Work Plan: Tomales–Drake Bays 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
FEMA	Federal Emergency Management Agency
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-Sutcliffe Model Efficiency Coefficient
PBIAS	Percent Bias
PEVT	Potential Evapotranspiration
POD	Point of Diversion
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RAWS	Remote Automated Weather Stations

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

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1. INTRODUCTION

1.1 Project Objectives

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

This work plan presents the available data and methodology that will be used to develop a hydrologic model of the Tomales-Drake Bays 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 Tomales-Drake Bays watershed is located on the California Coast, 40 miles north of San Francisco. The watershed shares a boundary with the San Pablo Bay in the east, Russian River watershed to the north-east, and San Francisco Coastal South watershed to the south. The non-estuarine watershed area drains approximately 216 square miles and is made up of 19 sub catchments: the San Geronimo Creek (HUC-12: 180500050103) and its major tributary, Drakes Bay (HUC-12: 180500050502) (Figure 1-1). The Tomales-Drake Bays watershed has four major drainage areas: Lagunitas Creek to the southeast, Olema Creek near the head of the Bay, Walker Creek to the northeast, and smaller tributaries along the west and east shores. Tomales Bay originates from the Lagunitas-Olema Creek drainage where Park Lagunitas Creek meets with Haggerty Gulch Creek which then discharges into the wetlands at the southeast end of Tomales Bay.

The Tomales-Drake Bays watershed ranges in elevation from near sea level in Bodega Bay to over 700 meters at the southernmost portion of the watershed near Mount Tamalpais. The watershed has a Mediterranean climate with distinct wet and dry seasons with a mean annual precipitation total of 47.5 in. (USGS 2019). The valley floor of the watershed is dominated by shrubland and grassland, which cover approximately 38% and 24% of the total area, respectively. Beyond the valley floor, the watershed is predominantly evergreen forest (20%), mixed forest (7%), or developed, open space (3%).

Tomales Bay's western shore serves as a habitat for some of the most ecologically significant coastal areas in California, with two major habitats in the watershed: Point Reyes National Seashore and Tomales Bay State Park. The Tomales-Drake Bays watershed also serves as a critical habitat for anadromous fish, with the largest run of coho salmon in the Central California Coast found in Lagunitas Creek. Both salmon and steelhead spawn within the watershed, specifically in Lagunitas Creek, San Geronimo Creek, Olema Creek, and several other tributaries across the watershed. Point Reyes National Seashore, located in the southwestern most of the watershed, contains a diverse mix of native upland and aquatic habitats, with the Baylands primarily being occupied by seals and sea lions. Tomales Bay also supports a vital shellfish industry and is a popular destination for recreation, yet the Bay faces water quality challenges from pathogens, nutrients, and sediments. Potential sources causing water quality concerns include agricultural runoff from dairy farms and grazing lands nearby, residential runoff, and failing septic systems from overburdened wastewater treatment facilities. These factors led to the development of a Total Maximum Daily Load (TMDL) for pathogens in 2007 (Ghodrati & Tuden 2005), a sediment quality provision in 2018, and the construction of Marshall Community Wastewater Treatment System to mitigate failing septic systems and reduce the spread of pathogens.

The Tomales Bay watershed supports a rich natural resource system. It serves as a critical water supply source for domestic consumers, some agricultural users within the watershed, and urban areas of Marin County outside the Tomales Bay region. Approximately 70% of the Marin Municipal Water District's (MMWD) water supply comes from the Tomales Bay watershed, with most of MMWD's watershed lands located in the Lagunitas Creek sub-watershed. This area is vital for providing and safeguarding the primary domestic water source for 190,000 residents in southern and central Marin County (Tomales Bay Watershed Council 2007).

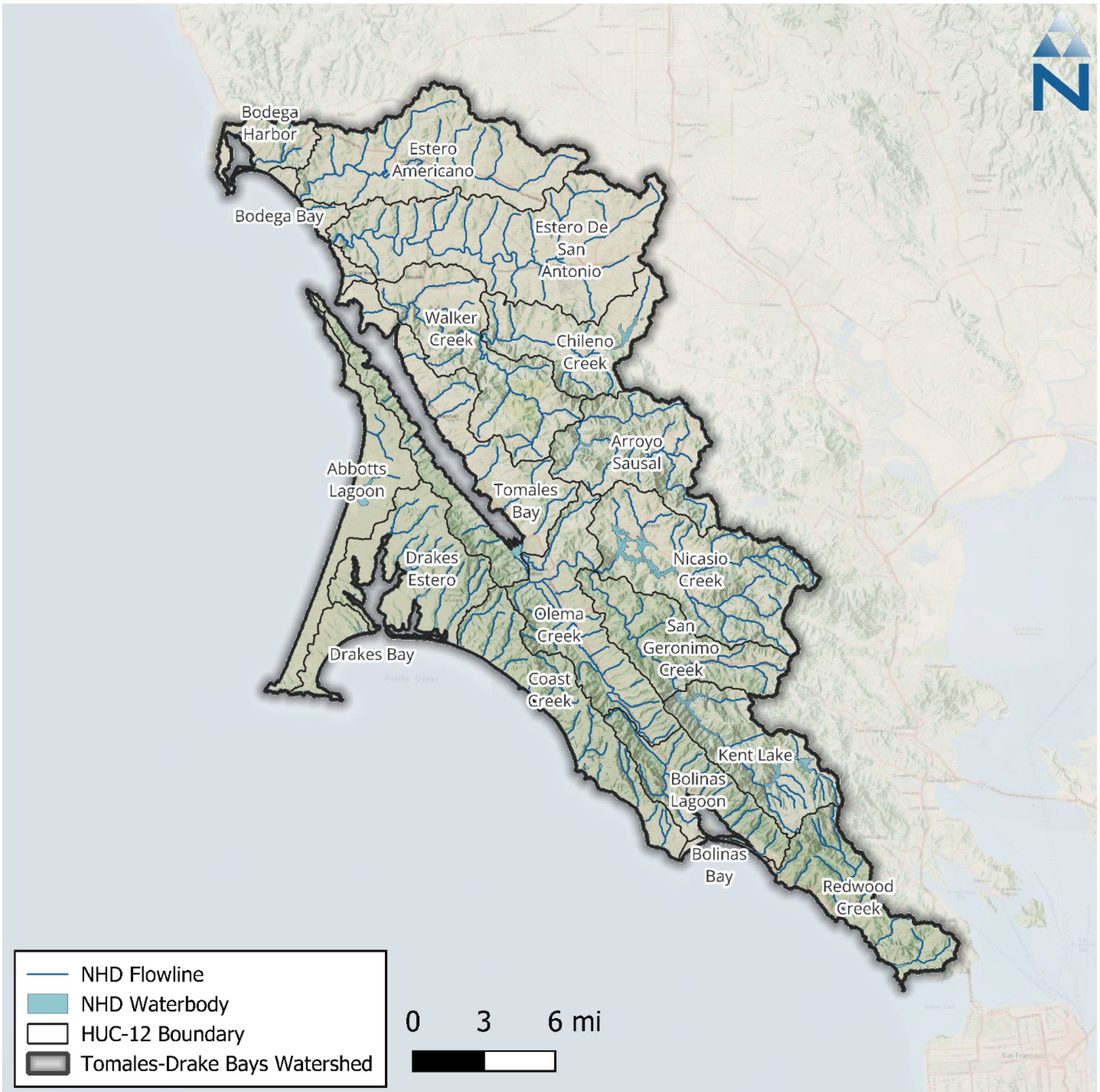

Figure 1-1. Tomales-Drake Bays watershed.

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

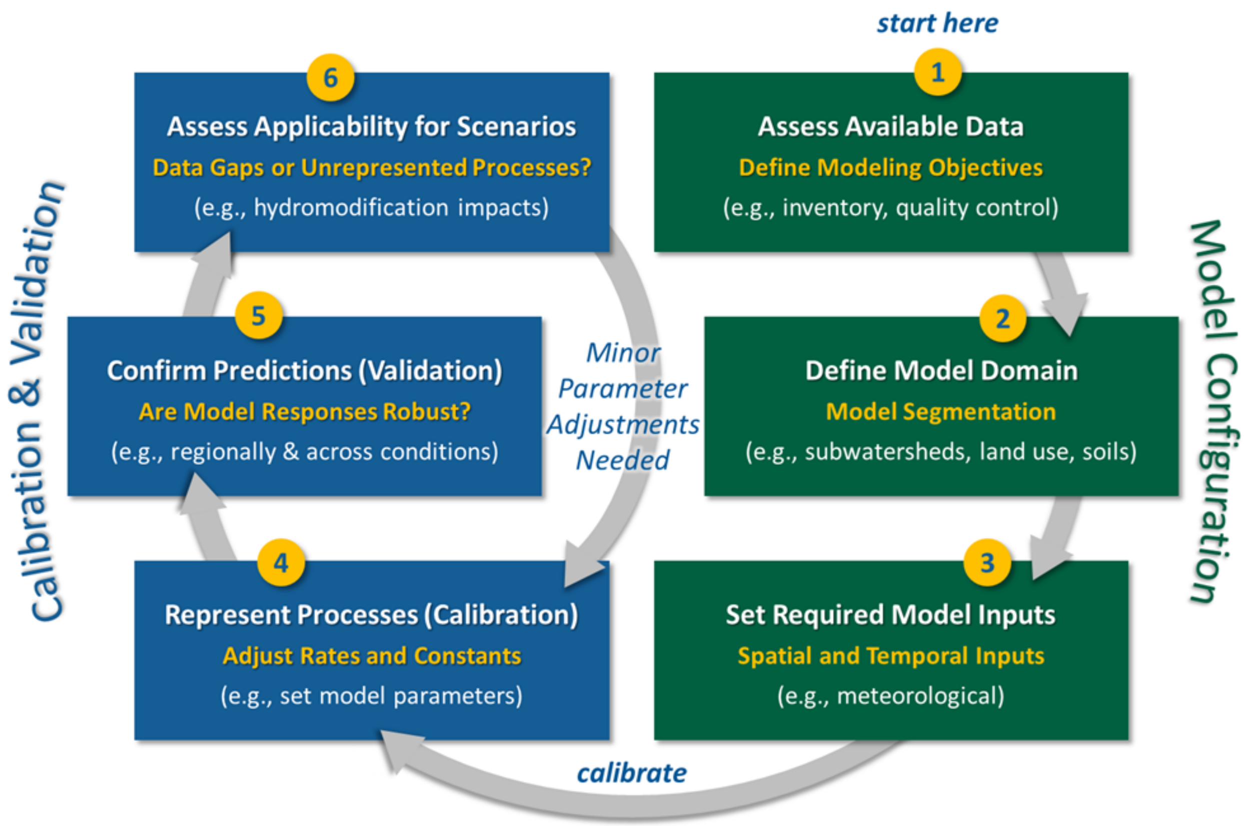

Figure 1-2. Conceptual schematic of model development cycle proposed for assessing instream flow needs in the Tomales-Drake Bays watershed.

