
Work Plan: Petaluma River Ground Water Model Development Addendum

SUBMITTED TO:

State Water Resources Control Board
1001 I Street, 14th Floor
Sacramento, CA 95814

PREPARED BY:



Paradigm Environmental
9320 Chesapeake Drive, Suite 100
San Diego, CA 92123



S.S. Papadopoulos & Associates, Inc.

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1 INTRODUCTION

To support State Water Resources Control Board (Water Board) actions to address emergency drought conditions across California, 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 the State. The models 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. As part of this effort, Paradigm is developing a watershed model using Loading Simulation Program in C++ (LSPC). The LSPC model domain includes both the Petaluma River and Novato Creek watersheds, which are collectively referred to in this workplan as the Petaluma River watershed model domain. Due to significant interaction of surface water and groundwater in Petaluma River watershed, integration of a detailed process-based groundwater model with LSPC is needed to simulate surface water, particularly during low flow. Groundwater model development and coupling with LSPC will cover an expanded LSPC domain, as detailed in Section 5.3, to reduce uncertainties in groundwater boundaries and coupled flow exchanges.

This workplan addendum outlines the details on how groundwater flow processes will be incorporated within the watershed modeling framework developed by Paradigm using LSPC. The groundwater domain will be modeled using an existing MODFLOW model developed by the United States Geological Survey (USGS) and coupled with LSPC to simulate the integrated surface water-groundwater hydrologic system. The MODFLOW model supports the development of the Groundwater Sustainability Plan (GSP) for the Petaluma Valley Groundwater Sustainability Agency (GSA) which operates within Petaluma Valley groundwater subbasin (Sonoma Water, 2021a). This workplan was developed with the assumption that any supporting data and information, in addition to what is publicly available, such as observed groundwater and streamflow data, well and boring log data, land surface elevation data, conceptual model, available aquifer test data (if any), and any other relevant information/data will be provided by the GSA.

The objective of incorporating groundwater flow processes using MODFLOW within the watershed modeling system is to benefit from MODFLOW's strengths in simulating the groundwater processes dynamics and enhance the modeling system capabilities in simulating the effects of groundwater stresses on surface water flows. The anticipated use of the integrated LSPC-MODFLOW model is to assess short and long-term changes in groundwater conditions and evaluate the effects of these changes on surface water flows. The LSPC-MODFLOW model will be used for supply and demand planning purposes. This will include running various scenarios for supply (e.g., dry, average, and wet year conditions) and demand (e.g., water rights and environmental flows) to inform the Water Board's decision-making.

2 GEOLOGIC SETTING

This section summarizes the geology and hydrogeology of the Petaluma River watershed to support development of the conceptual groundwater model. The discussion is based primarily on the U.S. Geological Survey report Hydrologic and Geochemical Characterization of the Petaluma River Watershed, Sonoma County, California (Traum et al. 2022), with additional information from published regional geologic and fault mapping.

The generalized geologic map of the Petaluma River Watershed model domain shown in [Figure 2-1](#) was derived from a regional compilation of published U.S. Geological Survey mapping for Marin County and Scientific Investigations Map 2956 for eastern Sonoma County. The regional layer was

reviewed and modified, where needed, using California Geological Survey maps of the Petaluma, Petaluma River, Cotati, Glen Ellen, Sears Point, and Novato quadrangles. The original units were consolidated and renamed for watershed-scale display as Quaternary alluvium and surficial deposits (Qal), estuarine and bay mud deposits (Qbm), landslide deposits (Qls), Tertiary volcanic rocks (Tv), Petaluma Formation (Tp), Wilson Grove Formation (Twg), Great Valley Sequence and Novato Conglomerate (KJgv), Franciscan Complex (KJf), and ultramafic rocks and serpentinite (um).

2.1 Geology

The Petaluma River watershed occupies a northwest-trending structural depression that opens southeastward toward San Pablo Bay. The valley floor is underlain by Holocene and Pleistocene alluvial and estuarine deposits and older basin-fill sedimentary rocks, while Tertiary volcanic rocks and Mesozoic basement rocks form much of the surrounding uplands. The Novato Creek portion of the model domain is underlain mainly by Franciscan Complex bedrock, with narrower areas of Quaternary alluvium along valleys and local volcanic, ultramafic, and Great Valley Sequence rocks.

The youngest mapped units are Quaternary alluvium and surficial deposits (Qal), estuarine and bay mud deposits (Qbm), and landslide deposits (Qls). The Qal unit includes stream-channel, floodplain, terrace, fan, basin, colluvial, older alluvial, and bay-margin deposits. Younger alluvium occurs mainly along the Petaluma River, Novato Creek, their tributaries, and adjacent valley floors and consists of gravel, sand, silt, and clay. Near the tidal marshes and San Pablo Bay, the Qbm unit includes fine-grained estuarine deposits and bay mud composed primarily of clay, silt, fine sand, and peat. Older alluvial deposits occur along valley margins, while Qls landslide deposits are widespread on steeper upland slopes and consist of disrupted soil, weathered rock, and bedrock blocks.

