Work Plan: Navarro River Watershed Hydrology Model Development

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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
CASGEM	California Statewide Groundwater Elevation Monitoring Program
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
KGE	Kling-Gupta Model Efficiency
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
NMFS	National Marine Fisheries Service
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutclife Model Efficiency Coefficent
PBIAS	Percent Bias
PEVT	Potential Evapotranspiration
POD	Point of Diversion

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
UCCE	University of California Cooperative Extension
USDA	United States Department of Agriculture
USFS	United States Forest Service
USGS	United States Geological Survey
WBD	Watershed Boundary Dataset

Contents

ACRONYMS i
1. Introduction 1
1.1 Project Objectives 1
1.2 Watershed Background 1
1.3 Model Approach 3
1.4 Data Availability 4
2 Meteorology 9
2.1 Precipitation 9
2.2 Evapotranspiration 13
3 Surface Hydrology 15
3.1 Watershed Segmentation 15
3.2 Streams and Channels 16
3.3 Streamflow 17
3.4 Surface Water Withdraws 18
4 Subsurface Hydrology 20
5 Landscape Characterization 22
5.1 Elevation & Slope 22
5.2 Soils & Geology 23
5.3 Land Cover 25
5.4 Tree Canopy Cover 28
5.5 Agriculture & Crops 28
6 Data Gaps and Limitations 31
7 Model Configuration 32
7.1 Model Selection 32
7.2 Model Configuration 33
8 Model Calibration 34
9 Summmary & Next Steps 36
10 References 37

Figures

Figure 1-1. Navarro River watershed. 2
Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Navarro River watershed. 4
Figure 2-1. Identified rainfall gauges and CIMIS ET Zones near the Navarro River watershed. 11
Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products. 12
Figure 2-3. Final spatial coverage of precipitation timeseries. 13
Figure 3-1. Initial catchment segmentation for the Navarro River watershed. 16
Figure 3-2. USGS streamflow stations in the Navarro River watershed. 17
Figure 3-3. Water users in the Navarro River watershed. 19
Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118. 21
Figure 5-1. Digital elevation model of the Navarro River watershed. 23
Figure 5-2. SSURGO hydrologic soil groups within the Navarro River watershed. 25
Figure 5-3. NLCD 2021 land cover within the Navarro River watershed. 27
Figure 5-4. USDA 2022 Cropland Data within the Navarro River watershed. 29

Tables

Table 1-1. Inventory of meteorology datasets 5
Table 1-2. Inventory of surface water datasets 6
Table 1-3. Inventory of geospatial datasets 7
Table 2-1. Summary of precipitation stations with observations available after 2000 10
Table 3-1. Summary of NHDPlus catchment sizes (acres) within the Navarro River HUC-10 15
Table 3-2. Summary of USGS daily streamflow data 18
Table 3-3. Summary of surface water points of diversion in the Navarro River watershed 18
Table 5-1. NRCS Hydrologic soil group descriptions 24
Table 5-2. NRCS Hydrologic soil groups in the Navarro River watershed 24
Table 5-3. National Land Cover Database 2021 land cover summary in the Navarro River watershed 26
Table 5-4. USDA 2022 Cropland Data summary within the Navarro River watershed 30
Table 8-1. Summary of qualitative thresholds for performance metrics used to evaluate hydrology calibration 35
Table 9-1. Proposed schedule and summary of deliverables 36

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 Navarro River watershed. This model will use historical data inputs of precipitation and potential evapotranspiration (PEVT) for the 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

The Navarro River watershed (HUC-10: 1801010804) is a coastal watershed in southern Mendocino County, California and the Pomo Tribal territory with a drainage area of approximately 315 square miles (Figure 1-1). The Navarro River originates at the confluence of Rancheria and Anderson Creeks just south of Philo before quickly being joined by Indian Creek. The Navarro River then flows north-west through the Anderson Valley and is joined by the North Fork Navarro River approximately 10 miles from its outlet at the Pacific Ocean.

As part of the Big-Navarro-Garcia Rivers Watershed complex, the watershed divides with the Russian (east), Gualala-Salmon (south-west), Big (north), and Garcia watersheds and smaller watersheds to the west bordering the Pacific Ocean.

The Navarro River watershed ranges in elevation from less than 300 feet along the riverbed in the northern-most part of the watershed to over 3,000 feet at the highest elevation peaks in the southern portion of the watershed and along the eastern edge. The watershed has a Mediterranean climate with distinct wet and dry seasons with a mean annual precipitation total of 46.7 in. (USGS 2019). Timber production, livestock grazing, and other agricultural activities have been present in the Navarro River watershed since the mid-1800s. The watershed has since retained its rural nature with close to 97% of land use remaining as native vegetation and less than 5% of land cover being developed area. More recent land-use data in the watershed includes forestland (70%), rangeland (25%), and agriculture (5%) with a small percentage devoted to rural residential development (Entrix Inc. et al. 1998). Currently, commercial timber harvesting, viticulture, orchards, grazing, and tourism are the principal economic enterprises.

As part of the Northern California/Southern Oregon Coasts Evolutionarily Significant Unit (ESU), the Navarro River Watershed represents an important spawning ground for anadromous fish, especially coho salmon and steelhead trout. However, there have been substantial declines in salmonid populations over time. In 1996, the National Marine Fisheries Service (NMFS) listed coho salmon within the Northern California ESU as a threatened species under the federal Endangered Species Act with steelhead trout being listed as a threatened species in 2000 (RWQCB North Coast Region 2000). The decline in anadromous fish populations within the Navarro River watershed was linked to management-related activities that contributed to a declining trend of streamflow in the Navarro River over time (Hines & Kohlsmith 2012; Jackson 2013). This resulted in an increase in sediment delivery and stream temperatures above that which supports salmonid life. These factors led to the implementation of a Total Maximum Daily Load (TMDL) for temperature and sediment in 2000 (USEPA 2000).

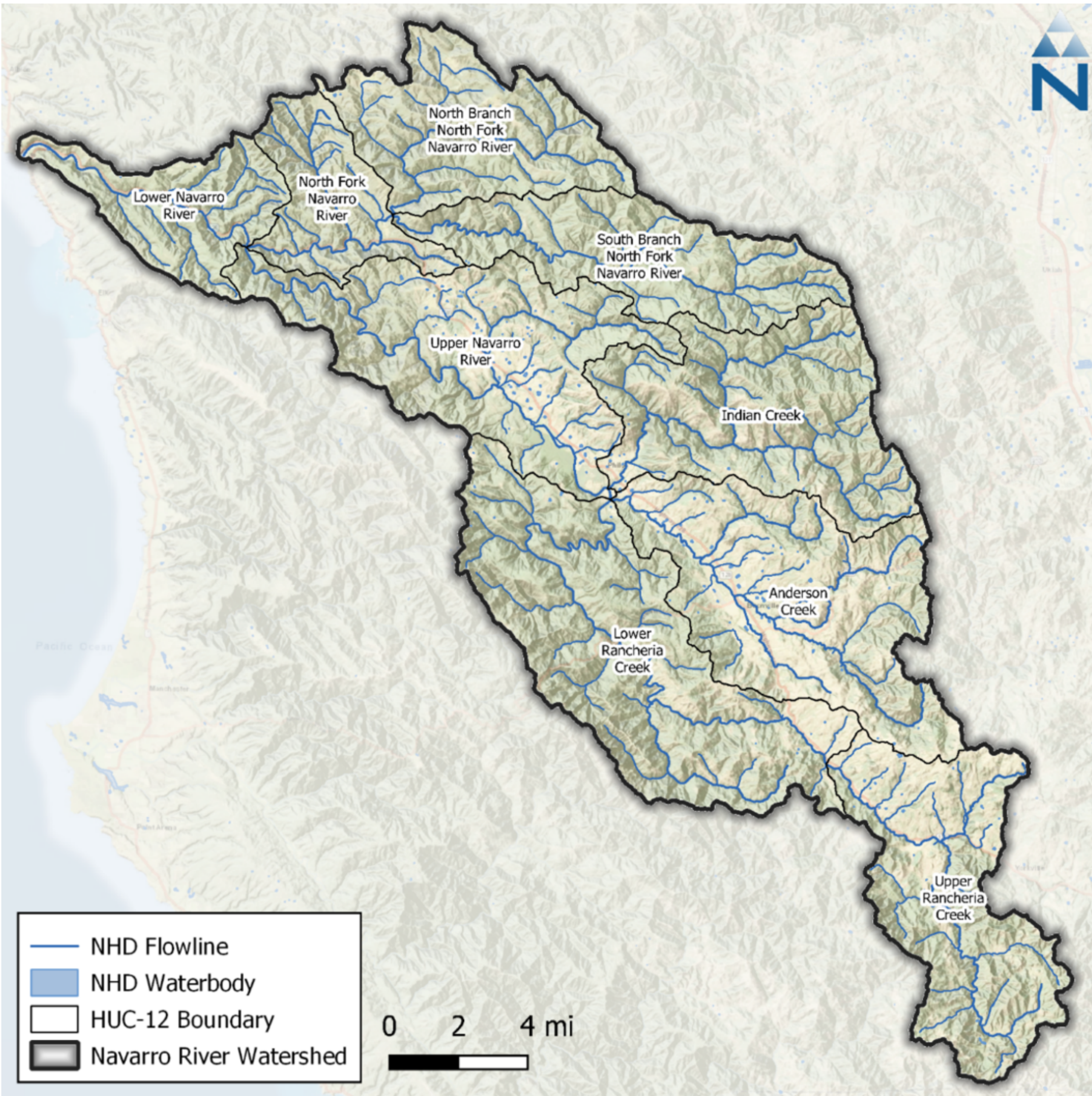

Figure 1-1. Navarro River watershed.

