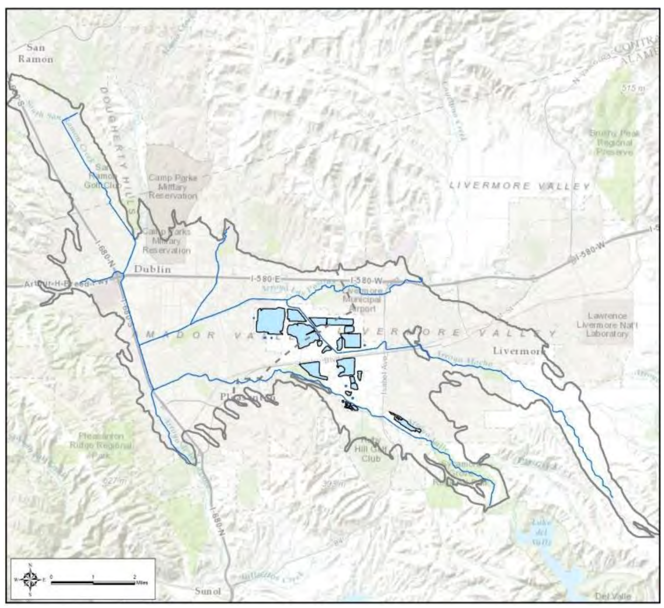
Groundwater Model for Groundwater and Salt Management in the Livermore Valley Groundwater Basin: Upgrades, Calibration, and Application

Prepared for:
Zone 7 Water Agency



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ABBREVIATIONS

AC_NP ....Alamo Canal Gaging and Sampling Station
ADLL ....Arroyo de la Laguna Gaging and Sampling Station
ADVP..................................Arroyo Valle Gaging and Sampling Station
ALPL ....Arroyo Las Positas Headwater Gaging and Sampling Station
ALP_ELCH ....Arroyo Las Positas Gaging and Sampling Station
AMNL.................................Arroyo Mocho Headwater Gaging and Sampling Station
AMHAG..............................Arroyo Mocho Gaging and Sampling Station
AM_KB ....Arroyo Mocho Gaging Station
AMP ....Arroyo Mocho Gaging and Sampling Station
AVNL..................................Arroyo Valle Headwater Gaging and Sampling Station
CWS ....California Water Service
DEM ....Digital Elevation Model
DWR...................................California Department of Water Resources
GWMP ....Groundwater Management Plan
ft...feet
HFB ....MODFLOW Horizontal Flow Barrier Package
ICALC.................................Stream depth calculation method in MODFLOW SFR package
KwL/b ....Conductance
K/b ....Leakance
L ....Lake Number
LAK.....................................MODFLOW Lake-Aquifer Interaction Flow Package
LIDAR.................................Light Detection and Ranging surveying technology
LKT.....................................MT3D-USGS Lake-Aquifer Interaction Transport Package
LMT....................................MODFLOW-NWT/MT3D-USGS Surface Water Flow-Transport Link Package
MAE ....Mean Absolute Error
ME ....Mean Error
MNW ....MODFLOW Multi-Node Well Package
mg/l ....milligrams per liter
model ....Livermore Value Basin Groundwater Model
RCH ....MODFLOW Areal Recharge Package
RMSE ....Root Mean Squared Error
Seg ....Stream Segment
SFR ....MODFLOW Stream Flow Routing Package
SFT......................................MT3D-USGS Stream Flow Transport Package
STD.....................................Standard Deviation
STRTOP ....Stream bed top elevation in MODFLOW SFR package

Ss..Specific storage
TDS..Total Dissolved Solids
TRVG ....Tri-Valley Retail Group
Zone 7 ....Zone 7 Water Agency

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EXECUTIVE SUMMARY

Zone 7 Water Agency (Zone 7) manages the Livermore Valley Groundwater Basin based on its Groundwater Management Plan (GWMP, 2005). One of Zone 7's tools in implementing the GWMP is its groundwater model. This report documents the project to enhance and improve the ability of the groundwater model to meet the goals of the GWMP. Upgrades were implemented in the Livermore Valley Basin Groundwater Model (model) to address two specific groundwater management issues:

1. The model was converted to open source software MODFLOW-NWT and MT3D-USGS to use packages for surface water flow and transport and stream-aquifer interactions for planning of conjunctive use of surface water and groundwater;
2. The number of model layers was increased to improve the model's capability for simulating salt transport to help address the salt balance of the basin.

Surface water packages for streamflow and stream-aquifer interaction (SFR) and lake-aquifer interaction (LAK) were implemented in MODFLOW-NWT. Implementation included defining the stream network, defining stream rating curves, estimating headwater inflows, estimating runoff, defining lake geometry, and defining connections for lake to lake and lake to stream transfers. Zone 7 previously funded development of the stream transport (SFT) and lake transport (LKT) packages included in MT3D-USGS to be released by the US Geological Survey this year. These packages were used in the updated model to simulate salt transport based on modeled flow conditions. Implementation included estimating headwater salt concentrations in the streams.

The number of model layers was increased to ten from three layers in previous versions of the model. Updated Layer 1 represents lacustrine clay overburden deposits in the western portion of the Basin. Layers 2 and 4 represent coarse-grained aquifer units within the Upper Aquifer, while Layer 3 represents a fine-grained aquitard unit within the Upper Aquifer. Layer 5 represents the fine-grained aquitard between the Upper and Lower Aquifers. Layers 6, 8, and 10 represent coarse-grained aquifer units within the Lower Aquifer, while Layers 7 and 9 represent fine-grained aquitard units within the Lower Aquifer. Adding the fine-grained aquitard units within the Upper and Lower Aquifers will better simulate resistance to vertical salt transport

The model was calibrated to historical flow and water quality conditions for Water Years 1974-2014. Hydraulic conductivity, storage properties, and porosity were calibrated using the pilot point method. Fault, streambed, and lakebed conductances were also calibration parameters. The model was calibrated to data for groundwater levels, streamflows, lake stages, and total dissolved solids (TDS) concentrations in groundwater, streams, and lakes.

The model is calibrated for the model's intended purpose of evaluating groundwater conditions for various groundwater and salt management alternatives. The main use of flow model results is to evaluate groundwater levels throughout the Main Basin (Mocho II, Amador, and Bernal Sub-basins) for changes in hydrology affecting areal recharge and stream inflows as well as pumping. The main use of transport model results is to evaluate salt balance and groundwater TDS concentration trends for sub-basins and vertically through identified hydrostratigraphic layers for flow changes as well as salt management alternatives.

The calibration to general groundwater levels and trends as well as streamflows shows that the model structural upgrades to refine layers and simulate surface water features represent the groundwater system well. Calibration to TDS concentrations shows that the model generally simulates concentration magnitudes and trends observed in monitoring well data. This level of calibration supports use of model to evaluate salt balance and the calibration to wells in different layers supports use of the model to evaluate salt transport through layers.

The model does not simulate the full range of fluctuations in groundwater levels observed in some areas of the basin. Therefore, evaluations of drought or wet period simulations should consider this calibration error. An evaluation of the model water budget and streamflow calibration suggests that calibration may be improved with changes to the stream (SFR1) package setup.

Other limitations of the model include a recommendation to not use the transport model to predict groundwater TDS concentrations at specific wells as localized sources of salt are not included in the model. Use of surface water results from the model should also be limited as the inclusion of surface water flow and transport packages are meant to simulate surface water effects on groundwater conditions. Furthermore, using the model to plan operation of future recharge lakes will likely require additional calibration.

The calibrated model was used to run four simulations that will help Zone 7 with setting groundwater resource planning criteria and managing the salt balance in the basin. Three alternative simulations are compared to a baseline simulation based on the average monthly conditions of the calibrated model. The alternative runs were:

1. **1 Year Drought Optimization Simulation.** A simulation designed to estimate the maximum volume Zone 7 can pump during a worst-case one year drought. Evaluation of the water budget in consideration of the calibration error shows that the simulation may not represent the worst-case as designed, but does represent a historically severe one year drought.
2. **6 Year Drought Simulation.** A simulation designed to evaluate Zone 7's pumping plans during a six year drought
3. **No Groundwater Demineralization Simulation.** A simulation designed evaluate the effectiveness of the Mocho Groundwater Demineralization Plant operations on the Basin's salt balance

Predicted groundwater levels and TDS concentrations as well as water balance and salt balance are shown for each of these simulations to guide Zone 7 in groundwater and salt balance management.

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SECTION 1
BACKGROUND AND BASIC INFORMATION

1.1 BACKGROUND

Zone 7 Water Agency (Zone 7) manages the Livermore Valley Groundwater Basin based on its Groundwater Management Plan (GWMP, 2005). One of Zone 7's tools in implementing the GWMP is its groundwater model. The groundwater model supports the following goals of the GWMP:

- to maintain the balance between the combination of natural and artificial recharge and withdrawal;
- to maintain water levels high enough to provide emergency reserves adequate for the worst credible drought;
- to protect and enhance the quality of the groundwater;
- to develop information, policies and procedures for effective long-term management of the groundwater basin; and
- to inform the public and relevant governmental agencies (e.g., the Tri-Valley Retail Group [TVRG], which includes Dublin-San Ramon Services District, California Water Service, Livermore and Pleasanton) of Zone 7's water supply potential and management policies, and to solicit their input and cooperation.

This report documents the project to enhance and improve the ability of the groundwater model to meet the goals of the GWMP. Two specific management issues are addressed by the upgrades:

1. planning for conjunctive use of surface water and groundwater; and
2. the salt balance of the basin.

1.1.1 CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER

Zone 7 uses surface water, including imported water from the State Water Project, to recharge its groundwater basin via a network of streams or arroyos as well as lakes formed as gravel mining pits. Zone 7 plans to expand the use of the lakes as recharge ponds in the future. The surface water supply is a critical component of Zone 7's GWMP for keeping the groundwater basin in balance. When less surface water supply is available during droughts, groundwater storage is used to meet demand in the basin.

1.1.2 BASIN SALT BALANCE

Salt management is an important issue in the Livermore Valley Basin. Despite practicing sensible surface water importation, conducting artificial recharge with imported water containing low total dissolved solids (TDS), limiting groundwater pumping, and managing wastewater disposal and recycled water use within the watershed, there has been a gradual degradation in water quality through the accumulation of "salts" from the various sources. The net effect of the aforementioned management practices on the salt loading from urban and agricultural irrigation over the groundwater basin, natural and artificial stream recharge, and subsurface inflow of poor quality water into the basin, has resulted in an average salt loading of approximately 2,000 tons per year since 1974, and an average TDS increase from 450 mg/l to 650 mg/l based on salt loading calculations (Zone 7, 2012).

Net salt loading has decreased slightly since the operation of Zone 7's newly constructed groundwater desalination facility beginning after 2012; however, salt loading is projected to increase as the Valley becomes more urbanized and the use of recycled water increases. Zone 7 updated its Salt and Nutrient Management Plan in 2014 to meet requirements of the State Water Resources Control Board's Recycled Water Policy, and to include updated local land and water development plans.

1.1.3 Previous Model Versions

The Livermore Valley Basin MODFLOW model was originally created in 1996 by CH2M Hill as a conversion of an older three-dimensional finite-difference model developed in the 1980's to evaluate potential groundwater management policies for the Livermore Valley Groundwater Basin. The 1996 version was calibrated with historic water level data (1976-1995), and used to simulate various salt loading scenarios and salt management strategies during the development of Zone7's Salt Management Plan (EOA/Zone 7, 2004). This model version was also used in Zone 7's Well Master Plan effort to assess the impacts of installing and operating additional municipal supply wells (CH2MHill, 2003).

In 2005, HydroMetrics LLC recalibrated the model to groundwater elevation data from 1974 to 2004 using the pilot point method to vary the model's hydrogeologic properties to represent heterogeneity. The model grid was composed of a uniform grid of square cells of 500 feet. The outer boundaries of the active model cells encompassed the Bernal, Amador, Mocho II, Castle, Dublin, Camp and Bishop Subbasins. This version 2.0 utilized the three-dimensional MODFLOW-SURFACT numeric code (Panday and Huyakorn, 2008) to simulate groundwater flow, and simulate solute (salt) transport in the basin under specified stresses. Version 2.0 was used to evaluate alternatives for sizing and siting potential future groundwater desalination facilities as an effective means to remove salts from the basin and potentially restore groundwater quality (Rooze, 2006).

Previous versions of the model did not simulate surface water flow. Instead, surface water-aquifer interactions such as stream recharge and discharge were calculated by Zone 7 and entered into the model so that the fluxes were specified and not calculated by the model.

Version 2.0 of the model contained three active layers that represent two aquifers, an upper unconfined aquifer and a lower confined aquifer that includes the many productive intervals used by local municipal wells, and an intervening aquitard. Layer thicknesses were based on mapped thicknesses of the aquifers and aquitard.

1.1.4 Need for Model Upgrades

An evaluation of version 2.0 recommended upgrades to the model so that it simulates surface water and surface water-groundwater interactions for better conjunctive use planning (Zone 7 and HydroMetrics LLC, 2006). Upgrading this portion of the model will allow direct simulation of flow interactions between these groundwater and surface water features as they are important features for moving water and salt into and around the Livermore Valley Groundwater Basin. Neither the proprietary code MODFLOW-SURFACT nor MT3DMS (Zheng, 2010), the public domain fate and transport code that works with MODFLOW, supported solute transport in lakes and streams. However, Zone 7 funded the development of this software capability for MT3DMS, which was incorporated in the forthcoming public release of a version of MT3DMS by the U.S. Geological Survey (Bedekar et al., 2016). Therefore, the model was converted from MODFLOW-SURFACT to the open source versions of MODFLOW and MT3DMS to take advantage of the new software capability. Packages in these versions of MODFLOW and MT3DMS to simulate flow and transport in streams and lakes and their interactions were implemented for this project.