Another Quaternary unit underlying the Petaluma Valley consists of interbedded conglomerate, sand, and mudstone and has been interpreted to correlate with the Huichica and Glen Ellen Formations exposed in the adjacent Sonoma Creek watershed. It occurs beneath the mapped alluvium and is distinct from the underlying Petaluma and Wilson Grove Formations.

The principal Tertiary sedimentary units are the Petaluma Formation (Tp) and Wilson Grove Formation (Twg). The late Miocene to Pliocene Petaluma Formation underlies much of central and eastern Petaluma Valley and consists mainly of silty and clayey mudstone with discontinuous sandstone, gravel, conglomerate, tuff, and minor limestone. Its lower, middle, and upper intervals represent lacustrine, fluvial, estuarine, and transitional marine deposition and are combined as Tp on the generalized map. The late Miocene Wilson Grove Formation occurs mainly in the northwestern watershed and consists of fine to medium grained, moderately to well-sorted marine sandstone.

Tertiary volcanic rocks are grouped as an undivided unit (Tv). The younger late Miocene to Pliocene Sonoma Volcanics occur primarily along the northeastern watershed and include lava flows, breccias, tuffs, and volcanoclastic deposits ranging from basaltic to rhyolitic in composition. The Sonoma Volcanics locally interfinger with sedimentary deposits of the Petaluma Formation. Older middle to late Miocene volcanic rocks include the Tolay and Donnell Ranch Volcanics, which occur mainly in the southeastern watershed and consist primarily of mafic lava flows, breccia, scoria, and tuff, with local silicic rocks. Volcanic rocks of Burdell Mountain occur in the southern part of the model domain and include basalt, andesite, dacite, and rhyolite.

Mesozoic bedrock units includes the Great Valley Sequence and Novato Conglomerate (KJgv), the Franciscan Complex (KJf), and ultramafic rocks and serpentinite (um). The Great Valley Sequence and Novato Conglomerate consist mainly of consolidated sandstone, siltstone, shale, and locally well-cemented conglomerate and occur primarily in the southern and southeastern model domain. The Franciscan Complex is the dominant bedrock unit in the southern and western uplands, including much of the Novato Creek watershed, and consists of graywacke, shale, mélangé, greenstone, chert,

and metamorphic rocks. Ultramafic rocks and serpentinite are mapped separately because their composition differs from the surrounding Franciscan rocks.

The geologic framework is strongly influenced by northwest-trending folding and faulting. The concealed Petaluma Valley Fault extends beneath the valley axis and offsets subsurface stratigraphic units. The Rodgers Creek Fault lies along the northeastern side of the watershed near the Sonoma Mountains, while the Tolay Fault occurs in the southeastern watershed. Additional faults occur in the northern and southern parts of the watershed. Collectively, these structures offset and juxtapose geologic units, contributing to the basin's complex subsurface geometry.