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 Navarro River watershed. This is presented first through a comprehensive inventory of available hydrologic, meteorological, and geographic information system (GIS) data available for the Navarro River watershed. The data compilation and assessment process 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 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.

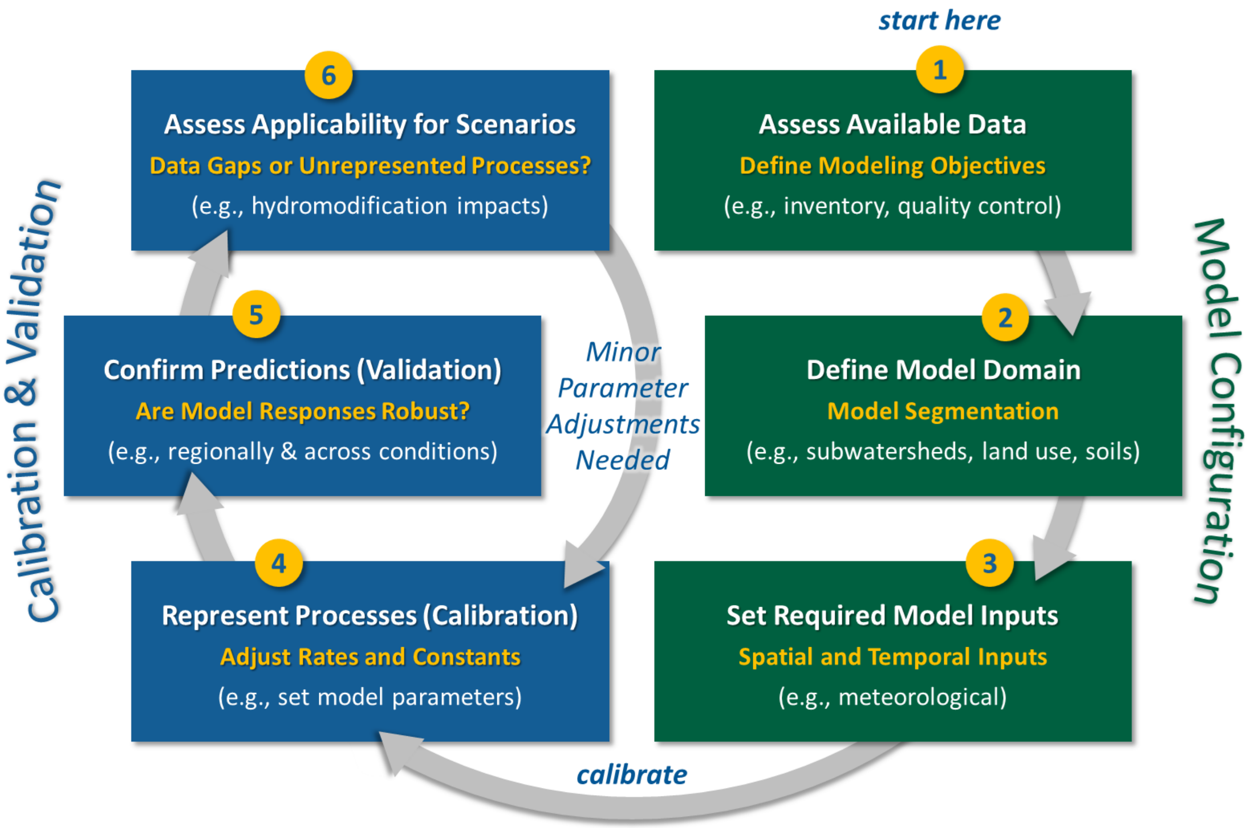

Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Navarro River watershed.

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 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 the Navarro River. Time series observations of instream responses for the Navarro River are often used as calibration and validation datasets for hydrologic models.
- **Geospatial Datasets**: Spatial datasets describing the landscape of the Navarro River 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)	10/13/2017	Daily precipitation and temperature data (31 nearby gauges, varied data quantity/quality).	Rainfall forcing input time series.
National Climatic Data Center (NCDC)	Local Climate Data (LCD)	10/13/2017	Hourly precipitation, temperature, wind speed, dewpoint, cloud cover (Ukiah only).	Rainfall forcing input time series.
Remote Automated Weather Stations (RAWS)	Hourly Climate Data	10/27/2017	Meteorological records (wind speed and direction, air temperature, precipitation, relative humidity, solar radiation) available for Boonville December 1990 – Present).	Climate forcing input time series.
California Data Exchange Center (CDEC)	Precipitation, Temperature	--	Meteorological records available for YORKVILLE (may be duplicate of GHCN).	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.
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	c. 1990 – Present	Relative evapotranspiration spatial zones and monthly scaling factors. Two stations located near the Navarro River watershed (Hopland & Sanel Valley). These stations are located one CIMIS Zone to the east of most of the Navarro River watershed area. There is also a grid-based model data product.	Deriving PEVT forcing input time series.

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	1959 – Current	Observed Streamflow at one active location (near the mouth of Navarro River) and two other historic locations with data form the 1960s (Rancheria Creek and Soda Creek).	Hydrology calibration.	LINK
Habitat	State	CDFW	Stream Inventory Reports	1994 – 2015	Stream reports that document the current habitat and stream conditions and recommendations for potential enhancement of habitat.	Hydrology calibration & validation.	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 digital elevation models (DEM) CA FEMA R9 Mendocino HF 2017	2017	1-meter, 10-meter, and 30-meter resolution digital elevation models (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 National Climatic Data Center (NCDC) 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 21 GHCN, Co-Op, CoCoRaHS, or other NOAA gauges identified within and around the Navarro River watershed. These gauges all have data with varied quantity and quality. In addition to the daily precipitation gauges, NCDC also reports hourly observations from one gauge located at the Ukiah Municipal Airport, which is outside of the watershed. The California Data Exchange Center (CDEC) and Remote Automated Weather Stations (RAWS) networks also report precipitation at 4 locations within or near the watershed. Table 2-1 is an inventory of precipitation stations with data available after 2000; Figure 2-1 shows the location of stations near the Navarro River watershed.

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:23275	UKIAH MUNICIPAL AIRPORT, CA US	9/11/1949	Present	39.128	-123.200	183.7	91%
NOAA-CoCoRaHS	GHCND:US1CAMD0042	ALBION 1.1 S, CA US	2/15/2020	Present	39.206	-123.770	60.7	95%
	GHCND:US1CAMD0021	ALBION 4.0 SE, CA US	12/3/2012	11/9/2022	39.188	-123.710	193.9	93%
	GHCND:US1CAMD0003	BOONVILLE 2.2 WSW, CA US	1/1/2009	Present	39.006	-123.408	323.4	92%
	GHCND:USR0000CBOO	BOONVILLE CALIFORNIA, CA US	4/30/1990	Present	38.988	-123.349	196.3	97%
	GHCND:US1CAMD0050	GUALALA 3.7 NW, CA US	4/9/2022	Present	38.812	-123.579	144.8	100%
CDEC	COY	COYOTE (LAKE MENDOCINO)	1/9/1989	Present	39.197	-123.186	219.5	100%
	YOR	YORKVILLE	10/1/2003	Present	38.905	-123.231	335.3	100%
RAWS	BNVC1	BOONVILLE	5/1/1990	Present	38.987	-123.348	202.4	99%

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.

