Work Plan: Gualala River Watershed Hydrology Model Development

SUBMITTED TO:

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ACRONYMS

3DEP	3D Elevation Program
ASCE-PM	American Society of Civil Engineers version of the Penman-Monteith equation
CAL FIRE	California Department of Forestry and Fire Protection
CDEC	California Data Exchange Center
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
ET	Evapotranspiration
ET_0	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
LCD	Local Climate 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
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutclife Model Efficiency Coefficient
PBIAS	Percent Bias
PEVT	Potential Evapotranspiration
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Stations
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

Contents

Figures

Tables

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 Gualala River 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

The Gualala River is one of the nine watersheds that line the Mendocino Coast. The watershed shares a boundary with the Big-Navarro-Garcia watershed to the north, Navarro River watershed to the northeast, and the Russian River watershed to the southeast. The coastal watershed area drains approximately 298 square miles and is made up of nine main catchments: the Rockpile Creek (HUC-12: 180101090105) and its major tributary, Buckeye Creek (HUC-12: 180101090106) being one example (Figure 1-1). The Gualala River is a free-flowing river with three main forks: the South Fork, North Fork, and the largest of the three, the Wheatfield Fork. It flows approximately 40 miles to the town of Gualala before draining to the Pacific Ocean.

The Gualala River watershed ranges in elevation from near sea level in Salt Point State Park to over 800 meters at the easternmost portion near Gube Mountain. It has a Mediterranean climate with distinct wet and dry seasons and a mean annual precipitation total of 41.86 inches (USGS 2019). The watershed is dominated by evergreen forest and shrubland which cover approximately 67% and 18% of the total area, respectively; other land cover types include developed, open space (3%), grassland (4%), and mixed forest (7%).

The Gualala River watershed represents an important habitat for native aquatic species and spawning ground for anadromous fish, especially steelhead trout. It once was a breeding ground for coho salmon which are now nearly extinct. The decline in anadromous fish populations within the Gualala River watershed has been linked to extensive logging and road-building practices that increased sediment delivery and excessive stream temperatures above that which supports salmonid life and low dry season flows (Sonoma Resource Conservation District 2024). These factors led to a multi-agency watershed assessment program under the North Coast Watershed Assessment Program from 1999 to 2002 and the development of a Total Maximum Daily Load (TMDL) for sediment in 2001 (NCRWQCB 2018). It also led to partnership programs with the Gualala River Watershed Council (GWRC) and the Conservation Fund, which manages 44,000 acres of forest in the Gualala River Watershed, to control sedimentation.

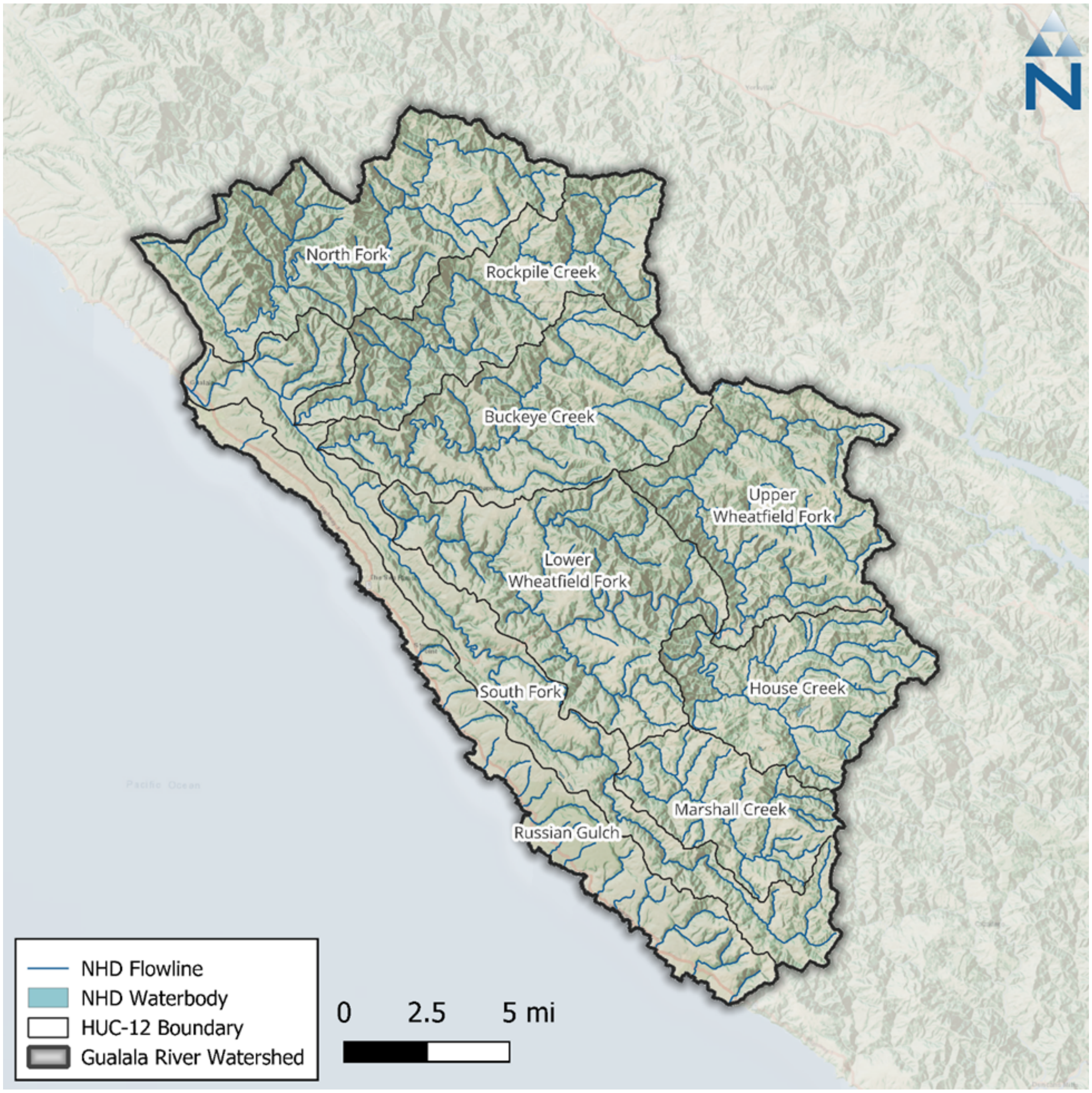

Figure 1-1. Gualala River watershed.