In order to improve the model's capability for simulating salt transport, the need to increase the number of layers was identified. Solute transport modeling generally requires more model layers than groundwater flow modeling. Layers that represent the basin's gross hydrostratigraphy may be too thick to accurately represent the depth variation of salt concentrations. Accordingly, the model layers were refined and subdivided to better represent clay overburden in the southwestern portion of the basin and the variability of well screen placements and TDS concentrations with respect to depth in the lower aquifer. By simulating the low conductivity overburden, and aquitard layers within the upper aquifer and lower aquifer units, the model is better able to simulate delays in downward salt migration.

1.2 BASIC MODEL INFORMATION OF THE LIVERMORE VALLEY GROUNDWATER MODEL

Zone 7 Water Agency maintains a numerical groundwater model of the basin for predicting the consequences of potential groundwater basin management actions on groundwater levels and salt concentrations in the basin. The model uses MODFLOW/MT3D to solve flow and transport equations. The active part of the groundwater model encompasses the Amador, Bernal, Bishop, Camp, Castle, Dublin, and Mocho II Subbasins of the Valley (Figure 7). The groundwater model consists of a grid comprising 120 rows, 166 columns and 10 layers. The horizontal grid is the same as version 2.0 of the model with a lateral grid spacing of 500 feet by 500 feet. Version 2.0 of the model consisted of three layers: the upper aquifer (Layer 1), an aquitard (Layer 2), and the lower aquifer (Layer 3). Most municipal water supply production wells in the basin are screened in the lower aquifer (version 2.0 Layer 3). Many small private wells are screened in the upper aquifer (version 2.0 Layer 1). This update includes an increase of the model layers from 3 to 10 layers to better simulate the vertical salt gradient present in the groundwater basin. Further discussion on the updated layering of the model is presented in Section 2.6.1(Update of Model Layering).

The groundwater flow within the Livermore Valley Groundwater Basin is modeled using MODFLOW-NWT (Niswonger et al., 2011), which is public domain code released by U.S. Geological Survey that addresses issues with solving groundwater flow equations for drying and re-wetting cells that previously necessitated using the proprietary MODFLOW-SURFACT code (Panday and Huyakorn, 2008) used for model version 2.0. The surface water and groundwater interactions are modeled using SFR and LAK MODFLOW packages. A detailed discussion on the implementation of these packages is presented in Sections 2.8 (Stream Flow Modeling (SFR)), 2.9 (Lake Modeling (LAK)), and 2.10 (Implementation of the Lake to Stream, Lake to Lake and Stream to Lake Connections).

The fate and transport of salt as represented by Total Dissolved Solids (TDS) within the Livermore Valley Groundwater Basin is modeled using MT3D along with two recently developed packages (LKT and SFT) to model the groundwater and surface water (lakes and streams) interactions. Zone 7 funded development of these recently developed packages that will be included in the upcoming public release of MT3D-USGS by the US Geological Survey (Bedekar, 2016). A detailed discussion on the implementation of these packages is presented in Sections 3.5 (Lake Transport (LKT)) and 3.5.4 (3.5.4.1

SECTION 2
FLOW MODEL CONSTRUCTION

2.1 HISTORICAL MODEL PERIOD

The groundwater flow model simulates historical conditions for Water Years 1974-2014. This period used for model calibration was selected based on availability of existing datasets. Previous versions of the groundwater model were calibrated to the 1974-1994 and 1974-2004 periods (Zone 7 and HydroMetrics LLC, 2006). Water Year 2014 was added to the model period as part of an extension of the California Department of Water Resources (DWR) grant to include the 3rd consecutive drought year.

2.2 STRESS PERIODS

Stress periods define a time period in the groundwater model over which hydraulic stresses such as pumping and recharge are held constant. Stress period selection depends on data availability, the model objectives and the time frame of interest. For the model to simulate interaction of surface water flows and groundwater flows, stress periods of shorter length are required and monthly stress periods are used for this model.

2.3 BOUNDARY CONDITIONS

The boundary conditions for the groundwater flow model are no flux for all model boundaries except for the boundary at the top of the basin, which is a specified flux. The flux is determined internally in the model by the specified rate of areal recharge inflow. Figure 1 shows the average areal recharge for the period of 1974-2014 in the Livermore Valley Groundwater Basin. Zone 7 calculated monthly values on the model grid for areal recharge from rainfall, applied water (including recycled water), and pipe leakages that were combined for use in the model.

2.4 INITIAL CONDITIONS

Initial conditions for the flow model simulating transient conditions for 1974-2014 are steady state heads simulated by the model run. In order to best represent known conditions at the start of the transient run, observed data are used as specified heads for the steady state run. This allows the transient run to start from heads that are consistent with the model as well as observations.

Data are limited in 1974 so first available measurement for the period of 1974-1978 are used as the specified heads for the steady state run. This period was selected to increase the number of data points (Figure 2) used to improve spatial coverage while representing conditions at the start of the transient run. Figure 3 through Figure 6 show the groundwater levels used as specified heads in the steady state run to create initial conditions.

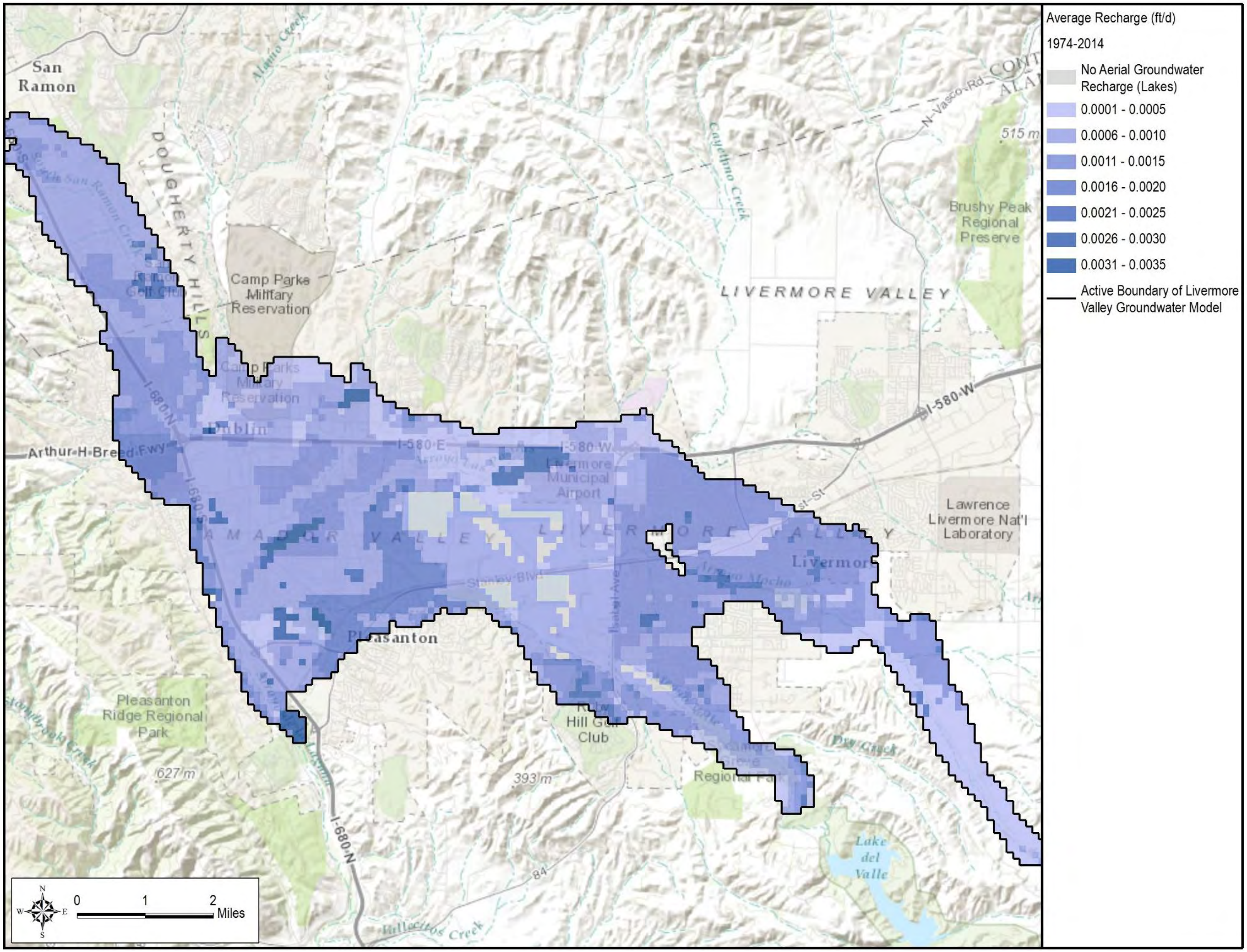

Figure 1: Average Areal Recharge in the Livermore Valley Groundwater Basin for the Period of 1974 to 2014

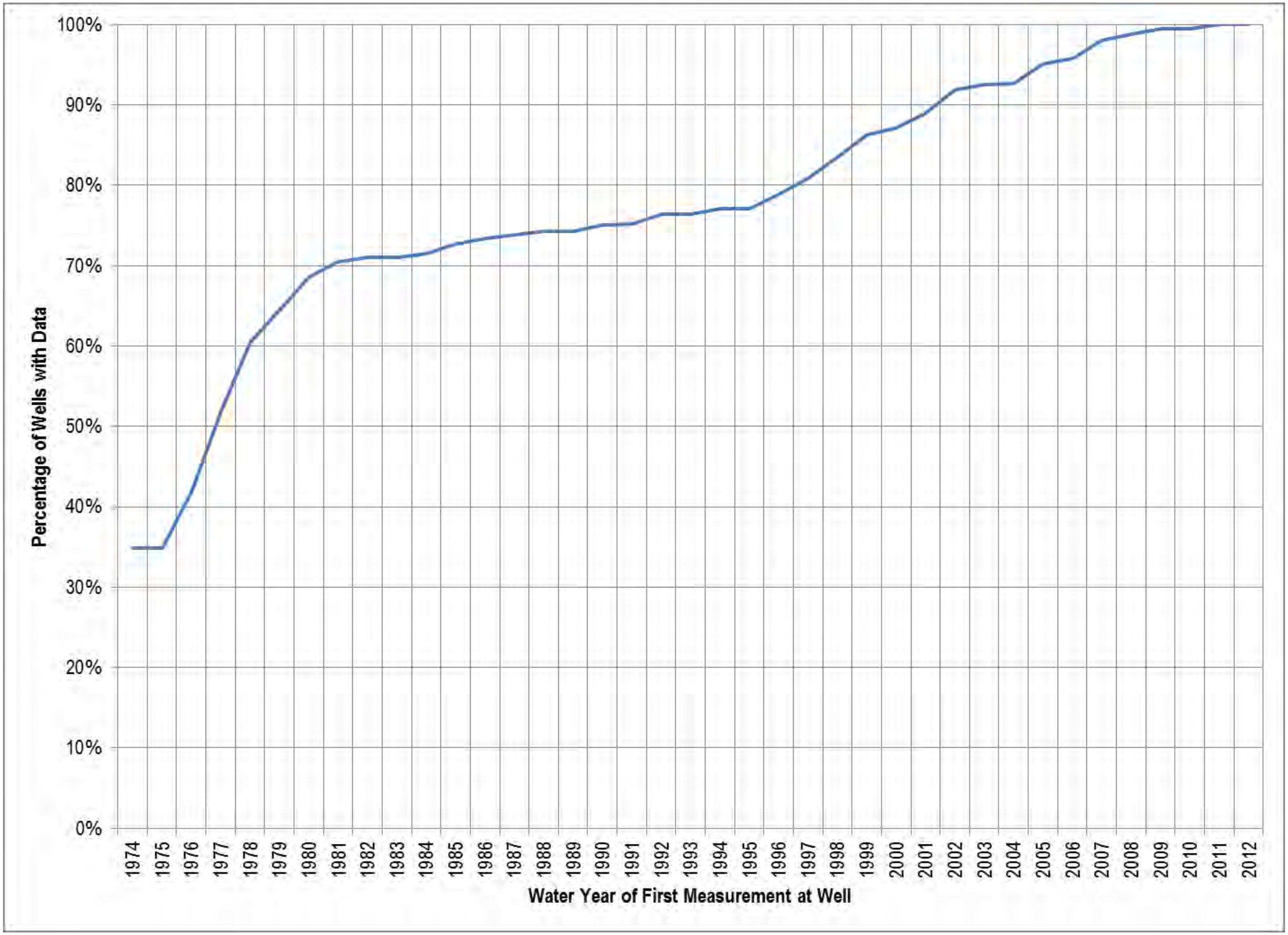

Figure 2. Percentage of Wells by Water Year of First Groundwater Level Measurement