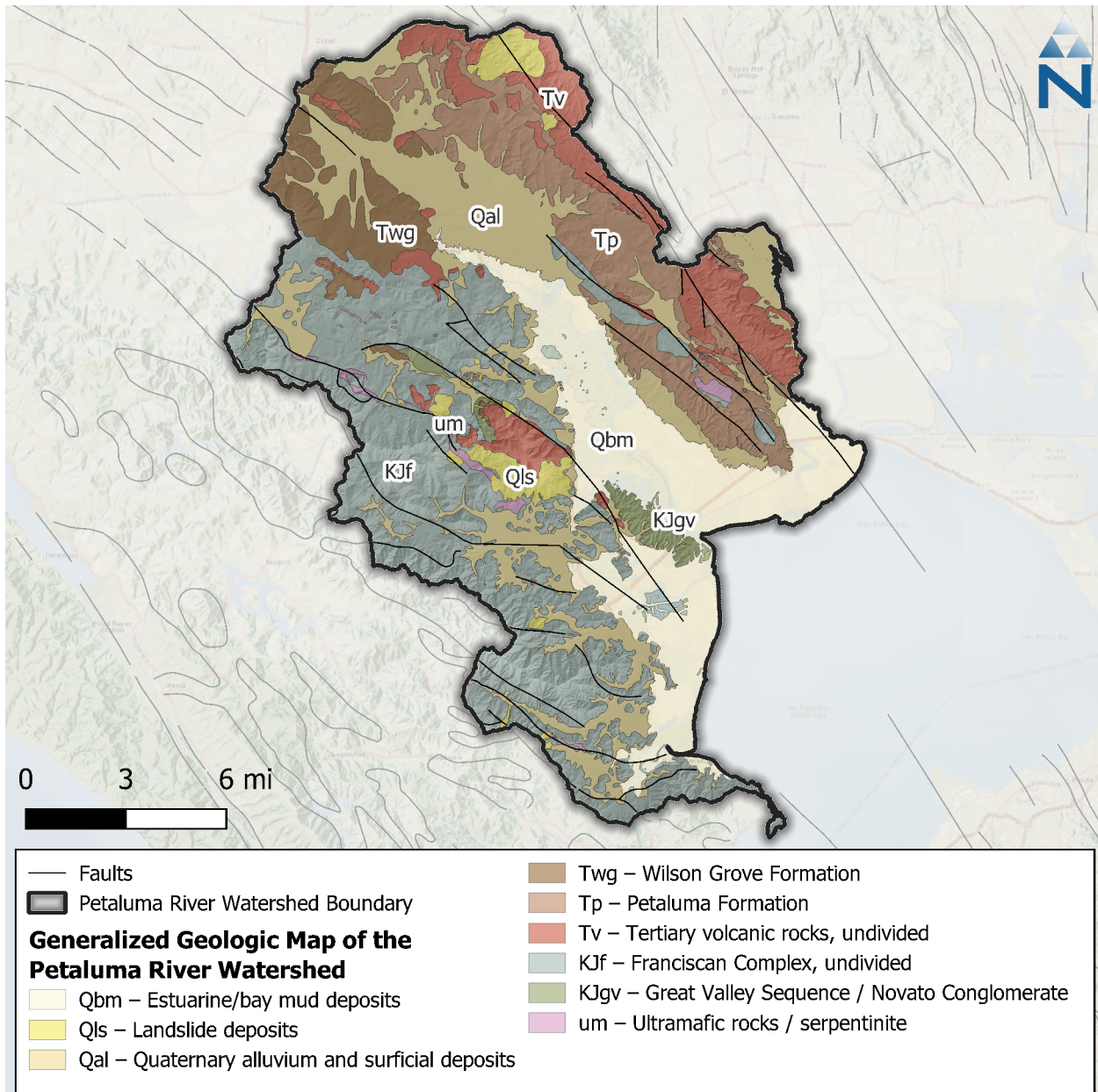


Figure 2-1. Generalized Geologic Map of the Petaluma River Watershed Study Area.

2.2 Hydrogeology

Within the Petaluma Valley Groundwater Basin, the principal aquifer system consists of Quaternary alluvium, the Quaternary mixed unit, the Wilson Grove Formation, the Petaluma Formation, and permeable zones within the Tertiary volcanic rocks. Outside the principal aquifer system, including much of the Novato Creek watershed and surrounding uplands, groundwater occurs locally within fractures and weathered zones of consolidated bedrock, including the Great Valley Sequence, Franciscan Complex, and ultramafic rocks, but these consolidated bedrock units generally produce lower well yields and store water mainly in fractures and weathered zones. Water-bearing conditions vary depending on the extent and connectivity of these features.

Quaternary alluvium forms the principal aquifer along the Petaluma River, Novato Creek, their tributaries, and adjacent valley floors. Sand and gravel zones readily transmit groundwater and may be connected to streams and underlying formations, whereas fine-grained floodplain, basin, and older alluvial deposits restrict groundwater movement. Near the tidal marshes and San Pablo Bay, bay mud and estuarine deposits have low permeability and may contain brackish or saline groundwater.

The Quaternary mixed unit beneath the main Petaluma Valley floor consists of discontinuous beds of conglomerate and sand separated by mudstone. It may broadly correlate with the Huichica and Glen Ellen Formations in nearby basins. Groundwater occurs mainly in the coarse-grained beds, while the mudstone restricts vertical flow and may locally confine deeper groundwater. As a result, the unit functions as a series of partly connected water-bearing layers separated by less permeable material.

The Wilson Grove Formation forms a relatively continuous aquifer in the northwestern watershed because of its laterally extensive sandstone. Groundwater generally moves toward the valley axis and may discharge to streams or adjacent basin-fill deposits. The Petaluma Formation is the most extensive aquifer unit but has highly variable water-bearing properties. Groundwater occurs mainly in discontinuous sandstone, gravel, and conglomerate beds within predominantly silty and clayey mudstone. Well yields vary with the thickness and continuity of these coarse-grained intervals.

Tertiary volcanic rocks have variable water-bearing properties. Groundwater occurs mainly within localized permeable zones, but these zones are discontinuous and can produce substantial differences in well yields over short distances.

The Great Valley Sequence, Franciscan Complex, and ultramafic rocks generally have low primary porosity and permeability. Groundwater occurs mainly in fractures, weathered zones, bedding or foliation partings, and local fault zones. Franciscan mélangé commonly consists of a low-permeability matrix containing isolated competent blocks, making productive fractures difficult to correlate between wells. These consolidated bedrock units generally support lower-yield domestic wells and springs rather than laterally continuous aquifers.

Groundwater generally moves from the surrounding uplands toward Petaluma Valley and the Petaluma River, then southeast toward the tidal marshes and San Pablo Bay. The Petaluma River generally gains groundwater along its non-tidal reach north of the City of Petaluma. Along the lower tidal reach, the river may gain or lose groundwater as river levels change with streamflow and the tidal cycle.

Geologic structures may influence groundwater movement by placing units with different hydraulic properties next to one another. Groundwater-level gradients steepen along parts of the basin margins, particularly in the northern and southeastern portions of the mapped area, where lower-permeability bedrock lies next to more permeable basin-fill deposits. Available data suggest that some faults have little effect on groundwater flow, while the effects of others remain uncertain because information is limited.