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

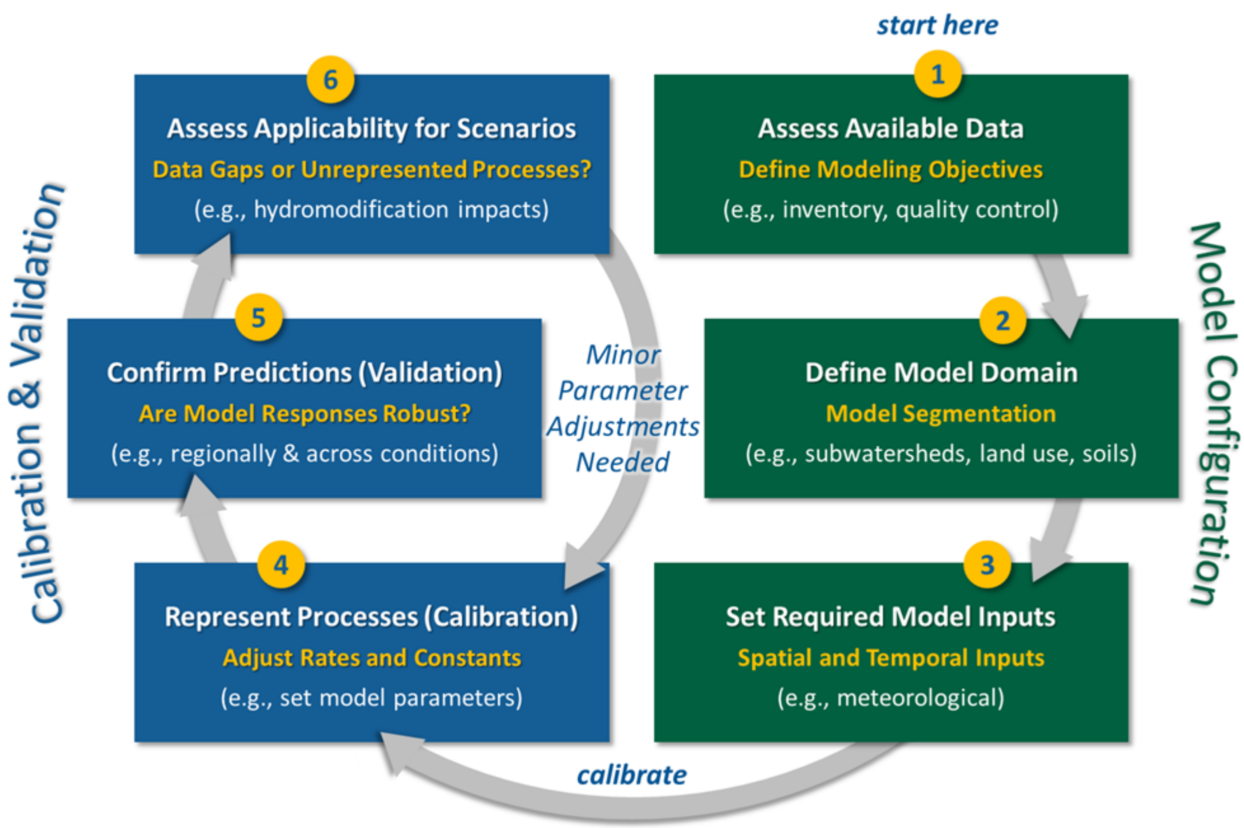

Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Gualala River watershed.

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 the Gualala River. Time series observations of instream responses for the Gualala River are often used as calibration and validation datasets for hydrologic models.
- **Geospatial Datasets**: Spatial datasets describing the landscape of the Gualala 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)	--	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 available for three stations.	Climate data boundary time series.
California Data Exchange Center (CDEC)	Precipitation, Temperature	--	Meteorological records available for three 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	1991 – Current	Observed Streamflow at two active locations on the Gualala River.	Hydrology calibration.	LINK
Habitat	Local	GRWC	GWRC Monitoring Program.	Current	Description of GWRC monitoring program including reach surveys.	Hydrology calibration & validation.	LINK
Water Budget	State	DWR	Well Completion Reports	Current	Well completion logs and reports.	Water budget.	LINK
			Interconnected Surface Water	2008	One (1) river stage CDEC station and one (1) rain CDEC station 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
		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	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
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 Gualala River 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 eight GHCN gauges identified within or near the Gualala River 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. However, there are no LCD stations within 10 miles of the Gualala River watershed. The California Data Exchange Center (CDEC) and Remote Automated Weather Stations (RAWS) networks also report hourly precipitation. CDEC reports at three locations and RAWS reports at three locations within and near the watershed. Table 2-1 is an inventory of the precipitation stations near the Gualala River 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 Gualala River Watershed will be the Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Daly et al. 2008, 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, 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	GHCND:US1CAMD0003	BOONVILLE 2.2 WSW, CA US	1/1/2009	8/1/2024	39.00623	-123.408	323.4	92%
	GHCND:USR0000CBOO	BOONVILLE CALIFORNIA, CA US	4/30/1990	8/2/2024	38.9875	-123.349	196.3	99%
	GHCND:US1CASN0098	CAZADERO 5.6 W, CA US	10/6/2012	8/2/2024	38.53186	-123.189	369.1	94%
	GHCND:US1CASN0159	CLOVERDALE 0.8 SSW, CA US	4/14/2019	8/2/2024	38.78942	-123.025	117	95%
	GHCND:US1CASN0029	CLOVERDALE 3.2 ESE, CA US	1/31/2009	8/2/2024	38.781	-122.963	242.9	98%
	GHCND:US1CASN0032	DUNCAN MILLS 1.4 NNE, CA US	1/31/2009	10/26/2010	38.47303	-123.052	124.7	96%
	GHCND:USC00043191	FORT ROSS, CA US	9/30/1895	7/30/2024	38.515	-123.245	34.1	93%
	GHCND:US1CAMD0050	GUALALA 3.7 NW, CA US	4/9/2022	8/1/2024	38.81182	-123.579	144.8	100%
CDEC	CLV	RUSSIAN RIVER AT CLOVERDALE	10/2/1987	3/1/2021	38.87935	-123.054	32.6	100%
	VEN	VENADO	1/2/1984	Present	38.6087	-123.018	384.1	100%
	YOR	YORKVILLE	1/3/1984	Present	38.905	-123.231	335.3	100%
RAWS	OAAC1	OAK RIDGE	7/18/2016	Present	38.73806	-123.308	576.1	100%
	BNVC1	BOONVILLE	12/2/1999	Present	38.98736	-123.348	196.3	100%
	TR110	CALFIRE PORTABLE 14	6/26/2001	Present	38.47908	-123.07	387.7	100%

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.

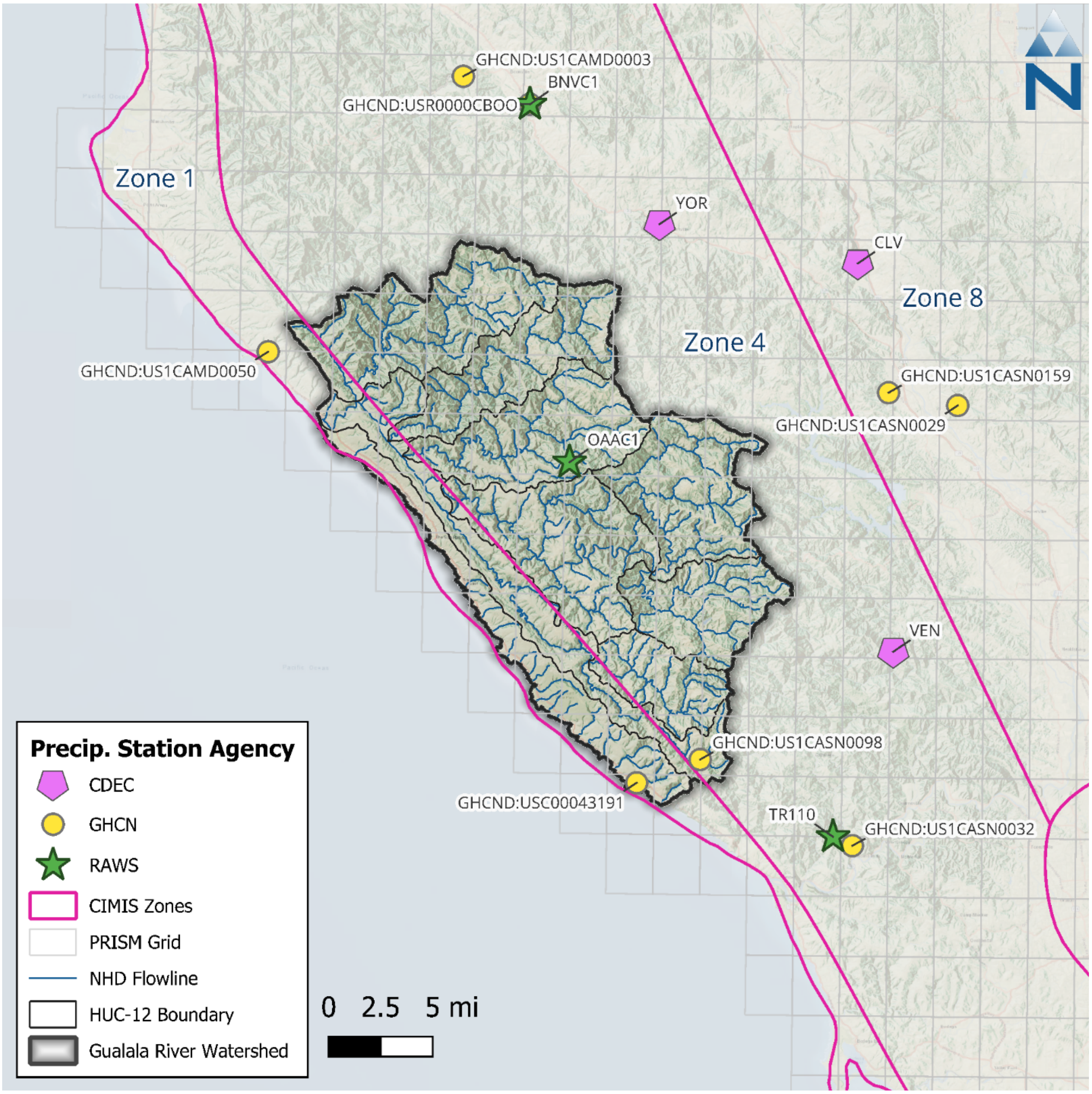

Figure 2-1 Identified rainfall gauges and CIMIS ET Zones near the Gualala River watershed.