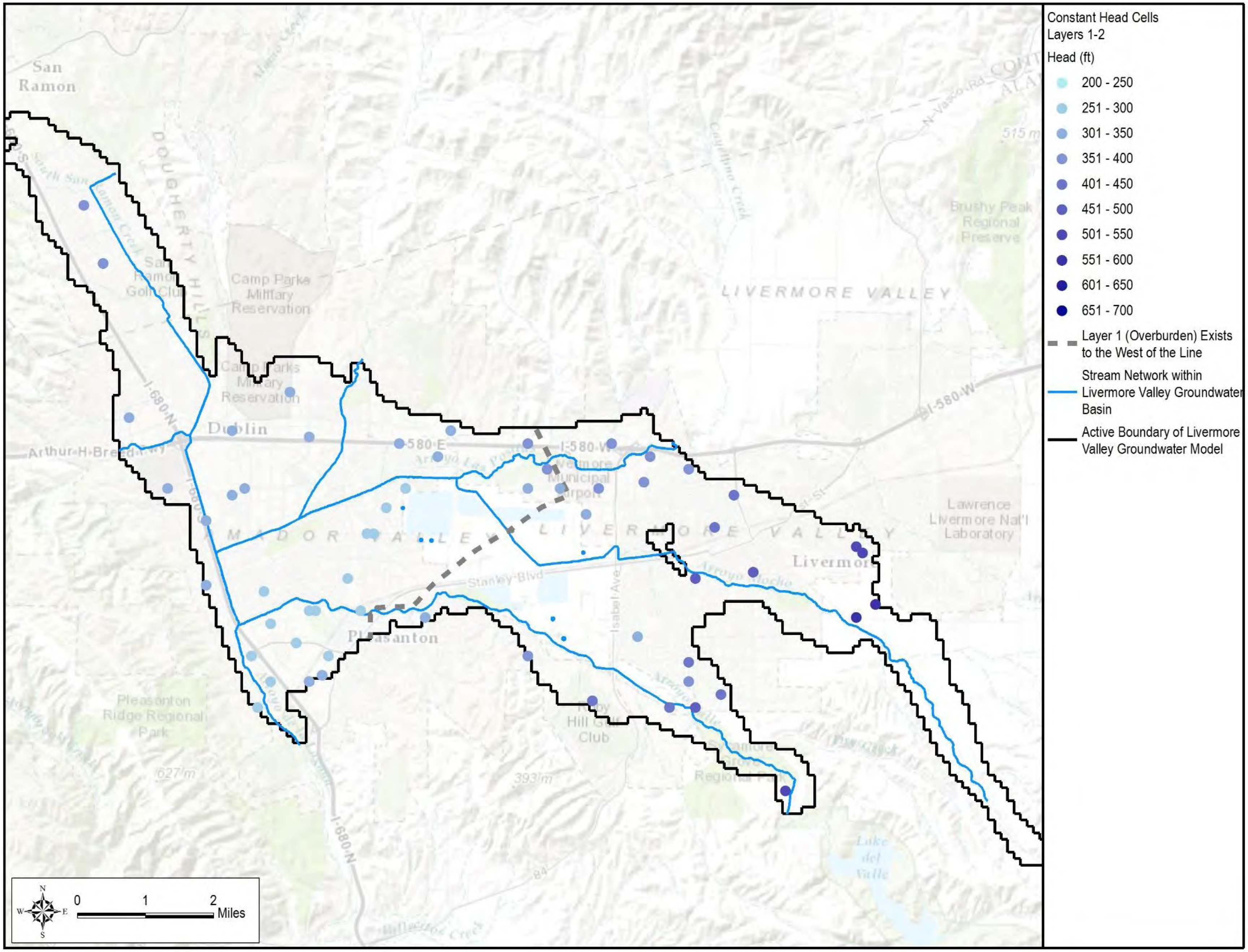

Figure 3: Constant Head Cells in Layers 1 to 2

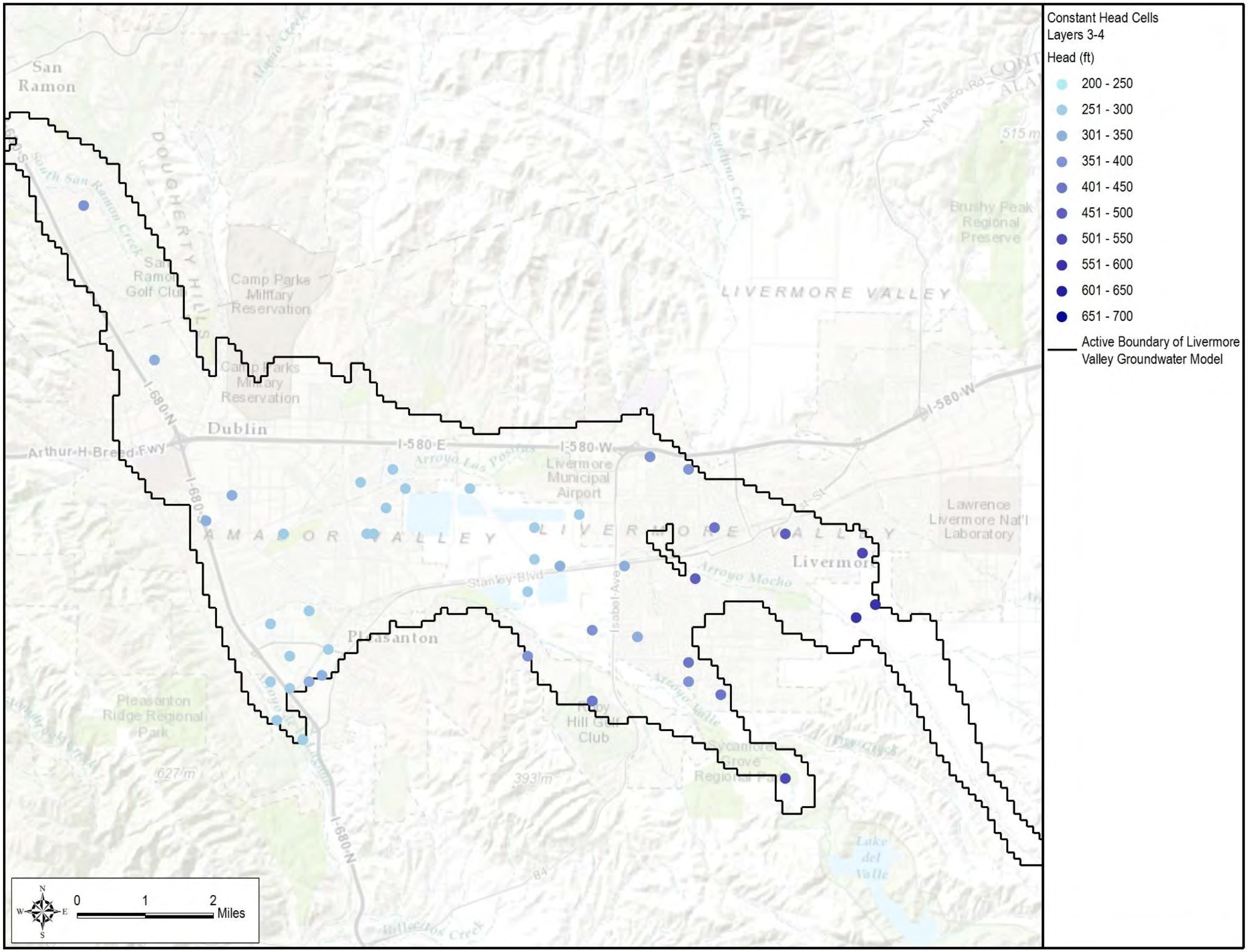

Figure 4: Constant Head Cells in Layers 3 to 4

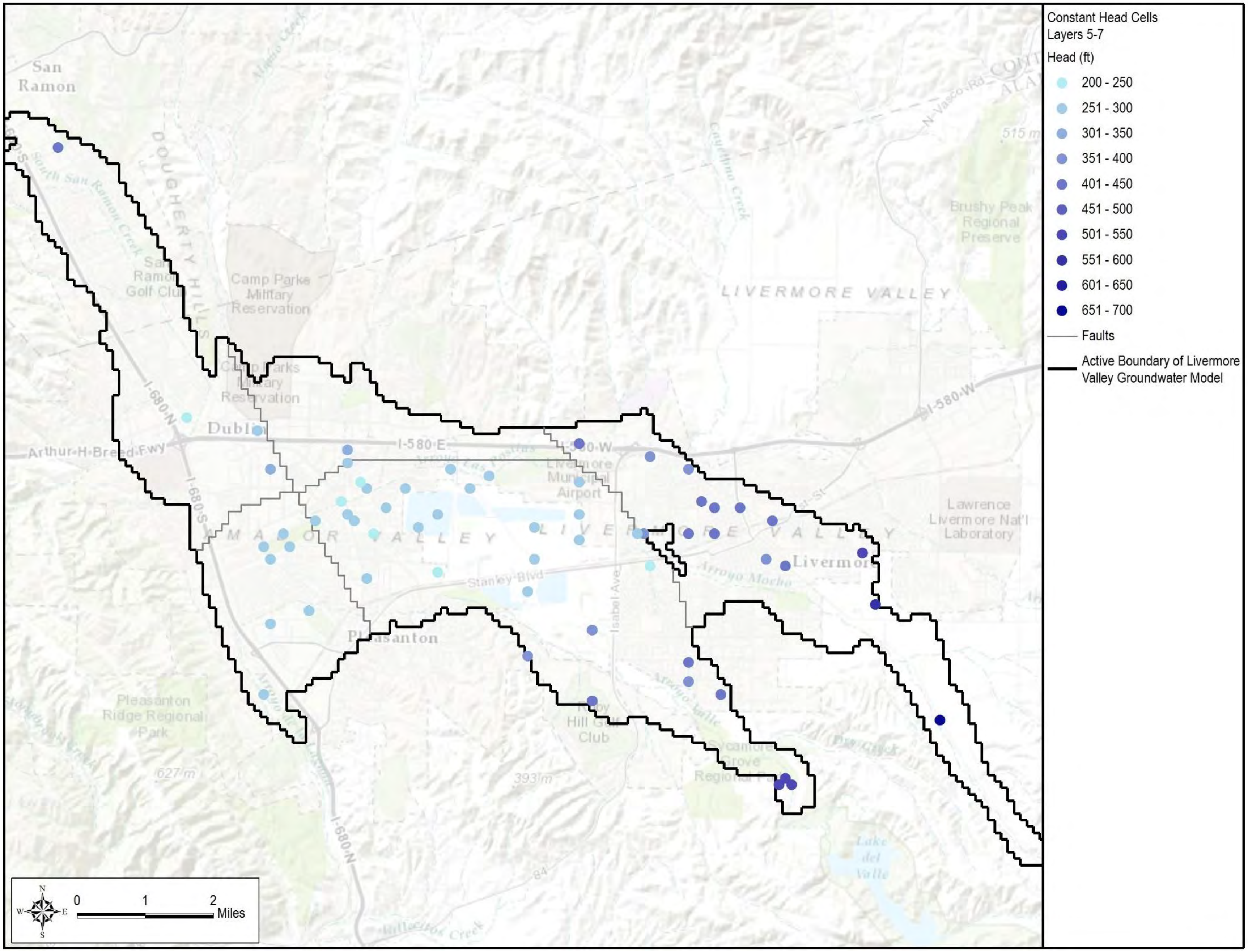

Figure 5: Constant Head Cells in Layers 5 to 7

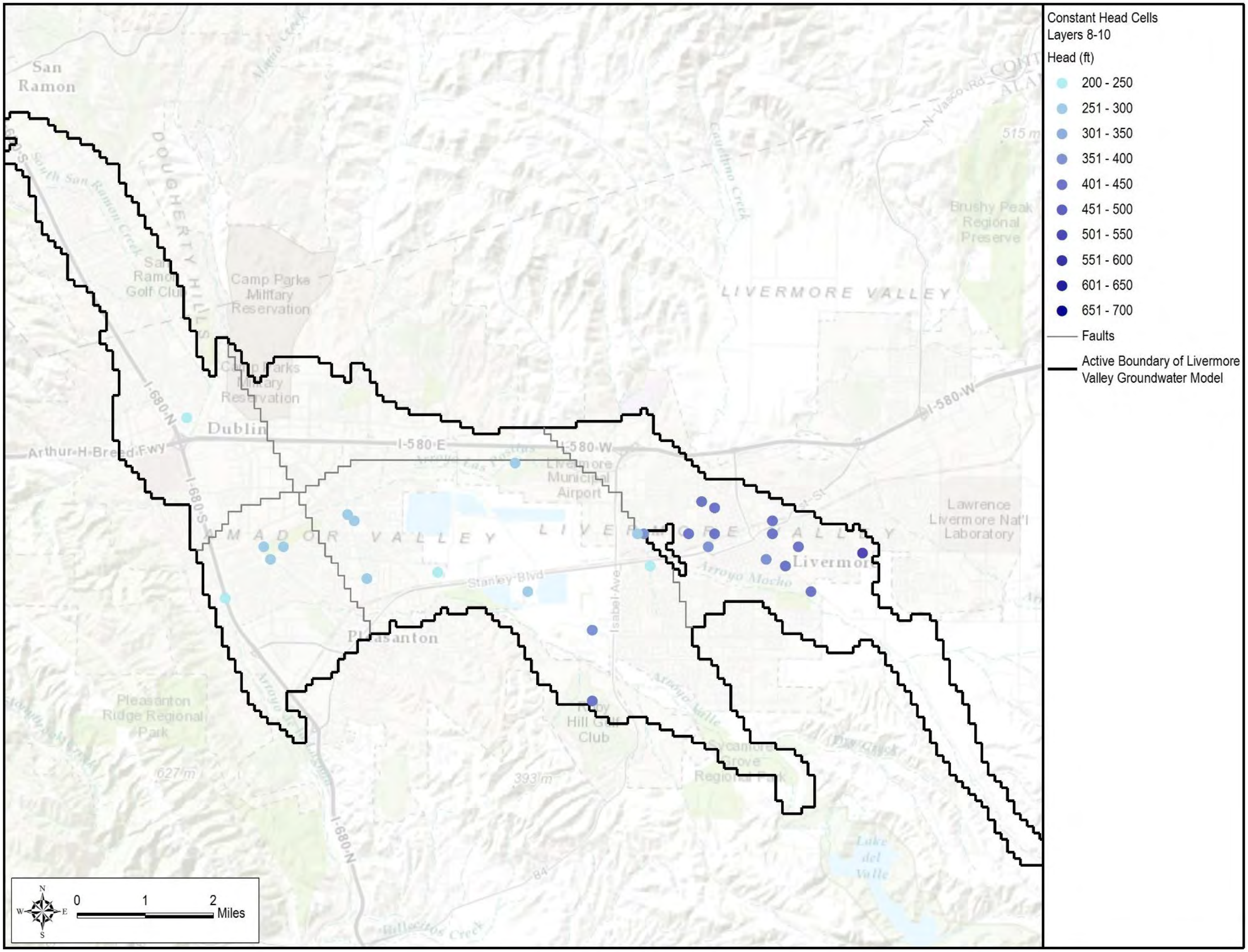

Figure 6: Constant Head Cells in Layers 8-10

2.5 Flow Model Settings

The flow and movement of the groundwater within the Livermore Valley Groundwater Basin is modeled using MODFLOW-NWT (Niswonger et al., 2011, version 1.0.9). Different MODFLOW packages were utilized to model sources and stresses in the basin as shown in Table 1. The LMT package is implemented here to provide the necessary linkages between the flow and transport models. The LMT package included in the latest version of the MF_NWT creates the flow-transport link (FTL) file that includes surface water flows needed to simulate surface water transport with the new package of the MT3D-USGS.