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 Tomales-Drake Bays watershed. Time series observations of instream responses for the Tomales-Drake Bays watershed are often used as calibration and validation datasets for hydrologic models.
- **Geospatial Datasets**: Spatial datasets describing the landscape of the Tomales-Drake Bays 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 seven stations.	Climate data boundary time series.
California Data Exchange Center (CDEC)	Precipitation, Temperature	--	Meteorological records available for two 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	1974 – Current	Observed Streamflow at five active locations.	Hydrology calibration.	LINK
Habitat	Local	CRWQCB	Pathogens in Tomales Bay Watershed TMDL: Staff Report.	2005	Report that documents staff report for stream conditions under the sediment TMDL.	Hydrology calibration & validation.	LINK
Water Budget	State	DWR	Well Completion Reports	Current	Well completion logs and reports.	Water budget.	LINK
			Interconnected Surface Water	2008	Two (2) rain CDEC stations within the watershed 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 Area Boundaries	2024	Public California drinking water systems and state small drinking water system boundaries and information.		LINK

Table 1-3. Inventory of geospatial datasets

Category	Scale	Data Source	Data Set	Data Date	Description	Model Use	Link
Watershed Boundaries	National	USGS	Watershed Boundaries (WBD)	2023	Hydrologic unit boundaries to the 12-digit (6th level).	Model segmentation	LINK
Hydrology	National	USGS	National Hydrography Dataset (NHD) Plus High-Resolution National Release 1	2023	The NHDPlus HR combines the NHD, 3DEP digital elevation models (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 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 Tomales-Drake Bays 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 13 GHCN gauges identified within or near the Tomales-Drake Bays watershed. These gauges all have data with varied quantity and quality. In addition to the daily precipitation gauges, NCDC also maintains the Local Climatological Data (LCD) network. There are three LCD stations within 10 miles of the Tomales-Drake Bays watershed. The California Data Exchange Center (CDEC) and Remote Automated Weather Stations (RAWS) networks also report hourly precipitation. CDEC reports at two locations and RAWS reports at seven locations within and near the watershed. Table 2-1 is an inventory of the precipitation stations near the Tomales-Drake Bays 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 Tomales-Drake Bays 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 - LCD	WBAN:93245	BODEGA 6 WSW, CA US	6/13/2008	11/25/2023	38.3208	-123.075	19.2	100%
	WBAN:00135	GNOSS FIELD AIRPORT, CA US	7/30/2014	Present	38.15	-122.55	1.2	100%
	WBAN:00320	PETALUMA MUNICIPAL AIRPORT, CA US	7/30/2014	Present	38.25	-122.6	27.1	100%
NOAA - GHCN	GHCND:USC00043578	GRATON, CA US	12/31/1925	Present	38.4305	-122.865	61	99%
	GHCND:USC00044500	KENTFIELD, CA US	12/31/1901	Present	37.9566	-122.545	44.2	97%
	GHCND:USC00046027	MUIR WOODS, CA US	11/30/1940	Present	37.8977	-122.569	67.1	94%
	GHCND:USC00046370	OCCIDENTAL, CA US	4/30/1943	4/5/2021	38.3858	-122.966	263.7	92%
	GHCND:USR0000CBAR	BARNABY CALIFORNIA, CA US	1/13/1997	Present	38.0281	-122.702	378	97%
	GHCND:USR0000CBIR	BIG ROCK CALIFORNIA, CA US	9/28/2003	Present	38.0394	-122.57	457.2	97%
	GHCND:US1CAMR0030	BOLINAS 0.2 W, CA US	11/10/2014	Present	37.90593	-122.701	57.9	98%
	GHCND:US1CASN0032	DUNCAN MILLS 1.4 NNE, CA US	1/31/2009	10/26/2010	38.47303	-123.052	124.7	96%
	GHCND:US1CAMR0018	FAIRFAX 0.6 SSE, CA US	1/23/2013	6/13/2017	37.98098	-122.591	44.5	98%
	GHCND:US1CASN0164	FORESTVILLE 1.4 SW, CA US	6/28/2020	Present	38.46563	-122.904	36.9	100%
	GHCND:US1CAMR0034	LAGUNITAS FOREST KNOLLS 0.4 S, CA US	10/30/2014	10/15/2015	38.00909	-122.688	- -	90%
	GHCND:US1CAMR0009	PETALUMA 10.1 W, CA US	3/14/2009	Present	38.24755	-122.812	36.3	99%

Agency	Station ID[1]	Name	Start Date	End Date	Lat.	Long.	Elevation (meters)	Data Coverage (%)[2]
	GHCND:US1CASN0079	ROHNERT PARK 0.9 ESE, CA US	3/30/2009	5/10/2016	38.34507	-122.681	38.1	92%
CDEC	PTR	POINT REYES	1/30/1989	10/19/2008	38.083	-122.95	24.4	--
	SFN	SAN FRANCISCO	8/8/2012	Present	37.77056	-122.427	45.7	--
RAWS	WDAC1	WOODACRE	2/20/2003	Present	37.99056	-122.645	427	--
	MDEC1	MIDDLE PEAK	3/25/2004	Present	37.92778	-122.587	713	--
	QSLC1	SRFD LLANO ROAD	5/2/2022	Present	38.37083	-122.764	29	--
	QSFC1	SRFD STATION 1	5/2/2022	Present	38.44028	-122.704	55	--
	OVYC1	OLEMA VALLEY	7/29/2004	Present	38.0425	-122.796	11	--
	TR110	CALFIRE PORTABLE 14	6/26/2001	Present	38.47908	-123.07	46	--
	NVHC1	NOVATO FIRE - ROBINHOOD	1/21/2016	Present	38.1125	-122.55	147	--

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

2. NCDC and NOAA data coverage as reported which is reflective of data availability between the reported start date and end date; CDEC and RAWS estimated based on data flagging and count of time steps, when possible. Data completeness will be further assessed under Task 3.2 and additional stations may be considered as required.

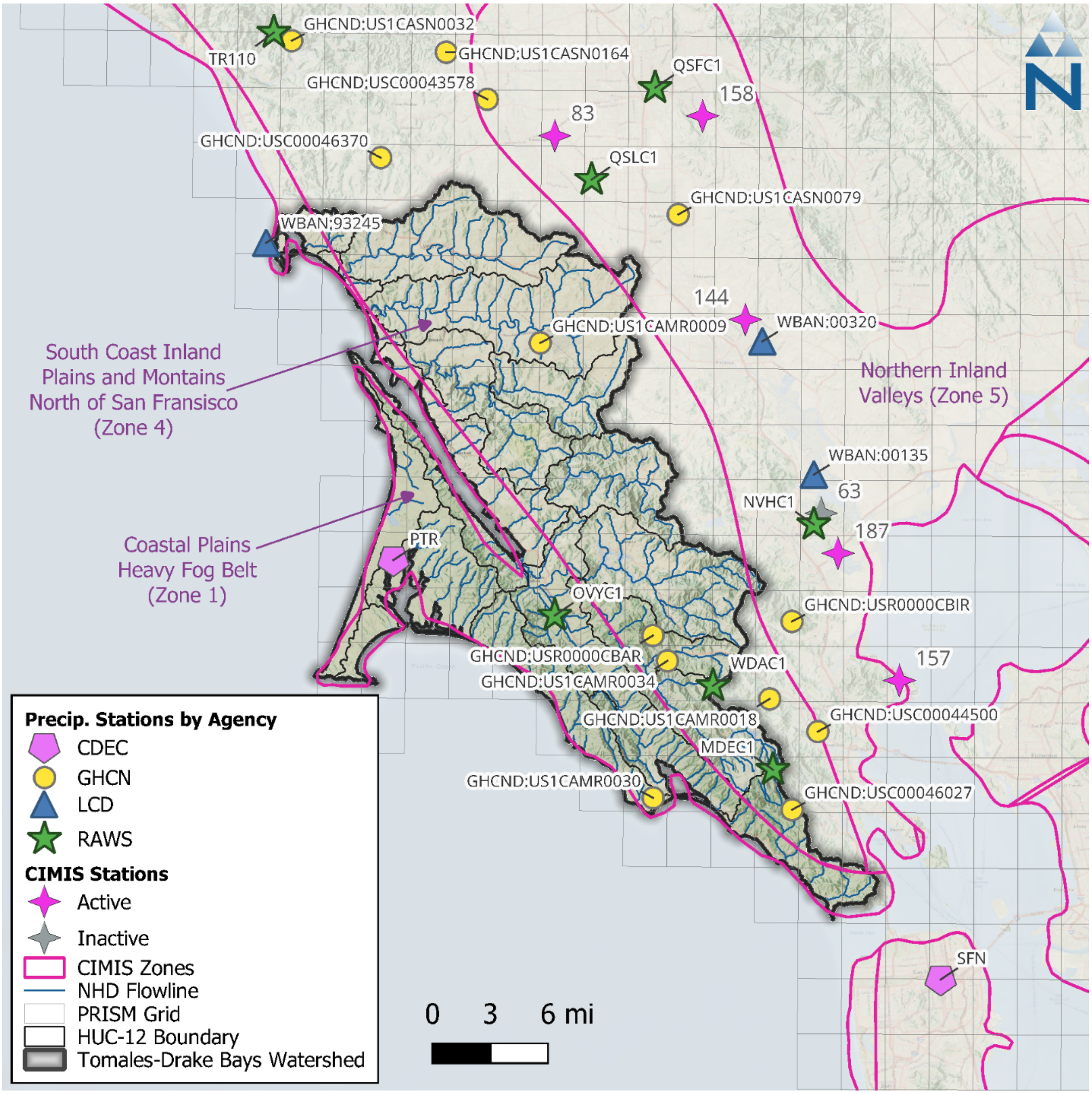

Figure 2-1 Identified rainfall gauges and CIMIS ET Zones near the Tomales-Drake Bays watershed.

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.

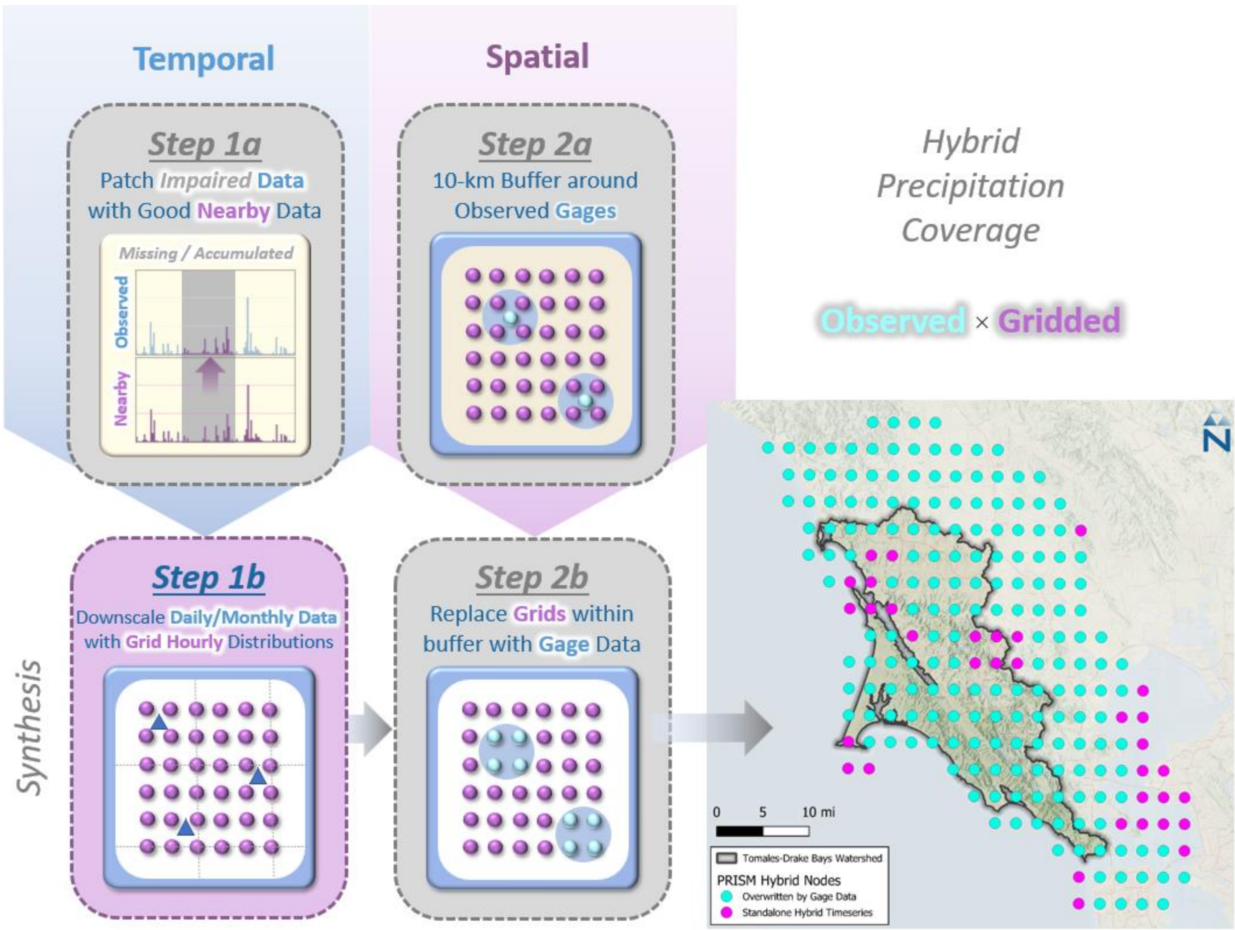

Figure 2-2. Hybrid approach to blend observed precipitation with gridded meteorological products.