The hybrid approach entails three main steps. First, impaired intervals (i.e., missing, or accumulated) at observed stations will be patched with quality-controlled data from nearby stations. 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 PRISM are used to fill any remaining spatial and temporal gaps in the observed station network as needed. It should be noted that while PRISM gridded data also provides estimates of precipitation on a 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.

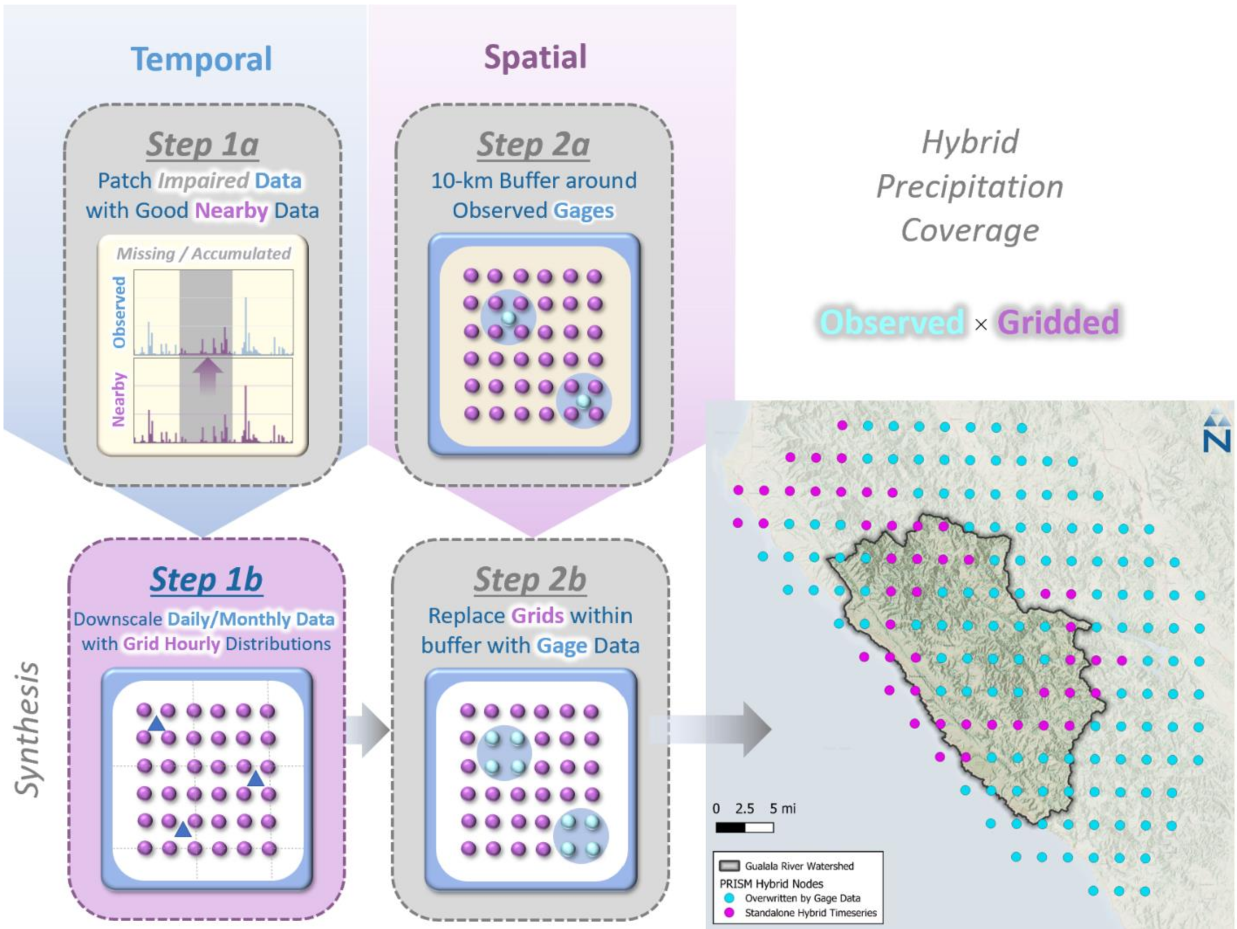

Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products.

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.

There are no CIMIS stations, active or inactive, within ten miles of the Gualala River Watershed. As shown in Figure 2-1, the Gualala River watershed intersects two CIMIS zones with 78% of the watershed area in Zone 4 (South Coast Inland Plains and Mountains North of San Francisco), and 22% of the watershed area in Zone 1 (Coastal Plains Heavy Fog Belt). Most of the Gualala River watershed falls within Zone 4, and the western, coastal edge of the watershed falls into Zone 1. These zones experience average annual reference evapotranspiration levels from 33.0 inches per year in Zone 1 to 46.6 inches per year in Zone 4 (DWR 2024).

CIMIS also has a newly derived gridded product, CIMIS Spatial, that expresses daily ET_o estimates calculated at a statewide 2-km spatial resolution using the American Society of Civil Engineers version of the Penman-Monteith equation (ASCE-PM) (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.

Representative potential evapotranspiration (PEVT) time series can be estimated for the Gualala River 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 (evapotranspiration). 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 through comparison 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 Gualala 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, flowlines, 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 411 catchments ranging in size between 0.2 acres 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 Gualala River watershed (HUC-10).

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.

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

HUC-12 Name	Count	Catchment Size (acres)			
		Minimum	Mean	Median	Maximum
Marshall Creek	40	0.7	316.5	261.3	963.4
House Creek	40	8.9	455.9	357.2	1,802.7
Upper Wheatfield Fork	53	4.9	461.5	425.2	2,150.3
Lower Wheatfield Fork	67	2.2	428.9	345.8	1,995.3
Buckeye Creek	35	2.9	735.3	567.5	1,959.5
Rockpile Creek	31	198.8	722.7	546.0	2,744.3
North Fork	46	2.4	666.0	495.2	3,158.8
South Fork	41	0.2	687.7	308.9	4,571.0
Russian Gulch	58	0.5	369.5	262.5	4,193.7