Table 1: MODFLOW Packages Used

Package Name	Descriptions	Notable Settings
Basic (BAS)	Array of active cells (IBOUND)	N/A
Discretization(DIS)	Grid and Stress Period Setup	1 time step per stress period
Upstream Weighting (UPW)	Flow Properties for MODFLOW-NWT	All layers convertible between confined and unconfined (LAYTYP>0)
Recharge (RCH)	Areal Recharge	Recharge applied to top active layer (NRCHOP=3)
Multi-Node Well (MNW2)	Pumping file for wells screened across multiple layers	Vertical low distribution calculated using Thiem method (LOSSTYPE=THIEM)
Stream Flow Routing (SFR1)	Streams	See Section 2.8
Lake (LAK3)	Lakes	See Section 2.9
Link Model Transport (LMT)	Outputs file for MT3D-USGS to read flow results including surface water flows	N/A

2.6 Domain and Discretization

2.6.1 Update of Model Layering

This model update includes an increase in the number of model layers to better simulate the vertical salt gradient present in the groundwater basin. To this aim, existing cross-sections and boring logs were reviewed to identify potential model layers and their depths (Figure 7). The new layering were mapped and contoured based on the depths of the layers in the boring logs. *ArcGIS* Raster Images were created using *ArcGIS*

Spatial Analyst for each of the layers based on the contours and layer elevations encountered in the boreholes. Layer minimum thicknesses were enforced in *Spatial Analyst* (Figure 7; 10 feet for layer 4 and 5 feet elsewhere), this ensured that model layers did not intersect each other. The new model layers were further revised to 1) create a basin shape that is more bowl like and 2) be consistent with stream elevations.

The number of model layers are increased to ten from the three layers used in version 2.0 of the model (Figure 7). The top and bottom of the new model are roughly the same as version 2.0 of the model. The model layers were developed starting from the highest layer and working downwards. The model layer elevations were checked for layer intersections automatically by enforcing a minimum layer thickness as discussed above. Top of the new model was updated using the Zone 7's Digital Elevation Model (DEM) of the ground surface (compiled from 2006 Alameda County LIDAR data and 2011 National Elevation Dataset (3 meter). The bottom elevation of the Layer one, which represents lacustrine clay overburden deposits in the western portion of the Valley, was then mapped by 1) enforcing the minimum thickness of 5 feet, and 2) consistency with the available stream elevations. To the east of the gray dashed line on Figure 8 the new Layer 1 is inactive representing the Layer 2 outcropping of shallow, water-bearing, course-grained deposits. APPENDIX A: includes figures of ARCGIS Rasters representing the bottom elevations of each new layer.

The new Layers 3, 5, 7 and 9 represent fine-grained aquitards that restrict vertical groundwater flow and salt migration. Vertical hydraulic conductivity of these layers are adjusted during calibration in order to provide resistance to flow between the overlying and underlying aquifer layers.

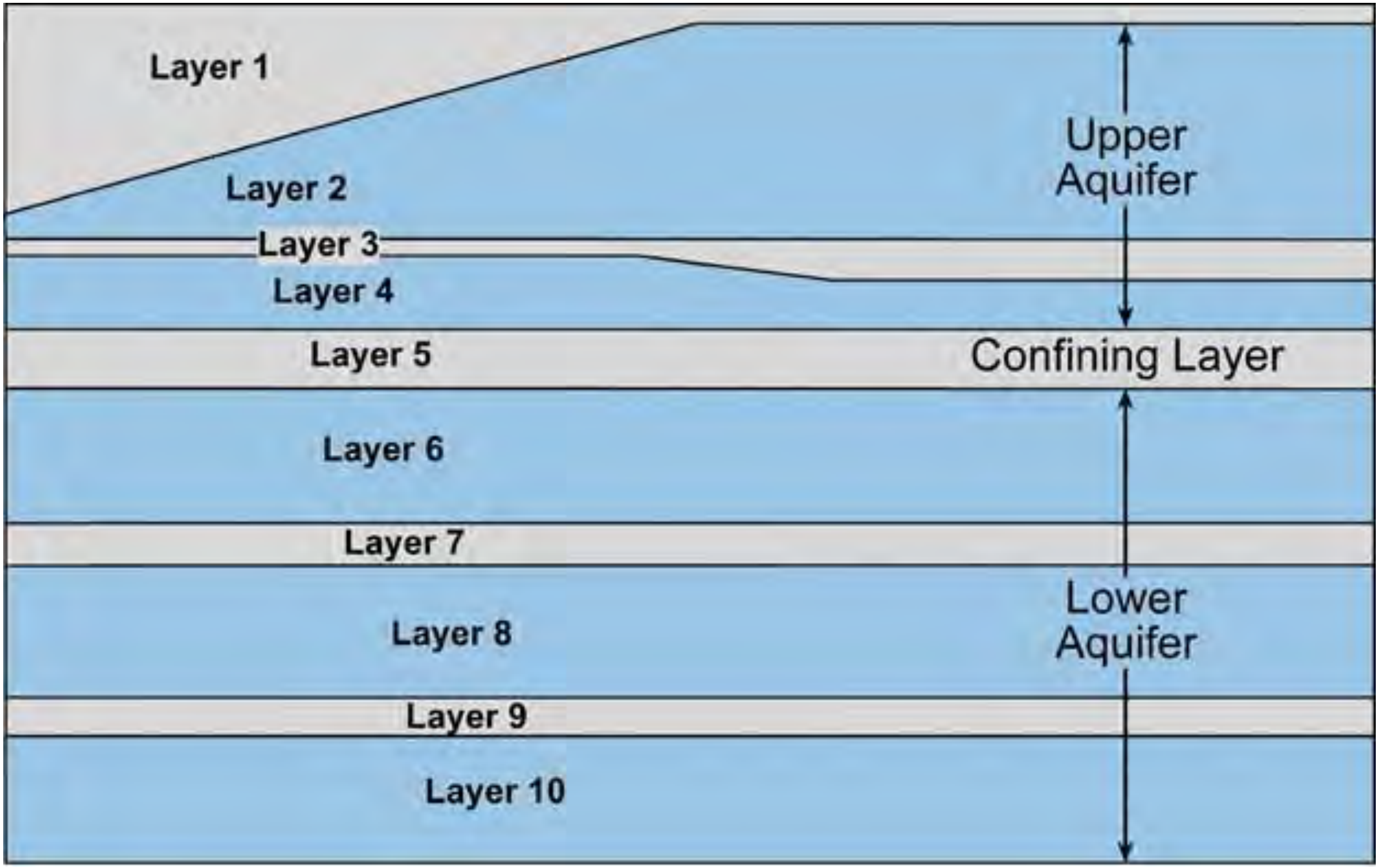

Figure 7 Schematic of the New Model Layers (as modified by Zone 7 and Todd, 2016)

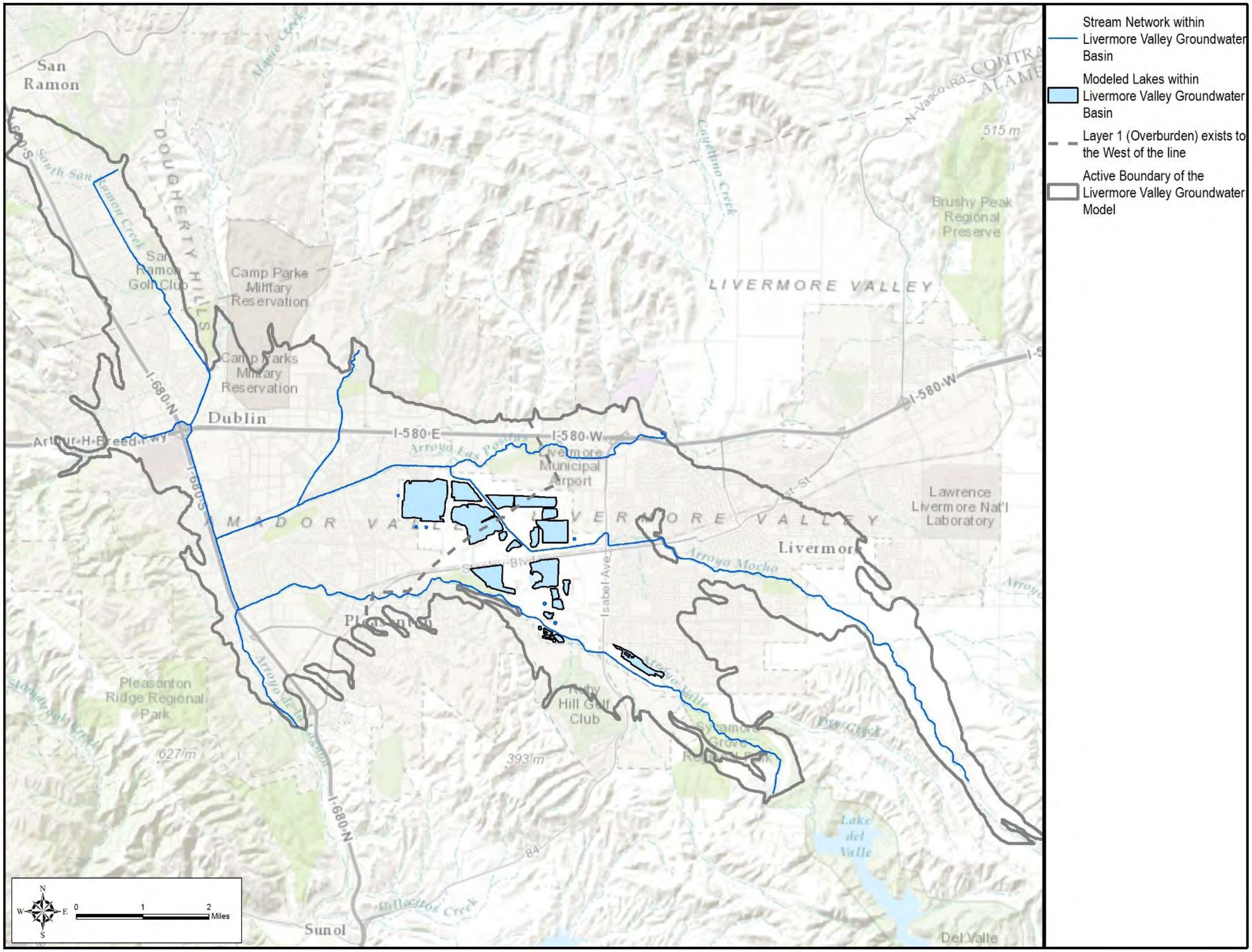

Figure 8: Livermore Valley Groundwater Basin

2.7 PUMPING DATA

Zone 7 provided data on pumping wells including locations and screen intervals. Are wells are implemented in the Multi-Node Well (MNW2, Konikow et al., 2009) package as having a single screen based on the top and bottom elevation of screens provided by Zone 7. Zone 7 also provided monthly pumping values at the wells for input into the model. The vertical distribution of flows for wells screened across multiplied was calculated using the Thiem method based on cell transmissivity and an assumed well radius of 8 inches.

2.7.1 MODIFICATION OF SIMULATED AGRICULTURAL PUMPING

In checking the water budget, it was noted that there is a significant discrepancy between the values of pumping in the hydrologic inventory and the simulated pumping especially between water years 1974 and 1987 (Figure 9). When the individual simulated pumping were checked against the recorded pumping of each well in the hydraulic inventory, it was clear that the problem could be related to some of the simulated agricultural wells mostly located in the southeastern portion of the Mocho Sub-Basin (Figure 10) where simulated groundwater levels resulted in simulated pumping from the wells being reduced from input amounts. The hydrologic inventory pumping versus simulated pumping for these wells is shown in APPENDIX B:. These simulated agricultural wells do not represent actual wells but instead represent the estimated total agricultural pumping in the Main Basin without knowledge of well details such as screen interval elevations. Zone 7 located these wells in the general area that is known for most agricultural pumping in the Main Basin. This means that the simulated location and screen depth of these wells can be modified in order to better match the simulated pumping to the hydrologic inventory pumping. Most of these wells were located in close proximity to the model boundary (Figure 10) and are concentrated close to the entrance of the Arroyo Mocho to the Basin. Furthermore, all of these wells were originally assigned a very short screen interval from layer 6 to 8. In an effort to match the desired and simulated pumping, the following modifications were applied to these imaginary agricultural wells:

1. The simulated wells were moved slightly away from the model boundary to decrease any model boundary effect
2. The simulated wells were moved slightly away from each other to remove any drawdown effect from nearby wells.
3. The screen intervals of the simulated wells were lengthened to allow the pumping from these wells from the entire depth of the model.

The modifications explained above greatly improved the individual pumping (APPENDIX B:) and the overall model budget (Figure 9). With these modifications the simulated total pumping matches very closely to the pumping reported in the hydrologic inventory (Figure 9).

