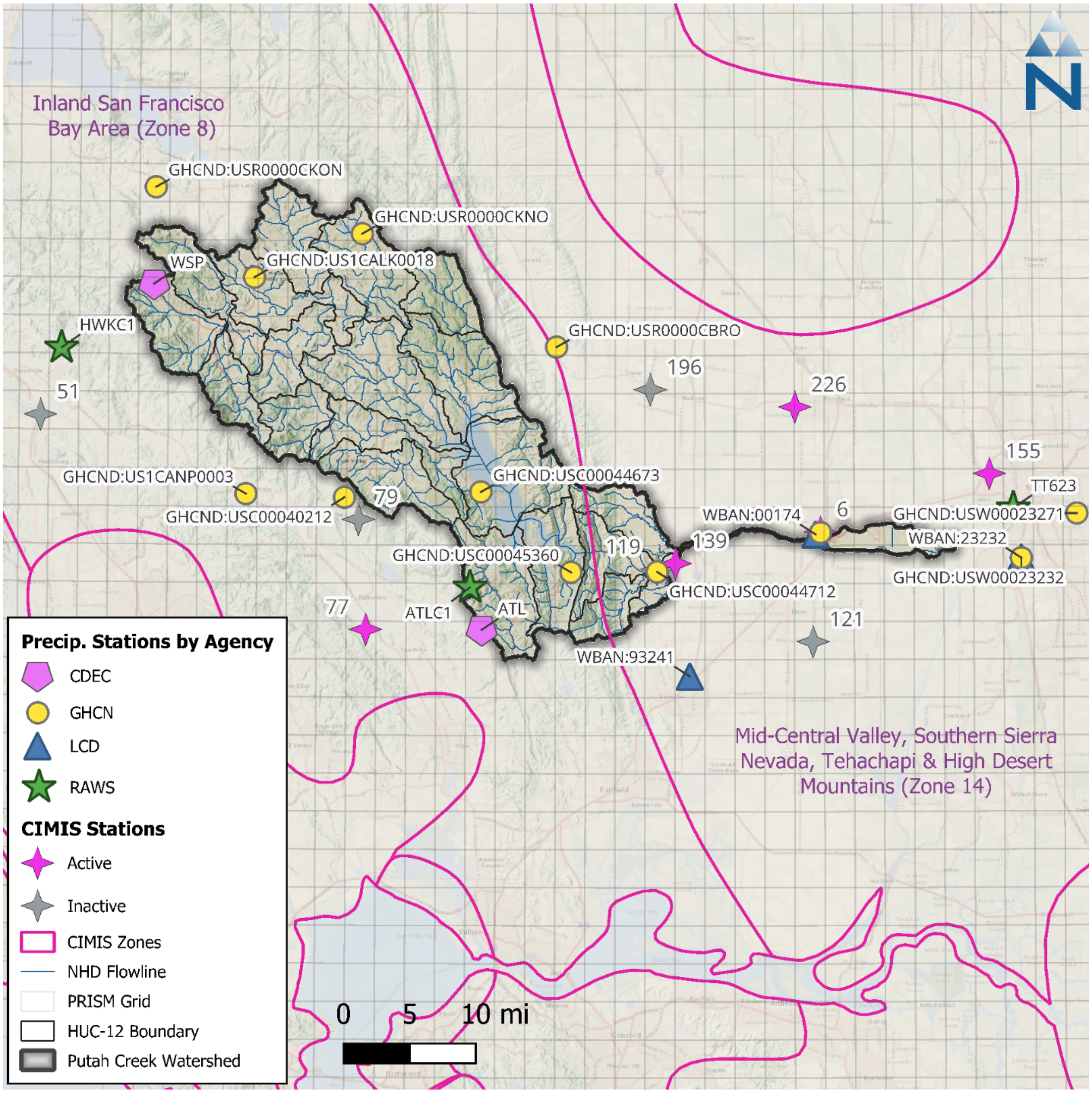

Figure 2-1 Identified rainfall gauges and CIMIS ET Zones near the Putah Creek watershed.

The hybrid approach entails three main steps. First, impaired intervals (i.e., missing, or accumulated) at observed stations will be patched with quality data from nearby gauges. Second, the PRISM grid cells and patched observed stations are mapped to the NLDAS grid cells to downscale the monthly PRISM and daily station data using normalized hourly data from NLDAS. Third, the downscaled gridded meteorological data from the PRISM are used to fill spatial and any remaining temporal 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 to be processed in parallel to: (1)

create a temporally complete set of hourly distributions and (2) identify spatial gaps in coverage to be supplemented with 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 also shows what a hybrid dataset of observed time series, supplemented by gridded products would look like.

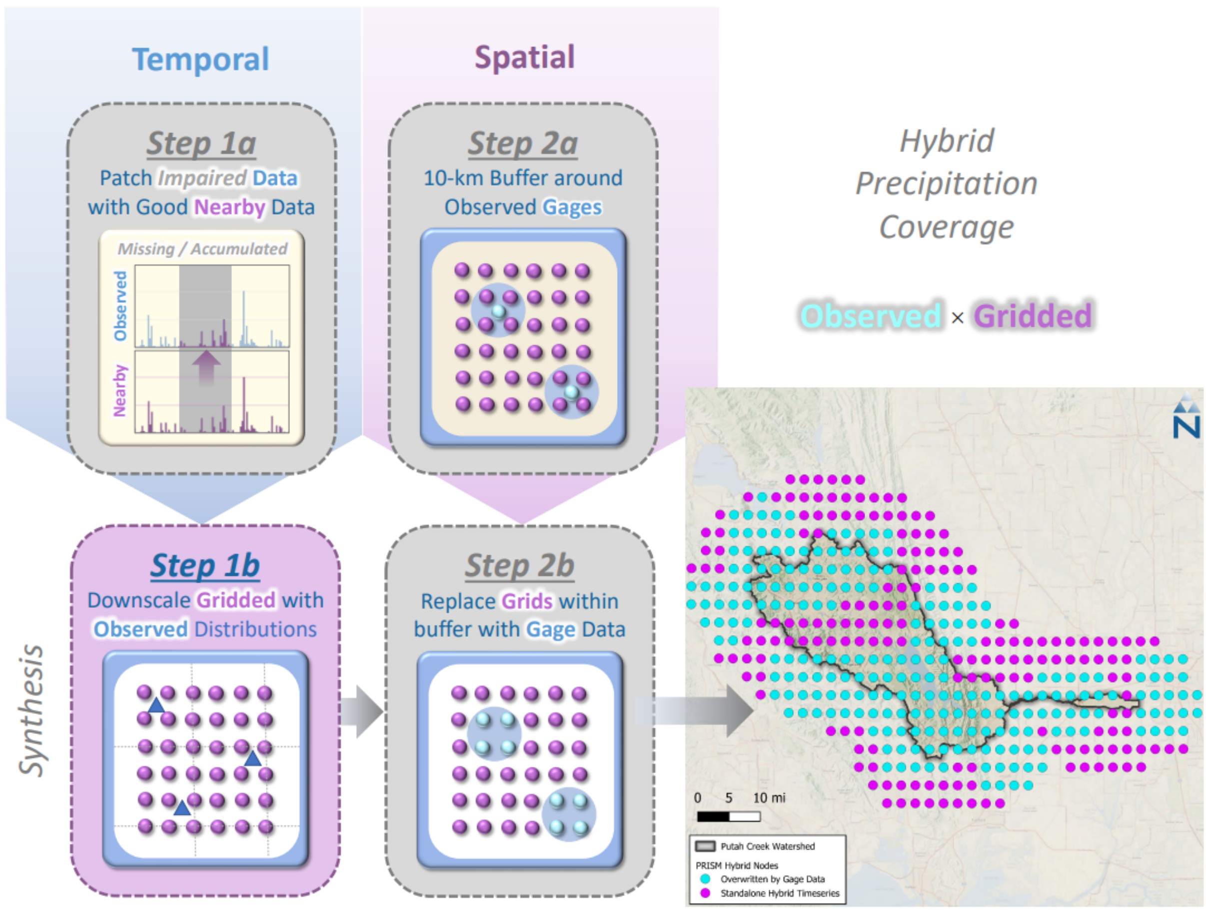

Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products.