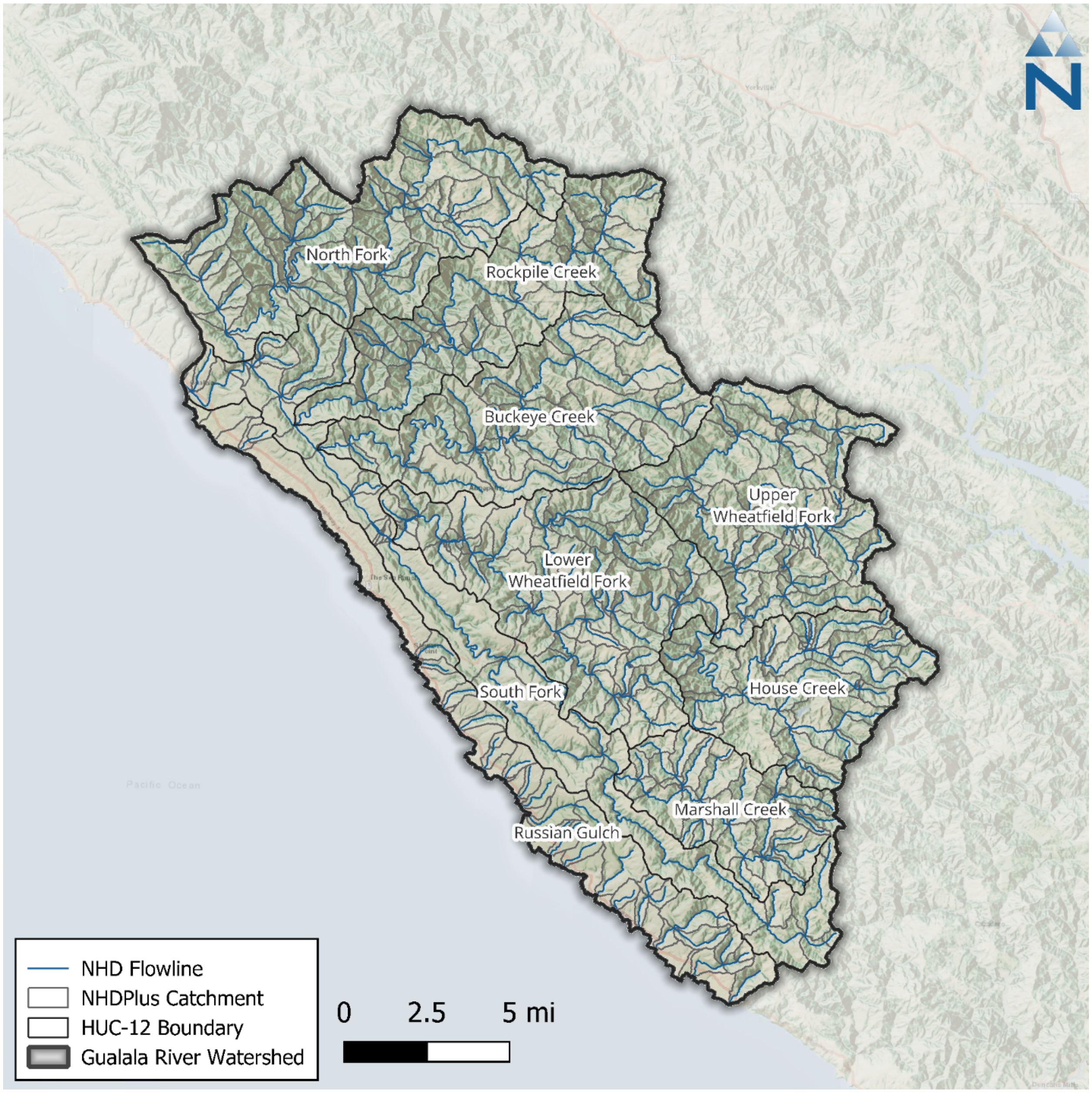

Figure 3-1. Initial catchment segmentation for the Gualala River watershed.

3.2 Streams and Channels

The hydrographic characteristics of the streams and rivers within the Gualala River 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 Gualala River and its major tributaries.

3.3 Streamflow

The primary source of streamflow data is from the USGS, which includes two current long-term gauges: the North Fork Gualala River above South Fork Gualala River near Gualala, CA (USGS 11467553) gauge and South Fork Gualala River near the Sea Ranch, CA (USGS 11467510). There are also two historical gauges within the watershed, with data ranging from October 2000 to September 2007. Table 3-2 presents a summary of the available USGS streamflow data. Figure 3-2 shows the locations of the four USGS gauges within the Gualala River watershed.

Table 3-2. Summary of USGS daily streamflow data after 2000

Gauge Description	Station ID	Drainage Area (mi^2)	Start Date	End Date	Gauge Active?
NF GUALALA R AB SF GUALALA R NR GUALALA CA	11467553	47.1	10/01/2000	Present	Yes
SF GUALALA R NR THE SEA RANCH CA	11467510	161	06/01/1991	Present	Yes
SF GUALALA R AB WHEATFIELD FK NR ANNAPOLIS CA	11467295	48.2	11/18/2000	05/30/2006	No
WHEATFIELD FORK GUALALA R AB SF NR ANNAPOLIS CA	11467485	111	10/01/2000	09/29/2007	No

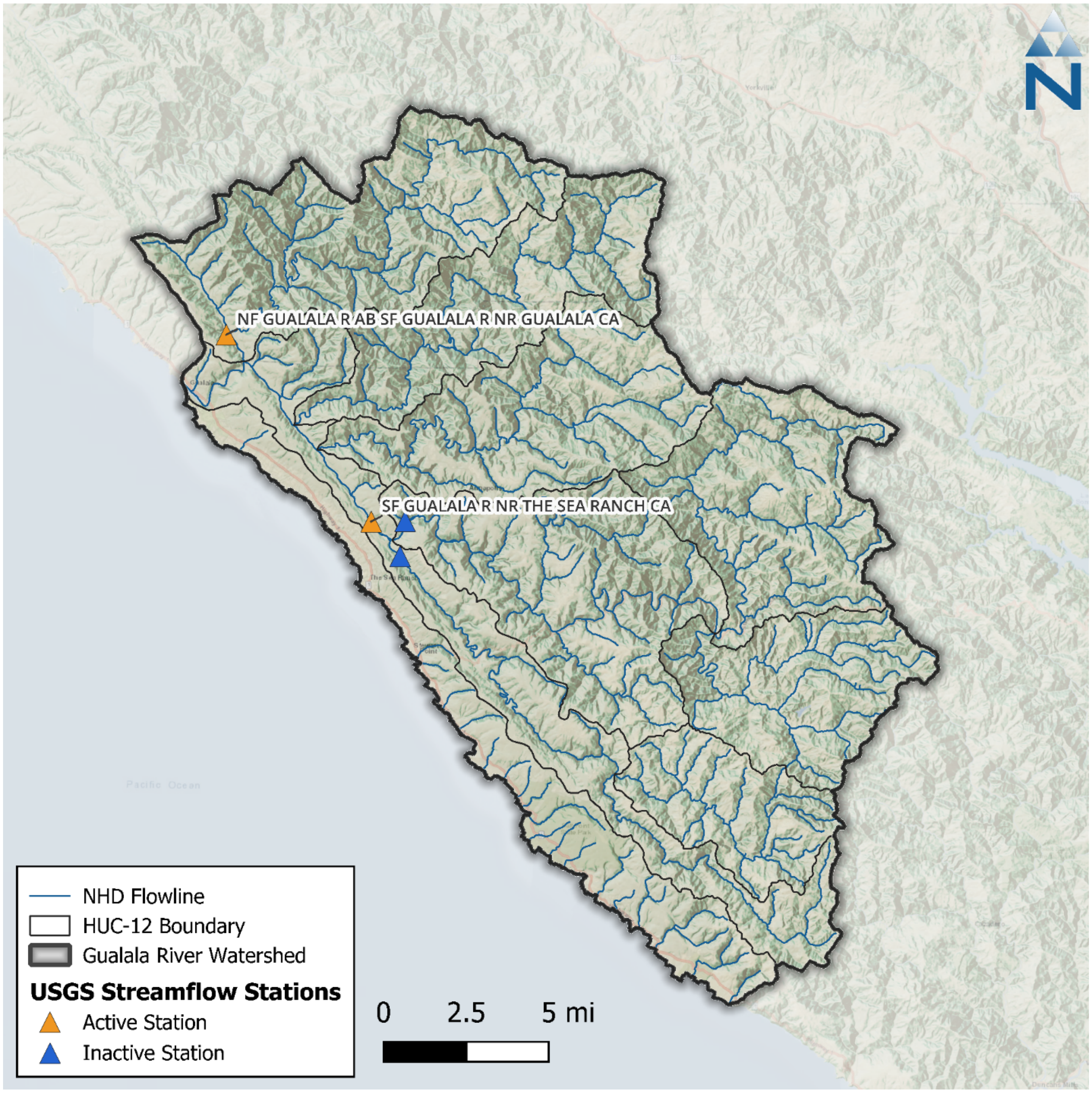

Figure 3-2. USGS streamflow stations in the Gualala River watershed.

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 CA DWR Agricultural Land and Water Use Estimates database (ALWU). 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 Gualala River 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 its water usage rates will be corrected against spatial variations in the observed evaporative deficit where necessary.

Figure 3-3 provides an overview of water systems distributed throughout the watershed and points of diversion (POD). The water systems include a mixture of surface water diversions from the Gualala River and its primary tributaries, as well as groundwater withdrawals for the Gualala River watershed groundwater basin. There are 16 drinking water systems in the watershed. For 11 out of the 16 drinking water systems, the water source is listed as groundwater, five have surface water listed as the source, and the remaining one system does not have a known source type.