3 GROUNDWATER HYDROLOGY

The Petaluma River watershed overlaps with four groundwater basins as delineated by Bulletin 118 (DWR 2020). The watershed contains most of the Petaluma Valley basin (# 2-001) and also overlaps with the Novato Valley basin (# 2-030), the Wilson Grove Formation Highlands (# 1-059), and the Sonoma Valley sub-basin (# 2-002.02), with a sliver containing negligible overlap at the border of the Santa Rosa Plain sub-basin (# 1-055.01). The watershed does not fully contain any basins. Approximately 39% of the watershed area falls within Bulletin 118 groundwater basins and subbasins. The remaining portions of the watershed are outside Bulletin 118 groundwater basin boundaries and are underlain primarily by consolidated bedrock units, including Franciscan Complex, Great Valley Sequence and Novato Conglomerate, ultramafic rocks and serpentinite, and Tertiary volcanic rocks.

Based on the Sustainable Groundwater Management Act (SGMA) Basin Prioritization Dashboard, the Petaluma Valley basin is designated as Medium priority due to declining groundwater levels and a large number of total wells. Approximately 70% of the Petaluma Valley basin falls within the Petaluma River watershed. The Novato Valley basin is designated as Low priority; approximately 40% of the Novato Valley basin falls within the Petaluma River watershed. The Wilson Grove Formation Highlands basin is designated as Very Low priority, with approximately 10 percent occurring within the watershed. The Sonoma Valley sub-basin is designated as High priority due to declining water levels, saline intrusion, and a large number of water supply and total wells. Approximately 5% of the Sonoma Valley sub-basin falls within the Petaluma River watershed. The Sonoma Valley Groundwater Sustainability Agency (GSA) operates within the Sonoma Valley sub-basin, and the Petaluma Valley GSA operates within the Petaluma Valley basin (Sonoma Valley GSA 2021 and Sonoma Water 2021a). [Figure 3-1](#) is a map overlaying the Petaluma River Watershed, the Bulletin 118 Petaluma Valley subbasin, and the USGS Petaluma Valley Integrated Hydrologic Model (PVIHM) MODFLOW active model domain.