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 10 stations within 10 miles of the Putah Creek watershed, including 5 active stations: Davis (ID 6), Oakville (ID 77), Winters (ID 139), Bryte (Experimental) (ID 155), and Woodland (ID 226). 5 additional stations in and around the watershed are no longer operating, but their collective historical time series data covers the period from August 1986 through July 2017. There are no active CIMIS stations directly within the Putah Creek watershed boundary, but the currently active CIMIS stations within the 10-mile watershed buffer have collected time series data near the Putah Creek watershed since 1982.

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) (Allen et. al. 2005). The ASCE-PM method calculates ET_o using solar radiation, air temperature, relative humidity, and wind speed at two meters height. 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. As shown in Figure 2-1, the Putah Creek watershed intersects two CIMIS zones with 89% of the watershed area in Zone 8 (Inland San Francisco Bay Area), and 11% of the watershed area in Zone 14 (Mid-Central Valley, Southern Sierra Nevada, Tehachapi & High Desert Mountains). Most of the Putah Creek watershed falls within Zone 8, and the southeastern end of the watershed falls into Zone 14. These zones experience average annual reference evapotranspiration levels from 49.4 inches per year in Zone 8 to 57.0 inches per year in Zone 14.

Representative potential evapotranspiration (PEVT) time series can be estimated for the Putah Creek watershed from daily data from CIMIS Spatial and downscaling the hourly time series using hourly distributions from land observation stations (e.g., RAWS, NCDC) or hourly distributions from NLDAS. Potential evapotranspiration is reported at 3-hour intervals; however, the hourly distributions of solar radiation from NLDAS, which have sinusoidal patterns over daylight hours, provide a sound basis for downscaling the daily CIMIS depths while maintaining the overall annual water budget reflected in CIMIS.

For LSPC, the user provides PEVT rates as model input. The LSPC model then uses these values along with other model parameters to estimate actual ET. Sometimes ET_o is provided instead, and HRU-specific coefficient multipliers are used to stratify those inputs based on physical HRU properties such as vegetation density. Additionally, for applications where the study area has significant agricultural practice, the user can provide irrigation water usage rates to represent additional water beyond precipitation that is added to the system—that water would also be available for evapotranspiration.

The actual ET estimated by an LSPC model can be validated by comparing it with data from OpenET. The OpenET project is an operational system for generating and distributing ET data at a field scale using an ensemble of six well-established satellite-based approaches for mapping ET (Melton et al. 2022). OpenET has undergone extensive intercomparison and accuracy assessment conducted using ground measurements of ET; results of these assessments demonstrate strong agreement between the satellite-driven ET models and observed flux tower ET data. Within California, OpenET has data beginning in 2016 and uses CIMIS meteorological datasets to compute ET_o. In addition to LSPC ET validation, OpenET data can be used to help inform irrigation estimation and parameterization.

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 (largest) at the region scale to 12-digit HUCs (smallest) at the subwatershed scale. The Putah Creek watershed is defined by a HUC-8 watershed that comprises 20 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. The NHD Plus v2 (NHDPlus) further discretizes the watershed into 682 catchments ranging in size between 0.0003 square miles, to approximately 7 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 Putah Creek watershed (HUC-8).

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

HUC-12 Name	Count	Catchment Size (acres)			
		Minimum	Mean	Median	Maximum
Upper Eticuera Creek	20	58.5	826.7	635.1	2,131.9
Lower Eticuera Creek	39	11.8	724.6	503.5	2,670.9
Upper Pope Creek	15	89.2	928.5	720.7	3,234.0
Maxwell Creek	43	3.1	521.6	397.9	1,781.1
Lower Pope Creek	42	4.0	492.7	276.9	2,452.3
Saint Helena Creek	23	3.3	593.0	584.9	1,617.5
Dry Creek-Putah Creek	31	23.6	659.6	525.1	3,141.7
Big Canyon Creek	26	20.2	801.2	816.5	2,721.4
Soda Creek	26	0.2	798.2	538.2	4,020.5
Bucksnort Creek	25	12.5	673.4	385.8	2,960.9
Hunting Creek	38	5.3	631.3	449.4	2,075.1
Crazy Creek	31	2.7	816.7	656.0	2,438.0
Butts Creek	72	4.7	492.4	379.3	1,950.6
Capell Creek	53	0.9	529.5	397.9	1,750.0
Jackson Creek	39	50.5	873.6	724.3	1,983.9
Wragg Canyon	33	0.2	657.1	451.9	2,539.2
Pleasants Creek	12	2.9	883.0	883.6	2,189.0
Dry Creek	22	11.8	638.9	576.1	2,815.8
McCune Creek	67	0.4	286.9	81.6	1,947.7
South Fork Putah Creek	25	0.7	463.2	55.2	4,559.0

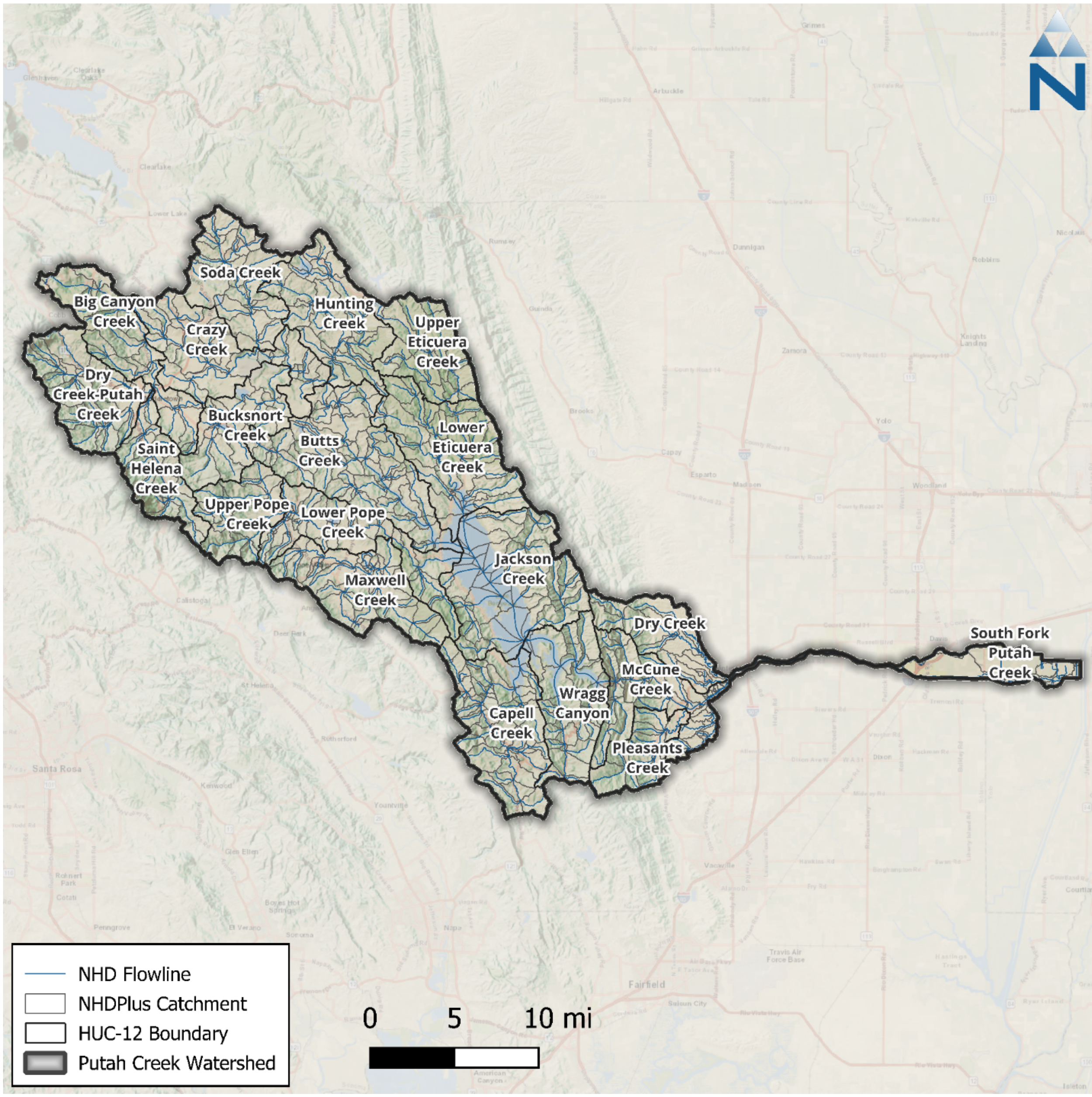

Figure 3-1. Initial catchment segmentation for the Putah Creek watershed.