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 six CIMIS stations near the Tomales-Drake Bays watershed: Novato (63), Santa Rosa (83), Petaluma (144), Point San Pedro (157), Bennett Valley (158), and Black Point (158). Novato is no longer operating, but its historical time series data covers the periods from July 1986 through January 2002. The remaining five stations are currently active and contain data from August 1990 through the present. As shown in Figure 2-1, the Tomales-Drake Bays watershed intersects three CIMIS zones with 61% of the watershed area in Zone 4 (South Coast Inland Plains and Mountains North of San Francisco), 36% of the watershed area in Zone 1 (Coastal Plains Heavy Fog Belt), and almost 1% of the watershed area in Zone 5 (Northern Inland Valleys). Most of the Tomales-Drake Bays watershed falls within Zone 4, the western, coastal edge of the watershed falls into Zone 1, and there are two small areas at the eastern edge of the watershed that fall into Zone 5. These zones experience average annual reference evapotranspiration levels of 33.0 inches per year in Zone 1, 43.9 inches per year in Zone 5, and 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 Tomales-Drake Bays watershed from daily data from CIMIS Spatial and downscaling the hourly time series using hourly distributions from land observation stations (e.g., RAWS, NCDC) or hourly distributions from NLDAS. Potential evapotranspiration is reported at 3-hour intervals; however, the hourly distributions of solar radiation from NLDAS, which have sinusoidal patterns over daylight hours, provide a sound basis for downscaling the daily CIMIS depths while maintaining the overall annual water budget reflected in CIMIS.

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

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

3 SURFACE HYDROLOGY

3.1 Watershed Segmentation

The United States Geological Survey (USGS) delineates watersheds nationwide based on surface hydrological features and organizes the drainage units into a nested hierarchy using hydrologic unit codes (HUC). These HUCs have a varying number of digits to denote scale ranging from 2-digit HUCs (largest) at the region scale to 12-digit HUCs (smallest) at the subwatershed scale. The Tomales-Drake Bays watershed is defined by a HUC-8 watershed that comprises 19 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 471 catchments ranging in size between 0.2 acres to approximately 3189 acres, almost 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 Tomales-Drake Bays watershed (HUC-8).

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 Tomales-Drake Bays HUC-8

HUC-12 Name	Count	Catchment Size (acres)			
		Minimum	Mean	Median	Maximum
Kent Lake	40	0.7	345.8	121.0	2,157.6
Nicasio Creek	38	2.7	620.4	589.4	1,679.5
San Geronimo Creek	14	115.7	980.9	711.3	2,353.8
Olema Creek	34	6.7	508.3	419.6	2,242.6
Arroyo Sausal	25	8.0	629.5	417.2	2,776.2
Chileno Creek	16	45.4	812.9	485.7	3,100.3
Walker Creek	21	1.8	911.6	753.2	3,034.5
Bodega Harbor	8	22.5	467.2	341.5	1,200.5
Estero Americano	26	5.6	931.6	595.3	3,110.1
Estero De San Antonio	41	4.7	805.0	680.1	3,037.5
Tomales Bay	37	1.7	657.7	458.8	3,189.2
Bodega Bay	8	0.6	361.6	461.7	838.4
Abbotts Lagoon	13	0.4	732.4	495.5	2,510.8
Drakes Estero	43	0.2	374.9	236.8	2,072.3
Drakes Bay	2	440.7	1,570.9	1,570.9	2,701.0
Coast Creek	41	0.2	375.4	311.1	1,428.8
Bolinas Lagoon	31	0.7	355.1	232.4	1,112.6
Bolinas Bay	1	278.6	278.6	278.6	278.6
Redwood Creek	32	3.8	398.5	350.4	1,083.7

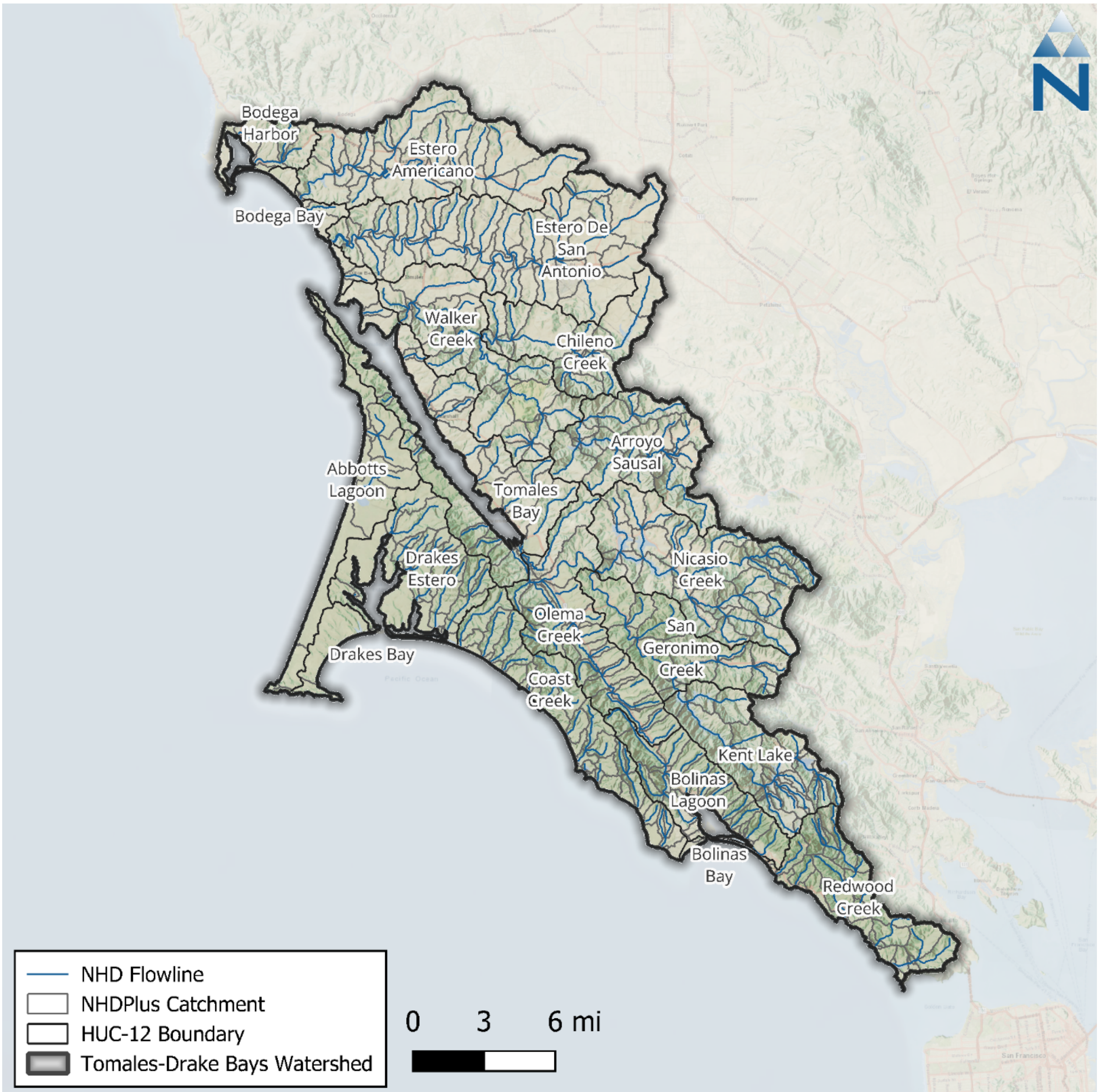

Figure 3-1. Initial catchment segmentation for the Tomales-Drake Bays watershed.

3.2 Streams and Channels

The hydrographic characteristics of the streams and rivers within the Tomales-Drake Bays 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.

3.3 Streamflow

The primary source of streamflow data is from the USGS, which includes five currently active long-term gauges: Walker Creek near Marshall, CA (USGS 11460750), Lagunitas Creek near Point Reyes Station, CA (USGS 11460600), Lagunitas Creek at Samuel P. Taylor State Park, CA (USGS 11460400), Olema Creek at Vedanta Bridge at Olema, CA (USGS 11460605) and Redwood Creek at Hwy 1 Bridge at Muir Beach, CA (USGS 11460151). There is also one historical gauge within the watershed, with data ranging from February 1999 to February 2001. Table 3-2 presents a summary of the available USGS streamflow data. Figure 3-2 shows the locations of the six USGS gauges near the Tomales-Drake Bays 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?
WALKER C NR MARSHALL CA	11460750	31.1	10/01/1983	Present	Yes
OLEMA C A VEDANTA BRIDGE A OLEMA CA	11460605	11.1	10/01/2017	Present	Yes
LAGUNITAS C NR PT REYES STATION CA	11460600	81.7	10/01/1974	Present	Yes
LAGUNITAS C A SAMUEL P TAYLOR STATE PARK CA	11460400	34.3	12/21/1982	Present	Yes
REDWOOD C A HWY 1 BRIDGE A MUIR BEACH CA	11460151	7.1	10/01/2014	Present	Yes
UNNAMED TRIB 1 TO UPPER ABBOTTS LAGOON PT REYES*	380738122560701	--	02/06/1999	02/22/2001	No

*Lake site

Two HUC-10 regions, the Tomales Bay-Bodega Bay and Drakes Bay-Frontal Pacific Ocean HUC-10 regions shown in Figure 3-2, do not contain active streamflow gauges that are available for model calibration. The Drakes Bay-Frontal Pacific Ocean region is also a coastal drainage with no single, well-defined stream to evaluate the upstream drainage area. Instead, this region comprises smaller, coastal drainages that drain to the Pacific Ocean in parallel and are often only as large as one or two NHDPlus catchments. Streamflow for any pour-point in the model could be estimated by scaling one of the existing streamflow gauges using a ratio of drainage areas to assess model performance. The characteristics of each gauged basin (e.g., slope, soils, precipitation, etc.) should be evaluated to determine the most representative gauged location to use for this estimate.