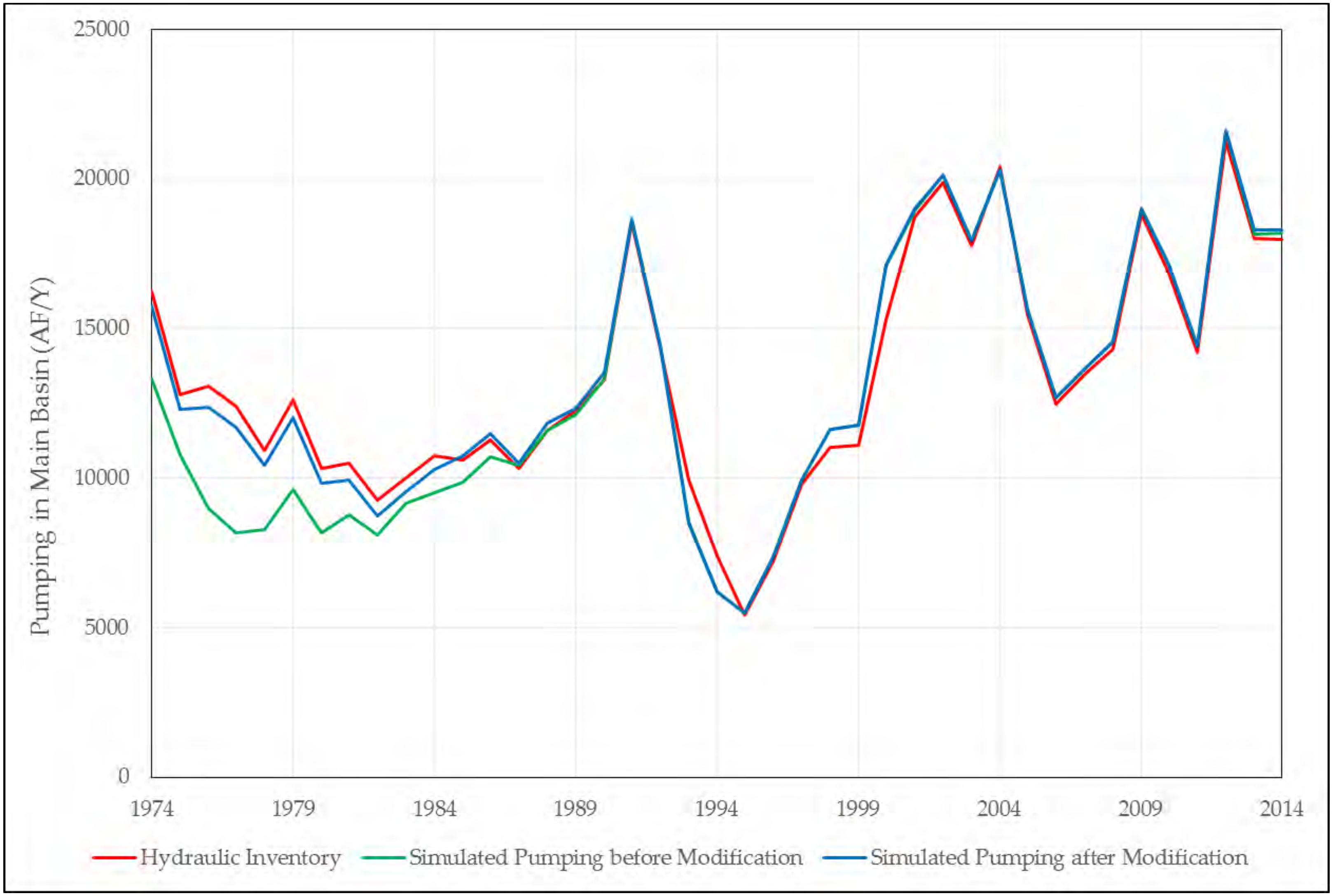

Figure 9: Pumping in the Main Basin

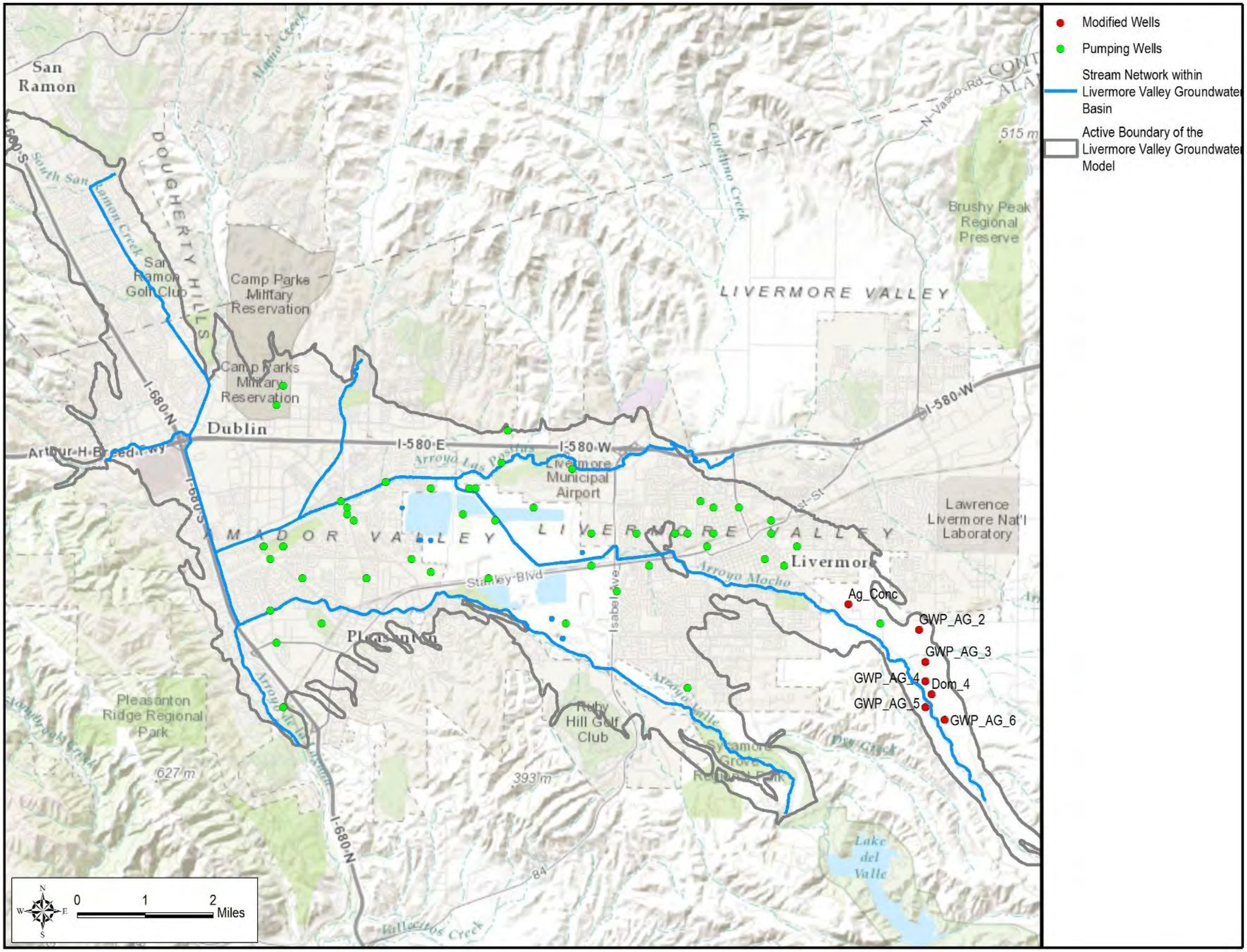

Figure 10: Location of the Modified Simulated Agricultural Pumping

2.8 STREAM FLOW MODELING (SFR)

The MODFLOW Stream Flow Routing (SFR1, Niswonger and Prudic, 2005) package was used to simulate the surface water and groundwater interactions. The program is designed to route streamflow through a network of channels, this network of channels is divided into reaches and segments. Special care was given to reach and segment numbering such that they were numbered sequentially from the farthest upstream segment/reach to the last downstream segment/reach (Figure 11), except for the segments 37 to 43 which do not represent actual stream segments but are added to simulate transfer of water between streams and lakes (these segments are not shown on Figure 11). The stream and lake connections are further discussed in the following sections. The basic information of the layer, row and column of the cell that corresponds to each reach and the length of the stream reach within that model cell is read for each reach and segment. The locations of the streams are assumed to remain fixed throughout the entire simulation.

2.8.1 STREAM NETWORK

Figure 11 represents the model channel network and segment numbering to simulate streams within the groundwater basin. The channel network consists of 43 segments and 588 reaches. Layer 1 representing overburden only exists to the west of the dashed line in the map, consequently the segment reaches to the east of the boundary are placed in the next active layer; Layer 2. Table 2 summarizes the stream network description. Streambed elevations are listed here for the first and last reach in each segment. SFR uses a linear interpolation to estimate the elevation at the midpoint of each reach.

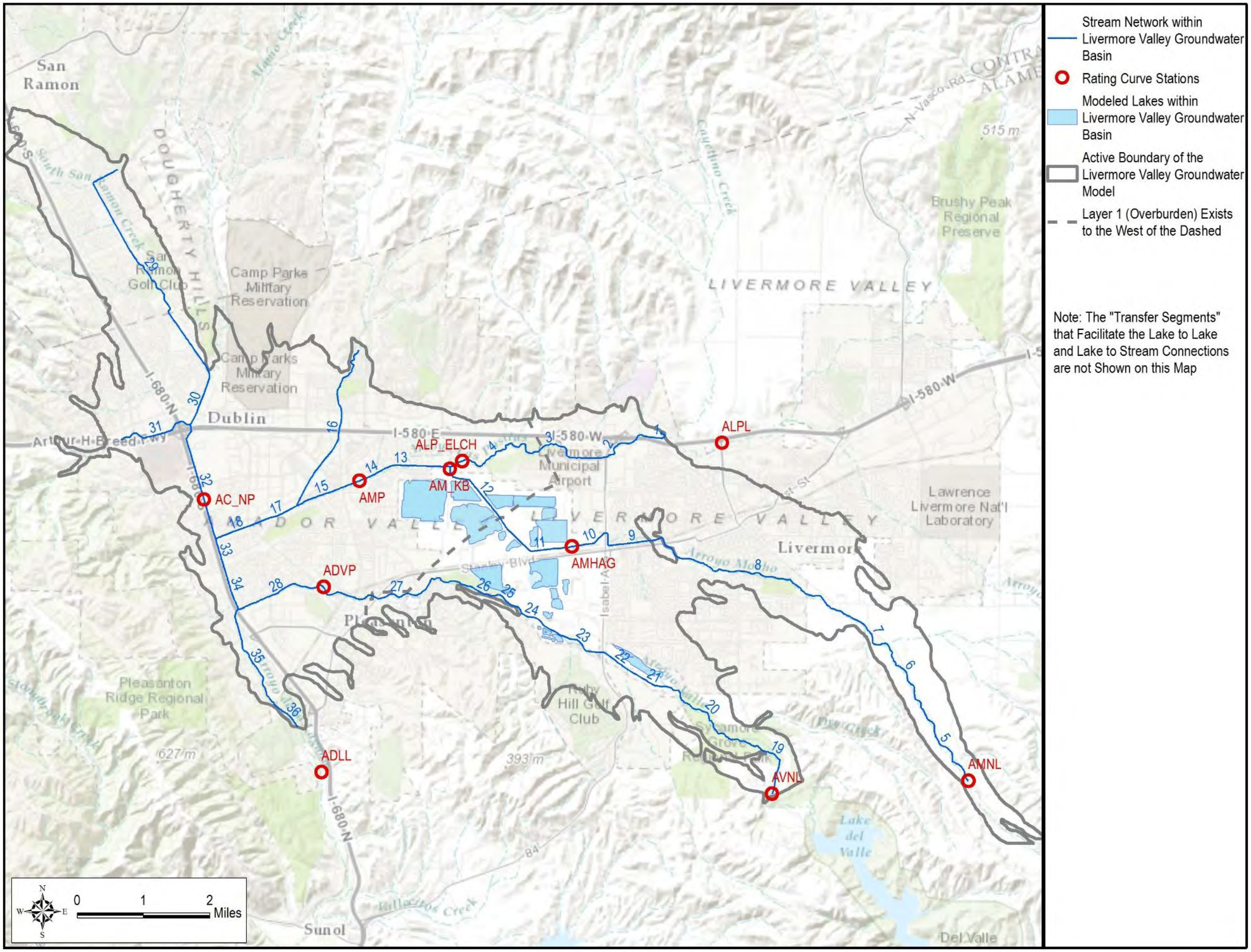

Figure 11: Livermore Valley Stream Network

Table 2: Zone 7 Stream Network Description

Stream	Segment Number	# of Reaches	Method (ICALC)	Headwater	Tributary to Segment	Diversion from Segment	Streambed Elevation at first reach (ft)	Streambed Elevation at last reach (ft)	Overland Runoff
Arroyo Las Positas	1	7	Rating Table	YES	2		412.40	403.50	YES
	2	13	Rating Table	NO	3		403.50	386.10	YES
	3	18	Rating Table	NO	4		386.10	365.50	YES
	4	15	Rating Table	NO	13		365.50	338.80	YES
Arroyo Mocho	5	21	Rating Table	YES	6		753.00	673.00	YES
	6	14	Rating Table	YES	7		673.00	624.00	YES
	7	11	Rating Table	NO	8		624.00	584.00	YES
	8	42	Rating Table	NO	9		584.00	438.20	YES
	9	9	Rating Table	NO	10		434.50	406.00	YES
	10	10	Rating Table	NO	11		406.00	393.20	YES
	11	13	Rating Table	NO	12		393.20	369.70	NO
	12	19	Rating Table	NO	13		369.70	338.80	NO
	13	11	Rating Table	NO	14		338.80	326.80	NO
	14	9	Rating Table	NO	15		326.80	324.40	NO
	15	15	Rating Table	NO	17		324.40	313.20	NO
Tassajara Creek	16	38	Constant Stage	YES	17		385.40	313.20	NO
Arroyo Mocho	17	8	Rating Table	NO	18		313.20	307.10	NO
	18	11	Rating Table	NO	34		307.10	299.30	NO
Arroyo Valle	19	17	Rating Table	YES	20		514.10	479.60	YES
	20	19	Rating Table	NO	21		479.60	440.00	YES
	21	11	Rating Table	NO	22		440.00	420.70	YES
	22	7	Rating Table	NO	23		420.70	405.50	YES
	23	14	Rating Table	NO	24		405.50	373.00	YES
	24	10	Rating Table	NO	25		373.00	351.20	YES
	25	5	Constant Stage	NO	26		351.20	350.20	YES
	26	18	Constant Stage	NO	27		349.50	349.00	YES
	27	22	Rating Table	NO	28		349.00	319.30	YES
	28	20	Rating Table	NO	35		319.30	294.00	NO
Alamo Canal	29	57	Rating Table	YES	30		430.00	322.70	NO
	30	13	Rating Table	NO	32		322.70	312.60	NO
Dublin Creek	31	17	Constant Stage	YES	32		385.40	312.60	NO
Alamo Canal	32	26	Rating Table	NO	33		312.60	299.30	NO
Arroyo De La Laguna	33	6	Rating Table	NO	34		299.30	297.40	NO
	34	10	Rating Table	NO	35		297.40	294.00	NO
	35	22	Rating Table	NO	36		294.00	281.80	NO
	36	4	Rating Table	NO			281.80	270.00	NO
"Transfer" Segments	37	1	Constant Stage	NO	12	-18	256.00	255.50	NO
	38	1	Constant Stage	NO	26	-18	256.00	255.50	NO
	39	1	Constant Stage	NO	11	-8	256.00	255.50	NO
	40	1	Constant Stage	NO	25	-4	233.00	232.50	NO
	41	1	Constant Stage	NO	-15	-18	260.00	259.50	NO
	42	1	Constant Stage	NO	-15	-3	303.50	303.00	NO
	43	1	Constant Stage	NO	-15	25	336.00	335.50	NO

2.8.2 Rating Curves

The SFR package is set up to compute the stream depths using the tabulated values relating stream depth (stage) and width to flow (discharge) for 32 segments ("Rating Table" in Table 2); and constant stage for the remaining segments ("Constant Stage" in Table 2). Stream widths are also simulated to be constant at different flows. The effect of stream width on stream-aquifer interactions is calibrated as a part of the stream conductance term (KwL/b).