The NHDPlus dataset provides a good foundation for model segmentation at a spatial scale that is suitable for representing the watershed for the purposes of modeling daily, seasonal, and annual streamflow. The NHDPlus catchment boundaries will be aggregated and/or adjusted as necessary to align with any 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 Putah Creek watershed (as shown in Figure 3-1) are primarily derived from NHDPlus. This dataset depicts primary 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. These characteristics will be important for creating representative reach segments within the hydrologic model. Figure 3-1 maps the location of the Putah Creek and its major tributaries.

Four creeks flow into Lake Berryessa: Capell Creek, Pope Creek, Eticuera Creek, and Putah Creek. Together, the lake spans 23 miles, 3 miles wide, with 165 miles of shoreline, which contributes to its astounding size (Kilkus 2021). More information about Lake Berryessa can be found in Table 3-2.

Table 3-2. Key Information of Lake Berryessa

Average Depth (feet)	Lake Capacity (acre-feet)	Surface Area (acres)	Average Annual inflow (acre-feet per year)
50-140	1,602,000	20,700	369,000

3.3 Streamflow

The primary source of streamflow data is from the USGS, which includes four currently active long-term gauges: Putah Creek near Guenoc, CA (USGS:11453500), Pope Creek at Walter Springs, CA (USGS:11453590), Putah Creek near Winters, CA (USGS:11454000), and Putah South Canal near Winters, CA (USGS:11454210). There are also three historical streamflow gauges located upstream on tributaries that have observations after the year 2000, which may be useful in calibrating the model. Table 3-3. presents a summary of the available USGS streamflow data. Figure 3-2 shows the locations of the USGS gauges within the Putah Creek watershed. Additional streamflow data sources include the Solano, Lake, Napa, and Yolo County websites which have data from discontinued stations along with others operated by the USGS.

Table 3-3. Summary of USGS daily streamflow data with observations available after 2000

Gauge Description	Station ID	Drain age Area (mi^2)	Start Date	End Date	Gauge Active?
BEAR CYN C A ANDERSON SPRINGS RD NR MIDDLETOWN CA	11453155	5.1	11/04/2015	10/03/2017	No
PUTAH C NR GUENOC CA[1]	11453500	113.0	10/01/1904	Present	Yes
HUNTING C NR KNOXVILLE CA	11453550	37.8	6/26/1969	9/29/1976	No
POPE C A WALTER SPRINGS CA	11453590	40.04	12/24/2020	Present	Yes
LK BERRYESSA NR WINTERS CA[2]	11453900	566.0	1/11/1957	9/30/2009	No
PUTAH C NR WINTERS CA	11454000	574.0	6/28/1930	Present	Yes
PUTAH SOUTH CN NR WINTERS CA	11454210	603.6	10/01/1994	9/30/2023	Yes

1. Although the Putah Creek near Guenoc CA (USGS-1145350) gauge has data beginning in 1904, two large gaps exist in the record where there is no data: 1907-1929 and 1977-1997.
2. May be used for representing reservoir

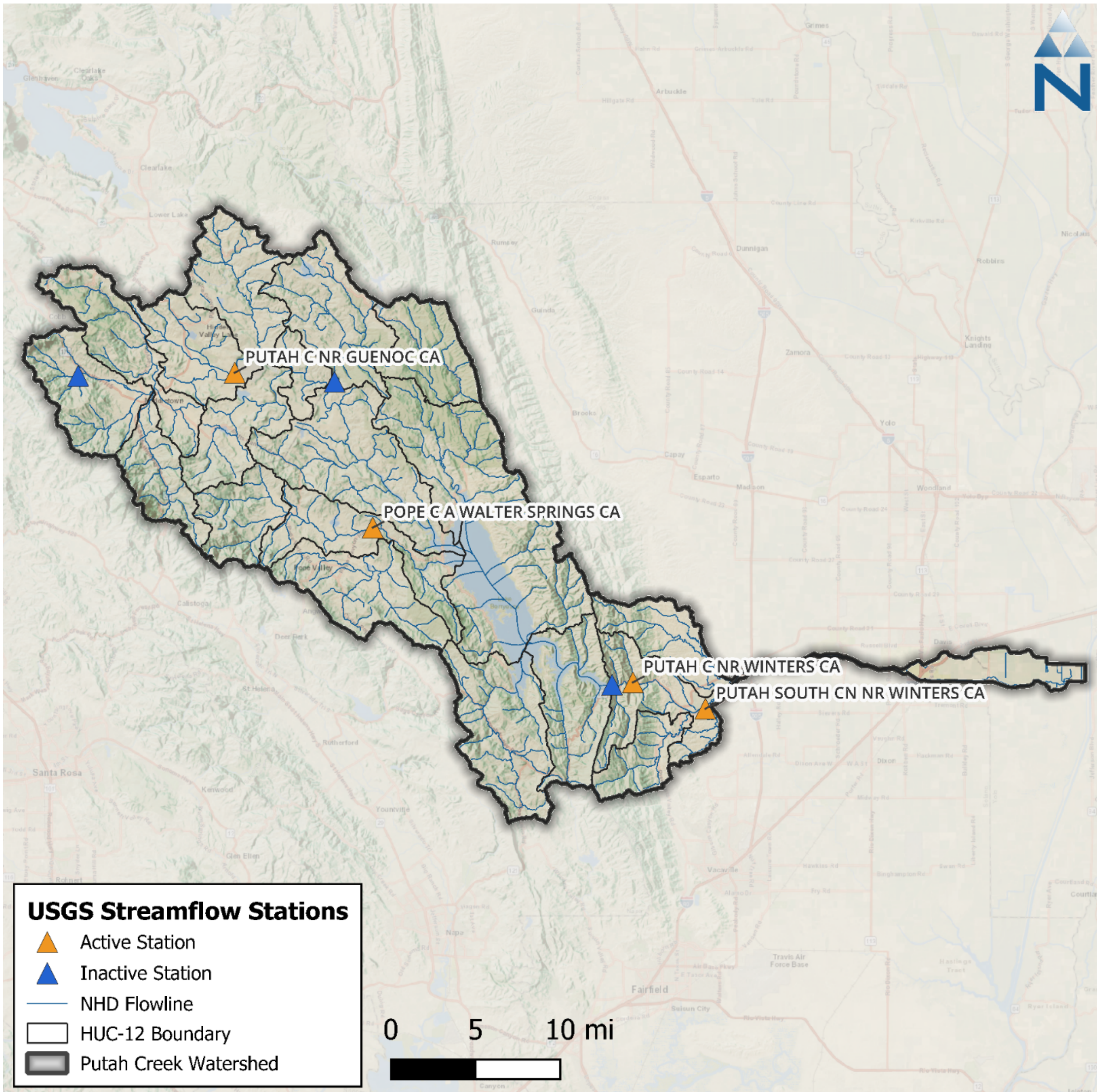

Figure 3-2. USGS streamflow stations in the Putah Creek watershed.

3.4 Surface Water Withdrawals

Datasets related to water rights, points of diversion, and surface withdrawals will be identified through searches of the Water Board's Electronic Water Rights Information Management System database (eWRIMS) while estimates of irrigated crop acreages will be obtained from the DWR Agricultural Land and Water Use Estimates database (ALWU) (DWR 2024). These datasets can represent diversions, withdrawals, and irrigation practices in the watershed model. The volumes quantified in those datasets can be compared to annual and seasonal water budget estimates in the Putah Creek watershed to assess the relative impacts based on observed precipitation, evapotranspiration, and streamflow data. The impact of diversions or water usage may be localized along specific tributaries; however, the temporal resolution of the data determines the resolution of those impacts in the model.

Additionally, the extent of modeled irrigation will depend on land-use classification, and water usage rates will be corrected against spatial variations in the observed evaporative deficit where necessary.

Figure 3-3 provides an overview of both water systems and points of diversion in the watershed. Water systems distributed throughout the entire watershed include a mixture of both surface water diversions from Putah Creek and its primary tributaries, as well as groundwater withdrawals for the Putah Creek watershed groundwater basin. There are 24 drinking water systems in the watershed. For 12 out of the 24 drinking water systems, the water source is listed as groundwater, 11 have surface water listed as the source, and the last remaining system does not have a known source type.