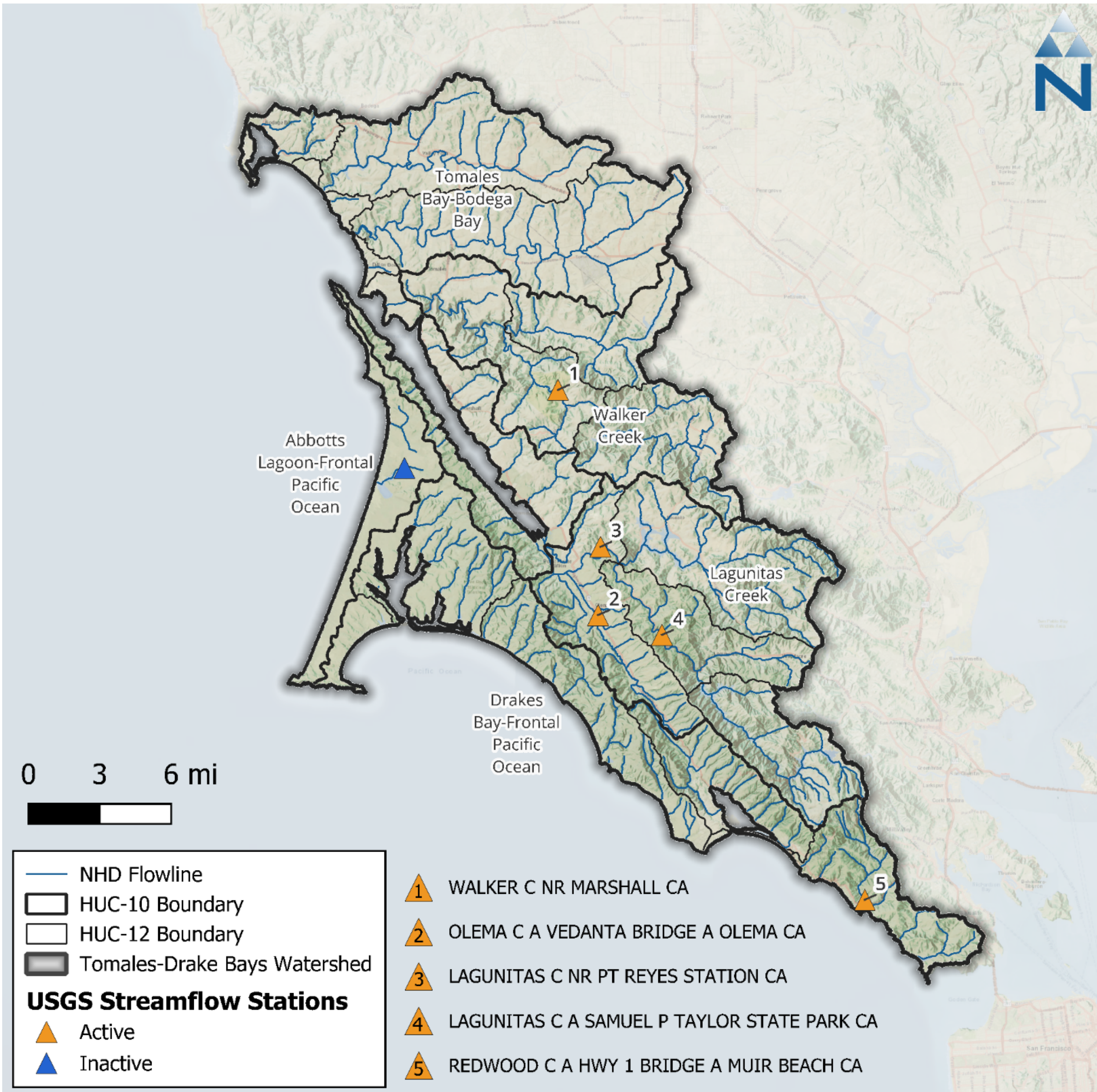

Figure 3-2. USGS streamflow stations in the Tomales-Drake Bays watershed.

3.4 Dams, Reservoirs, and Impoundments

The Tomales-Drake Bays watershed contains several large reservoirs that will require varying levels of representation within the hydrology model. The largest waterbodies are listed in Table 3-3; the dams and waterbodies are shown in Figure 3-3. Capturing the operation of these features will be important to accurately represent the movement of water throughout the watershed. For example, Nicasio Reservoir impounds Nicasio Creek and its tributary, Halleck Creek. Outflow from the lake controls the flow of Nicasio Creek, which is a major tributary of the Lagunitas Creek, below the dam. Having stage-storage relationships for reservoirs and any other outflow rates or operating conditions will allow for a more accurate model representation.

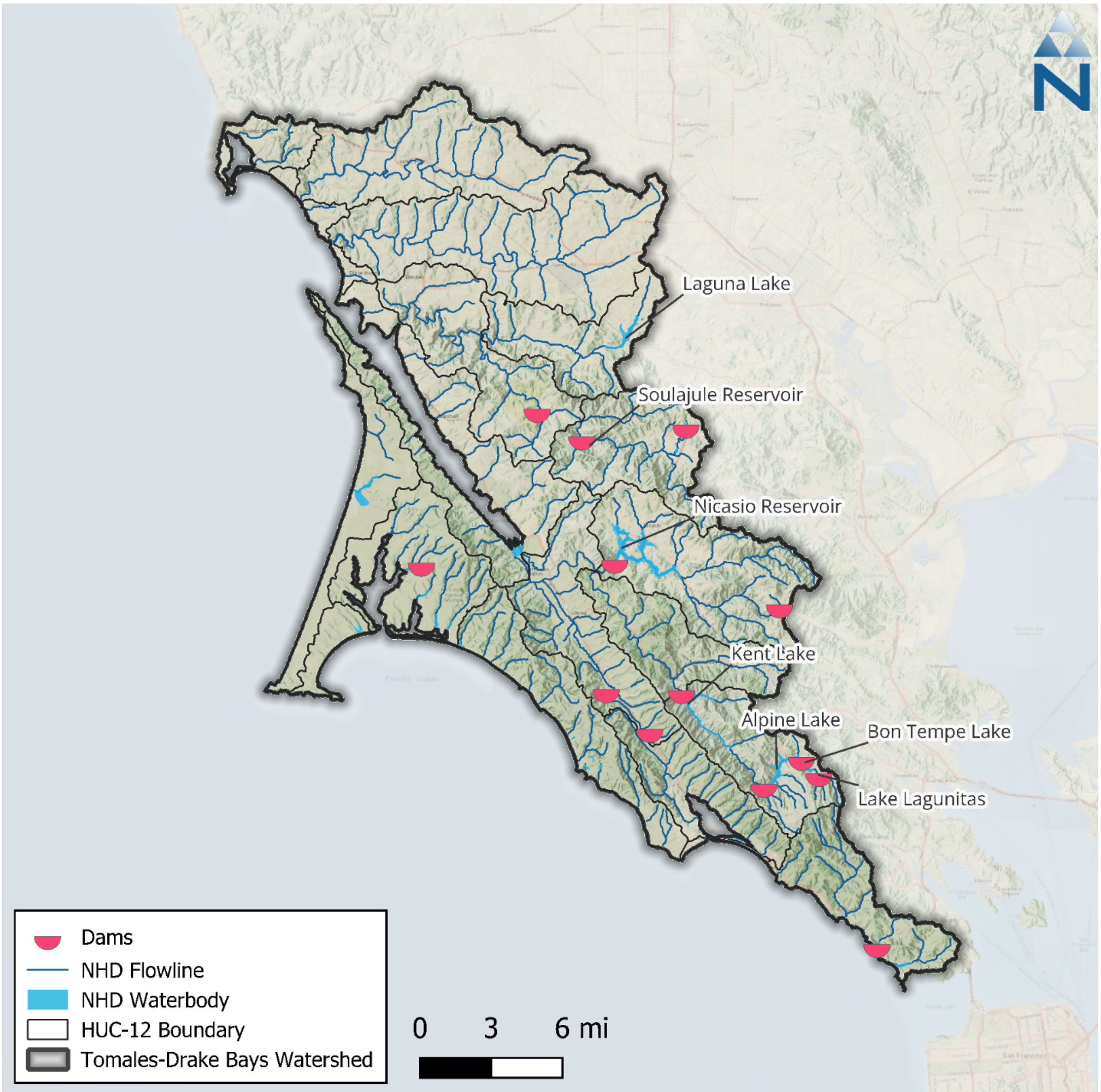

Figure 3-3. Dams, reservoirs, and impoundments in the Tomales-Drake Bays watershed

Table 3-3. Large waterbodies in the Tomales-Drake Bays watershed

Waterbody	Area (ac)	Average Elevation (m)
Nicasio Reservoir	828.6	51.5
Kent Lake	283.2	122.7
Alpine Lake	246.3	195.9
Laguna Lake	229.2	65.0
Bon Tempe Lake	120.3	217.3
Soulajule Reservoir	48.7	102.0
Lake Lagunitas	22.0	240.3

3.5 Surface Water Withdrawals

Datasets related to water rights, points of diversion, and surface withdrawals (i.e., wells and irrigation) were identified through searches of the Water Board's Electronic Water Rights Information Management System database (eWRIMS) and the DWR Agricultural Land and Water Use Estimates database (ALWU). These datasets can be used to 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 Tomales-Drake Bays 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 3-4 provides an overview of both water systems and points of diversion in the watershed. Water systems distributed throughout the watershed include a mixture of both surface water diversions from Tomales-Drake Bays and its primary tributaries, as well as groundwater withdrawals for the Tomales-Drake Bays watershed groundwater basin. There are 55 drinking water systems in the watershed. For 45 out of the 55 drinking water systems, the water source is listed as groundwater, nine have surface water listed as the source, and the remaining system does not have a known source type.