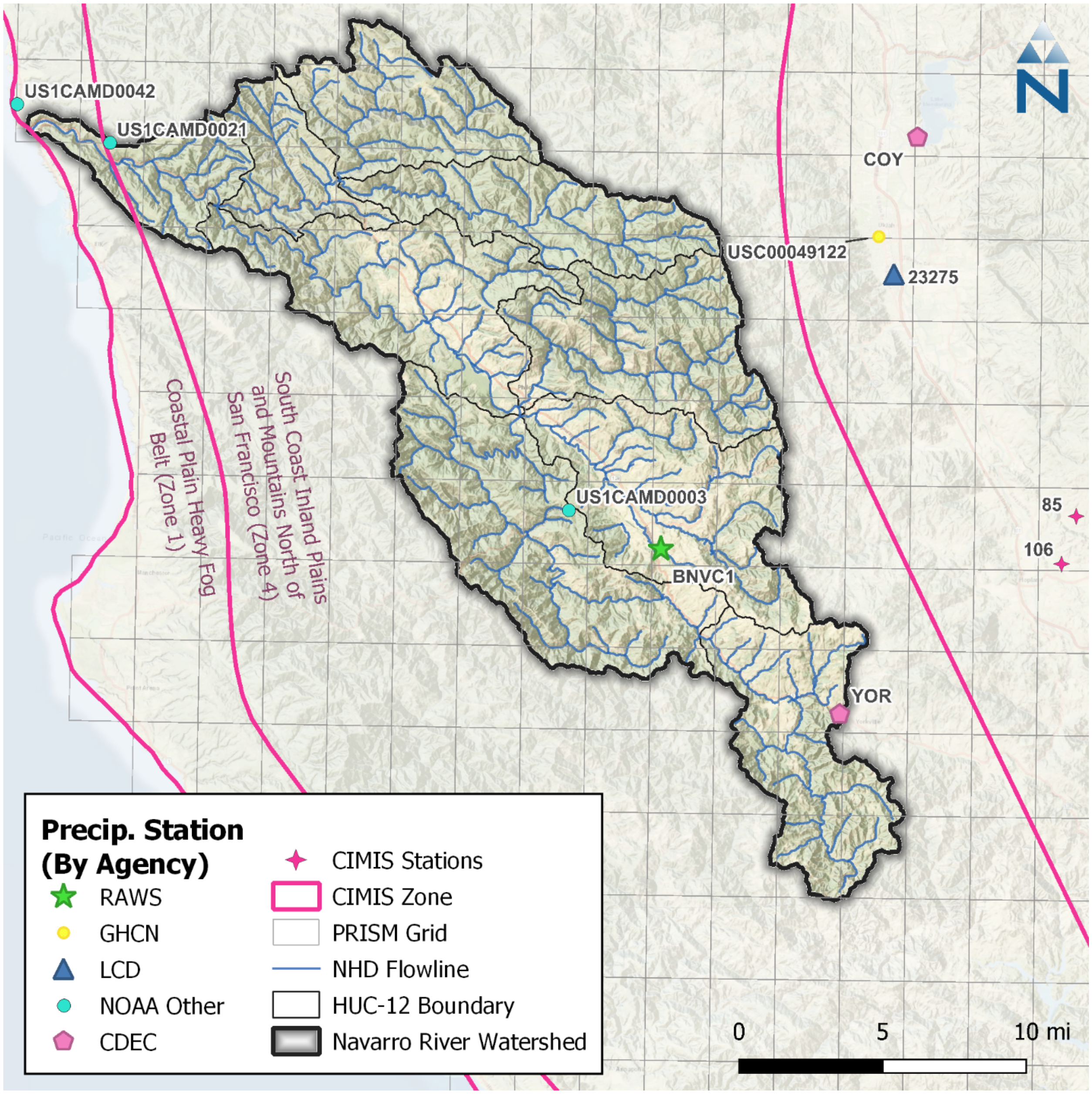

Figure 2-1. Identified rainfall gauges and CIMIS ET Zones near the Navarro River watershed.

A hybrid approach will be used to supplement spatial and temporal gaps in observed meteorological data. First, impaired intervals (i.e., missing, or accumulated) at observed stations are patched with good data from nearby gauges. Next, the temporally complete hourly observed data distributions are used to downscale the gridded data. Finally, gridded meteorological data from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) are used to fill spatial gaps in the observed station network as needed. 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). Observed precipitation distributions are mapped to the nearest PRISM grid cell and used to downscale monthly PRISM totals to hourly; the resulting set of gridded precipitation timeseries reflect monthly PRISM totals that have hourly distributions from the nearest observed gage. Using monthly PRISM totals 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. Use of a hybrid approach that blends ground-based stations with remotely sensed precipitation products preserves locally sampled gauge data while increasing the spatial and temporal quantity and quality over the basin. This approach has been applied for large watershed-scale modeling applications in Los Angeles County (LACFCD 2020).

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 Figure 2-3 shows what a hybrid of observed timeseries, supplemented by gridded products where spatial and temporal gaps occurred in the observed coverage, would look like.

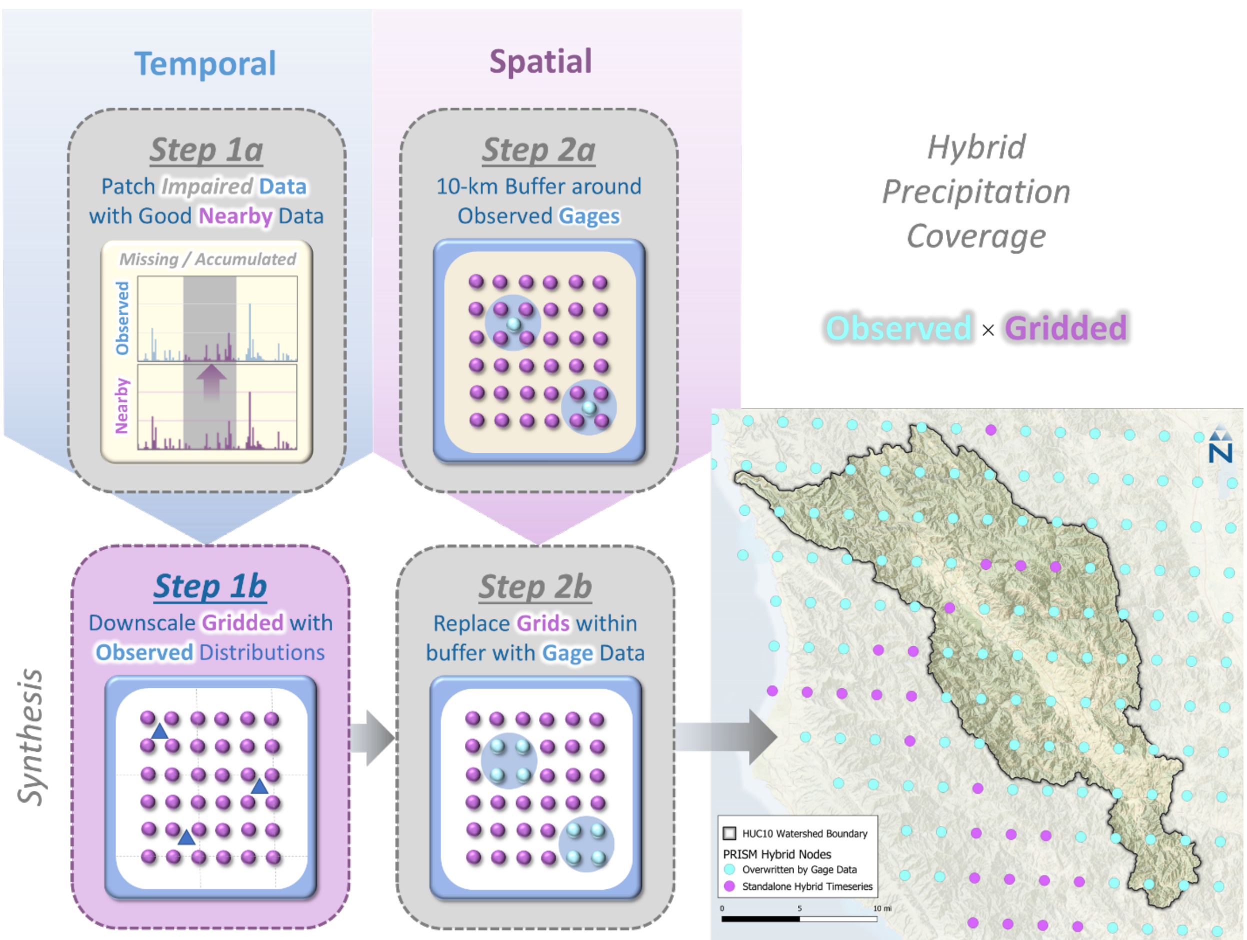

Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products.