The selection of the calculation method for stage based on flow is dependent on the availability of the rating table data for each SFR stream segment. The locations of stations with rating table data are shown on Figure 11. There are only 10 stations with rating table data available, thus each rating table is assumed to be representative of more than one segment. It should be noted that rating table data are not available for the Tassajara (segment 16) and Dublin (Segment 31) Creeks and thus the constant stage calculation method was selected for these streams. Table 3 summarizes some information about the stations and rating tables used to compute the stream depth. The SFR package only reads up to 50 entries of a rating table. All of the rating tables available for this study have more than 50 entries, thus 50 data points were selected to represent the overall shape of the rating curve. Figure 12 portrays the rating curves for the ten stations. The selected data points are shown as red solid circles on each rating curve presented in Figure 12. Figure 12 shows that the selected points well represent the curvature and shape of each rating curve.

Table 3 Summary of Stations with Rating Table used for each Stream

Stream Name	Station Name	Rating Table Data Points	Represents Segment #	Remarks
Arroyo Las Positas	ALPL	584	1-2	-
	ALP_ELCH	680	3-4	-
Arroyo Mocho	AMNL	1486	5-9	-
	AMHAG	604	10-11	-
	AM_KB	886	12	-
	AMP	1486	13-18	-
Arroyo Valle	AVNL	669	19-24	-
	ADVP	416	25-28	-
Alamo Canal	AC-NP	211	29-32	-
Arroyo De La Laguna	ADLL	2110	33-36	-
Tassajara Creek	N/A	N/A	N/A	No Rating Table is available/used for the Tassajara Creek
Dublin Creek	N/A	N/A	N/A	No Rating Table is available/used for the Dublin Creek

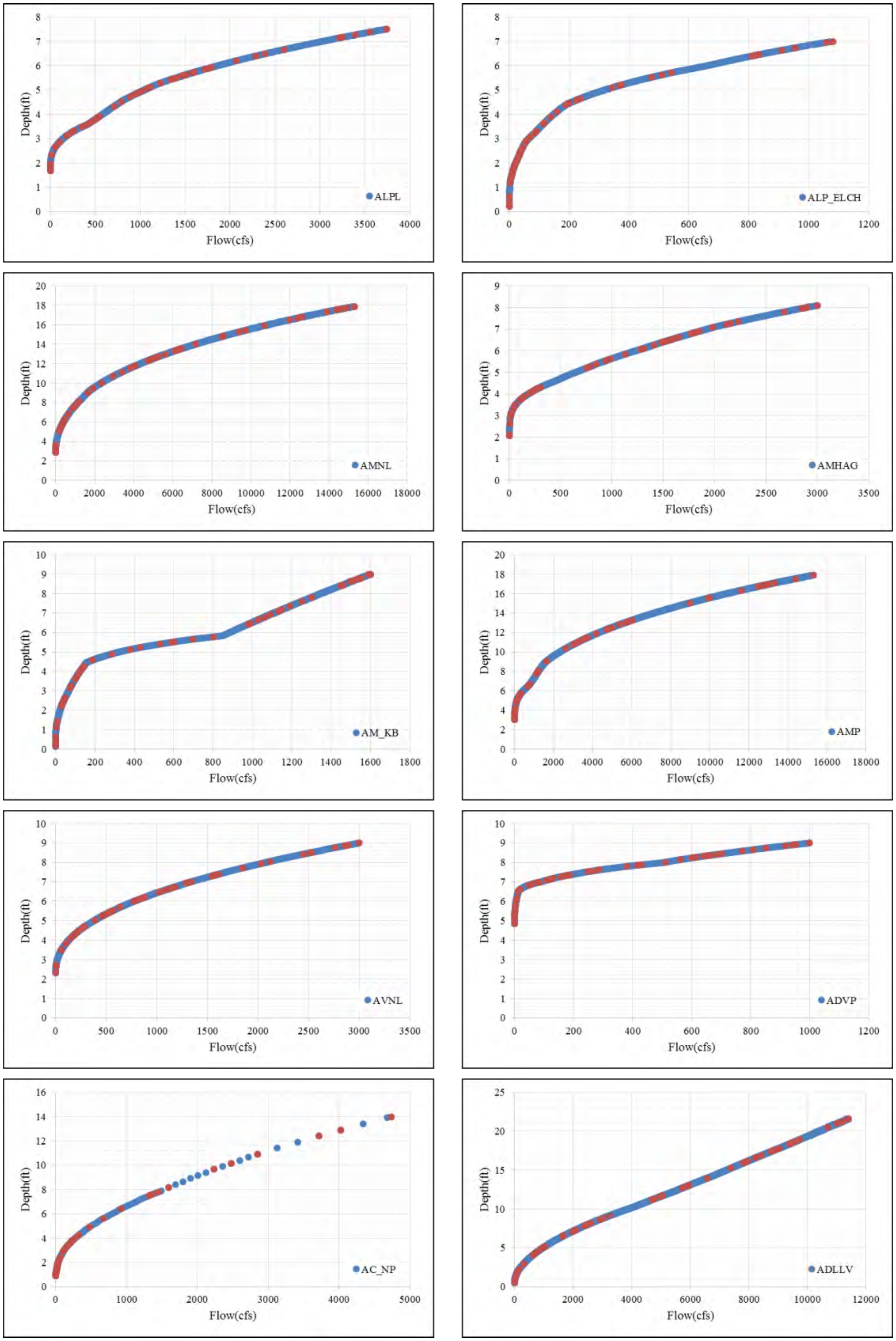

Figure 12: Rating Curves at Each Station, this data was used by the SFR package to relate the stream depth to flow

2.8.3 Transient Inflows at Headwater Segments

The stream water flows through six headwater streams into the system boundaries; 1) Arroyo Las Positas, 2) Arroyo Mocho, 3) Arroyo Valle, 4) Tassajara Creek, 5) Alamo Canal and 6) Dublin Creek. There is only one stream flowing out of the model boundaries: Arroyo De La Laguna. The general direction of the flow across the valley is from North-East to South-West. The transient flow of the headwater streams is one of the inputs that the user is required to provide to the SFR package.

Two stream gage stations recorded the monthly flow at the headwater segments for the Arroyo Mocho near Livermore (AMNL) and Arroyo Valle near Livermore (AVNL) during the entire period of 1974 – 2013. The data for the stream flow at the station at the headwater segment for the Arroyo Las Positas at Livermore (ALPL) is missing prior to 1980. Arroyo Mocho at Pleasanton (AMP) is the closest downstream stream gage to ALPL with sufficient flow data (Figure 11). Correlation between AMP and ALPL after 1980 is adequate enough to use the stream flow records at the AMP station for water years 1974 -1980 along with a correlation factor are used to represent the monthly headwater flow for the Arroyo Las Positas for the missing period.

No stream gage is installed at three of the headwater segments: Tassajara, Alamo and Dublin Creeks. Thus, transient inflow data are not available for these segments. The transient inflow at Alamo Canal was estimated based on the gaged inflows (AMP and Arroyo Del Valle at Pleasanton, ADVP, on Figure 11) and outflows (Arroyo De La Laguna, ADLL on Figure 11) to and from Alamo Canal (Table 4) as well as the estimated recharge rate along the Alamo Canal; -1 cfs (Zone 7, 2013, Figure 3.3-1). There was insufficient data available to base the inflow estimate for the Tassajara and Dublin Creeks (Table 4). These two streams are generally dry for most of the year (Rooze, verbal communication, 2015). Thus, the transient inflow at the Tassajara and Dublin Creek was assumed to be equal to zero and the creeks only become active when they gain water from the underlying groundwater system.

Figure 13 shows the monthly inflow at each of the headwater segments based on the available data.

Table 4 Summary of the Transient Inflow Data at the Headwater Segments

Stream Name	Segment #	Station Name	Period of Record	Missing Years	Action for Missing Data
Arroyo Las Positas	1	ALPL	1980-2013	1974-1980	Flow was correlated to flow records at AMP station for the missing period
Arroyo Mocho	5	AMNL	1974-2013	None	
Tassajara Creek	16	No station	NA	NA	Assumed to be mostly dry with no transient inflow
Arroyo Valle	19	AVNL	1974-2013	None	
Alamo Canal	29	No station at Alamo Canal entrance to the model domain	NA	NA	A simple mass balance equation was used to estimate the Alamo Canal inflow based on inflow from the Arroyo Mocho, inflow from the Arroyo Valle, outflow to the Arroyo De La Laguna, and the estimate of groundwater discharge rate along the Alamo Canal (ACsyn=ADLL-AMP-ADVP-Discharge Rate @ Alamo Creek)
Arroyo Valle	Used to calculate inflow at segment 29	ADVP	1974-2013	None	
Arroyo Mocho	Used to calculate inflow at segment 29	AMP	1974-2013	None	
Arroyo De La Laguna	Used to calculate inflow at segment 29	ADLL	1974-2013 with missing periods	Oct/84-Dec/87 Nov/97-Dec/02 Oct/03-Dec/03	The monthly averages of available data represent the missing periods
Dublin Creek	31	No station	NA	NA	Assumed to be mostly dry with no transient inflow

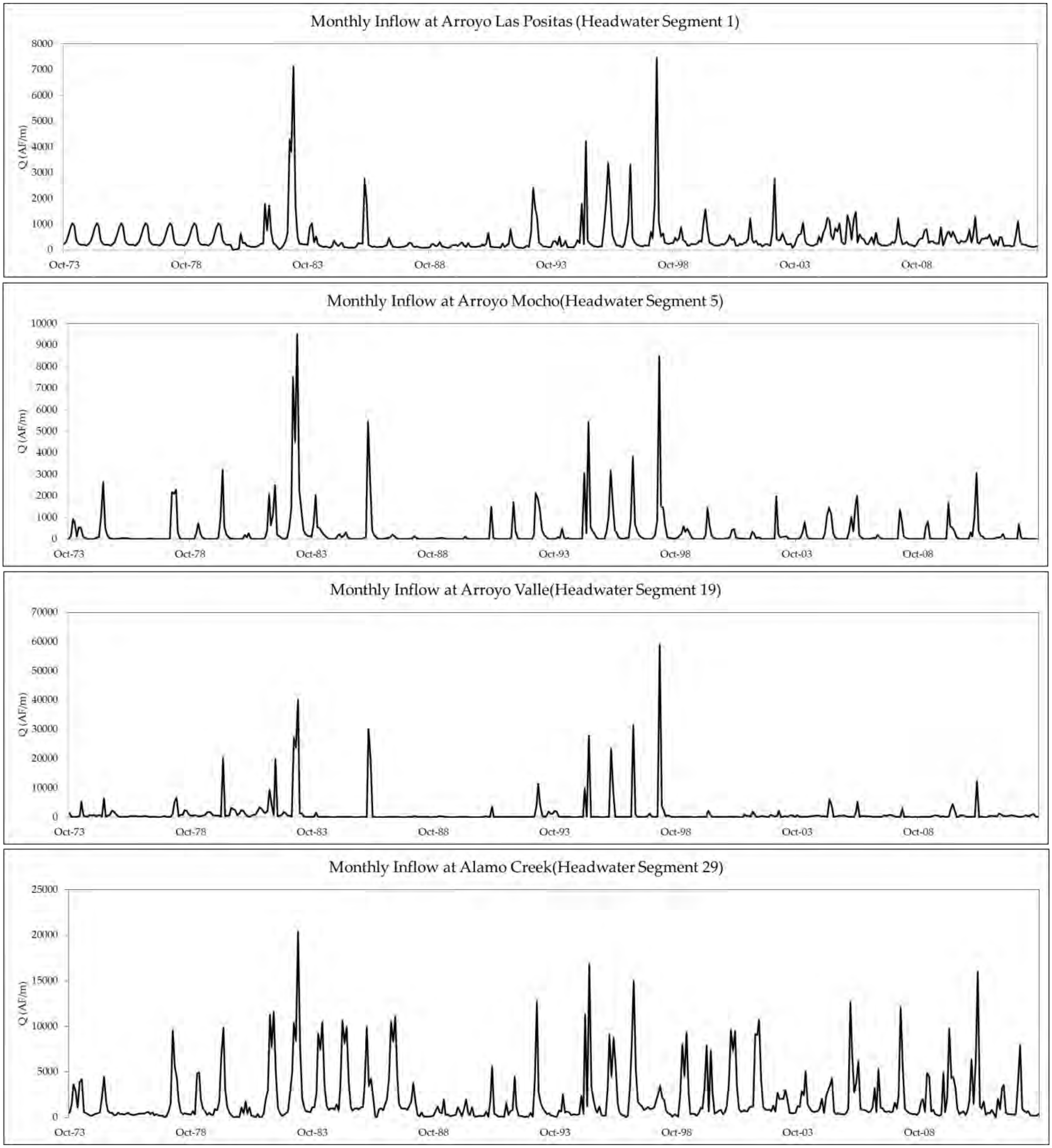

Figure 13: Monthly Inflow at Headwater Segments

2.8.4 TRANSIENT RUNOFF IN TO STREAMS

Additional flow is received by the modeled streams after they have entered the model area. Small ungauged tributaries, stormwater outflow from the cities of Livermore and Pleasanton, and overland flow in response to runoff all contribute runoff to the modeled streams. Independent estimates of these quantities are not available for the area and time scale required for the model, so monthly runoff terms were estimated as a part of this project. A mass balance, or water budget, method was used to estimate the monthly volume of runoff received by segments of the Arroyo Mocho, Arroyo las Positas, and Arroyo del Valle that are within the model and are between gaging locations. The portions of streams for which runoff is assigned are listed in Table 5.