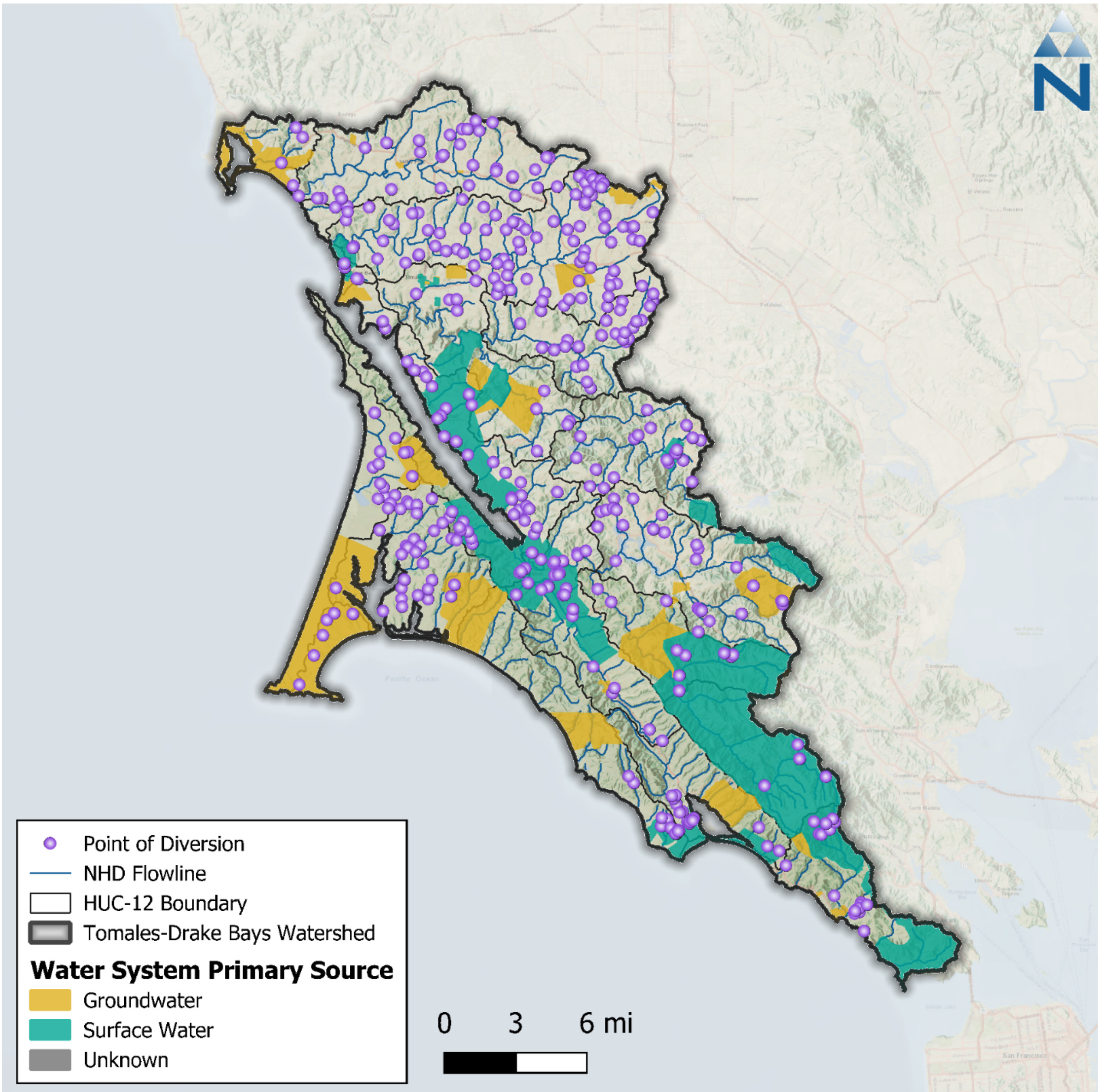

Figure 3-4. Primary Water System Sources in the Tomales-Drake Bays watershed.

4 SUBSURFACE HYDROLOGY

The Tomales-Drake Bays watershed overlaps with several groundwater basins as delineated by Bulletin 118 (DWR 2020). These groundwater basins primarily include the Sand Point Area (number 2-027) and the Bodega Bay Area (number 1-057). Very small portions of Wilson Grove Formation Highlands (number 1-059) and Santa Rosa Valley – Santa Rosa Plain subbasin (number 1-055.01) overlap with the Tomales-Drake Bays watershed. Approximately 10% of the watershed area falls within the groundwater basins delineated by Bulletin 118 and the remaining 90% is within the Franciscan Complex bedrock.

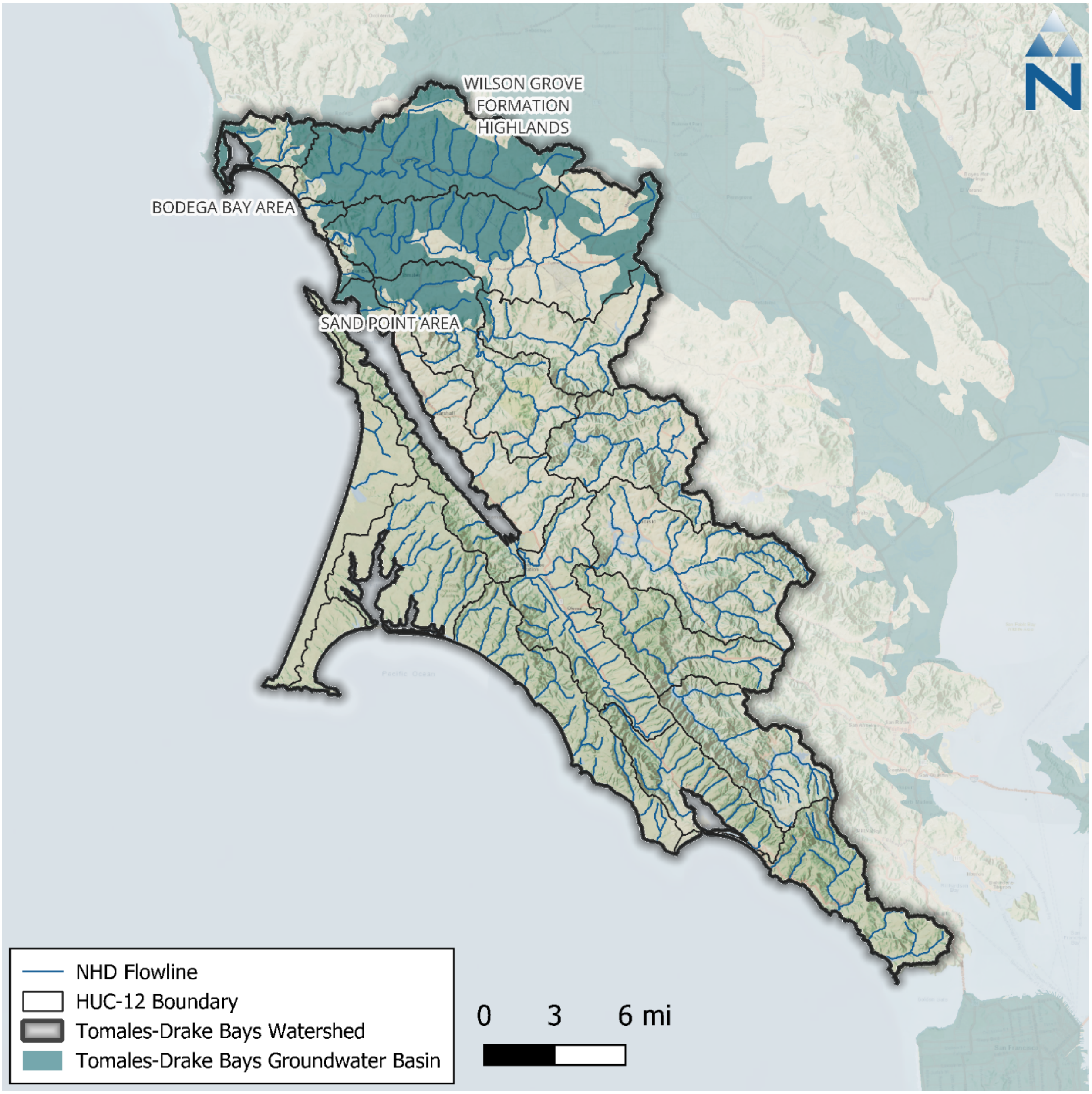

Figure 4-1. Groundwater basins delineated by DWR (2020), also known as Bulletin 118.

As per the respective basin priority details (Sustainable Groundwater Management Act (SGMA) Basin Prioritization Dashboard), the Sand Point Area, Bodega Bay Area, and Wilson Grove Formation Highlands basins are Very Low priority basins as designated by SGMA's basin prioritization. The Santa Rosa Valley – Santa Rosa Plain is a Medium priority basin. Although the Sand Point Area has a high density of public supply wells, and the Bodega Bay Area has a high density of public supply wells and relies on groundwater for 100% of its supply, the basins are prioritized at Very Low priority due to a groundwater use of less than 9,500 acre-feet per year. These basins have no documented impacts to groundwater supplies, such as declining groundwater levels, saline intrusion or subsidence. A very slight portion of the Santa Rosa Plain Groundwater Sustainability Agency (GSA) overlaps the Tomales-Drake Bays watershed.

4.1 Water Budget Components

No publicly available groundwater models were located focusing on the Tomales-Drake Bays watershed. A very small portion of the Santa Rosa Plain model overlaps the edge of the basin to the east. The Bulletin 118 reports for the Sand Point Area basin noted that no groundwater budget estimates were available, but the Bodega Bay Area was estimated to use between 384 and 439 acre-feet/year, as estimated in 1999. None of the US Geological Survey public domain models for Northern California (USGS 2024) overlap the Tomales-Drake Bays watershed.

4.2 Geology

The foregoing references provide coverage primarily within the groundwater basins delineated as per Bulletin 118. The Bodega Bay Area basin consists principally of Quaternary alluvium, sand dunes and terrace deposits. The Sand Point Area basin consists of beach sand and dune sand deposits. Outside the delineated basins, 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, 1991). 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.

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 Tomales-Drake Bays watershed.

5.1 Elevation & Slope

The USGS publishes DEMs expressing landscape elevation through a raster grid data product with 30-meter resolution. The Tomales-Drake Bays watershed ranges in elevation from sea level along the coastline and riverbed to over 760 meters in its southern region. 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 elevation across the Tomales-Drake Bays watershed.

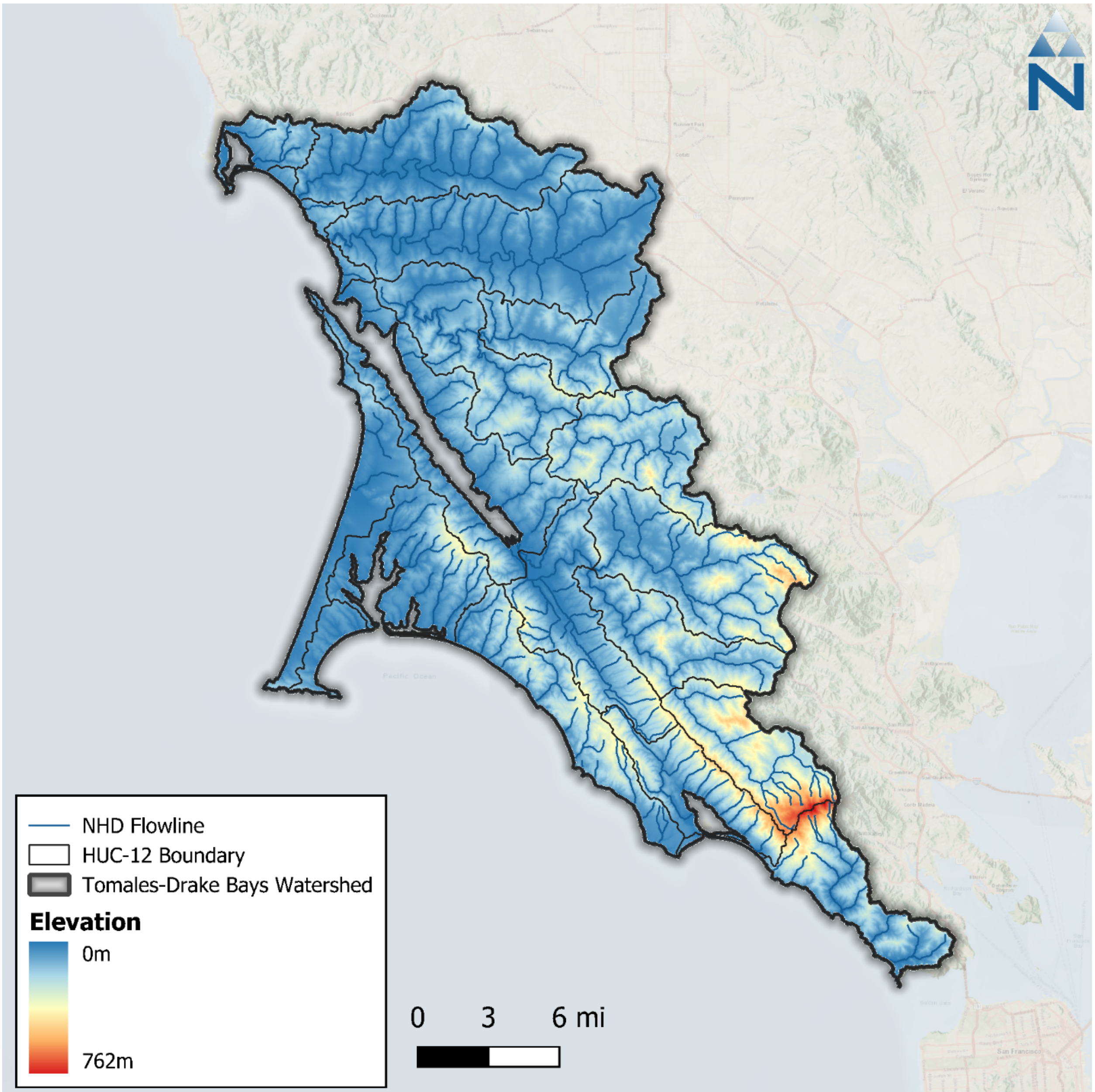

Figure 5-1. Digital elevation model of the Tomales-Drake Bays watershed.