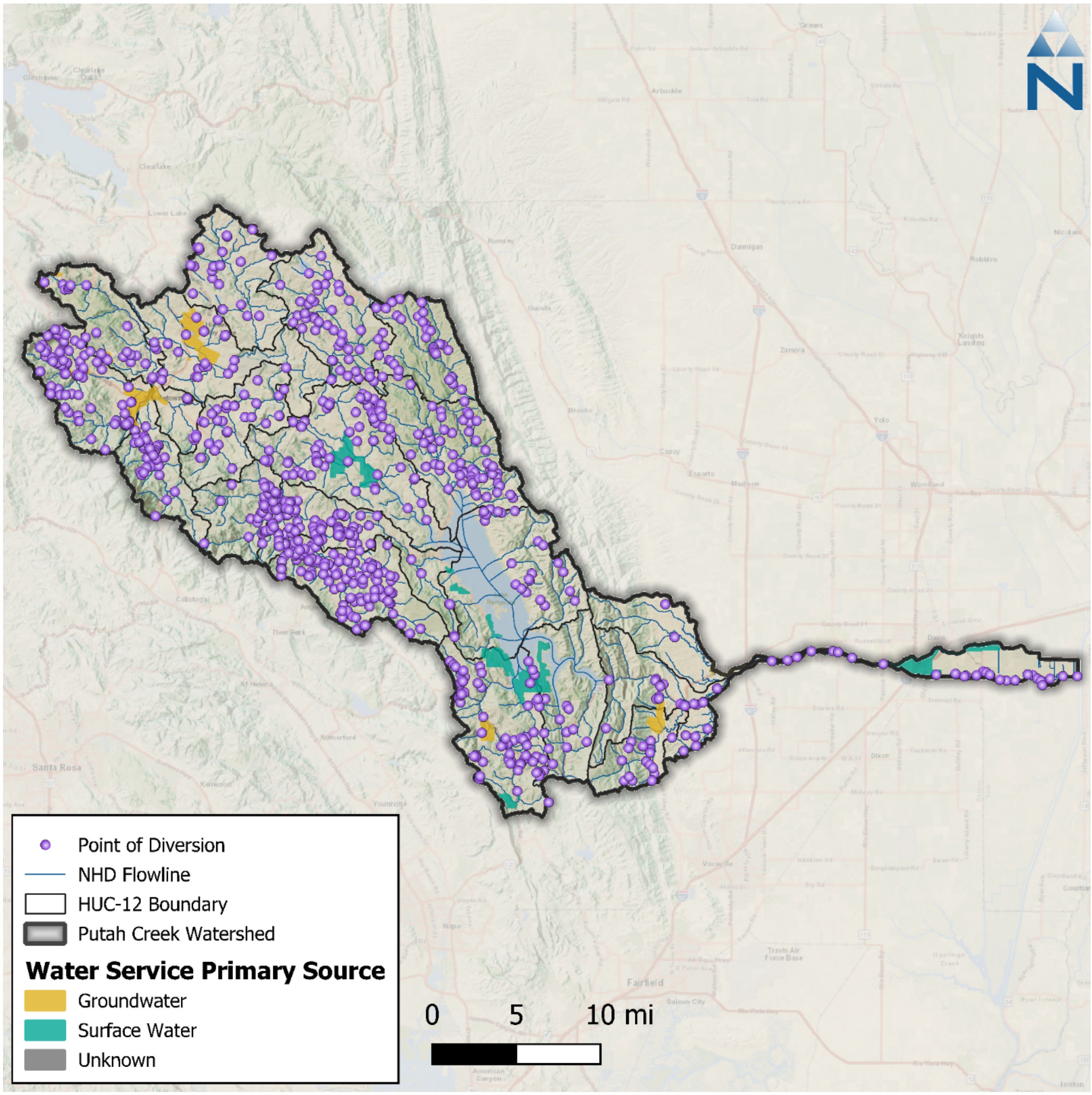

Figure 3-3. Points of diversion and water system types in the Putah Creek watershed.

4 SUBSURFACE HYDROLOGY

The Putah Creek watershed contains and overlaps with several groundwater basins as delineated by Bulletin 118 (DWR 2020c). These groundwater basins include Coyote Valley (number 5-018), Collayomi Valley (number 5-019), Berryessa Valley (number 5-020) and Pope Valley (number 5-068), which are fully contained within the Putah Creek watershed. The southwestern lower portion of the basin overlaps to a small degree with two subbasins of the Sacramento Valley watershed, Solano (number 5-021.66) and Yolo (number 5-021.67). Approximately 11% of the Putah Creek watershed area falls within the alluvial groundwater basins delineated by Bulletin 118 and the remaining 89% is composed of marine sedimentary rock, "generally considered to be non-water-bearing, but it does provide water through fractures" (DWR 2020c).

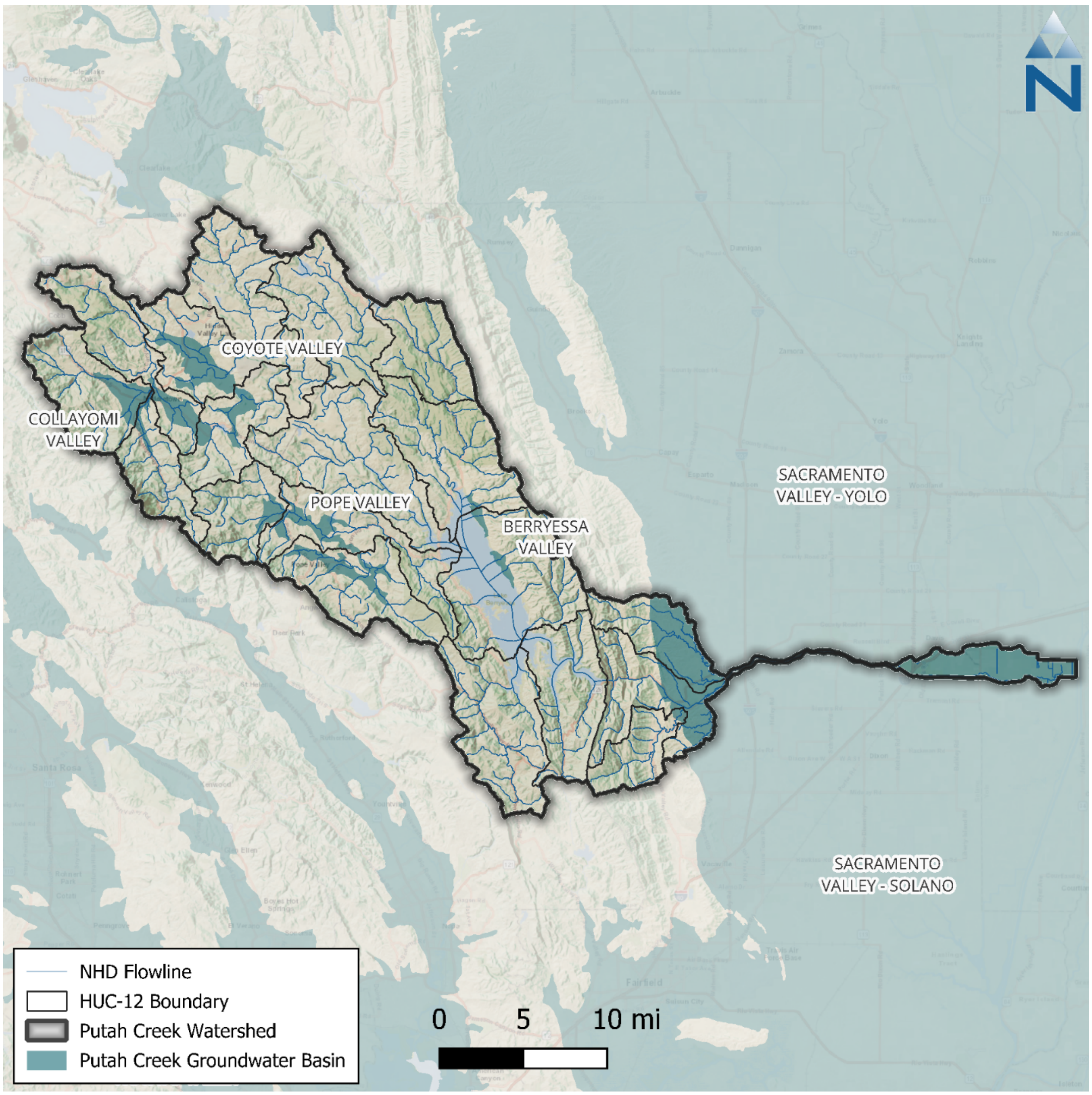

Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118.