Table 5: Streams Simulated to Receive Additional Runoff

Stream	Upstream Gage	Downstream Gage
Arroyo Valle	AVNL	ADVP
Arroyo Mocho	AMNL	AMHAG
Arroyo Las Positas	ALPL	ALP_ELCH

The application of the water budget method consisted of three steps. First, a streamflow water budget equation was developed for each of the three streams. Within this water budget all inputs of water to the stream and outputs of water from the stream were identified. Second, measured or estimated values were for all budget terms except for runoff were collected from databases compiled by Zone 7 staff. These were filled in as known values in the equation, with the runoff as the closure term of the equation. Finally, runoff was estimated by calculating the value needed to balance the equation. The general form of the water balance equations is the simple statement of conservation of mass with the assumption of no change in storage:

$$\text{Inflows} = \text{Outflows}$$

The sources of inflow to the stream segments include:

- Upstream Inflow
- Zone 7 Releases from Del Valle Reservoir or the South Bay Aqueduct
- Mining Releases
- Runoff

The outflows of water from the stream segment exit as:

- Downstream Outflow
- Seepage to Groundwater
- Diversions

- Evaporation loss

Due to the lack of adequate measurements, outflows from streams to diversions and evaporation loss are not simulated in this study. In order to calculate runoff, the water budget equations for each stream including the exact sources and sinks of water are:

Arroyo Las Positas:

ALPL + RO = ALP_ELCH + S-GW

Arroyo Mocho:

AMNL + Z7Rel + Mine + RO = AM_KB + S-GW

Arroyo Del Valle:

AVNL + Z7Rel + Mine + RO = ADVP + S-GW

Where:

- ALPL, ALP_ELCH, AMNL, AM_KB, AVNL, and ADVP are streamflow rates measured at stream gaging stations
- Z7Rel is Zone7's release of water from reservoirs or the South Bay Aqueduct
- Mine is the release of water from gravel mining operations
- RO is runoff that is calculated from these equations
- S-GW is seepage to groundwater.

Monthly values for each of the terms of the three water budget equations were provided by Zone 7 staff, with the exception of runoff and streamflow volumes at three stream gauge locations for periods when no data was available. Data is unavailable for ALPL from Oct-73 to Aug-80, for ALP_ELCH from Oct-73 to Dec-77 and from Oct-83 to Feb-91, and for AM_KB from Oct-73 to Dec-96. For the purpose of completing the water budget calculation of runoff, the monthly flow rates for these periods were estimated by developing a linear relationship at each of these three locations to flow at the downstream gage AMP, as demonstrated in Figure 14. The equations are:

ALPL = 0.2817*AMP

ALP_ELCH = 0.4069*AMP

AM_KB = 0.9839*AMP – ALP_ELCH

For some months the estimated volume of runoff needed to completed the streamflow water budget was a negative number, meaning that the stream would have to lose water (instead of gain runoff) in order to balance the water budget equation. Since runoff cannot be negative, the runoff was instead set to zero for these months.

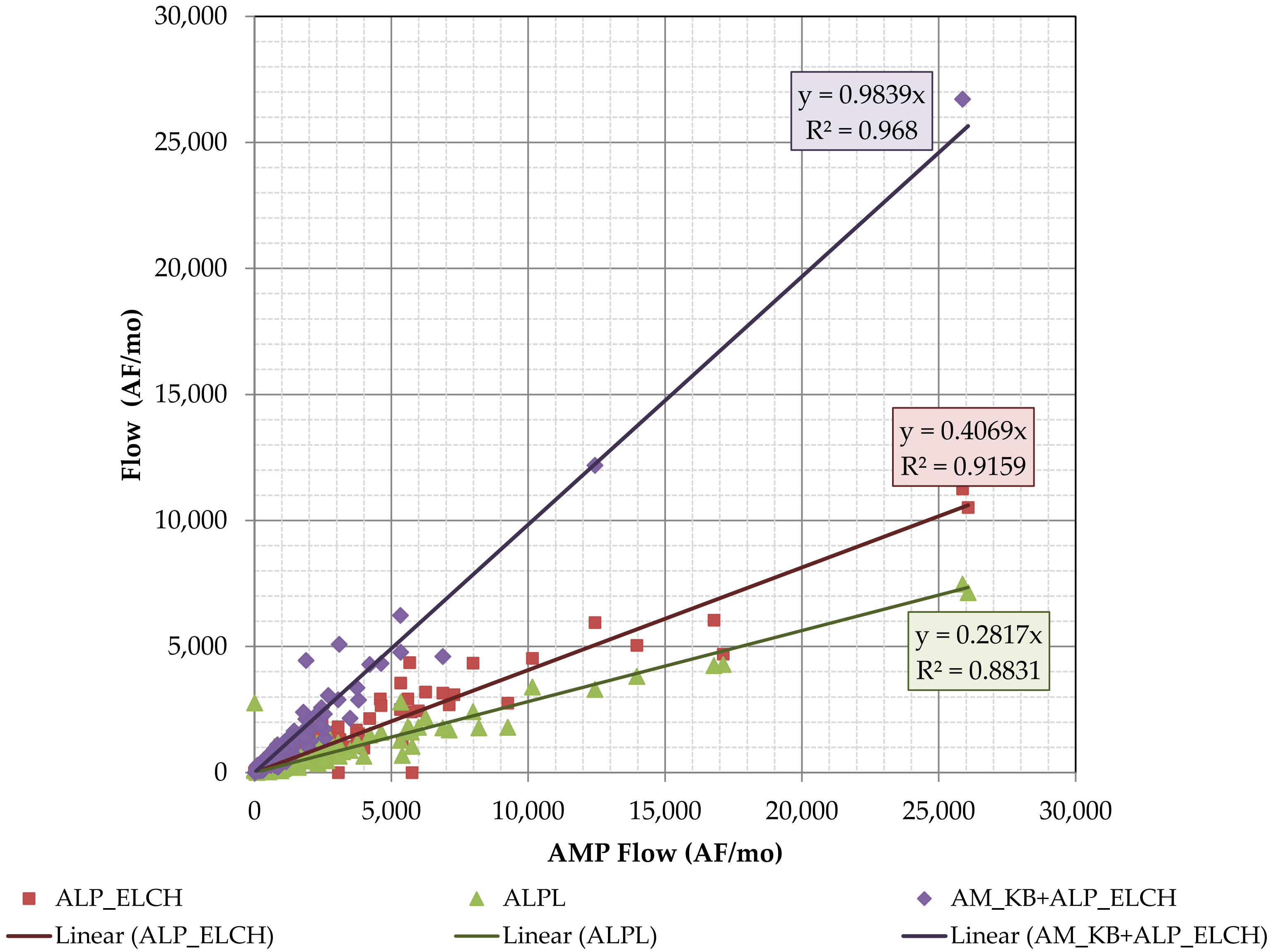

Figure 14: Linear Equations Relating Streamflow to Streamflow in Arroyo Mocho Gage AMP

2.9 LAKE MODELING (LAK)

The MODFLOW Lake package (LAK3, Merritt and Konikow, 2000) was used to simulate the lake and groundwater interactions. In the Lake Package, a lake is represented as a volume of space within the model grid. The body of each lake cannot be overlain by another lake or aquifer, such that either the lake or aquifer occupies the entire volume of a grid cell or they do not overlap within a grid cell. The lakebed is not specified to have explicit dimension within the model grid, instead it is defined by its assigned leakance value, the property that represents the ability of the lakebed to transmit flow between the lake and groundwater. The lake exchanges water with aquifer cells both laterally adjacent and below the lake cells. The lake-aquifer exchange occurs at a rate determined by the relative heads and the grid cell dimensions, hydraulic conductivities of the aquifer material, and the lakebed leakance. The lakes can dry and rewet as a consequence of reduction in lake stage and aquifer head rise. The changes in lake stages are computed using the independent water budgets for each lake. The rate of lake atmospheric recharge and evaporation, overland runoff, and the rate of any direct withdrawal from, or augmentation of, the lake volume are four elements required to compute the lake water budget. All sources of the water entering the lakes, may have solute concentrations associated with them for use in solute-transport simulations using the newly developed LKT package in MT3D-USGS that is pending release.

The locations of the major lakes in the Livermore Valley Groundwater Basin are shown in Figure 15. These lakes are ponds or pits created by the activities of the gravel mining companies in the Livermore Valley area. As a result of many years of mining, the bottom of some lakes has become impervious (lined), due to accumulation of finer material such as silt or clay at the bottom. However, the lined lakes can eventually become unlined if something disturbs the silt lining. Although the change between lined and unlined conditions does not happen in the existing model, the model has the capability to model such changes. In this study we use a lakebed leakance equal to zero for the lined lakes. As the lake package defines leakance for each aquifer cell laterally adjacent to one or more lakes, the leakance defined for an aquifer cell laterally adjacent to both a lined and unlined lake is set to zero to ensure no flow exchange between the cell and the lined lake. The lined and unlined lakes are labeled with black and red font respectively in Figure 15.

The lakes in the Livermore Valley Groundwater Basin are divided into four groups based on either their location or the historical operators of the lake (Figure 15). The group names are Calmat/Vulcan/PGC, Kaiser/Hanson, Lonestar/Cemex, and Shadow

Cliffs. Zone 7 now owns and operates lakes 16 and 18 that were historically operated by Kaiser/Hanson.

Figure 16 and Figure 17 portray the evaporation and rainfall rates for lakes within the Livermore Valley Groundwater Basin from water year 1974 to 2014. It is assumed that the rainfall and evaporation occur at the same rate for all ponds/pits within the Livermore Valley Groundwater Basin.

The maximum lake stage is specified by the top of uppermost active cells representing and surrounding the lake. The model's top layer elevations are based on Zone 7's DEM for ground surface as discussed in Section 2.6.1. However, the DEM shows lower elevations for the lake cells than surrounding cells so actual maximum stage may be higher than what is simulated in the model. This is not an issue for simulations run for this report, but could be an issue for future simulations. Simulations with more active use of the lakes such as filling for groundwater recharge will require increasing the maximum stage. This can be accomplished by increasing top layer elevations of lake and surrounding cells to be consistent with maximum stage or using the external tabular bathymetry input option in the LAK package.