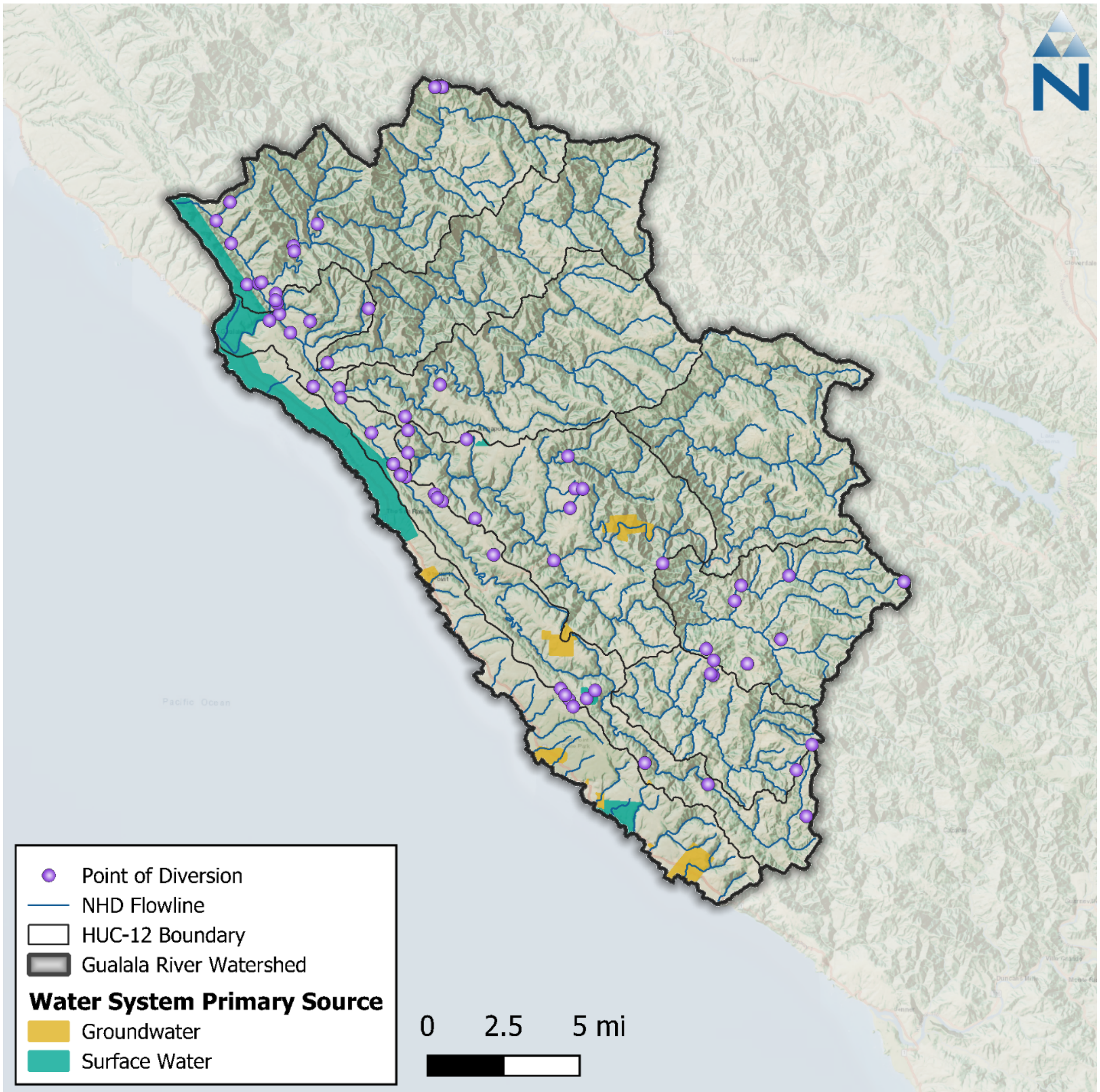

Figure 3-3. Points of diversion and water system types in the Gualala River watershed.

4 SUBSURFACE HYDROLOGY

The Gualala watershed overlaps with two groundwater basins as delineated by Bulletin 118 (DWR 2020). The watershed contains the Annapolis Ohlson Ranch Formation Highlands (number 1-049). Very small portions of Fort Ross Terrace Deposits (number 1-061) overlap with the Gualala River watershed. Approximately 6% of the Gualala River watershed area falls within the groundwater basins delineated by Bulletin 118, and the remaining 94% is within the Franciscan Complex, as described below.

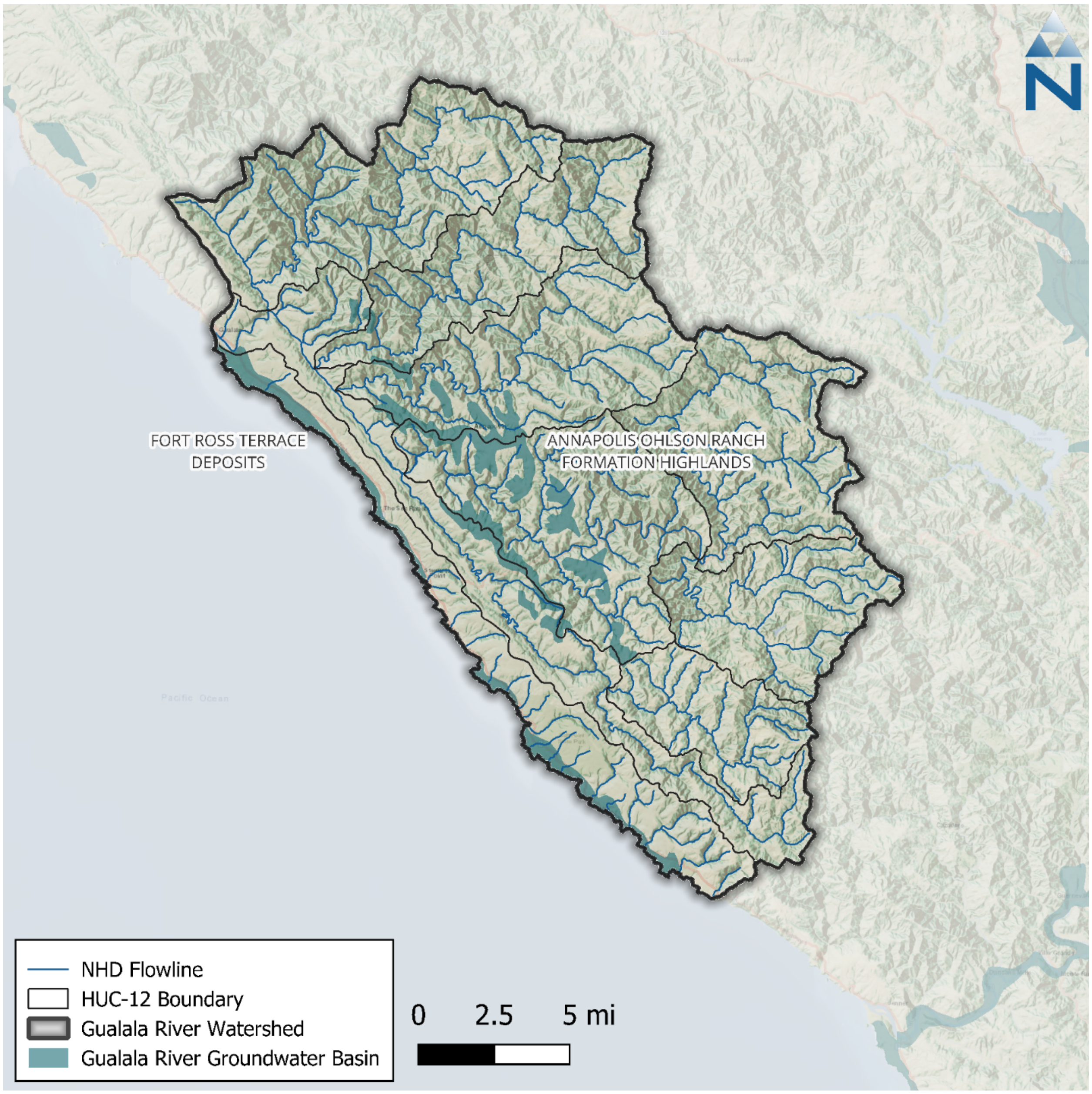

Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118.