As per the respective basin priority details (Sustainable Groundwater Management Act (SGMA) Basin Prioritization Dashboard), the Coyote Valley, Collayomi Valley, Berryessa Valley and Pope Valley are Very Low Priority basins as designated by SGMA's basin prioritization. Sacramento Valley-Solano is a Medium Priority basin and Sacramento Valley-Yolo is a High Priority basin. Coyote Valley has a growing population and groundwater makes up an estimated 68% of supply. Collayomi Valley has a growing population, a high well density, and groundwater makes up an estimated 67% of supply. Pope Valley has groundwater that makes up 95% of supply. Nevertheless, these basins were classified as Very Low priority due to groundwater use of less than 9,500 acre-feet/year and no documented groundwater impacts.

Available water level trends from statewide databases show some groundwater declines especially in the lower basin, while other wells near the headwaters have been more stable with time. The reported groundwater level declines indicate that groundwater depletion has played a role in the water budgets of the Putah Creek watershed, and therefore, considering groundwater flow in the current study would contribute to understanding the comprehensive hydrologic system.

4.1 Water Budget Components

No published groundwater models are available for the Putah Creek watershed. A minor downstream portion of the watershed overlaps with the Central Valley Hydrologic Model (CVHM2) (Faunt et al 2024), the California Central Valley Groundwater-Surface Water Simulation Model (C2VSimCG) (Brush et al 2013, DWR 2020b) and the Sacramento Valley Groundwater-Surface Water Simulation Model (SVSIM) (Bedekar et al, 2021).

The Collayomi Groundwater Basin was assessed in 1995 to have 1,000 acre-feet/year of water extracted for agricultural uses and 94 acre-feet/year extracted for municipal/industrial uses, with 250 acre-feet/year of deep percolation from applied water (DWR 2020a). The Coyote Valley Groundwater Basin was assessed in 1995 to have 1,400 acre-feet per year extracted for agricultural uses and 290 acre-feet/year extracted for municipal/industrial uses, with 1,100 acre-feet/year of deep percolation from applied water (DWR 2020a). No water budget information was available for Berryessa and Pope Valley basins as per the Bulletin 118 assessment (DWR 2020a).

4.2 Geology

The groundwater basins 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. 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. Figure 4-2 is a map of geology types within the Putah Creek watershed.

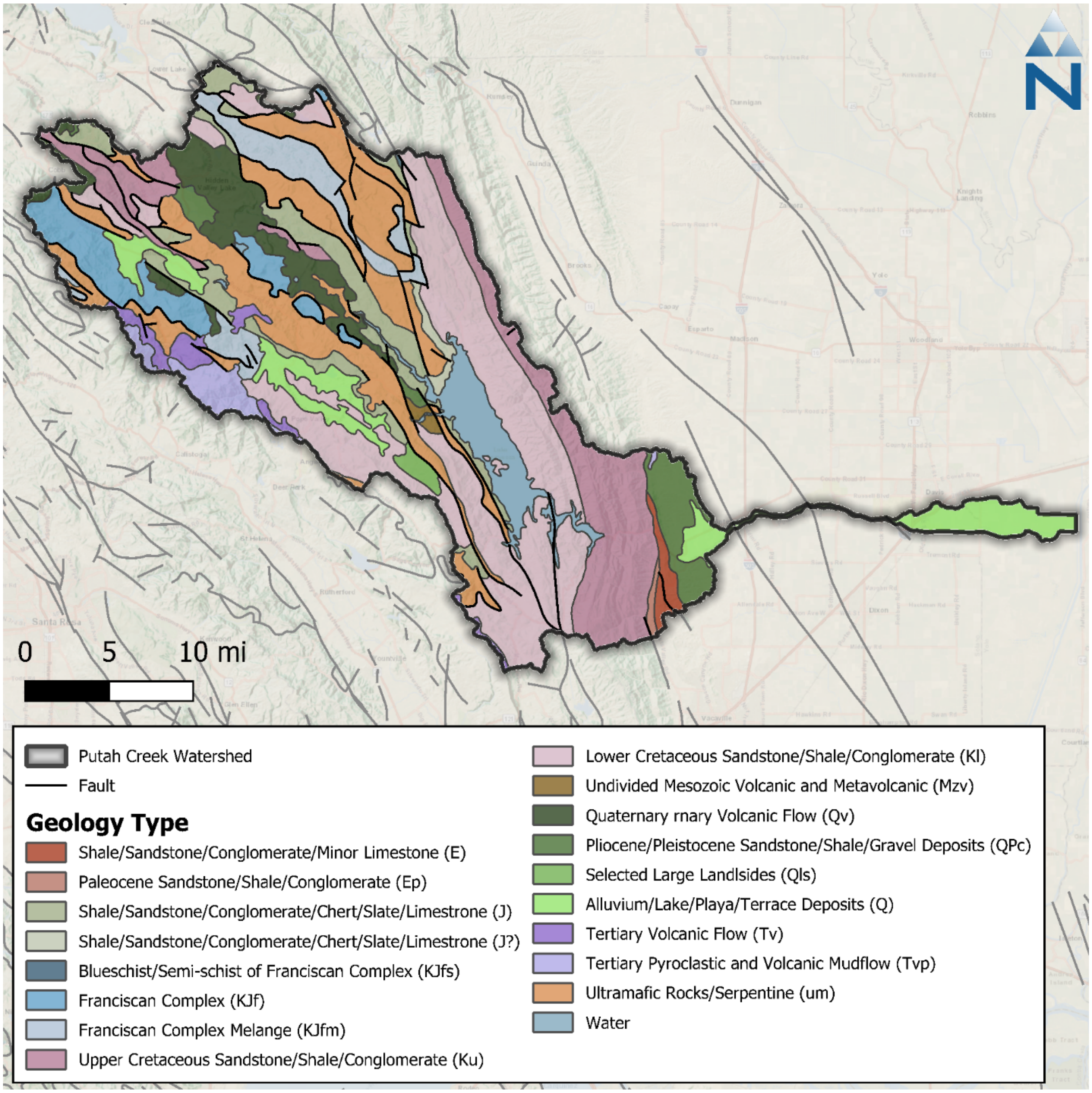

Figure 4-2. Geology types delineated by the California Geological Survey (CGS 2010).

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. Hydrologic Response Units (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 spatial combinations of these 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 Putah Creek watershed.

5.1 Elevation & Slope

The USGS publishes DEMs expressing landscape elevation through a raster grid data product with 30-meter resolution. The Putah Creek watershed ranges in elevation from sea level (0 meters) along the southeastern end of the watershed to over 1,400 meters in the northwestern 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 Putah Creek watershed.