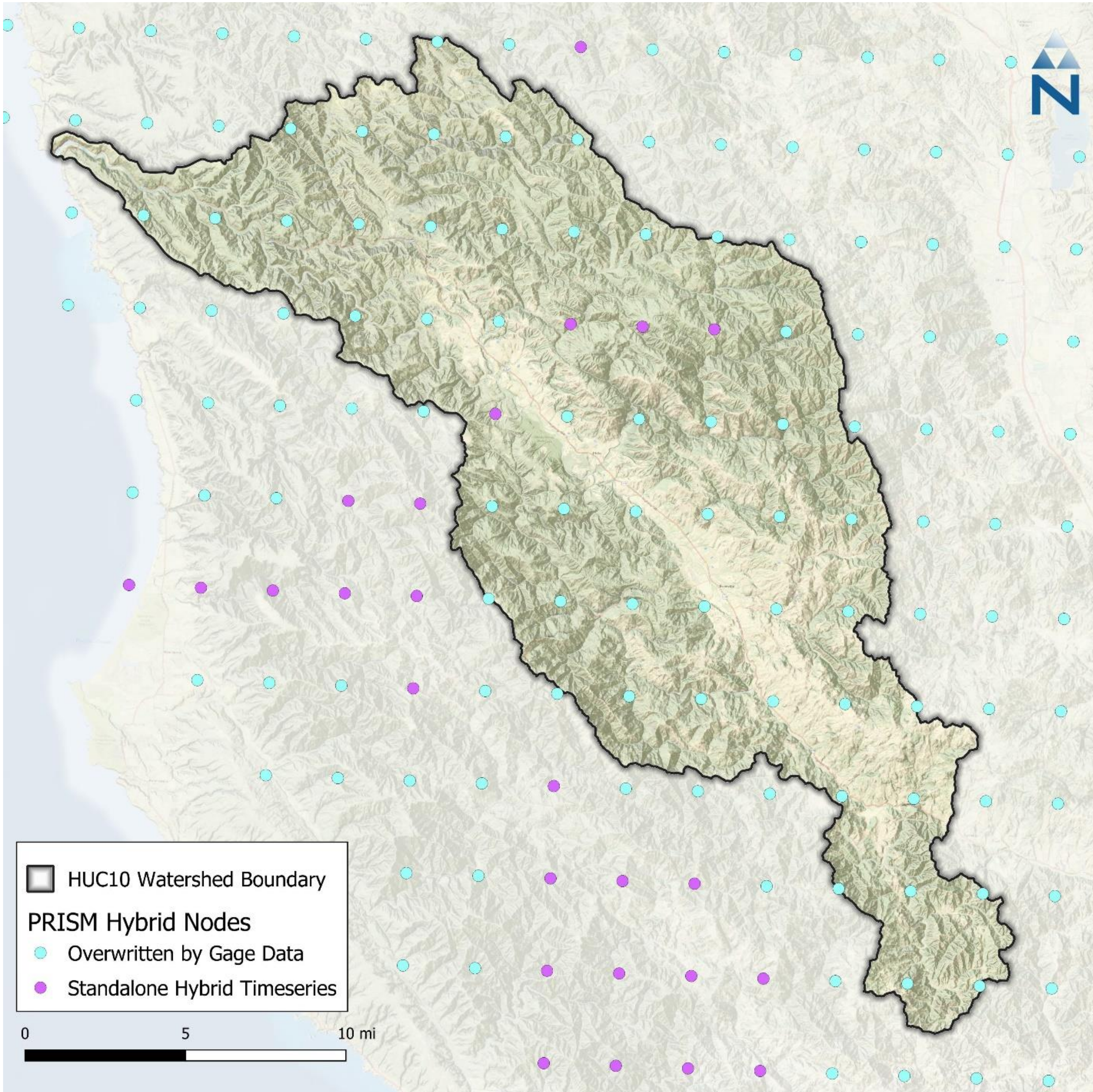

Figure 2-3. Final spatial coverage of precipitation timeseries.

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 two stations near the Navarro River watershed, which include Hopland and Sanel Valley. Hopland is no longer operating, but its historical time series data cover the period from September 1989 through April 2016. The Sanel Valley gage in the nearby Russian River watershed is still active and contains data from February 1991 through the present. Representative potential ET time series can also be estimated for the Navarro watershed by first using data from RAWS meteorological data from Boonville 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 Navarro River watershed intersects two CIMIS zones with 1.2% of the watershed area in Zone 1 (Coastal Plains Heavy Fog Belt) and 98.8% of the watershed area in Zone 4 (South Coast Inland Plains and Mountains North of San Francisco). The westernmost portion of the Navarro River watershed that is closest to the coast falls under CIMIS Zone 1. The marine cloud layer in this region results in a lower ET_o due to limited solar radiation exposure.

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 (https://cimis.water.ca.gov/SpatialData.aspx). 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 timeseries 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.

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 Navarro River watershed is defined by a HUC-10 watershed that comprises 9 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 373 catchments ranging in size between 0.001 square miles to over 5 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 Navarro River watershed (HUC-10).

Table 3-1. Summary of NHDPlus catchment sizes (acres) within the Navarro River HUC-10

HUC-12 Name	Count of Catchments	Catchment Size (acres)			
		Minimum	Mean	Median	Maximum
Anderson Creek	55	1.2	535.2	310.5	2,355.9
Indian Creek	57	0.4	443.2	346.3	1,994.3
Lower Navarro River	39	<0.1	292.8	241.5	1,208.7
Lower Rancheria Creek	56	0.7	631.7	469.6	3,706.7
North Branch North Fork Navarro River	45	0.2	404.8	296.0	1,874.6
North Fork Navarro River	28	15.8	375.1	284.8	1,677.5
South Branch North Fork Navarro River	34	19.1	552.8	380.0	2,711.0
Upper Navarro River	56	3.3	511.8	340.9	3,713.2
Upper Rancheria Creek	58	0.2	411.6	205.9	2,440.3

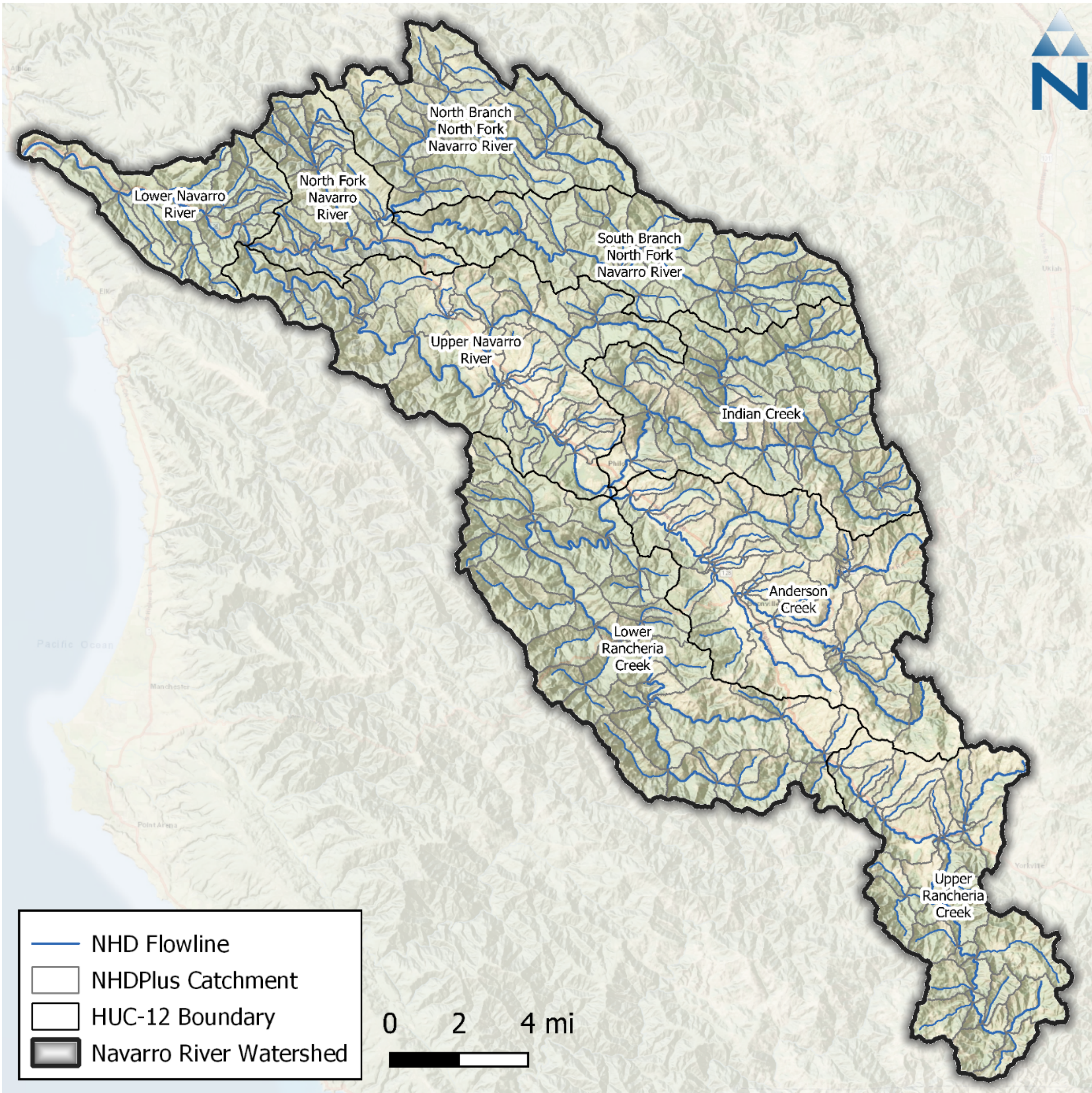

Figure 3-1. Initial catchment segmentation for the Navarro River watershed.

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 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 Navarro River watershed (as shown in Figure 3-1) is primarily derived from NHDPlus. This dataset depicts flow paths based on a nation-wide 10m 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.

3.3 Streamflow

The primary source of streamflow data is from the United States Geological Survey (USGS), which includes one current long-term gage operating near the mouth of Navarro River (approximately 6.5 miles upstream from the mouth) and two historical streamflow gauges located upstream on tributaries. Figure 3-2 shows the locations of these three USGS gauges in the Navarro River watershed. The active long-term gage, Navarro River near Navarro CA (USGS 11468000), has daily streamflow data for the period 10/1/1950 through present. The two historical tributary locations, Rancheria Creek near Boonville CA (USGS 11467800) and Soda Creek Tributary near Boonville CA (USGS 11467850), have data from the 1960s. Table 3-2 presents a summary of the available daily streamflow data.