As per the respective basin priority details (https://gis.water.ca.gov/app/bp-dashboard/final/) both basins are Very Low priority basins as designated by the Sustainable Groundwater Management Act's (SGMA) basin prioritization. Although the Annapolis Ohlson Ranch Formation Highlands basin relies on groundwater for 98% of water supply, the basin is prioritized at Very Low priority due to a groundwater use of less than 9,500 acre-feet per year and no documented impacts to groundwater supplies, such as declining groundwater levels, saline intrusion or subsidence. No Groundwater Sustainability Agencies (GSAs) overlap with the Gualala watershed.

4.1 Water Budget Components

No publicly available groundwater models were located for the Gualala basin. The Bulletin 118 reports for the three intersecting basins noted that no groundwater budget estimates were available. None of the US Geological Survey public domain models for Northern California (USGS 2024) overlap the Gualala basin.

4.2 Geology

The references mentioned in previous sections primarily cover the groundwater basins delineated as per Bulletin 118. The Annapolis Ohlson Ranch Formation Highlands basin is comprised of the Ohlson Ranch Formation, consisting of marine deposits capping ridge tops. Outside of the basin, the main formation is the Franciscan Complex, described by the California Geological Survey in their 1982 regional Santa Rosa map as "a tectonically disrupted subduction complex composed of diverse rock types including sandstone, shale, conglomerate, greenstone (altered basalt) chert, limestone, metagraywacke (semischist), schist, blueschist, gabbro and serpentinized peridotite." (CA Mines 1982). In addition to this fault-disrupted mélange, there are coherent belts of sandstone, shale, conglomerate, and greenstone within the Gualala basin. 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, noting that "The Franciscan Complex is considered non-water-bearing, although it can yield enough water to wells for domestic uses" (DWR 2020).

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 Gualala River watershed.

5.1 Elevation & Slope

The USGS publishes DEMs expressing landscape elevation through a raster grid data product with 30-meter resolution. The Gualala River watershed ranges in elevation from sea level along the coast in the western part of the watershed to over 800 meters in the eastern part. 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 Gualala River watershed.

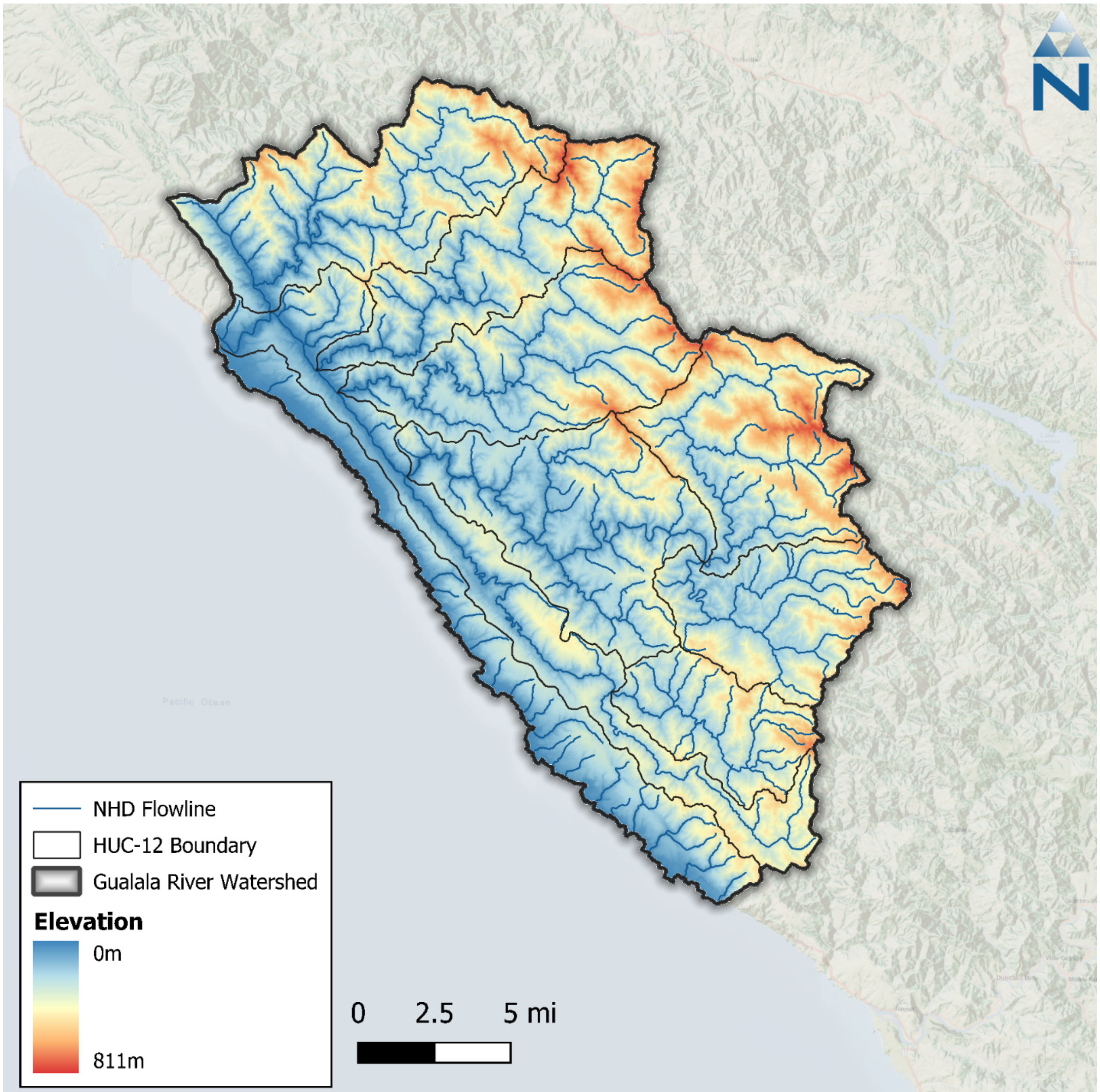

Figure 5-1. Digital elevation model of the Gualala River watershed.

5.2 Soils & Geology

Soils data for the Gualala River 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 Gualala River watershed. The dominant soil group in the watershed is Group B (57%), containing moderately well to well-drained silt loams and loams. Group C, making up 32% of the watershed, contains sandy clay loam with typically low infiltration rates. Group D makes up 9% of the watershed, and includes soils with the lowest infiltration rates, such as clay loam, silty clay loam, sandy and silty clay, and clay. Group A, which consists of well-draining sand, loamy sand, and sandy loam, constitutes nearly 1.5% of the watershed. Only 0.14% of the watershed areas have mixed soils. For modeling purposes, mixed soils will be grouped with the nearest primary group as follows: C/D → D. Finally, approximately 1% 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 Gualala River watershed

Hydrologic Soil Group	Area (acres)	Percent Area
A	2,696.49	1.27%
B	121,295.21	57.08%
C	67,853.22	31.93%
C/D	302.41	0.14%
D	18,620.12	8.76%
N/A	1,736.41	0.82%
Total	**212,503.86**	**100.0%**