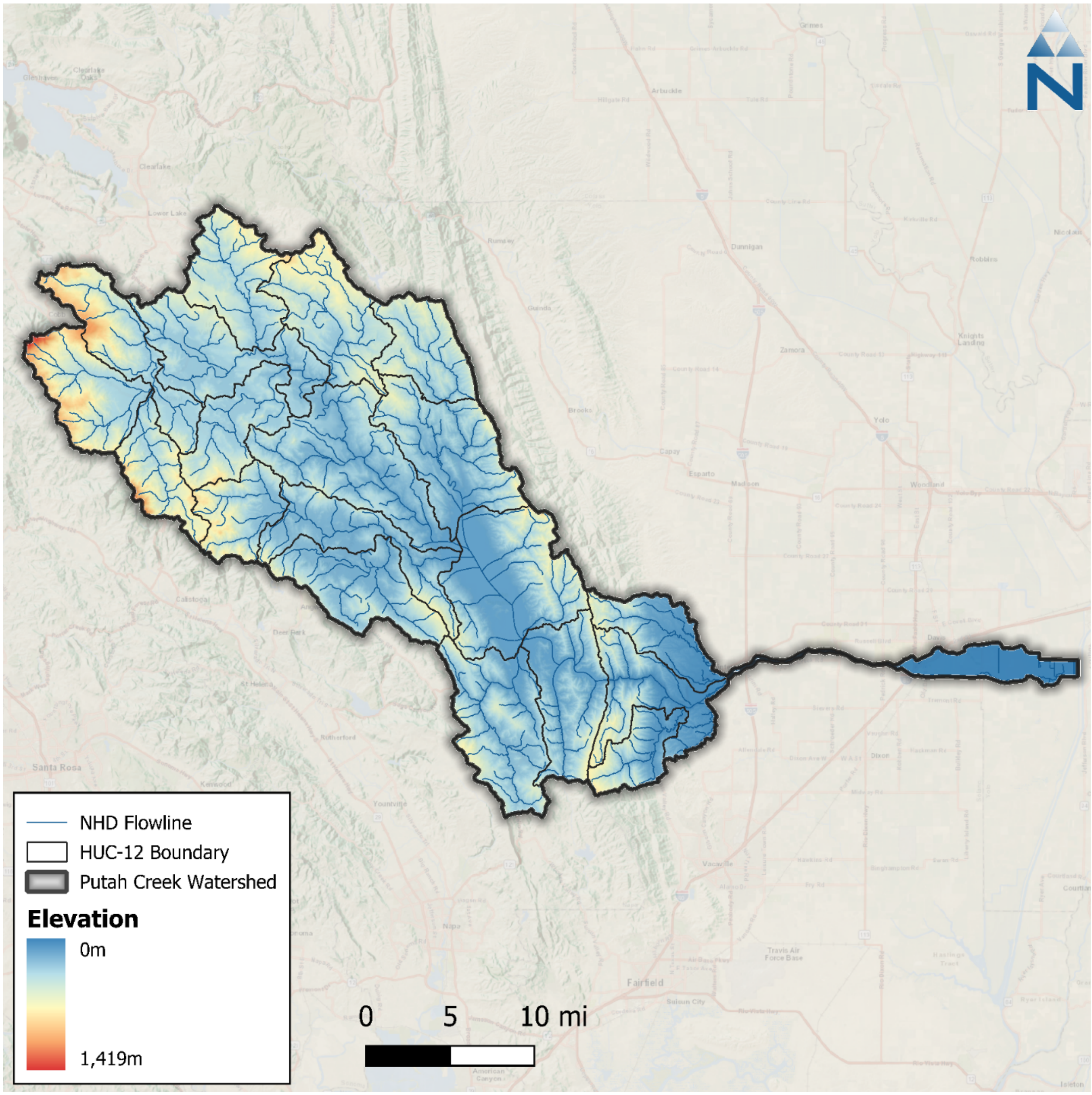

Figure 5-1. Digital elevation model of the Putah Creek watershed.

5.2 Soils

Soils data for the Putah Creek watershed were obtained from the Soil Survey Geographic Database (SSURGO) (USDA 2024a) and State Soil Geographic Database (STATSGO) (USDA 2024b) 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 for predominant hydrologic soil groups 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 provides a summary of areas occupied by each SSURGO HSG, and Figure 5-2 shows the spatial distribution of these groups throughout the Putah Creek watershed. The dominant soil group in the watershed is Group D (52%), with the lowest infiltration rates, containing clay loam, silty clay loam, sandy and silty clay, and clay. Group C (35%) is the next most common soil group in the watershed, containing sandy clay loam that typically have low infiltration rates. Group B makes up almost 3% of the watershed, containing moderately well to well-drained silt loams and loams, and Group A, containing well-draining sand, loamy sand, and sandy loam, makes up just over 1.5%. Only 0.04% 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 8% of the watershed HSG area is classified as unknown in the soils database and reside primarily within mountainous areas. For these areas, the corresponding HSG from the STATSGO dataset will be used to supplement the data gaps; some of these unknown soil areas may correspond to waterbodies.

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

Hydrologic Soil Group	Area (acres)	Percent Area
A	6,682.58	1.60%
B	10,565.16	2.52%
C	147,323.87	35.19%
C/D	166.64	0.04%
D	218,632.99	52.22%
N/A	35,324.88	8.44%
Total	**418,696.12**	**100.0%**

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

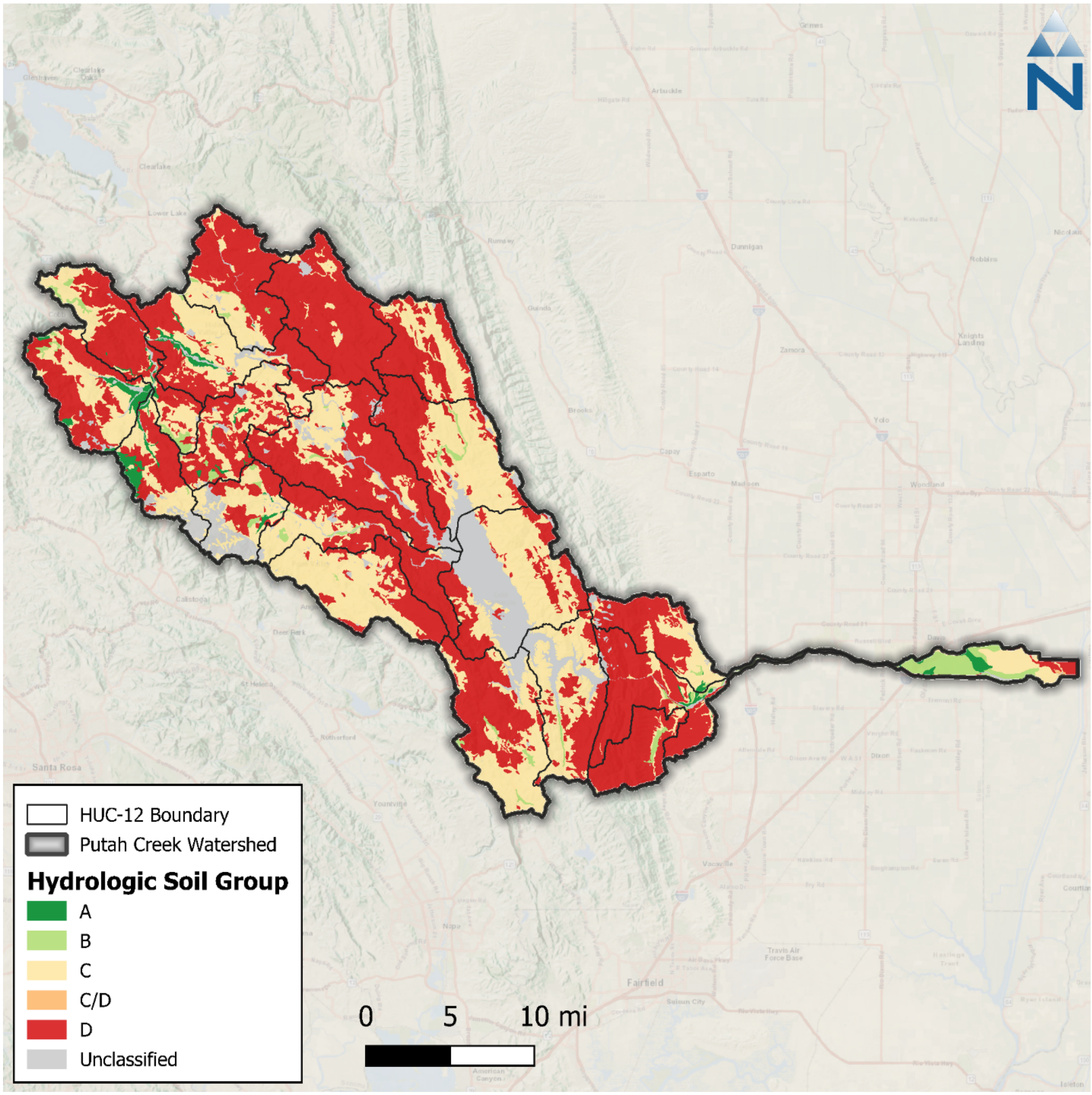

Figure 5-2. SSURGO hydrologic soil groups within the Putah Creek watershed.

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 areal coverage of land use classes from a subset of the 2021 NLCD dataset that covers the Putah Creek watershed, and Figure 5-3 shows the spatial distribution of these classifications. Grassland/Herbaceous is the dominant land cover class covering approximately 55% of the watershed. When combined, deciduous forest, evergreen forest, mixed forest, shrub/scrub, and grassland/herbaceous account for 88% of the total watershed area. Developed land cover makes up approximately 3% of the total watershed, and of this total, the majority is developed open space (<20% impervious). Approximately 4% of the total watershed area is cultivated crop land, which potentially underestimates the true cultivated area because many individual cultivated areas in the watershed may be smaller than the NCLD's 2.7-acre minimum mapping unit.