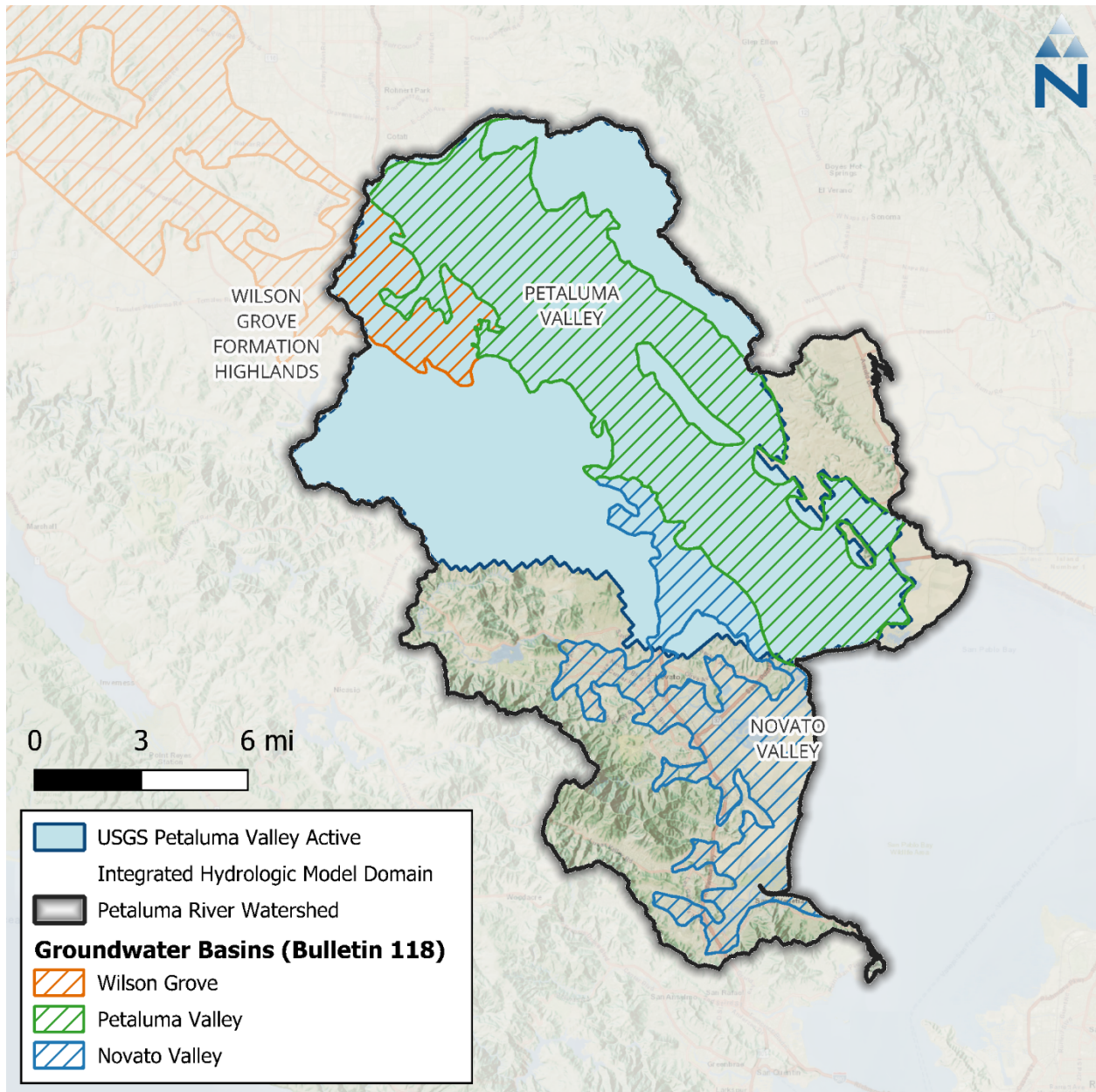


Figure 3-1. Outlines of Petaluma River Study Area, Petaluma River Sub-Basin Boundary (Bulletin 118), and Petaluma Valley integrated hydrologic model (PVIHM) MODFLOW Active Model Domain Boundary.

3.1 Water Budget Components

The publicly available USGS Petaluma River model overlaps the watershed (Traum 2022). The average annual groundwater budget presented in the USGS model report indicated that stream seepage to groundwater makes up 83% of groundwater inflows, with the remaining inflow coming from upland and San Pablo Bay boundaries (Traum et al. 2022). Agricultural groundwater pumping in the simulation makes up 4% of groundwater outflows, with urban and rural pumping accounting for less than 1%. The remaining modeled outflow is predominantly groundwater discharge to streams. [Figure 3-2](#) shows the annual water budget components reported in the USGS groundwater analysis for Petaluma Valley (Traum et al. 2022).