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

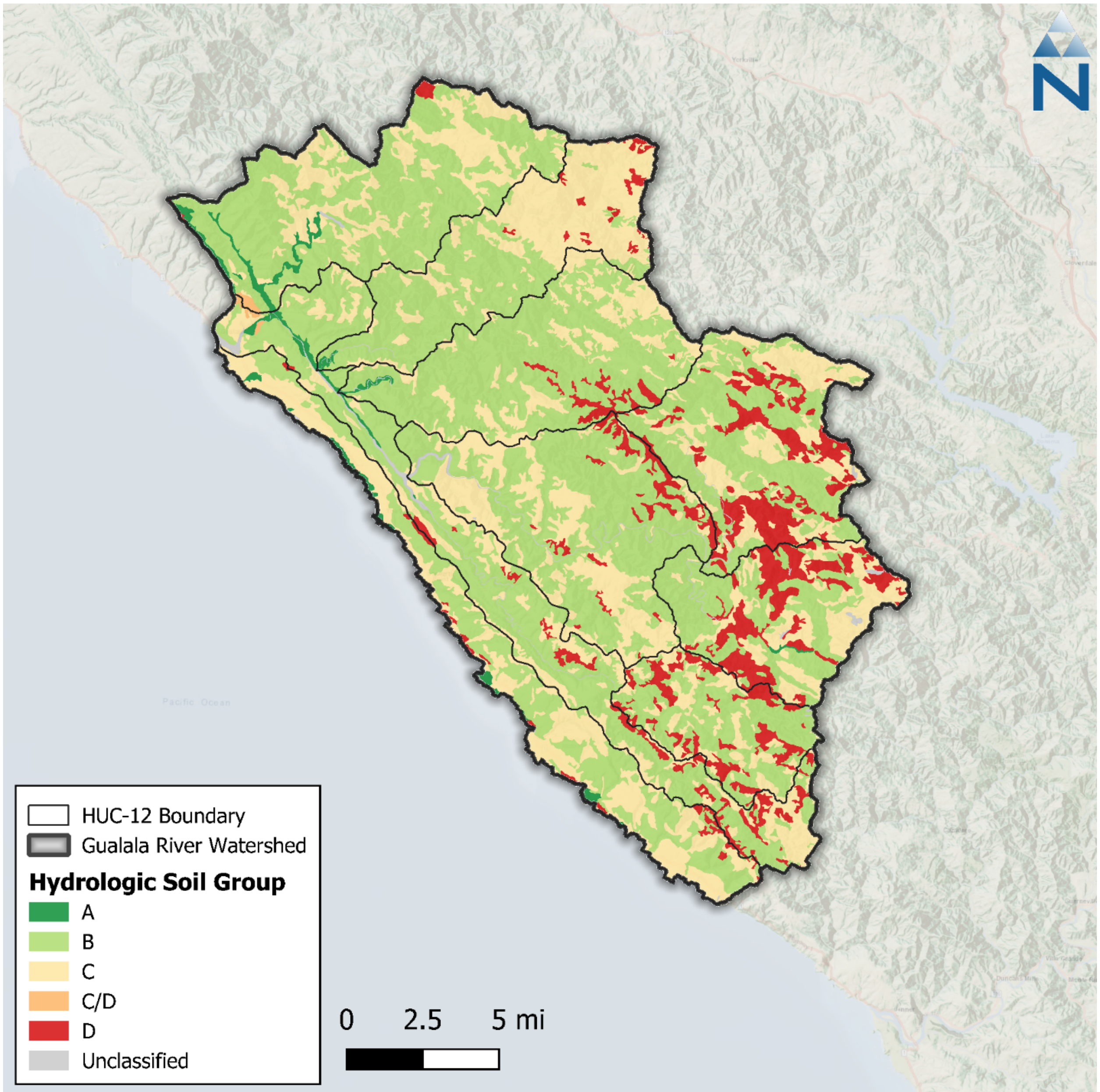

Figure 5-2. SSURGO hydrologic soil groups within the Gualala River watershed.

5.3 Land Cover

Land cover data are a key layer 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 Gualala River Watershed and Figure 5-3 shows the spatial distribution of these classifications. 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 96% of the total watershed area. Developed land cover makes up less than 4% of the total watershed area and is classified mostly as "Developed, Open Space," which suggests that much of the developed area is dispersed.

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

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	378.59	0.18%
21	Developed, Open Space[1]	6,189.07	2.91%
22	Developed, Low Intensity[1]	732.93	0.34%
23	Developed, Medium Intensity[1]	223.77	0.11%
24	Developed, High Intensity[1]	100.32	0.05%
31	Barren Land (Rock/Sand/Clay)	16.02	0.01%
41	Deciduous Forest	646.84	0.30%
42	Evergreen Forest	141,637.44	66.62%
43	Mixed Forest	15,136.35	7.12%
52	Shrub/Scrub	39,013.55	18.35%
71	Grassland/Herbaceous	7,495.66	3.53%
81	Pasture/Hay	2.00	0.00%
90	Woody Wetlands	702.68	0.33%
95	Emergent Herbaceous Wetlands	320.98	0.15%
TOTAL*		**212,596.18**	**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 16 acres less than the model domain.

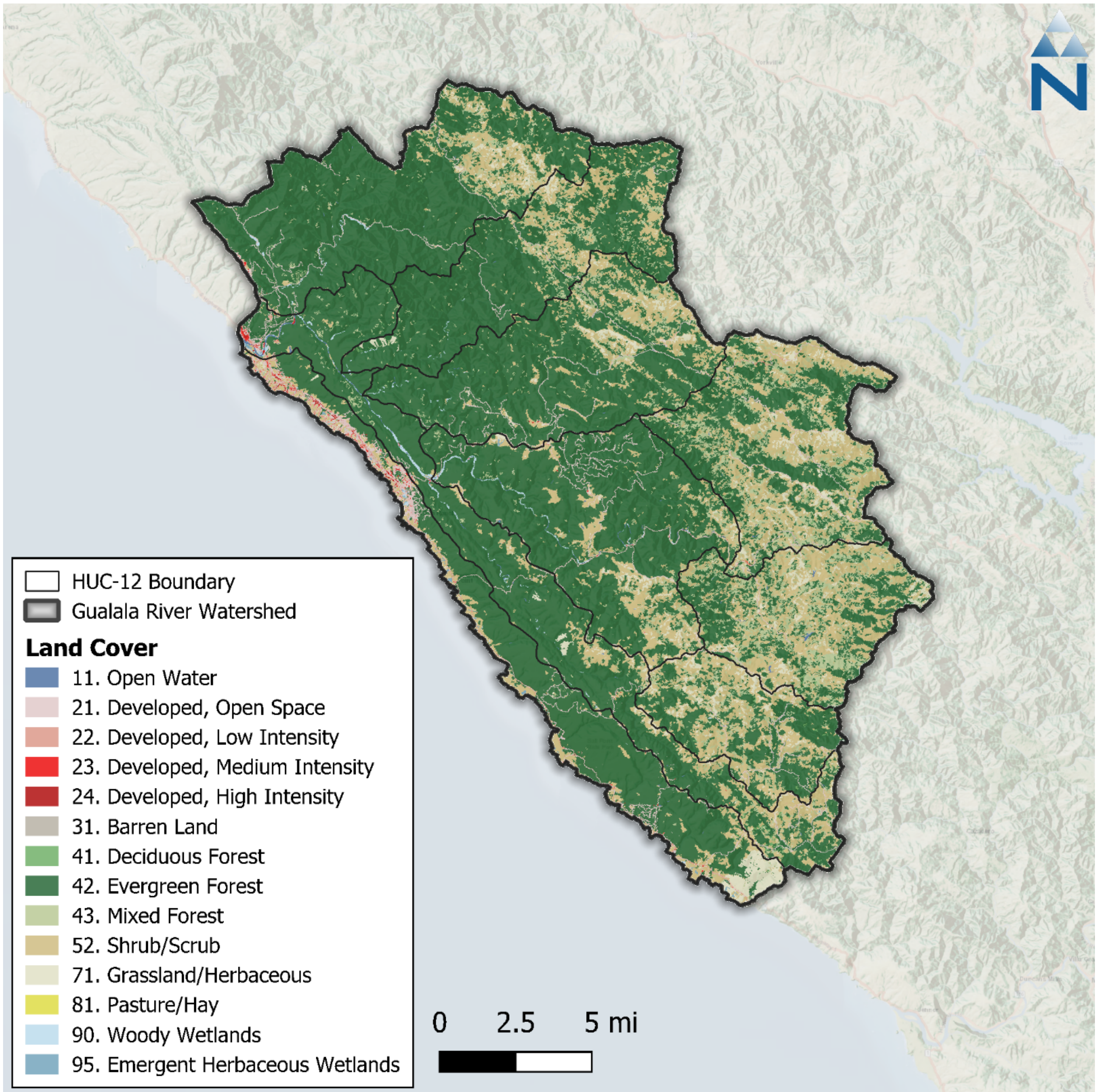

Figure 5-3. NLCD 2021 land cover within the Gualala River watershed.