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

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	18,081.77	4.32%
21	Developed, Open Space[1]	8,729.78	2.09%
22	Developed, Low Intensity[1]	2,872.64	0.69%
23	Developed, Medium Intensity[1]	1,197.71	0.29%
24	Developed, High Intensity[1]	233.94	0.06%
31	Barren Land (Rock/Sand/Clay)	231.05	0.06%
41	Deciduous Forest	1,155.02	0.28%
42	Evergreen Forest	17,132.67	4.09%
43	Mixed Forest	10,766.07	2.57%
52	Shrub/Scrub	110,495.78	26.39%
71	Grassland/Herbaceous	228,780.91	54.65%
81	Pasture/Hay	417.62	0.10%
82	Cultivated Crops	15,495.77	3.70%
90	Woody Wetlands	881.72	0.21%
95	Emergent Herbaceous Wetlands	2,179.05	0.52%
	TOTAL*	**418,651.50**	**100%**

Source: 2021 National Land Cover Database

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

* Note that because of the raster resolution, this total is approximately 45 acres less than the model domain.

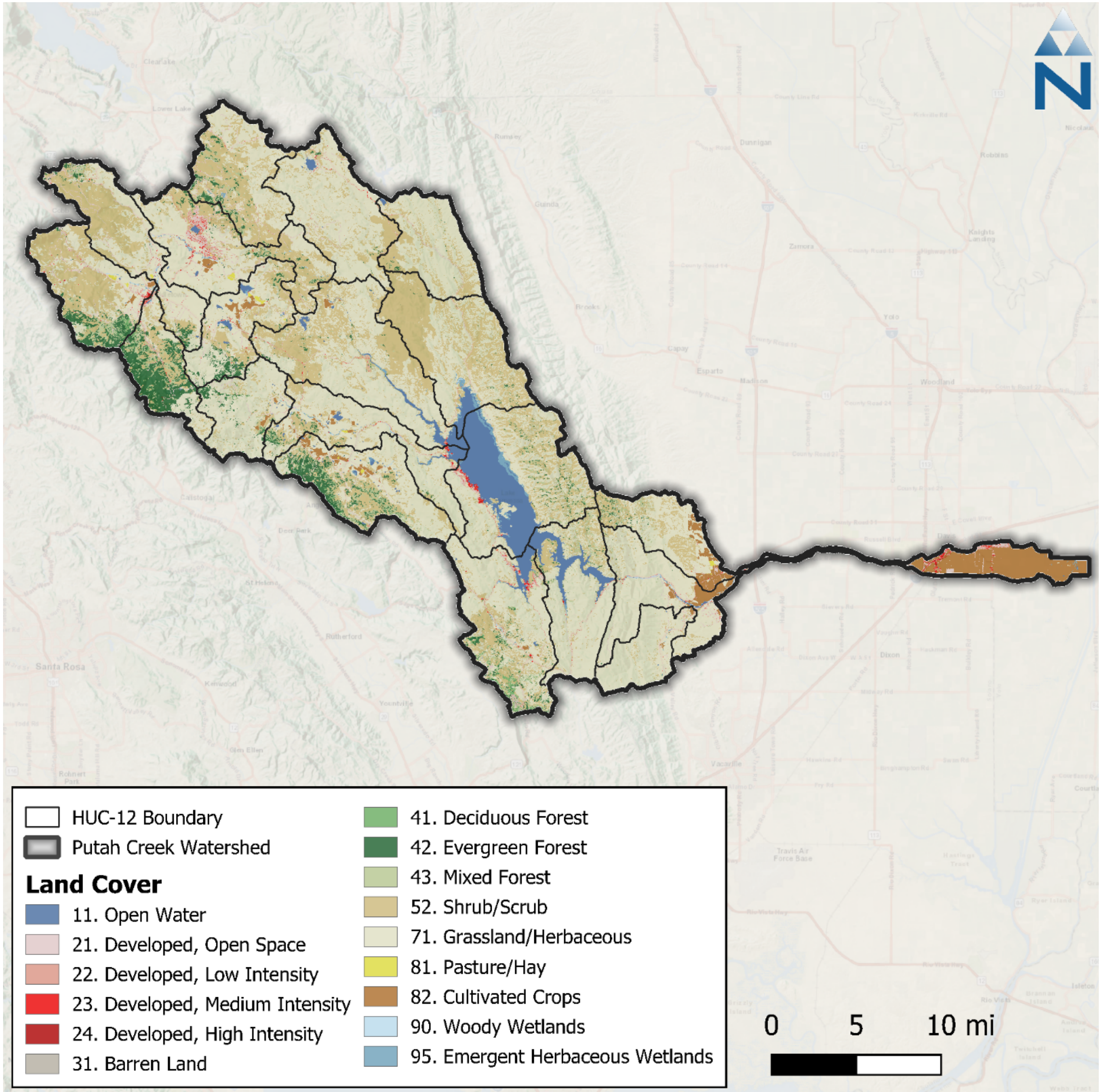

Figure 5-3. NLCD 2021 land cover within the Putah Creek watershed.

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 Putah Creek watershed using this dataset shows that just over 3% of the area is developed, or impervious. The developed area is classified further into open space, and low, medium, and high intensity 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 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 Putah 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 1-3) 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.

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 (Housman et al. 2023). Across the Putah Creek watershed, an average of 14% of the total watershed area is covered by tree canopy. Tree canopy cover data can be used to estimate model parameters like interception storage and lower-zone evapotranspiration rates.

5.5 Agriculture & Crops

Land cover data for the Putah Creek watershed (see Section 5.3) was analyzed to identify predominant cropland vegetation classes. Figure 5-4 shows the spatial distribution of these classes through the study area, and Table 5-4 summarizes their areal coverage. This analysis revealed that most of the Putah Creek watershed is classified as either Shrubland (class 152) at 53% coverage, Grassland/Pasture (class 176) at 20% coverage, or Forest (class 141-143) at 15% coverage. Of the area that is classified as shrub or grassland, a portion 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 Cropland Data Layer (CDL) (USDA 2024) is an annual updated raster dataset that geo-references crop-specific land use. The dataset comes as 30-meter resolution raster with a linked lookup table of 85 standard crop types which can be used to classify the major crops. The purpose of the CDL dataset is to provide a supplemental estimate of annual acreage used for major crop commodities. Additionally, a large-scale crop and land use identification dataset for the year 2020 is made available by DWR and could be used to supplement data gaps if necessary (DWR 2022). This dataset is intended to quantify crop acreage statewide and was constructed by analyzing remote sensing data gathered at the field scale.