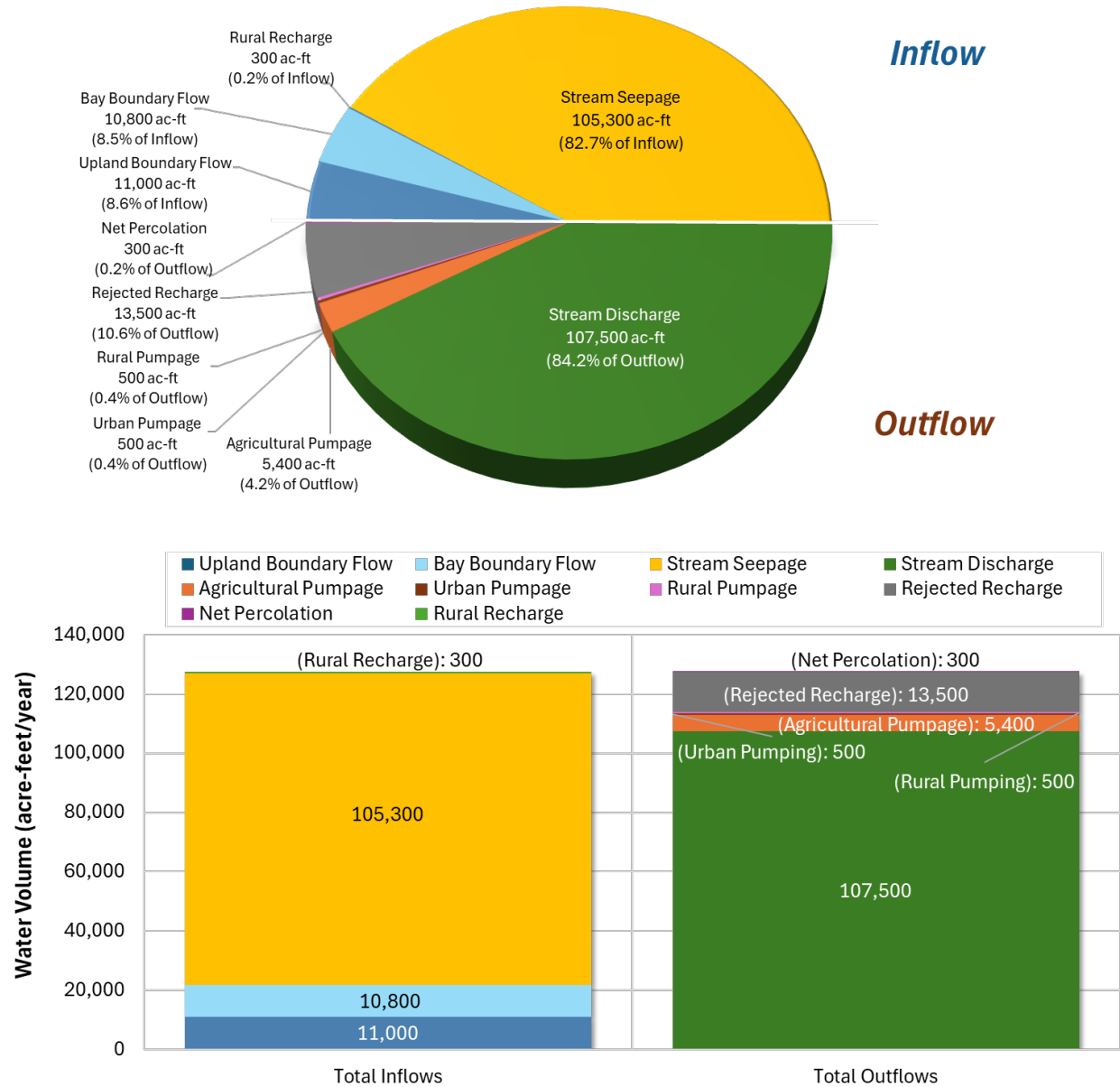


Figure 3-2. Annual Groundwater Budget Components as per the USGS Petaluma Model Report (Traum et al. 2022: Table D17).

4 DATA NEEDS

Several geological, spatial, and temporal data sets are needed for LSPC-MODFLOW model configuration and calibration. [Table 4-1](#) is a summary of data needs:

Table 4-1. Anticipated data needs for LSPC-MODFLOW configuration and calibration

Type	Data Source	Application/Usage
Model Files	All MODFLOW model input and output files	LSPC-MODFLOW model development
Geology	Hydrogeologic Conceptual Model (HCM) data and information	These data will provide the underpinnings for numerical groundwater model development
Other Supporting Data	Digital Elevation Model (DEM) data or Lidar data	For land surface and streambed elevations
	Aquifer pumping test data, if available, or any other aquifer properties datasets	For parameterizing associated subsurface properties
	Digitized well logs with texture information	Used for developing aquifer parameters
	Airborne electromagnetic (AEM) data	Used for developing aquifer parameters
	Shapefiles that are relevant for model development and calibration	Used for data processing
Observation Data	Groundwater elevation data	Groundwater model calibration
	Streamflow data	Surface water model calibration
	Spring flow data, if any.	Spring flow parameterization

A few data gaps and limitations are noted here. Wells reporting water levels are concentrated within the groundwater basin, and hence water levels and groundwater storage change information are generally not available within the non-basin areas. All available water level information outside the subbasin will be used to support the model calibration. The data presented in Table 4-1 are partially available to the public. Any data not currently accessible will be requested from the GSA.

5 MODEL DEVELOPMENT

The groundwater model will be developed and integrated with the existing LSPC model. [Figure 5-1](#) shows a schematic of the integrated modeling approach.

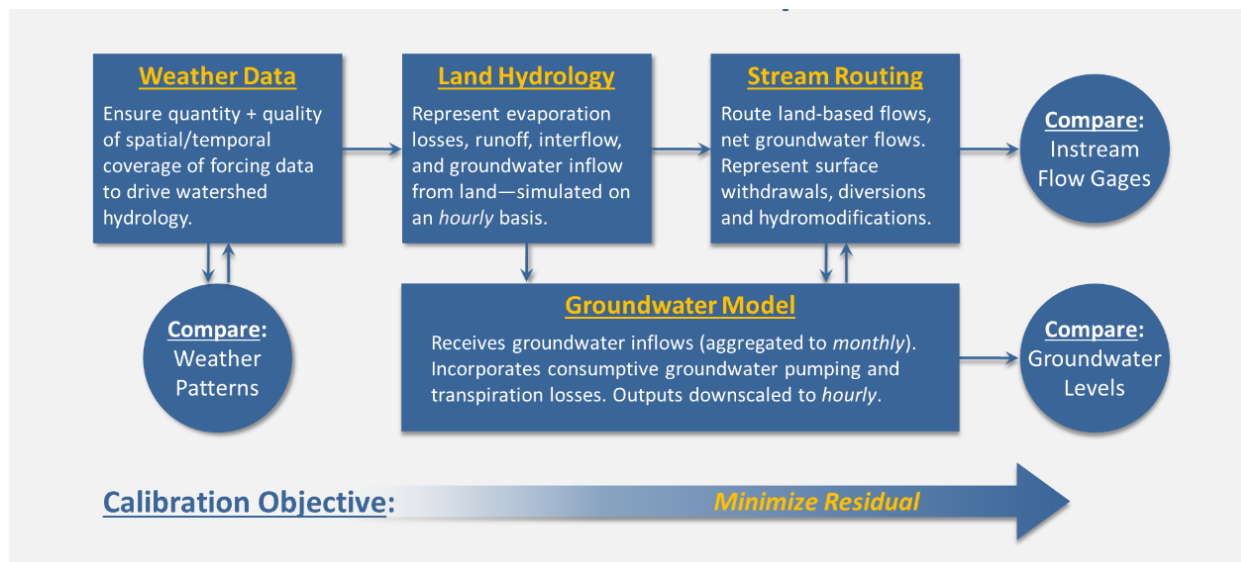


Figure 5-1. Integrated modeling approach for the Petaluma River Watershed Model.