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 Gualala River watershed using this dataset shows that just over 3% of the area is developed. 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 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 Gualala 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 1-3) 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 Gualala River watershed, an average of 60% 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 Gualala River Watershed (see Section 5.3) was analyzed to identify predominant cropland vegetation classes. This analysis revealed that less than 0.01% of the Gualala River watershed area is classified as Pasture/Hay (class 81) and 22% of the watershed was classified as either Shrub/Scrub (class 52) or Grassland/Herbaceous (class 71); 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 2024c) 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 agricultural land. The purpose of the CDL dataset is to provide a supplemental estimate of annual acreage used for major crop commodities. Figure 5-4 shows the spatial distribution of these classes through the study area, and Table 5-4 summarizes their areal coverage. Additionally, a large-scale crop and land use identification dataset for the year 2020 is made available by DWR (DWR 2019) and could be used to supplement data gaps if necessary. This dataset is intended to quantify crop acreage statewide and was constructed by analyzing remote sensing data gathered at the field scale.

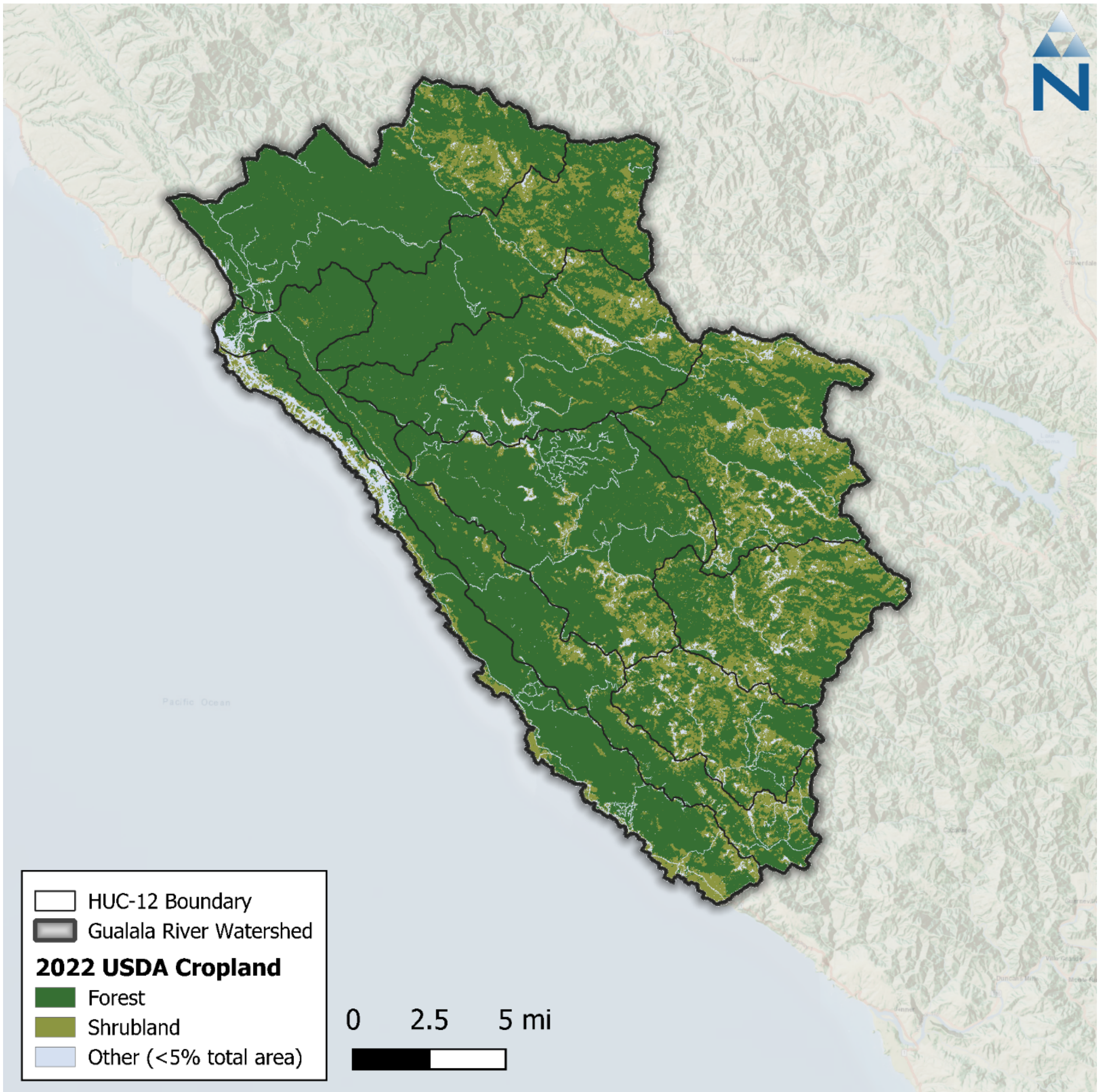

Figure 5-4 USDA 2022 Cropland Data within the Gualala River watershed.

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

Crop Type	Area (ac)	Area(%)
Forest	157,225.6	74.02%
Shrubland	42,390.4	19.95%
Other (<5% Total Area)	12,808.6	6.03%
Totals	**212,454.5**	**100.00%**

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. The Gualala River Watershed Council has numerous active programs in the watershed and should be engaged to inquire about additional streamflow data (i.e., on Wheatfield Fork) that may have been collected which could support model development either as inputs or for comparison and validation of model predictions. The organization also conducts reach surveys that include stream cross-sections, which would be valuable for configuring reach geometry in LSPC.

Another potential limitation is the availability, quality, and temporal resolution of data for surface water diversions within the watershed. The eWRIMS point of diversion dataset 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.

7 MODEL CONFIGURATION

Model configuration encompasses model selection and data integration. Model selection considered not only available data and the ability of available models to address key study objectives, but also, considered how existing or on-going modeling efforts could be leveraged to address the specific objectives of this study (Section 1). This section elaborates further on model selection and 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) (Barnwell and Johanson 1981), the LSPC (Shen et al. 2005; USEPA 2009), the Precipitation-Runoff Modeling System (PRMS) (Markstrom et al. 2015), and the 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, 2013b, 2013a, and 2015; LARWQCB and USEPA 2005a, 2005b, 2006, and 2011; Tariq et al. 2017), the San Jacinto River watershed in the Santa Ana Region (SAWPA 2003 and 2004), and most coastal watersheds of the San Diego Region (City of San Diego and Caltrans 2016; City of Vista 2008; Los Peñasquitos Responsible Agencies 2015; San Diego Bay Responsible Parties 2016; SDRWQCB 2008, 2010, and 2012). These efforts have included comprehensive peer review processes and public comment, requiring demonstration of model accuracy based on standard practices for quantifying and documenting model performance. All the modeling documentation and reports cited here have withstood peer review and have supported amendments to Water Quality Control Plans or the approval of watershed plans submitted to the Water Board or Regional Water Quality Control Boards to demonstrate regulatory compliance. Additionally, the Water Board recently utilized LSPC to perform analyses of hydrology within the South Fork Eel River and Shasta River watersheds.

LSPC is a modernized version of the HSPF platform 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. 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. 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 5. A hydrologic analysis will 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 the hourly NLDAS time series. 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 from NLDAS.

- **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 Gualala River 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 Gualala River 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 Gualala 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]	Twelve (12) weeks after completing Task 3.1
4	4.1	Draft Calibration Slide Deck	Six (6) weeks after completing Task 3.2
		Final Calibration Slide Deck	Four (4) weeks after receiving comments on Draft Calibration Slide Deck
5	5.1	Partial Draft Model Development Report[1]	Twelve (12) weeks after completing Task 3.1
		Draft Model Development Report	Six (6) weeks after completing Task 3.2
	5.2	Final Model Development Report	Four (4) weeks after receiving comments on Task 5.1 Draft MDR
	5.3	Final LSPC Model Code & Software	Two (2) weeks after Task 5.2
	5.4	Final Model Files, including LSPC executable, LSPC database, LSPC model inputs, final GIS files	Two (2) weeks after Task 5.2

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

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