5.2 Soils & Geology

Soils data for the Tomales-Drake Bays 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 Tomales-Drake Bays watershed. The dominant soil group in the watershed is Group D (33%), characterized by soils with the lowest infiltration rates, such as clay loam, silty clay loam, sandy and silty clay, and clay. Group B comprises 32% of the watershed and consists of moderately well to well-drained silt loams and loams. Group C accounts for 23% of the watershed and contains sandy clay loam, which also has relatively low infiltration rates. Group A, consisting of well-draining sand, loamy sand, and sandy loam, represents nearly 3% of the watershed. Additionally, around 5% of the watershed consists of areas with mixed soils. For modeling purposes, mixed soils will be grouped with the nearest primary group as follows: A/D → B, and C/D → D. Finally, approximately 5% 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 Tomales-Drake Bays watershed

Hydrologic Soil Group	Area (acres)	Percent Area
A	7,539.21	2.76%
A/D	1,710.32	0.63%
B	86,220.09	31.53%
C	63,551.76	23.24%
C/D	12,625.84	4.62%
D	89,242.00	32.64%
N/A	12,556.49	4.59%
Total	**273,445.71**	**100.0%**

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

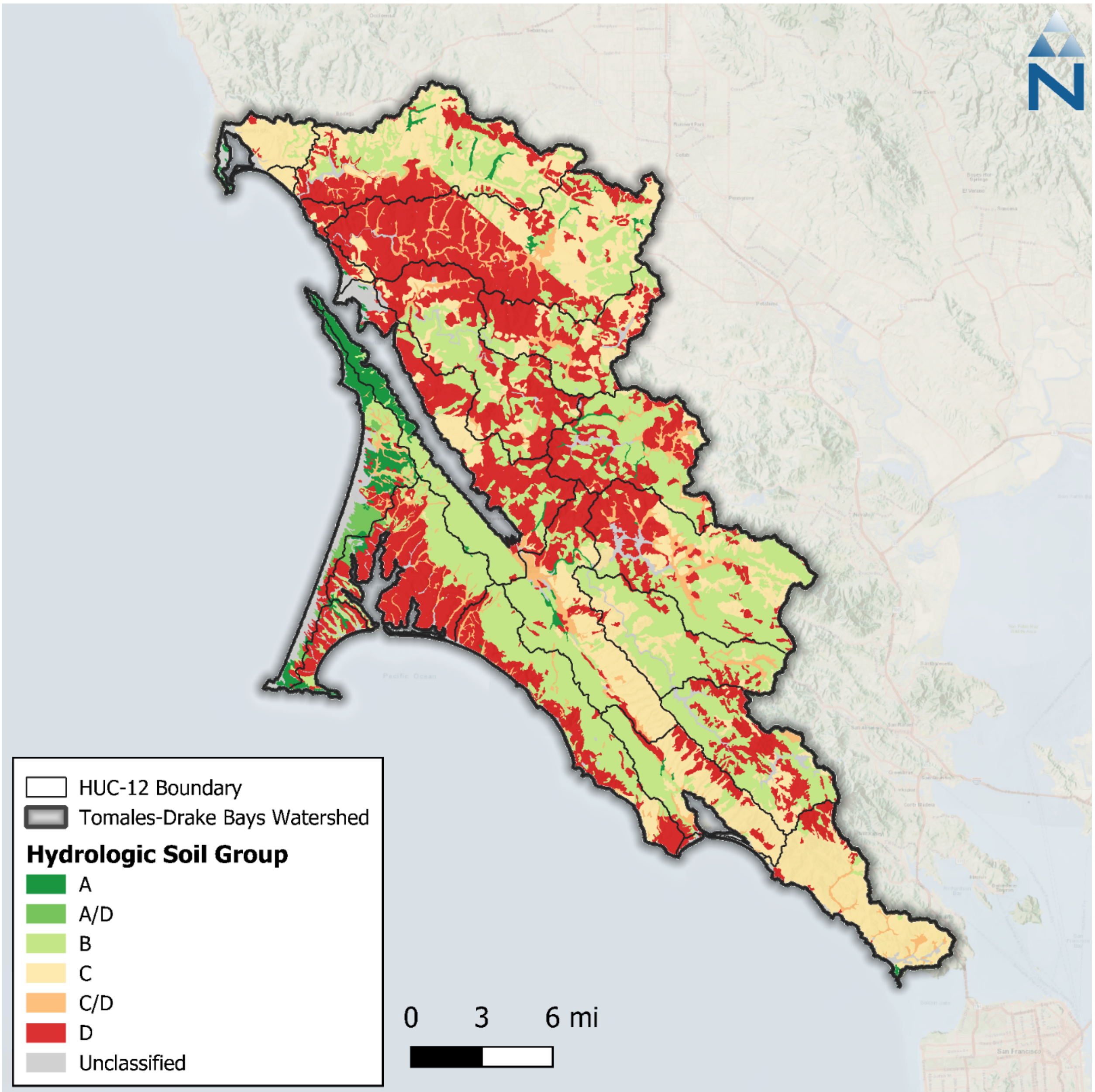

Figure 5-2. SSURGO hydrologic soil groups within the Tomales-Drake Bays watershed.

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 Tomales-Drake Bays watershed and Figure 5-3 shows the spatial distribution of these classifications. Shrub/Scrub is the dominant land cover classification covering approximately 39% 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 0.04% 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 Tomales-Drake Bays watershed

NLCD Class	Classification Description	Area (acres)	Percent
11	Open Water	2,853.24	1.04%
21	Developed, Open Space[1]	7,550.83	2.76%
22	Developed, Low Intensity[1]	2,591.51	0.95%
23	Developed, Medium Intensity[1]	1,032.91	0.38%
24	Developed, High Intensity[1]	191.91	0.07%
31	Barren Land (Rock/Sand/Clay)	184.79	0.07%
41	Deciduous Forest	3,846.13	1.41%
42	Evergreen Forest	55,435.52	20.26%
43	Mixed Forest	18,992.93	6.94%
52	Shrub/Scrub	105,886.16	38.69%
71	Grassland/Herbaceous	64,364.39	23.52%
81	Pasture/Hay	2,303.76	0.84%
82	Cultivated Crops	116.97	0.04%
90	Woody Wetlands	2,293.76	0.84%
95	Emergent Herbaceous Wetlands	6,029.81	2.20%
TOTAL*		**273,674.61**	**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 15 acres more than the model domain.

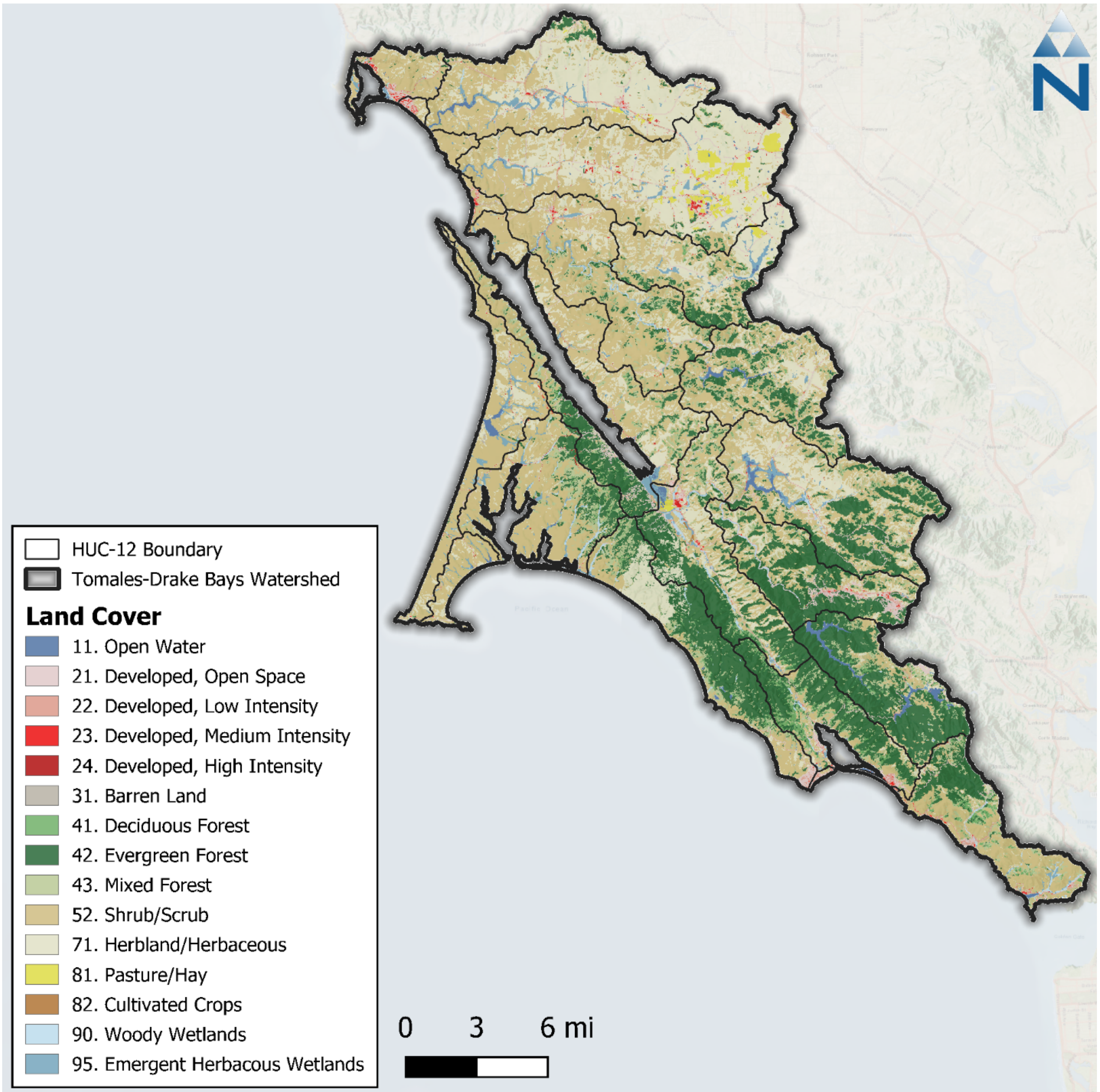

Figure 5-3. NLCD 2021 land cover within the Tomales-Drake Bays watershed.