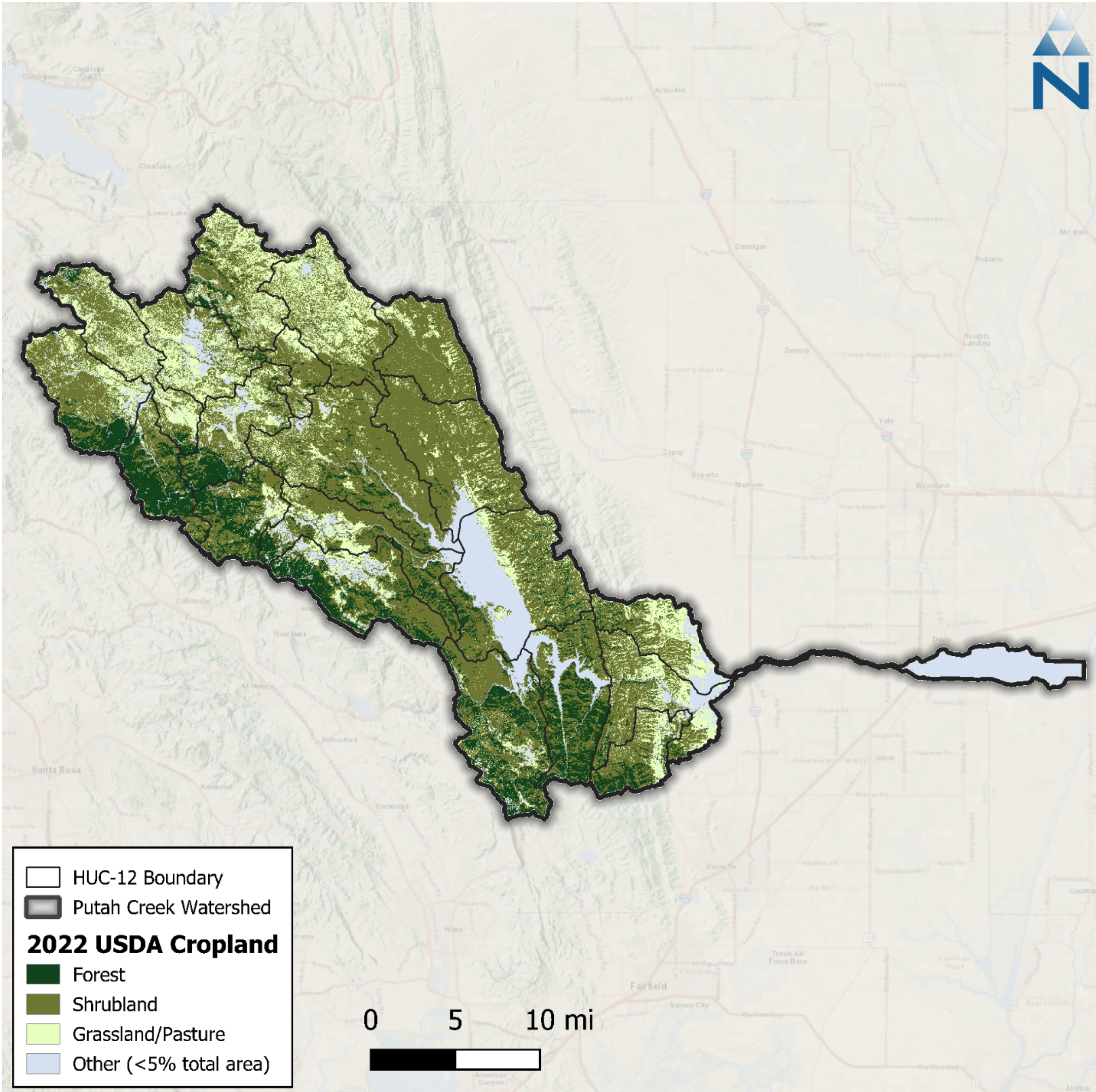

Figure 5-4 USDA 2022 Cropland Data within the Putah Creek watershed.

Table 5-4 USDA 2022 Cropland Data summary within the Putah Creek watershed

Crop Type	Area (ac)	Area (%)
Forest	62,472.75	14.92%
Shrubland	219,846.10	52.51%
Grassland/Pasture	83,788.30	20.01%
Other (>5% Total Area)	52,542.58	12.55%
Totals	**418,649.72**	**100.00%**

6 DATA GAPS AND LIMITATIONS

The Putah Creek watershed contains one of the largest reservoirs in California which significantly alters the natural flow regime of the watershed. Representing a reservoir with such large impact poses various challenges when modeling watershed hydrology and streamflow. Accurately modeling reservoir operations requires detailed data on reservoir management practices, such as release schedules, storage capacity, and operational rules, which may not always be available. Furthermore, datasets such as stage-volume relationships and lake bathymetry, spillway characteristics, and detailed flow release rates are essential for a realistic representation of such reservoirs in the model. Lack of robust datasets to support these details could complicate the calibration and validation process for the model.

Another potential limitation is the availability, quality, and temporal resolution of data for surface water diversions within the watershed. The eWRIMS database identifies major surface water diversions that are likely to have data to integrate into the model; however, other surface water diversions, such as water use to support cannabis cultivation, 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.

No published groundwater models are available for the Putah Creek watershed, and no AEM lines were flown across it. Limited well completion information and water level records are available in clustered locations but not across the majority of the basin.

7 MODEL CONFIGURATION

7.1 Model Selection

This modeling study's objectives influence hydrologic model selection and technical approach development. The available data presented in Section 2 through Section 6 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)
- The model simulation period should be long enough to capture variability between water years to represent conditions such as dry and wet year flows, environmental flows, drought curtailment, and other hydrological impacts.

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) (Barnwell and Johanson 1981), LSPC (Shen, Parker, and Riverson 2005), the Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2015), and Soil and Water Assessment Tool (SWAT) (Neitsch et al. 2011). 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 TMDLs 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, 2013a, 2013b, 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 hydrology analyses within the South Fork Eel River and Shasta River watersheds.

LSPC is a modernized version of the HSPF platform that is now organized around a Microsoft Access relational database; 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 a feature that can vary land use over time when needed to explicitly represent dynamic processes such as timber harvests and wildfires—that feature needs supporting spatial and temporal data to represent dynamic land use changes. Additionally, LSPC was the selected modeling platform for other Water Board studies, including the South Fork Eel River, Shasta River, Navarro River, and several others that were under development at the writing of this work plan. Those two watershed models utilize data from many of the same sources compiled in this study plan for the Putah 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 data sets presented in Section 2 through Section 4.1. 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. The following briefly 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 Forcing Inputs:** Climate forcing inputs to the model will include both precipitation and evapotranspiration. Precipitation will be represented using the observed GHNC, RAWS, and CDEC gauge data identified in Section 2. A hybrid approach using the 4-km gridded PRISM monthly precipitation to promote the most accurate representation of the long-term water balance will be used in areas where gauge data are not available. Monthly PRISM precipitation totals will be downscaled using daily and hourly NCDC observed timeseries. 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**: watershed delineations will be based on HUC-12 boundaries and use NHDPlus catchment boundaries to subdivide the HUC-12 boundaries to represent key points of interest in the network (e.g., confluence of tributaries, points of diversion, etc.). One primary reach segment will be represented per catchment and will use a cross-section calculated using trapezoidal geometry as a function of cumulative upstream drainage area. If additional cross-sectional information is available, these geometries can be updated per catchment in the model.
- **Hydrologic Response Units**: HRUs represent unique combinations of landscape characteristics that will be derived by overlaying GIS data sets 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. Due to the relatively small area of land cover with a specific crop type, we anticipate relying on the 2021 NLCD data to represent land cover; However, the USDA 2022 CDL may be considered if necessary during model configuration and calibration based on results. In the final model configuration, some HRUs may be reclassified and grouped when appropriate for model parameterization (e.g., multiple types of forest 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 & 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.

Based on the current understanding of the groundwater basins presented in Section 4 and associated data gaps describing the groundwater system, a fully linked groundwater model is not planned for this effort. However, if initial calibration efforts suggest a groundwater model would benefit the analysis, the information obtained from well data available from well completion reports will be useful in estimating the depth of aquifers and water production zones. A MODFLOW model (Langevin et al 2017) would be constructed approximating the bedrock units and the alluvial groundwater basins and will be integrated with a surface water model. Groundwater pumping would be estimated from water demand calculations based on land use information.

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 of modeled vs. observed data (e.g., time-series plots, flow duration curves, cumulative distribution plots, and others), quantitative metrics, and qualitative thresholds recommended by Moriasi et al. (2015) and Duda et al. (2012), which are considered highly conservative. Moriasi et al. (2015, 2007) 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 a 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. Qualitative thresholds for KGE have been used by Kouchi et al. (2017).

Both modeled time series and observed data will be binned into subsets of time to highlight seasonal performance and different flow conditions. Hydrograph separation was also performed to assess stormwater runoff vs. baseflow periods to isolate model performance on stormflows and low flows. Table 8-1 summarizes performance metrics that will be used to evaluate hydrology calibration; as shown in this table, "All Conditions" (i.e., annual interval) for R-squared 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 R-squared and NSE qualitative assessments of sub-annual intervals.

The LSPC calibration performance in the Putah 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 any 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 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]				
	Days Categorized as Storm Flow [4]				
	Days Categorized as Baseflow [4]				
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
Kling-Gupta Efficiency (KGE)	All Conditions [5]	≥0.90	0.90 - 0.75	0.75 - 0. 50	<0.50

1. All Flows considers all daily time steps in the model time series.
2. Seasonal Flows consider daily flows during a predefined, six-month seasonal period (e.g., Wet Season and Dry Season). The Wet Season includes the months of October through April. The Dry Season includes the months of May through September.
3. Highest 10% of Flows consider the top 10% of daily flows by magnitude as determined from the flow duration curve.
4. Baseflows and Storm flows were determined from analyzing the daily model time series by applying the USGS hydrograph separation approach (Sloto and Crouse 1996).
5. KGE evaluated using thresholds developed for monthly aggregated time series (Kouchi et al. 2017).

9 SUMMARY & NEXT STEPS

This work plan presented the available data and proposed methods for developing a hydrologic model of the Putah Creek watershed. Once this work plan is finalized, the data sets described in this memo will be used to develop an LSPC model 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, gauge locations, and the like). 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 Putah Creek watershed.

Table 9-1. Proposed schedule and summary of deliverables

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

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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