5.1 Background

The groundwater domain will be modeled using an existing MODFLOW model called the Petaluma Valley Integrated Hydrologic Model (PVIHM). The model initially developed by the USGS in cooperation with the Sonoma County Water Agency and the City of Petaluma (Traum, 2022) simulated groundwater conditions from October 1960 through September 2015. On behalf of Sonoma Water, the USGS later extended the simulation time frame through 2018 (Sonoma Water, 2021b). The PVIHM was developed using the MODFLOW-OWHM2 (Boyce, 2022) code.

5.2 Code Selection

MODFLOW (Langevin et al., 2017) is an open source, publicly available, three-dimensional code that can represent spatial and temporal variability of groundwater heads, aquifer properties, and all relevant boundary conditions needed to appropriately simulate flow conditions in the relevant basins and to meet the modeling objectives. MODFLOW is recommended for simulating groundwater flow conditions and integrating flow between groundwater and surface water. Specifically, MODFLOW-NWT (Niswonger et al., 2011) will be used for the integrated LSPC-MODFLOW model. Given that the underlying groundwater simulation code for MF-OWHM2 is MODFLOW-NWT, it can be seamlessly integrated with LSPC as an explicitly coupled process iterating between the two simulators, ensuring that integrated water budgets for the surface water—groundwater system are conserved.

5.3 Model Extent and Discretization

The model domain of the integrated LSPC-MODFLOW model will be expanded to include all portions of the Petaluma River watershed as shown on [Figure 3-1](#). The existing active PVIHM domain primarily encompasses the alluvial formations of Petaluma Valley, portions of the Wilson Grove Formation Highlands, and adjacent non-basin areas. However, portions of the watershed including parts of the

Novato Creek subwatershed to the south and tidal wetland areas to the east, lie outside the existing PVIHM active domain and/or broader PVIHM domain ([Figure 3-1](#)).

The integrated model will retain the existing PVIHM grid geometry, spacing, and overall grid extent while expanding the active MODFLOW domain southeasterward (see [Figure 5-2](#)). This expansion will include relevant non-basin areas, portions of the Novato Valley groundwater basin, and the tidal wetland region. Activating these areas will allow recharge and other groundwater boundary conditions to be represented using spatially consistent LSPC simulation outputs rather than simplified external estimates. This expansion is particularly important in the tidal wetland region, where groundwater interactions are expected to be an important component of the hydrologic system and may influence model results.

Within the existing PVIHM active domain, the vertical discretization and model depths will generally be retained for the integrated model. In areas activated outside the existing PVIHM active domain, an initial uniform model depth of 100 feet will be assigned to represent groundwater recharge and flow within fractured bedrock. A different depth may be assigned to the alluvial portions of the Novato Valley based on available supporting data. Model depths in the newly activated areas may be refined following further review of hydrogeologic information and other relevant data.

The simulation period for the integrated LSPC-MODFLOW model will extend from Water Year 2003 through Water Year 2023, with monthly stress periods used for the groundwater simulation. Additional data will be developed as needed to establish boundary conditions for Water Year 2023. Faults represented in PVIHM will be retained, and additional faults may be incorporated where needed to represent groundwater flow within bedrock portions of the expanded active domain.