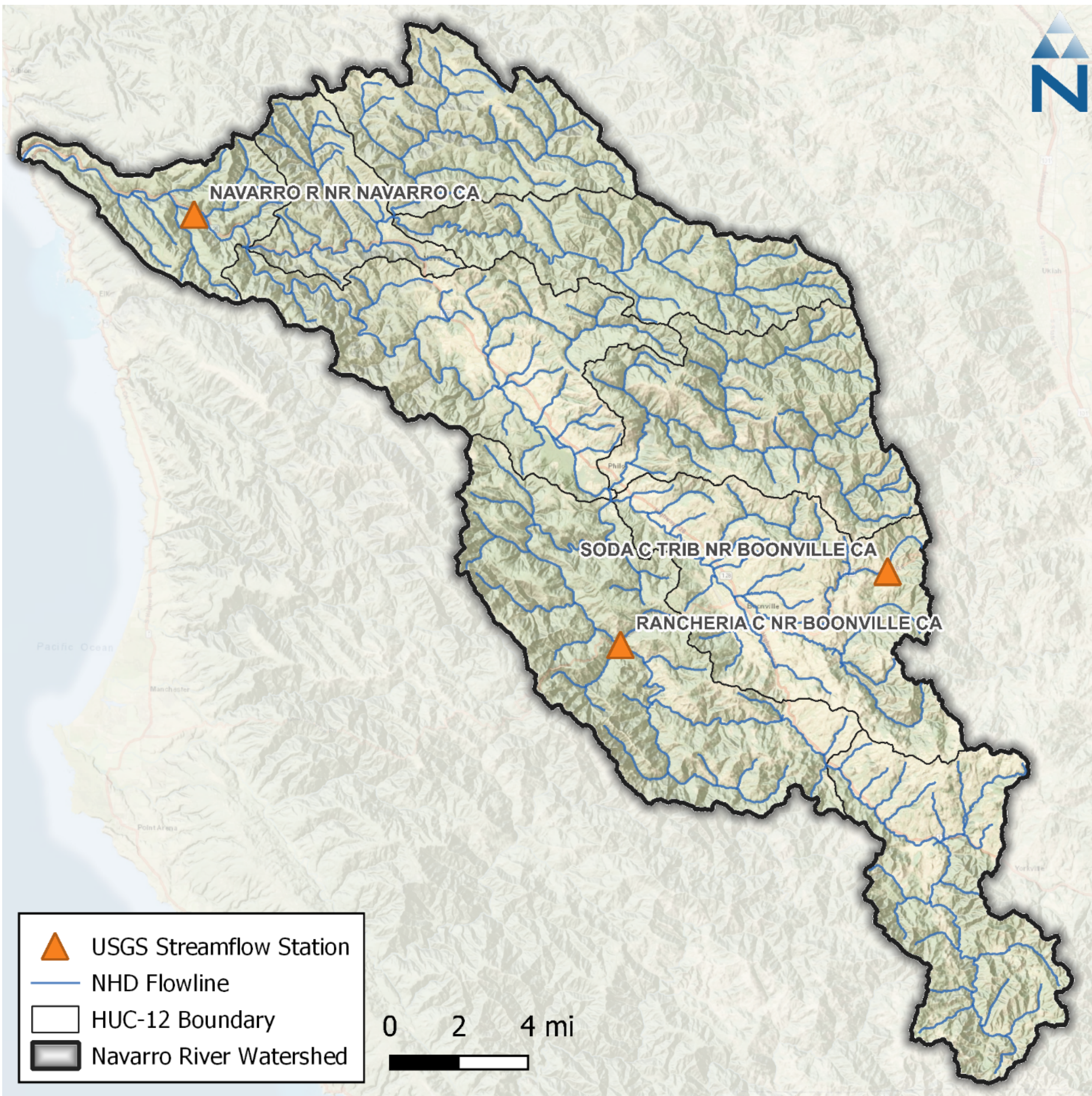

Figure 3-2. USGS streamflow stations in the Navarro River watershed.

Table 3-2. Summary of USGS daily streamflow data

Gage Description	Station ID	Drainage Area (mi^2)	Start Date	End Date	Gage Active?
NAVARRO R NR NAVARRO CA	11468000	303	10/1/1950	10/22/2023	Yes
RANCHERIA C NR BOONVILLE CA	11467800	65.6	9/1/1959	9/29/1968	No
SODA C TRIB NR BOONVILLE CA	11467850	1.5	10/1/1964	9/29/1968	No

3.4 Surface Water Withdraws

Datasets related to water rights, points of diversion, and irrigation use were identified through searches of the Water Board's eWRIMS database and in the University of California Cooperative Extension (UCCE) study assessing agricultural water needs in the Navarro River watershed (McGourty et al. 2020). Those 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 Navarro River 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 cannabis has the potential to impact summer low flows. These areas will be mapped, to the extent possible, in coordination with the North Coast Regional Water Quality Control Board (RWQCB) 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 Anderson Valley groundwater basin and Navarro River and Anderson Creek, all of which pass through approximately the middle of the watershed. There are 25 water systems in the watershed serving approximately 2,600 individuals in residential, agricultural, commercial, and institutional areas. The primary water source for these systems is groundwater. However, one (1) water system's primary source is also influenced by surface water and six (6) systems do not have a primary source listed. Additionally, eWRIMS reports that there are three (3) active surface water points of diversion in the watershed with active water rights statuses. These points of diversion are summarized in Table 3-3.

Table 3-3. Summary of surface water points of diversion in the Navarro River watershed

POD ID No.	Stream	POD Status	Water Right Status	Water Right Type	Entity Type
56545	Elkhorn Creek	Active	Active	Not Determined	Individual
58570	Unnamed	Active	Active	Non-Jurisdictional	Individual
58596	Unnamed	Active	Active	Non-Jurisdictional	Individual

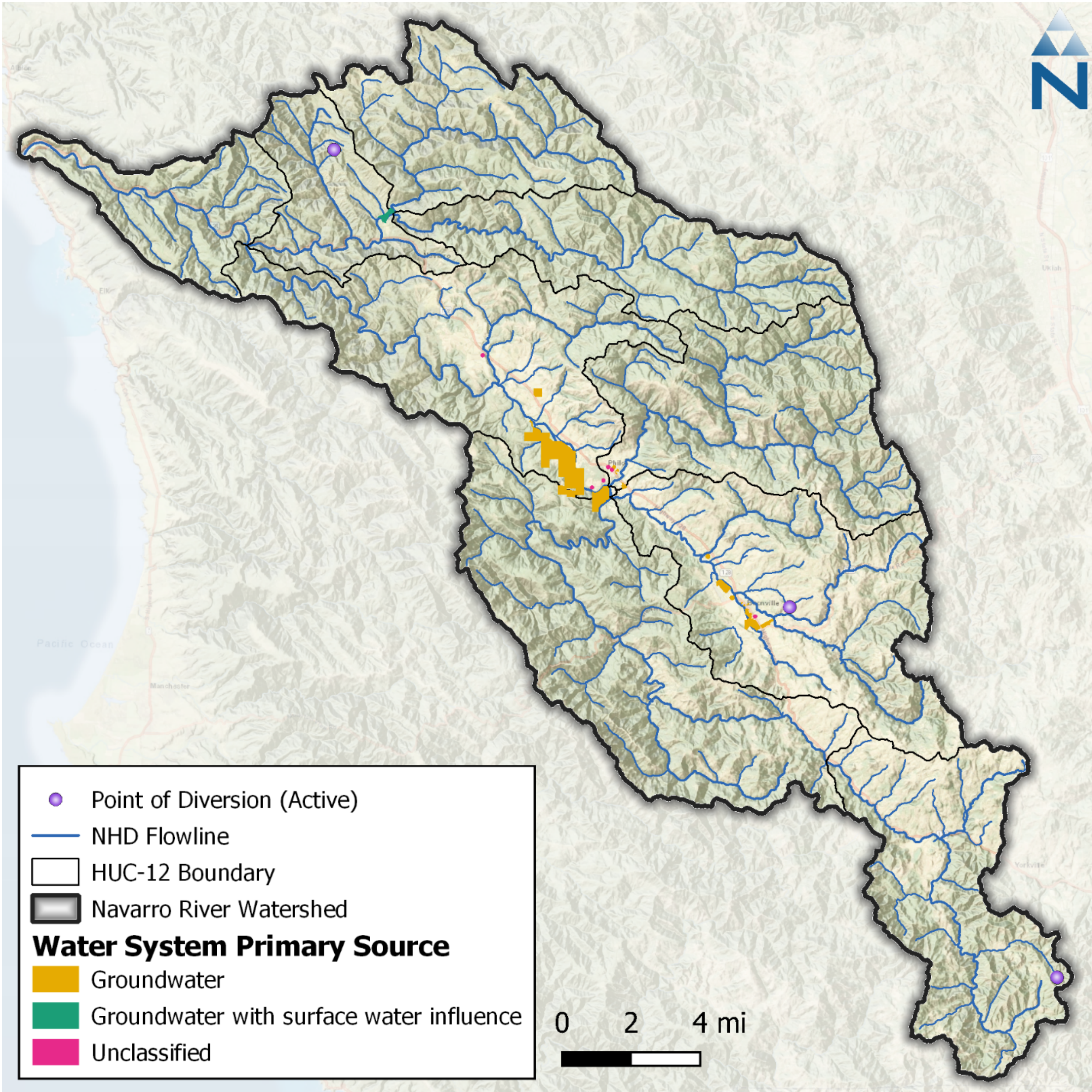

Figure 3-3. Water users in the Navarro River watershed.