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 Tomales-Drake Bays watershed using this dataset shows that just over 4% 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 Tomales-Drake Bays 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 Tomales-Drake Bays watershed, an average of 26% 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 Tomales-Drake Bays watershed (see Section 5.3) was analyzed to identify predominant cropland vegetation classes. This analysis revealed that less than 1% of the Tomales-Drake Bays watershed area is classified as Pasture/Hay (class 81) and 62% 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.

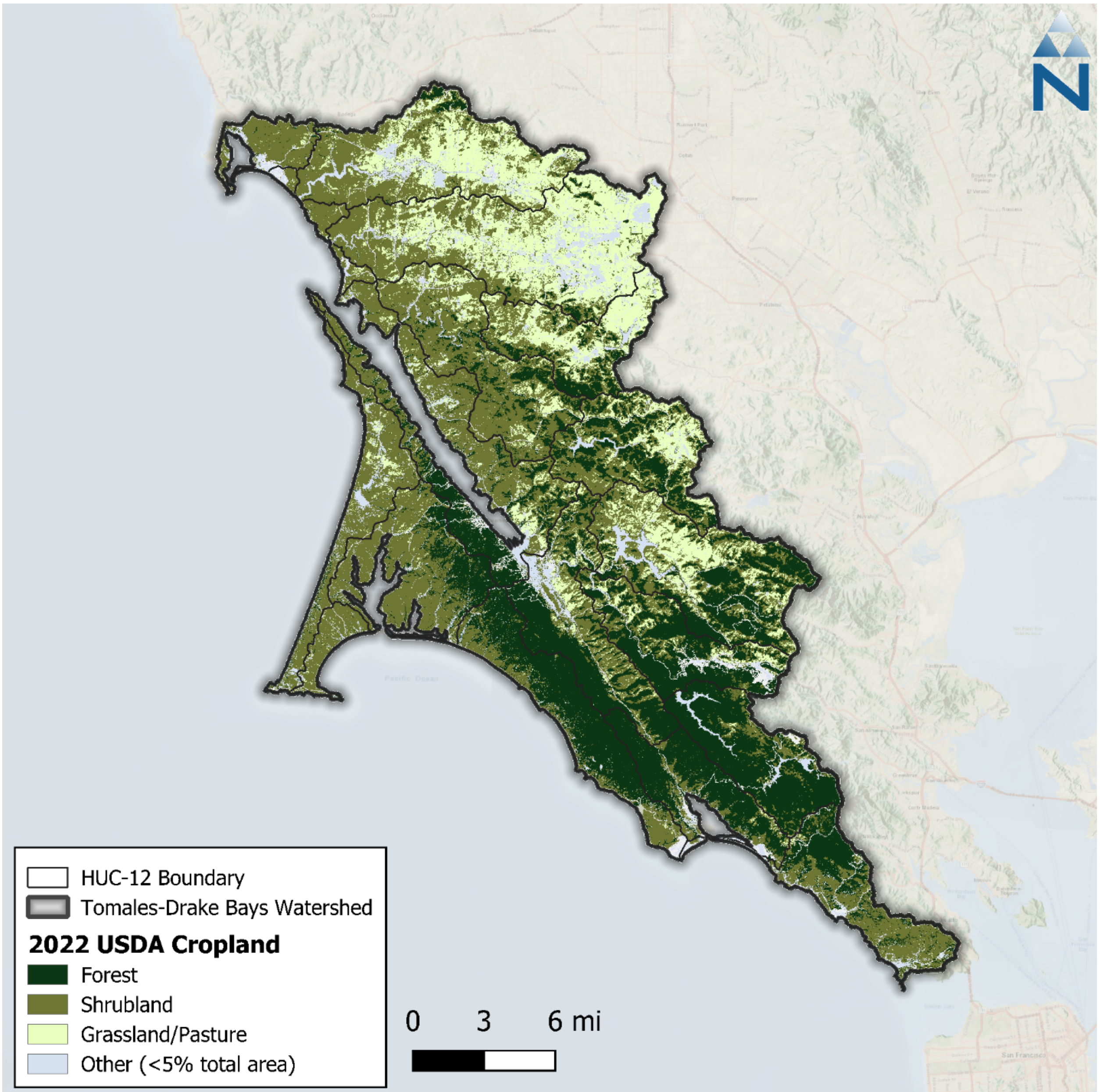

Figure 5-4 USDA 2022 Cropland Data within the Tomales-Drake Bays watershed.

Table 5-4 USDA 2022 Cropland Data summary within the Tomales-Drake Bays watershed

Crop Type	Area (ac)	Area (%)
Forest	78,258.8	28.70%
Shrubland	118,648.5	43.52%
Grassland/Pasture	49,085.9	18.00%
Other (<5% Total Area)	26,640.7	9.77%
Totals	**272,633.9**	**100.00%**

6 DATA GAPS AND LIMITATIONS

Based on a 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 operates five active gauges in the watersheds with daily streamflow records, including coverage of Walker Creek, Olema Creek, Redwood Creek, and Lagunitas Creek. The calibration would need to be extrapolated outside of these tributaries to other waterbodies of interest unless other gauge data is available.

The Tomales-Drake Bays watershed contains several reservoirs that may significantly alter the watershed's natural flow regime. Accurately modeling reservoir operations requires detailed data on reservoir management practices, such as release schedules, storage capacity, and operational rules, which may not always be available. Furthermore, datasets such as stage-volume relationships and lake bathymetry, spillway characteristics, and detailed flow release rates are essential for a realistic representation of such reservoirs in the model. The lack of robust datasets to support these details could complicate the calibration and validation process for the model.

No groundwater model is available for the Tomales-Drake Bays basin, and no AEM flight lines were flown across it. The California state database of well logs does not include any locations within the basin, but the California state database of groundwater levels includes six locations within the entire basin.

Another potential limitation is the availability, quality, and temporal resolution of data for surface water diversions within the watershed. The eWRIMS database identifies major surface water diversions that are likely to have data to integrate into the model; however, other surface water diversions 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 hydrology analyses within the South Fork Eel River and Shasta River watersheds.

LSPC is a modernized version of the HSPF platform that is now organized around a Microsoft Access relational database; otherwise, the LSPC model is functionally identical to the HSPF model. The relational database provides efficient data management, model maintenance, and development of alternative scenarios. The LSPC model runs using hourly input boundary conditions and can be sufficiently configured using the meteorological datasets discussed in Section 2. LSPC also has a feature that can vary land use over time when needed to explicitly represent dynamic processes such as timber harvests and wildfires—that feature needs supporting spatial and temporal data to represent dynamic land use changes. Additionally, LSPC was the selected modeling platform for other Water Board studies, including the South Fork Eel River, Shasta River, Navarro River, and several others that were under development at the time of writing this work plan. 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 LCD, 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 $-\infty$ 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 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 Tomales-Drake Bays 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 Tomales-Drake Bays 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 Tomales-Drake Bays 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	Ten (10) 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	Eight (8) 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.

10 REFERENCES

Allen, R. G., Walter, I. A., Elliott, R., Howell, T., Itenfisu, D., & Jensen, M. 2005. The ASCE Standardized Reference Evapotranspiration Equation.

Barnwell, T. O., & Johanson, R. 1981. HSPF: A comprehensive package for simulation of watershed hydrology and water quality.

Behnke, R., Vavrus, S., Allstadt, A., Albright, T., Thogmartin, W. E., & Radeloff, V. C. 2016. Evaluation of downscaled, gridded climate data for the conterminous United States. Ecological Applications, 26(5), 1338–1351. https://doi.org/10.1002/15-1061

CA Mines (California Division of Mines and Geology). 1982. Geologic Map of the Santa Rosa Quadrangle, California,1:250,000.

CA Mines (California Division of Mines and Geology). 1991. Regional Geologic Map Series, San Francisco Quadrangle.

City of San Diego and Caltrans. 2016. Mission Bay Watershed Management Area Water Quality Improvement Plan. Submitted to the San Diego Regional Water Quality Control Board by the City of San Diego and Caltrans. San Diego, CA.

City of Vista. 2008. Agua Hedionda Watershed Management Plan – Final. Prepared by Tetra Tech for the City of Vista, CA.

Cosgrove, B. A., Lohmann, D., Mitchell, K. E., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Marshall, C., Sheffield, J., Duan, Q., Luo, L., Higgins, R. W., Pinker, R. T., Tarpley, J. D., & Meng, J. 2003. Real-time and retrospective forcing in the North American Land Data Assimilation System (NLDAS) project. Journal of Geophysical Research: Atmospheres, 108(22), 8842. https://doi.org/10.1029/2002jd003118

CVRWQCB (Central Valley Regional Water Quality Control Board). 2006. Amendment to the Water Quality Control Plan for the Sacramento River and San Joaquin River Basins for The Control of Nutrients in Clear Lake. California Water Quality Control Board, Central Valley Region. Rancho Cordova, CA.

Daly, C., Halbleib, M., Smith, J. I., Gibson, W. P., Doggett, M. K., Taylor, G. H., Curtis, J., & Pasteris, P. P. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology, 28(15), 2031–2064. https://doi.org/10.1002/joc.1688

Daly, C., Neilson, R. P., & Phillips, D. L. 1994. A Statistical-Topographic Model for Mapping Climatological Precipitation over Mountainous Terrain. Journal of Applied Meteorology, 33(2), 140–158. https://doi.org/10.1175/1520-0450(1994)033<0140:ASTMFM>2.0.CO;2

Duda, P. B., Hummel, P. R., Donigian Jr., A. S., & Imhoff, J. C. 2012. BASINS/HSPF: Model Use, Calibration, and Validation. Transactions of the ASABE, 55(4), 1523–1547. https://doi.org/10.13031/2013.42261

DWR (California Department of Water Resources). 2019. Statewide Crop Mapping - Datasets - California Natural Resources Agency Open Data. https://data.cnra.ca.gov/dataset/statewide-crop-mapping

DWR (California Department of Water Resources). 2020. California's Groundwater Basin Boundary Descriptions. https://data.cnra.ca.gov/dataset/ca-gw-basin-boundary-descriptions

DWR (California Department of Water Resources), 2024. "California Irrigation Management Information System (CIMIS)." https://cimis.water.ca.gov/SpatialData.aspx (April 1, 2024).

Farhad Ghodrati, & Rebecca Tuden. 2005. Pathogens in Tomales Bay Watershed TMDL. https://www.waterboards.ca.gov/sanfranciscobay/water_issues/programs/TMDLs/tomalespathogens/12-21-05finalstaffreport.pdf

Gibson, W. P., Daly, C., Kittel, T., Nychka, D., Johns, C., Rosenbloom, N., McNab, A., & Taylor, G. (2002). Development of a 103-year high-resolution climate data set for the conterminous United States.

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. 2009. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of Hydrology, 377(1–2), 80–91. https://doi.org/10.1016/j.jhydrol.2009.08.003

Housman, I., K. Schleeweis, J. Heyer, B. Ruefenacht, S. Bender, K. Megown, W. Goetz, & S. Bogle, 2023. National Land Cover Database Tree Canopy Cover Methods. Salt Lake City, Utah. https://data.fs.usda.gov/geodata/rastergateway/treecanopycover/docs/TCC_v2021-4_Methods.pdf.