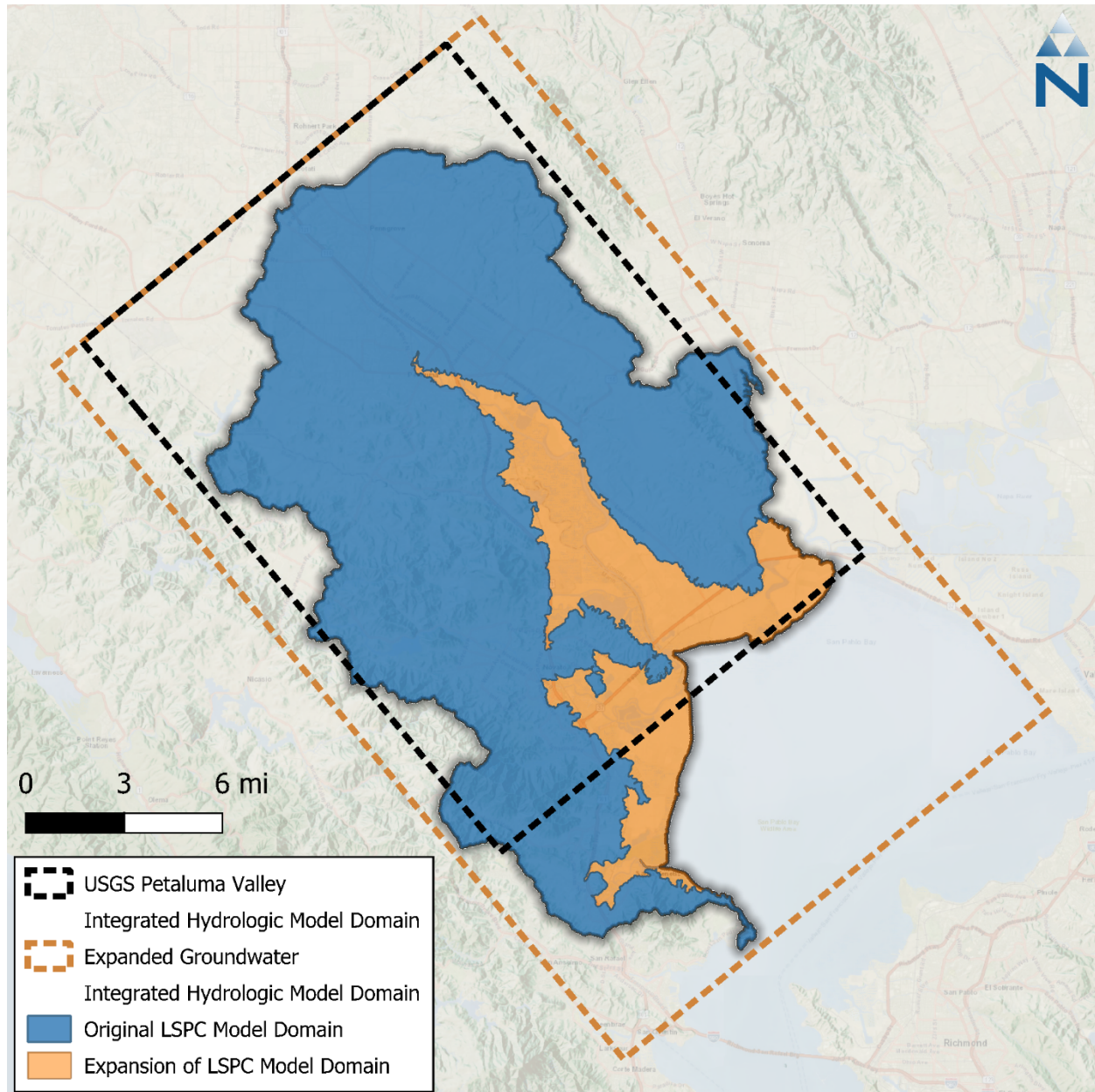


Figure 5-2. MODFLOW grid and LSPC model domain and expansions

5.4 Aquifer Properties

Available aquifer data in the form of lithologic logs, well logs, boring logs, and AEM-inferred data will be reviewed to assess the viability of using a tool called Texture2Par (Scantlebury et al, 2022; CDWR, 2026) to develop and refine aquifer properties. Texture2Par is a basin characterization tool developed for California Department of Water Resources (CDWR). It has been successfully implemented in several regional scale CDWR's Central Valley models such as the Sacramento Valley Simulation Model (SVSim) and the Fine-Grid version of the Central Valley Simulation Model (C2VSim-FG). Zonal representation of alluvial basins for fractured systems is available in Texture2Par and will be utilized to represent basin and non-basin areas. Any additional information such as aquifer tests will be utilized to develop aquifer properties.

5.5 Boundary Conditions

Groundwater recharge will be provided by LSPC. Evapotranspiration will be represented by LSPC and therefore, will not be considered for the MODFLOW model. Streams will be represented using the streamflow routing (SFR) package of MODFLOW and will provide the stream-aquifer flow rates. Lateral flow boundaries will be represented either as no-flow boundaries along the periphery of the watershed on the upgradient end and will be represented as a general-head boundary (GHB) package where flow is expected to occur across the model domain at the southern end of the model and within the Petaluma Valley that is impacted by tidal influences. Well head information available from monitoring wells close to the boundary will be used to inform the time varying GHB boundary values. Groundwater pumping locations, depths, and rates will be obtained from PVIHM. Pumping data derived from PVIHM will be compared against LSPC water demand assessment as a quality assurance check. Additionally, the delivery location of the water, on-farm storage of stormwater and recycled water as well as the relevant canal system through the valley floor will be accounted for consistent with the PVIHM model. Any major differences observed will be discussed with the State Board and the GSA staff.

5.6 Initial Conditions

Initial heads will be generated that appropriately represent the head distribution for the selected simulation starting time. Any head and flow observations available for the starting time will be used for generating initial heads for the groundwater model. A ‘warm-up’ period may be simulated to achieve equilibrium within groundwater heads to create reasonable starting conditions.

6 MODEL CALIBRATION

Groundwater calibration will aim to improve the model performance in simulating groundwater head values, vertical head differences (if any paired well observations are available), stream-aquifer flow, streamflow, and any other pertinent information such as, but not limited to, water budget estimates. Parameter ESTimation (PEST) software (Doherty, 2009) will be used for model calibration. A PEST-facilitated calibration approach will be used, in which simulated and observed values will be matched to achieve goodness of fit, while ensuring that the generated parameters are within a plausible physical range. The objective function will be reduced up to the point that the calibrated parameters are meaningful, thus avoiding ‘overfitting’ of parameters. Overfitted models may improve history matching at the cost of distorting simulation results during scenario application or predictive analyses. The objective of the calibration process will be to ensure that a robust model is developed that targets history matching while representing the parameter information that is independently available. Water budgets will be developed at both the watershed scale and at smaller spatial zones.

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