4 SUBSURFACE HYDROLOGY

The Navarro River Watershed consists of two groundwater basins as delineated by DWR (2020) in a document that is also known as DWR's Bulletin 118. In the context of the Sustainable Groundwater Management Act (SGMA), both of the groundwater basins are designated as very low priority basins. The groundwater basins are shown in Figure 4-1. A brief description of the two basins from DWR (2020) is as follows:

- The Anderson Valley Groundwater Basin (Number 1-019) is in the middle of the Navarro River Watershed and covers 2.5% of the total watershed area. The basin has 9 public supply wells and 225 total wells with no documented groundwater level declines. There are 11 monitoring well locations with potential water level data, 7 of which are under the California Statewide Groundwater Elevation Monitoring (CASGEM) program.
- The Navarro River Valley Groundwater Basin (Number 1-046) is located to the west of the Navarro River Watershed and covers 0.4% of the total watershed area. This groundwater basin has no public supply wells and a total of 15 wells with no documented groundwater level declines.

Water bearing units for both groundwater basins consist of Quaternary Alluvium surrounded by fractured bedrock. Across the State, the groundwater basins delineated as per Bulletin 118 are primarily comprised of alluvial basins and 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.

Analysis presented by USEPA (2000) supports the possibility of gaining streams within the Navarro Watershed but points to the lack of information; this is a data gap. Water budget analysis based on meteorological data, runoff, and streamflow will help ascertain whether there are any significant groundwater contributions to streamflow. These water budget estimates will guide the modeling process and help determine whether explicitly representing the groundwater system is warranted.

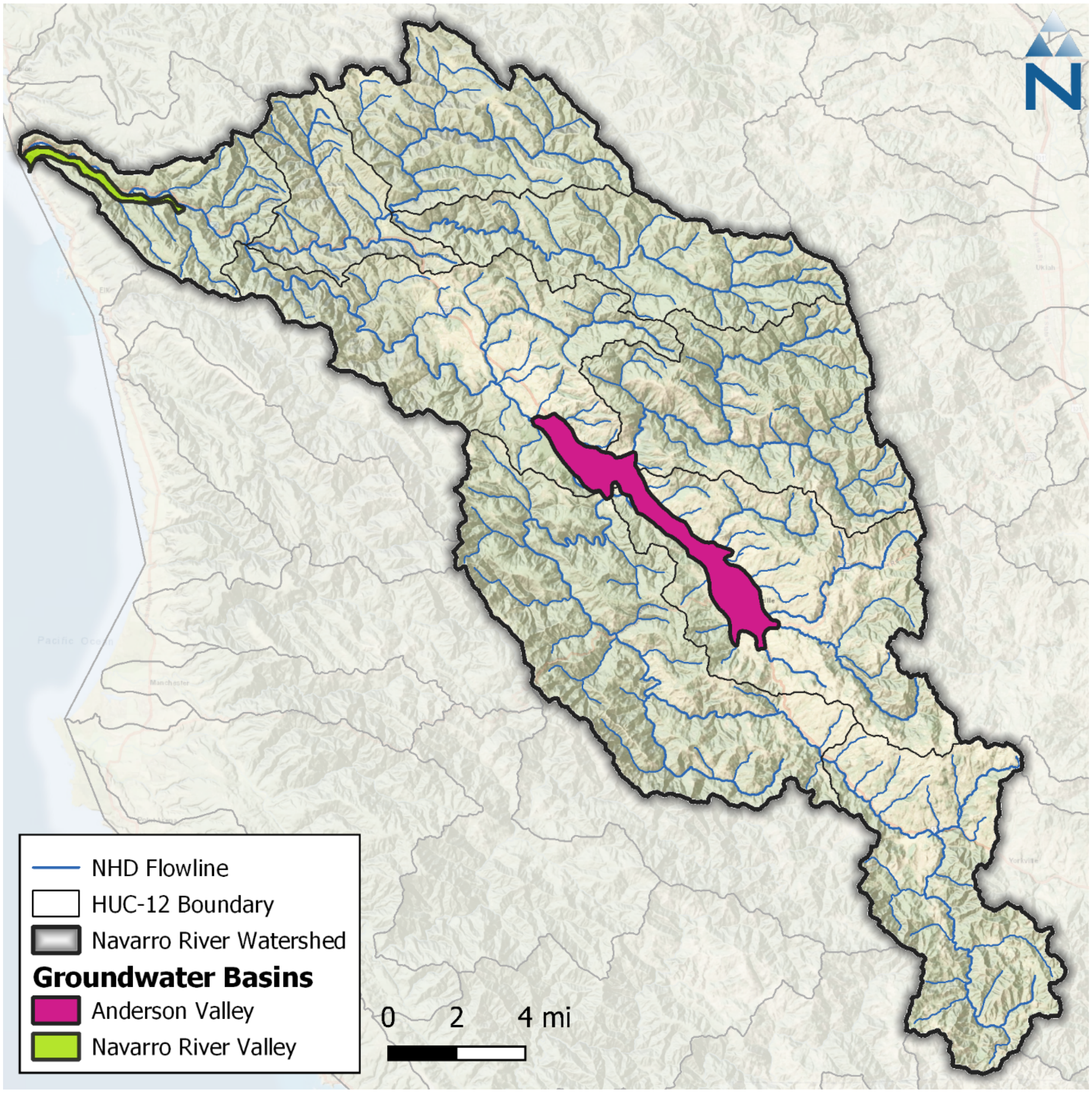

Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118.

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 areal combinations of those various characteristics ultimately determine the number of meaningful HRU categories considered for the model. The following sections describe the primary component layers available to derive HRUs for the Navarro River watershed.

5.1 Elevation & Slope

The USGS publishes DEMs expressing landscape elevation through a raster grid data product with 30-meter resolution. The Navarro River watershed ranges in elevation from less than 100 meters along the riverbed in the northern part of the watershed to over 1,000 meters at several of the highest elevation peaks in the southern portion of the watershed and along the eastern edge. 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 Navarro River watershed.

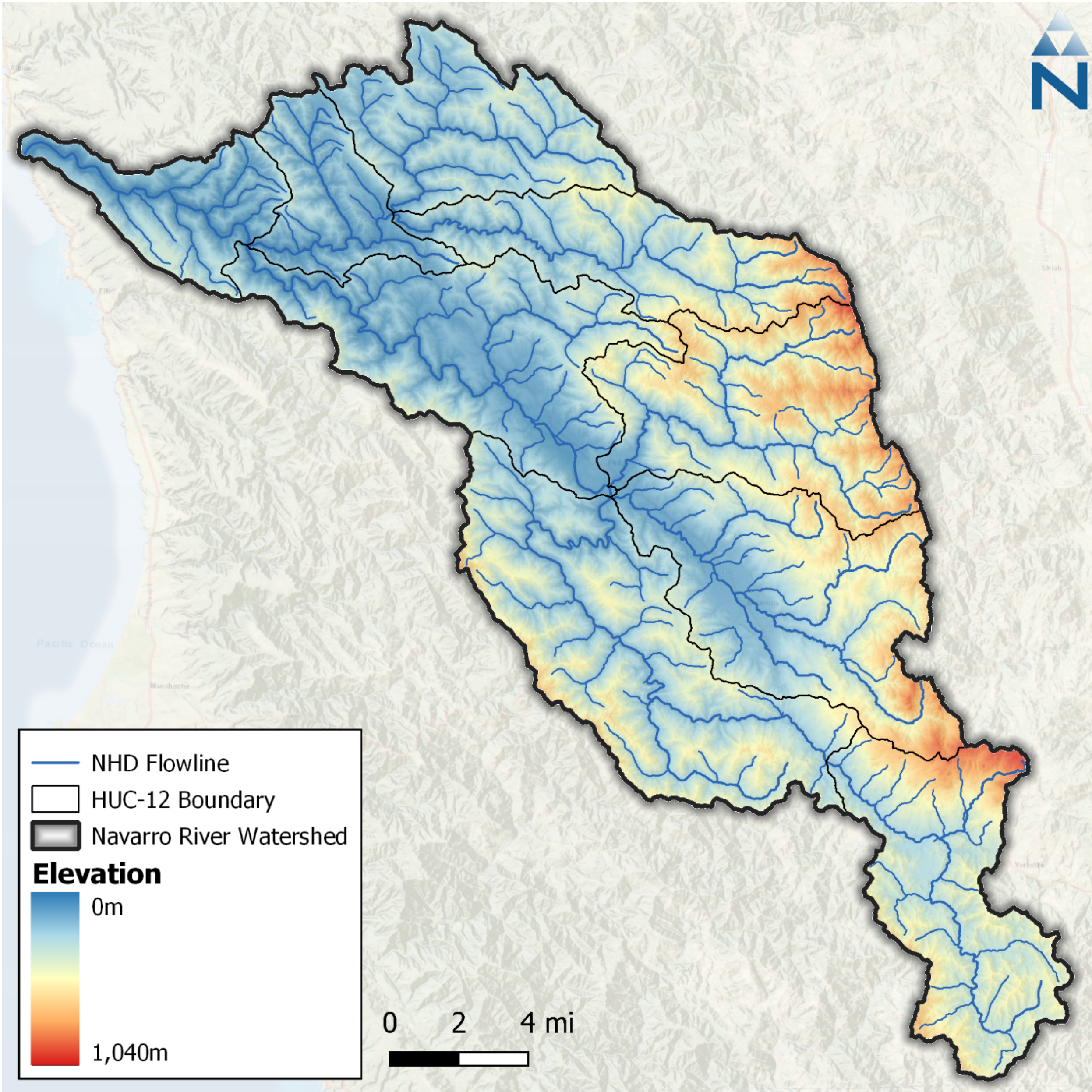

Figure 5-1. Digital elevation model of the Navarro River watershed.