Knoben, W. J. M., Freer, J. E., & Woods, R. A. 2019. Technical note: Inherent benchmark or not? Comparing Nash–Sutcliffe and Kling–Gupta efficiency scores. Hydrology and Earth System Sciences, 23(10), 4323–4331. https://doi.org/10.5194/hess-23-4323-2019

Kouchi, D.H., K. Esmaili, A. Faridhosseini, S.H. Sanaeinejad, D. Khalili, and K.C. Abbaspour, 2017. Sensitivity of Calibrated Parameters and Water Resource Estimates on Different Objective Functions and Optimization Algorithms. Water, 9. https://doi.org/10.3390/w9060384

LACFCD (Los Angeles County Flood Control District). 2020. WMMS Phase I Report: Baseline Hydrology and Water Quality Model. Prepared for the Los Angeles County Flood Control District by Paradigm Environmental. Alhambra, CA.

Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. 2017. Documentation for the MODFLOW 6 Groundwater Flow Model. U.S. Geological Survey Techniques and Methods, Book 6, Chap. A55, 197 p.

LARWQCB (Los Angeles Regional Water Quality Control Board). 2010. Los Angeles River Watershed Bacteria Total Maximum Daily Load. California Regional Water Quality Control Board, Los Angeles Region. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board). 2012. Reconsideration of Certain Technical Matters of the Malibu Creek and Lagoon Bacteria TMDL. California Regional Water Quality Control Board, Los Angeles Region. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board). 2013a. Reconsideration of Certain Technical Matters of the Santa Monica Bay Beaches Bacteria TMDLs; Marina del Rey Harbor Mothers' Beach and Back Basins TMDL; and the Los Angeles Harbor Inner Cabrillo Beach and Main Ship Channel Bacteria TMDL. California Regional Water Quality Control Board, Los Angeles Region. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board). 2013b. Reconsideration of Certain Technical Matters of the TMDL for Bacteria Indicator Densities in Ballona Creek, Ballona Estuary, and Sepulveda Channel. California Regional Water Quality Control Board, Los Angeles Region. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board). 2015. Total Maximum Daily Loads for Indicator Bacteria in San Gabriel River, Estuary and Tributaries. California Regional Water Quality Control Board, Los Angeles Region. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board) and USEPA (U.S. Environmental Protection Agency). 2005a. Total Maximum Daily Load for Metals in Ballona Creek. California Regional Water Quality Control Board, Los Angeles Region, and U.S. Environmental Protection Agency Region 9. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board) and USEPA (U.S. Environmental Protection Agency). 2005b. Total Maximum Daily Load for Metals in Ballona Creek. California Regional Water Quality Control Board, Los Angeles Region, and U.S. Environmental Protection Agency Region 9. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board) and USEPA (U.S. Environmental Protection Agency). 2006a. Total Maximum Daily Loads for Metals and Selenium, San Gabriel River and Tributaries. California Regional Water Quality Control Board, Los Angeles Region, and U.S. Environmental Protection Agency, Region 9. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board) and USEPA (U.S. Environmental Protection Agency). 2006b. Total Maximum Daily Loads for Metals and Selenium, San Gabriel River and Tributaries. California Regional Water Quality Control Board, Los Angeles Region, and U.S. Environmental Protection Agency, Region 9. Los Angeles, CA.

LARWQCB (Los Angeles Regional Water Quality Control Board) and USEPA (U.S. Environmental Protection Agency). 2011. Dominguez Channel and Greater Los Angeles and Long Beach Harbor Waters Toxics Total Maximum Daily Loads. California Regional Water Quality Control Board, Los Angeles Region, and U.S. Environmental Protection Agency Region 9. Los Angeles, CA.

Los Peñasquitos Responsible Agencies. 2015. Los Peñasquitos Watershed Management Area Water Quality Improvement Plan and Comprehensive Load Reduction Plan. Submitted to the San Diego Regional Water Quality Control Board by the City of San Diego, County of San Diego, City of Del Mar, Caltrans, and City of Poway. San Diego, CA.

LRWQCB (Lahontan Regional Water Quality Control Board) and NDEP (Nevada Division of Environmental Protection). 2010. Lake Tahoe Total Maximum Daily Load Technical Report. California Regional Water Quality Control Board, Lahontan Region. South Lake Tahoe, CA.

Markstrom, S. L., Regan, R. S., Hay, L. E., Viger, R. J., Webb, R. M., Payn, R. A., & LaFontaine, J. H. (2015). PRMS-IV, the precipitation-runoff modeling system, version 4.

Melton, F. S., Huntington, J., Grimm, R., Herring, J., Hall, M., Rollison, D., Erickson, T., Allen, R., Anderson, M., Fisher, J. B., Kilic, A., Senay, G. B., Volk, J., Hain, C., Johnson, L., Ruhoff, A., Blankenau, P., Bromley, M., Carrara, W., … Anderson, R. G. (2022). OpenET: Filling a Critical Data Gap in Water Management for the Western United States. JAWRA Journal of the American Water Resources Association, 58(6), 971–994. https://doi.org/10.1111/1752-1688.12956

Mitchell, K. E., Lohmann, D., Houser, P. R., Wood, E. F., Schaake, J. C., Robock, A., Cosgrove, B. A., Sheffield, J., Duan, Q., Luo, L., Higgins, R. W., Pinker, R. T., Tarpley, J. D., Lettenmaier, D. P., Marshall, C. H., Entin, J. K., Pan, M., Shi, W., Koren, V., … Bailey, A. A. (2004). The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system. Journal of Geophysical Research: Atmospheres, 109(7). https://doi.org/10.1029/2003jd003823

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE, 50(3), 885–900. https://doi.org/10.13031/2013.23153

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. 2015. Hydrologic and water quality models: Performance measures and evaluation criteria. Transactions of the ASABE, 58(6), 1763–1785. https://doi.org/10.13031/trans.58.10715

Nash, J. E., & Sutcliffe, J. V. 1970. River flow forecasting through conceptual models part I - A discussion of principles. Journal of Hydrology, 10(3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. 2011. Soil and Water Assessment Tool Theoretical Documentation.

Riverson, J., Coats, R., Costa-Cabral, M., Dettinger, M., Reuter, J., Sahoo, G., & Schladow, G. (2013). Modeling the transport of nutrients and sediment loads into Lake Tahoe under projected climatic changes. Climatic Change, 116(1), 35–50. https://doi.org/10.1007/s10584-012-0629-8

San Diego Bay Responsible Parties. 2016. San Diego Bay Watershed Management Area Water Quality Improvement Plan. Submitted to the San Diego Regional Water Quality Control Board by the San Diego Bay Responsible Parties. San Diego, CA.

SAWPA (Santa Ana Watershed Project Authority). 2003. Lake Elsinore and Canyon Lake Nutrient Source Assessment. Prepared by Tetra Tech for the Santa Ana Watershed Project Authority. Riverside, CA.

SAWPA (Santa Ana Watershed Project Authority). 2004. San Jacinto Nutrient Management Plan. Prepared by Tetra Tech for the Santa Ana Watershed Project Authority. Riverside, CA.

SCVURPPP (Santa Clara Valley Urban Runoff Pollution Prevention Program). 2019. Santa Clara Valley Reasonable Assurance Analysis Addressing PCBs and Mercury: Phase II Green Stormwater Infrastructure Modeling Report. Prepared by Paradigm Environmental for the Santa Clara Valley Urban Runoff Pollution Prevention Program. Sunnyvale, CA.

SDRWQCB (San Diego Regional Water Quality Control Board). 2008. Total Maximum Daily Loads (TMDLs) for Copper, Lead, and Zinc in Chollas Creek. California Regional Water Quality Control Board, San Diego Region. San Diego, CA.

SDRWQCB (San Diego Regional Water Quality Control Board). 2010. Revised Total Maximum Daily Loads for Indicator Bacteria Project I – Twenty Beaches and Creeks in the San Diego Region (Including Tecolote Creek). California Regional Water Quality Control Board, San Diego Region. San Diego, CA.

SDRWQCB (San Diego Regional Water Quality Control Board). 2012. Los Peñasquitos Lagoon Sediment/Siltation TMDL. California Regional Water Quality Control Board, San Diego Region. San Diego, CA.

Shen, J., Parker, A., & Riverson, J. 2005. A new approach for a Windows-based watershed modeling system based on a database-supporting architecture. Environmental Modelling & Software, 20(9), 1127–1138. https://doi.org/10.1016/j.envsoft.2004.07.004

Sloto, R. A., & Crouse, M. Y. 1996. HYSEP: A Computer Program for Streamflow Hydrograph Separation and Analysis: U.S. Geological Survey Water-Resources Investigations Report 1996–4040. https://doi.org/10.3133/wri964040

SMCWPPP (San Mateo Countywide Water Pollution Prevention Program). 2020. San Mateo County-wide Reasonable Assurance Analysis Addressing PCBs and Mercury: Phase II Green Infrastructure Modeling. Prepared by Paradigm Environmental and Larry Walker Associates for the San Mateo Countywide Water Pollution Prevention Program. Redwood City, CA.

Tomales Bay Watershed Council. 2007. Tomales Bay Integrated Coastal Watershed Management Plan. Submitted to State Water Resources Control Board by Tomales Bay Watershed Council, Point Reyes Station, CA.

Tariq, A., Lempert, R. J., Riverson, J., Schwartz, M., & Berg, N. 2017. A climate stress test of Los Angeles' water quality plans. Climatic Change, 144(4), 625–639. https://doi.org/10.1007/s10584-017-2062-5

USDA (United States Department of Agriculture). 1986. Urban Hydrology for Small Watersheds, Technical Release 55 (TR-55).

USDA (United States Department of Agriculture). 2024a. Digital General Soil Map of the United States (STATSGO2).

USDA (United States Department of Agriculture). 2024b. Digital General Soil Map of the United States (STATSGO2).

USDA (United States Department of Agriculture). 2024c. Cropland Data Layer. Accessed January 31, 2024. https://croplandcros.scinet.usda.gov/

USEPA (U.S. Environmental Protection Agency). 2009. Loading Simulation Program C++. Science Inventory. Record ID: 75860.

USGS (United States Geological Survey). 2019. The StreamStats program. The StreamStats Program. https://www.usgs.gov/streamstats

USGS (United States Geological Survey). 2024. Sustainable Groundwater, California Groundwater Model Archive. Sustainable Groundwater, California Groundwater Model Archive

Xia, Y., Mitchell, K., Ek, M., Cosgrove, B., Sheffield, J., Luo, L., Alonge, C., Wei, H., Meng, J., Livneh, B., Duan, Q., & Lohmann, D. 2012. Continental-scale water and energy flux analysis and validation for North American Land Data Assimilation System project phase 2 (NLDAS-2): 2. Validation of model-simulated streamflow. Journal of Geophysical Research Atmospheres, 117(3). https://doi.org/10.1029/2011JD016051

Zi, T., Braud, A., McKee, L., & Foley, M. 2022. San Francisco Bay Watershed Dynamic Model (WDM) Progress Report, Phase 2. Report prepared for the Sources Pathways and Loadings Workgroup of the Regional Monitoring Program for Water Quality. SFEI Contribution #1091. https://www.sfei.org/documents/san-francisco-bay-watershed-dynamic-model-wdm-progress-report-phase-2

Zi, T., McKee, L., Yee, D., & Foley, M. 2021. San Francisco Bay Regional Watershed Modeling Progress Report, Phase 1. Report prepared for the Sources Pathways and Loadings Workgroup of the Regional Monitoring Program for Water Quality. SFEI Contribution #1038. https://www.sfei.org/documents/san-francisco-bay-regional-watershed-modeling-progress-report-phase-1