5.2 Soils & Geology

Soils data for the Navarro River 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 Navarro River watershed. The dominant soil group in the watershed is Group B (51%), containing moderately well to well-drained silt loams and loams. Group C (36%) is the next most common soil group in the watershed, containing sandy clay loam that typically have low infiltration rates. Group D, with the lowest infiltration rates, makes up approximately 12% of the watershed. Less than 1% 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 Navarro River watershed

Hydrologic Soil Group	Area (acres)	Percent Area
A	1,580.91	0.8%
A/D	135.50	0.1%
B	101,787.90	50.5%
C	72,528.76	36.0%
C/D	407.29	0.2%
D	23,780.53	11.8%
N/A	1,399.28	0.7%
Total	**201,620.17**	**100.0%**

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

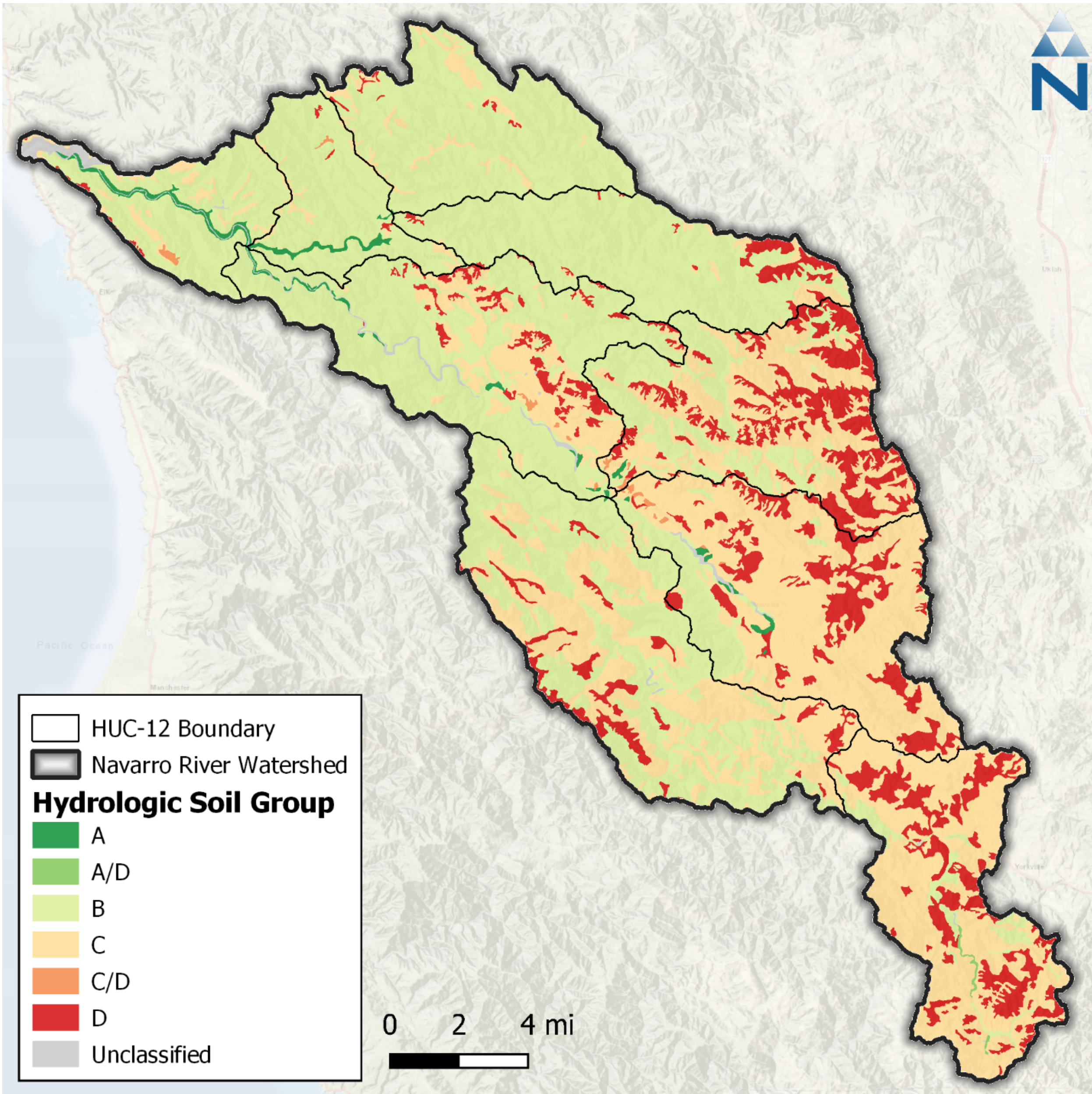

Figure 5-2. SSURGO hydrologic soil groups within the Navarro River watershed.

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 Navarro River watershed. Figure 5-3 shows the NLCD 2021 land cover for the Navarro River watershed. Evergreen forest is the dominant land cover classification covering approximately 67% of the watershed area. When combined, evergreen forest, the undeveloped categories of deciduous forest, mixed forest, shrub/scrub, and grassland/herbaceous account for close to 95% of the total watershed area. Developed land cover makes up less than 5% of the total watershed area and is classified mostly as "Developed, Open Space," which suggests that much of the developed area is dispersed. Approximately 0.3% 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 Navarro River watershed

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	96.30	0.05%
21	Developed, Open Space[1]	9,324.98	4.62%
22	Developed, Low Intensity[1]	416.99	0.21%
23	Developed, Medium Intensity[1]	143.22	0.07%
24	Developed, High Intensity[1]	24.69	0.01%
31	Barren Land (Rock/Sand/Clay)	23.13	0.01%
41	Deciduous Forest	603.58	0.30%
42	Evergreen Forest	134,539.89	66.73%
43	Mixed Forest	9,182.87	4.55%
52	Shrub/Scrub	32,974.13	16.35%
71	Grassland/Herbaceous	12,459.18	6.18%
81	Pasture/Hay	141.44	0.07%
82	Cultivated Crops	638.27	0.32%
90	Woody Wetlands	816.41	0.40%
95	Emergent Herbaceous Wetlands	237.52	0.12%
	TOTAL	**201,622.58**	**100%**

Source: 2021 National Land Cover Database

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

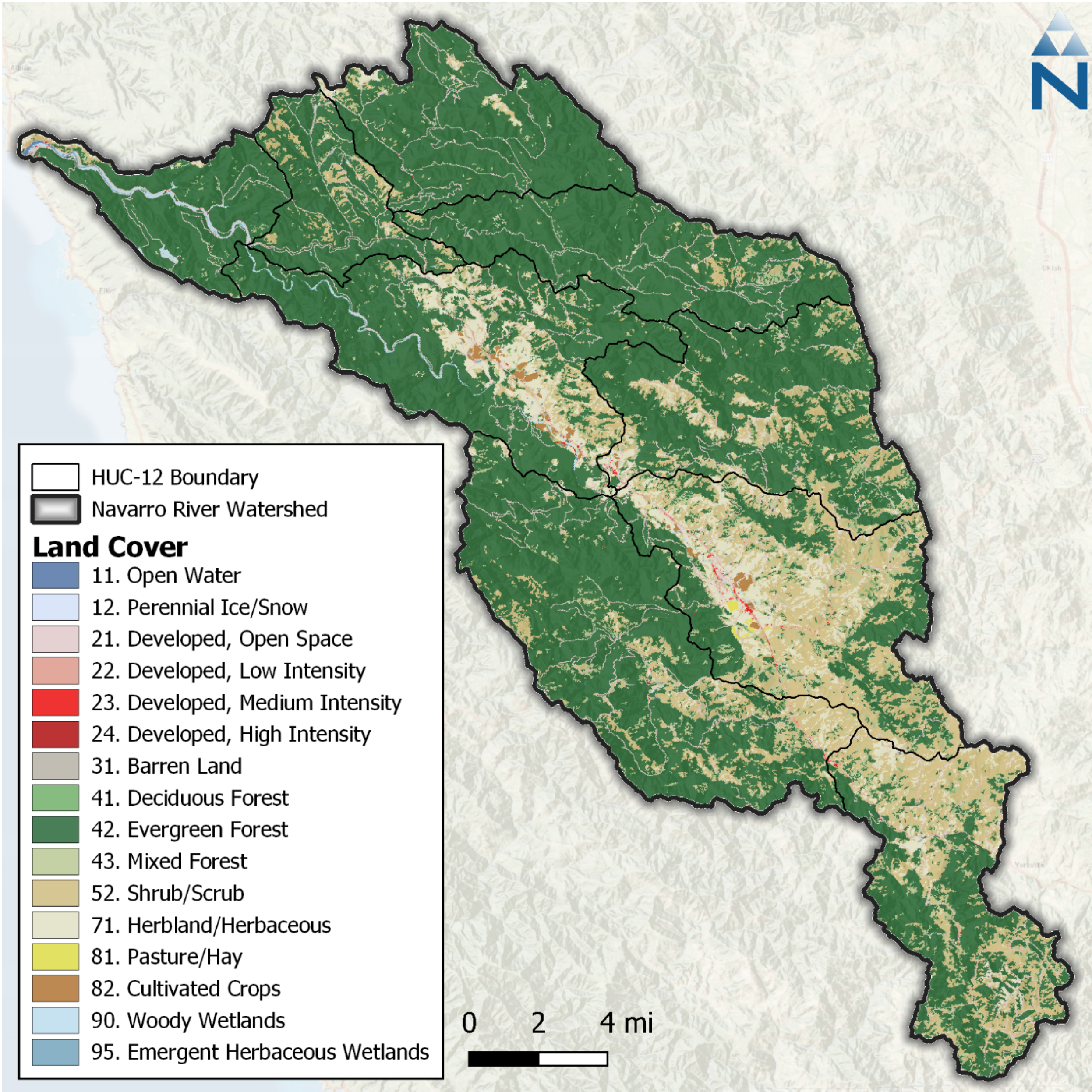

Figure 5-3. NLCD 2021 land cover within the Navarro River watershed.

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 Navarro River watershed using this dataset shows that less than 1% of the area is impervious.

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 Navarro River 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 less than 1% of the Navarro River watershed area is classified as Pasture/Hay and Cultivated Crops. However, NLCD classifies 23% of the watershed area as Shrub/Scrub (52) or Grassland/Herbaceous (71). Some portion of these 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 Cropland Data Layer (CDL) provides annual, crop-specific land cover data. CDL is a geo-referenced raster 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 supplement of acreage estimates for major crop commodities. The CDL distribution within the Navarro River watershed is shown in Figure 5-4 and Table 5-4. Additionally, large-scale crop and land use identification published by the California Department of Water Resources, in March 2023 for the year 2020, is available to supplement this analysis as needed. CA DWR developed a crop mapping dataset through remote sensing land use surveys performed at a field scale to quantify crop acreage statewide.

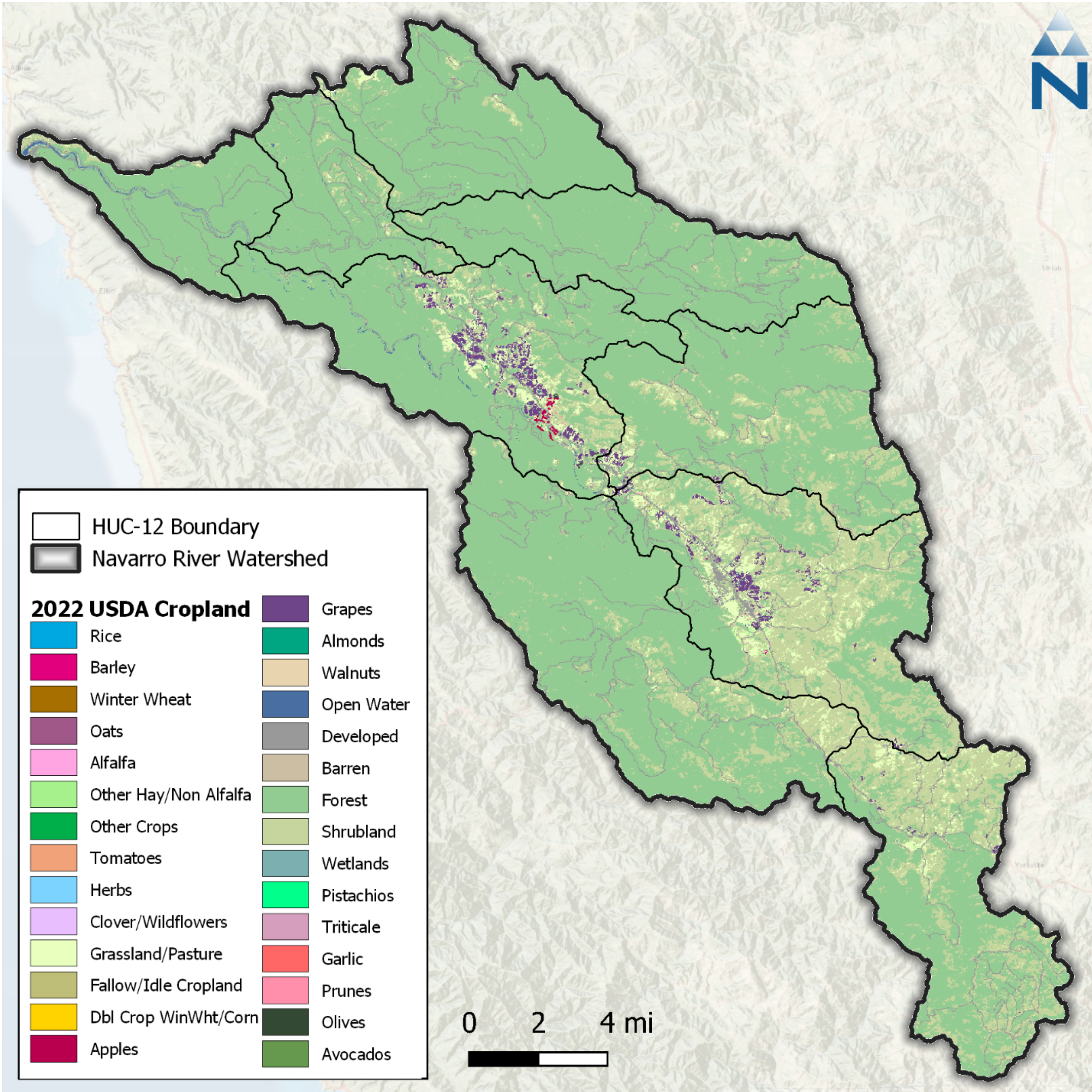

Figure 5-4. USDA 2022 Cropland Data within the Navarro River watershed.

Table 5-4. USDA 2022 Cropland Data summary within the Navarro River watershed

Crop Type	Area (ac)	Area (%)
Rice	0.2	0.0%
Barley	5.0	0.0%
Winter Wheat	3.2	0.0%
Oats	3.9	0.0%
Alfalfa	15.6	0.0%
Other Hay/Non Alfalfa	85.4	0.0%
Other crops	9.7	0.0%
Tomatoes	2.9	0.0%
Herbs	0.2	0.0%
Clover/Wildflowers	0.5	0.0%
Fallow/Idle Cropland	15.6	0.0%
Apples	119.0	0.1%
Grapes	1,897.7	0.9%
Almonds	24.0	0.0%
Walnuts	6.8	0.0%
Open Water	344.0	0.2%
Developed	9,848.7	4.9%
Barren	52.6	0.0%
Forest	144,782.3	71.8%
Shrubland	37,262.3	18.5%
Grassland/Pasture	6,668.9	3.3%
Wetlands	359.9	0.2%
Pistachios	0.2	0.0%
Triticale	3.4	0.0%
Garlic	1.6	0.0%
Prunes	65.0	0.0%
Olives	37.4	0.0%
Avocados	0.2	0.0%
Double Crop Winter Wheat/Corn	0.2	0.0%
Total	**201,616.6**	**100%**

6 DATA GAPS AND LIMITATIONS

Based on review of the hydrology datasets 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, Navarro River near Navarro CA (USGS 11468000), with long-term daily data for the period 10/1/1950 through Present. Two upstream historic gauges located in Lower Rancheria Creek (USGS 11467800) and Anderson Creek (USGS 11467850) provide limited data from the periods 9/1/1959 through 9/29/1968 and 10/1/1964 through 9/29/1968, respectively. Model calibration to observed data will therefore be focused at minimum on matching predicted discharges to Navarro River near Navarro CA (USGS 11468000) near the mouth of the Navarro River, meaning predictions downstream of this point will be subject to some uncertainty.

The Navarro Partnership, a collaboration between the Mendocino County Resource Conservation District, The Nature Conservancy, and Trout Unlimited has numerous active programs in the watershed and should be engaged to inquire about additional streamflow data that may have been collected which could support model development either as inputs or for comparison and validation of model predictions.

Another potential limitation is the availability, quality, and temporal resolution of data for surface water diversions within the watershed. The eWRIMS database identifies 3 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.

7 MODEL CONFIGURATION

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)
- The model simulation period should be long enough to capture the variability of the full range of water year such that it can represent varied conditions including 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 forest fires.

Public-domain models that can address those study objectives include the Hydrologic Simulation Program – Fortran (HSPF), the Loading Simulation Program in C++ (LSPC) (Shen et al. 2005; USEPA 2009), the Precipitation-Runoff Modeling System (PRMS), and the 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. Based on this history of successful LSPC model applications, LSPC is recommended as the model for this study.

LSPC is functionally identical to the HSPF model but has been modernized and organized around a Microsoft Access relational database. This structure provides efficient data management, model maintenance, and development of alternative scenarios. The LSPC model can be driven by hourly forcing input time series 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 forest fires. The South Fork Eel River and Shasta River watershed LSPC models previously mentioned have utilized data from many of the same sources compiled in this study plan for the Navarro River watershed.

7.2 Model Configuration

An LSPC model will be configured using the data sets 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. 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 to rely 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 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 $-\infty$ 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 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 RSR and NSE qualitative assessments of sub-annual intervals.

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.
5. 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 Navarro River 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 catchment 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 Navarro River 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]	Eight (8) weeks after completing Task 3.1
4	4.1	Draft Calibration Slide Deck	Four (4) 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]	Eight (8) 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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