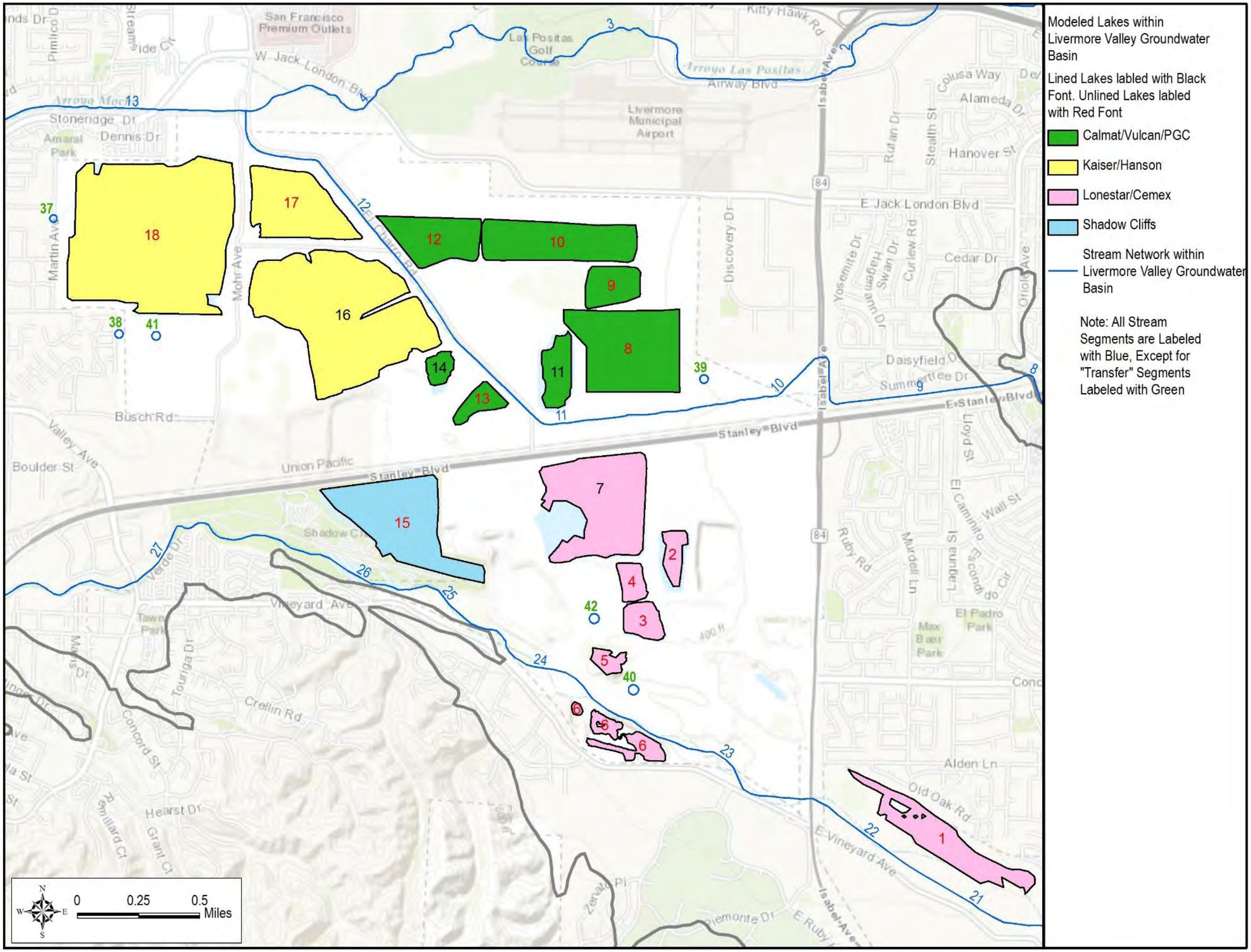

Figure 15: Location of Major Lakes within the Livermore Valley Groundwater Basin

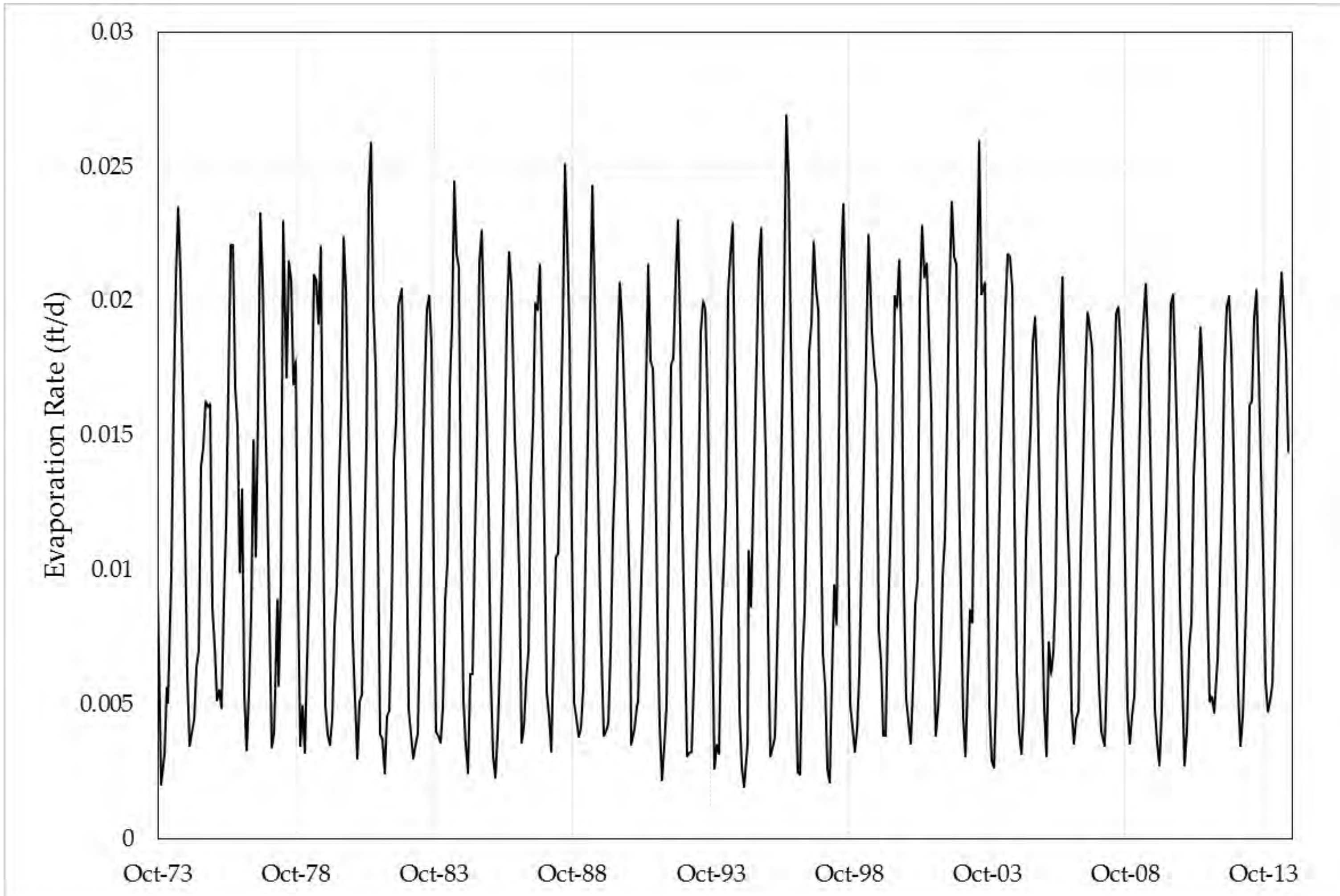

Figure 16: Evaporation rate for Lakes within the Livermore Valley Groundwater Basin from water year 1974 to 2014

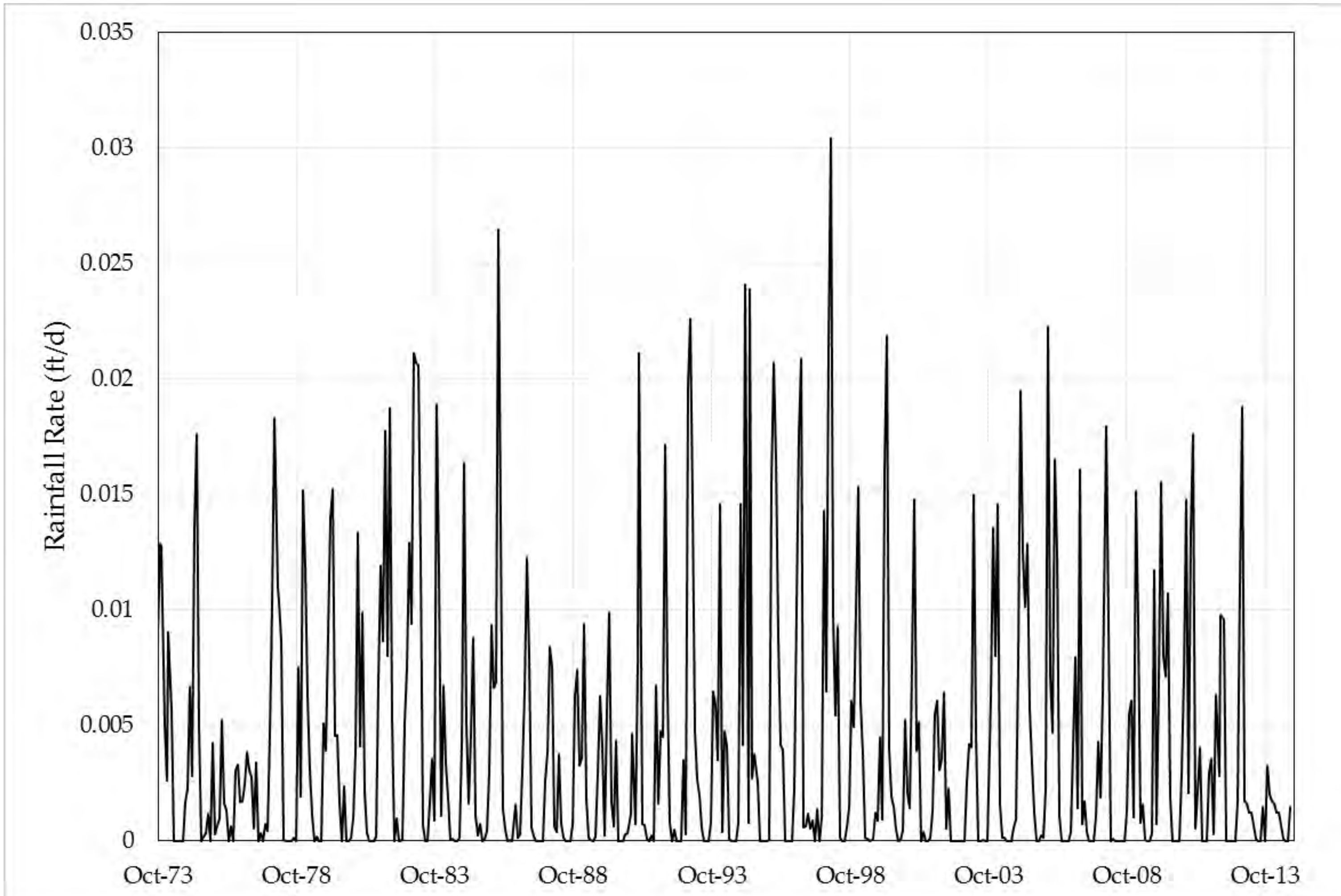

Figure 17: Rainfall rate for Lakes within the Livermore Valley Groundwater Basin from water year 1974 to 2014

2.10 Implementation of the Lake to Stream, Lake to Lake and Stream to Lake Connections

Historically there were many exchanges of water between the lakes of the same and different lake groups. However, most of these water exchanges between the ponds/pits are undocumented except for the water transferred from the Lonestar/Cemex and Kaiser/Hanson lakes to Shadow Cliffs. Even for these documented water exchanges for lake groups, the quantity of the water from any individual lake in a lake group is not clear. Based on our verbal communication with Zone 7 Agency we decided to choose an unlined lake from each of the Kaiser/Hanson and Lonestar/Cemex groups to represent the Kaiser/Hanson and Lonestar/Cemex groups as the supply for the total water transferred from each group to Shadow Cliffs. The lake to lake connections are shown on Figure 18 with brown arrow lines; Lake 18 is the source lake for Kaiser/Hanson and Lake 3 is the source lake for Lonestar/Cemex.

The lake to lake connections are defined using the SFR package because there is no option in the LAK package to explicitly connect a lake to another one. The only way to transfer water from a lake to another one in the LAK package is to augment the receiving lake with the same amount of water withdrawn from the providing lake. This method is not appropriate for this simulation because it would require assigning a concentration to the augmentation water. This would introduce a mass balance error to the transport model which will simulate the concentration in the source lake with MT3D-USGS. For the purpose of the simulation of the Lake to Lake connections for both flow and transport, we added two segments to the simulated stream network, these stream segments are herein called "Transfer Segments" and hypothetically pump the water from one lake to the other (Segments 41 and 42 in Figure 18). The use of the SFR package for this purpose makes sure no salt mass is lost as the results of the water exchange between the lakes.

Besides the water exchange between the lakes, the gravel mining companies in the Livermore Valley Groundwater Basin periodically transfer water from pits (lakes) to the nearby streams to facilitate quarry operations (Figure 18). Kaiser/Hanson lakes discharge water to both Arroyo Valle and Arroyo Mocho. Calmat/Vulcan/PGC and Lonestar/Cemex lakes discharge to Arroyo Mocho and Arroyo Valle respectively. Transfers from each of the three groups have been estimated but transfers from specific lakes have not. Therefore, as with lake to lake connections, one unlined lake from each of the three groups was chosen to represent source of lake water to be transferred to streams. The lake to stream connections are shown on Figure 18 with pink arrow lines;

Lake 18 is the source lake for Kaiser/Hanson. Lake 4 is the source lake for Lonestar/Cemex, and Lake 8 is the source lake for Calmat/Vulcan/PGC.

As explained above, the SFR package is linked to the LAK package and is used to deal with the lake to stream and stream to lake connections. Limitations in the SFR package design and formulation, prevent a direct water exchange from a lake to a stream segment if the lake stage is lower than the stream bed top elevation (STRTOP). The lakes modeled in the Livermore Valley Groundwater Basin are generally extended to a much deeper depth compared to the stream network. As a result, the STRTOP for the receiving stream segment can be much higher than the simulated lake stage, which results in the lake and stream being disconnected in the simulation. To overcome this problem, four transfer segments (Segments 37-40) were added to the stream package representing the lake to stream connections. These transfer segments are carefully located at close proximity to each discharging lake's bottom; this will ensure that the STRTOP for the transfer segment is always lower than the discharging lake.

The flow from each discharging lake is defined as a fixed rate of discharge diverted from the lake into the first reach of the receiving stream segment (unless all lake cells go dry). The flow from the lake is not dependent on the value of the stream depth calculation method (ICALC, see Table 2) used for the receiving segment. However, if during the model run, the flow from the lake is zero, then the lake outflow into the receiving segment will be calculated on the basis of lake stage relative to STRTOP for the first reach of the receiving stream segment using the method specified by ICALC. The outflows from the discharging lakes will vary by time and can be zero depending on the mining activities. To prevent SFR from overwriting zero lake outflows by a calculated flow, all zero lake outflows from discharging lakes were replaced by a diminutive number (1.0×10^{-7} ft^3/d) in the SFR package input file.

In addition to the water exchange between the lakes and water transfer from the lakes to the streams, Zone 7 Agency has periodically diverted stream water from Arroyo Valle to Shadow Cliffs (Stream Segment 25 to Lake 15) since Water Year 2002. Monthly transfers from the stream to lake has been estimated and documented. The stream to lake connection is shown on Figure 18 with light green arrow lines. An additional transfer segment was added to the stream package to facilitate the stream to lake connection (Segment 43). The SFR package formulation does not allow a direct diversion from a stream segment to a lake, thus a transfer segment was added to overcome this problem.

There is also transfer of water from unlined lakes to lined lakes within mining groups. Zone 7 estimates the transfer based on evaporation from the lined lakes. This transfer is simulated in the model as a withdrawal from the lake, which removes the water from the model. For Kaiser/Hanson, evaporation from Lake 16 is withdrawn from Lake 18. For Calmat/Vulcan/PGC, evaporation from Lake 11 is withdrawn from Lake 8. For Lonestar/Cemex, evaporation from Lake 7 is withdrawn from Lake 4.

Estimates for mining processing losses are simulated as pumping wells and are not part of the LAK package. Future revision of the model could simulate these losses as lake withdrawals instead of pumping wells.

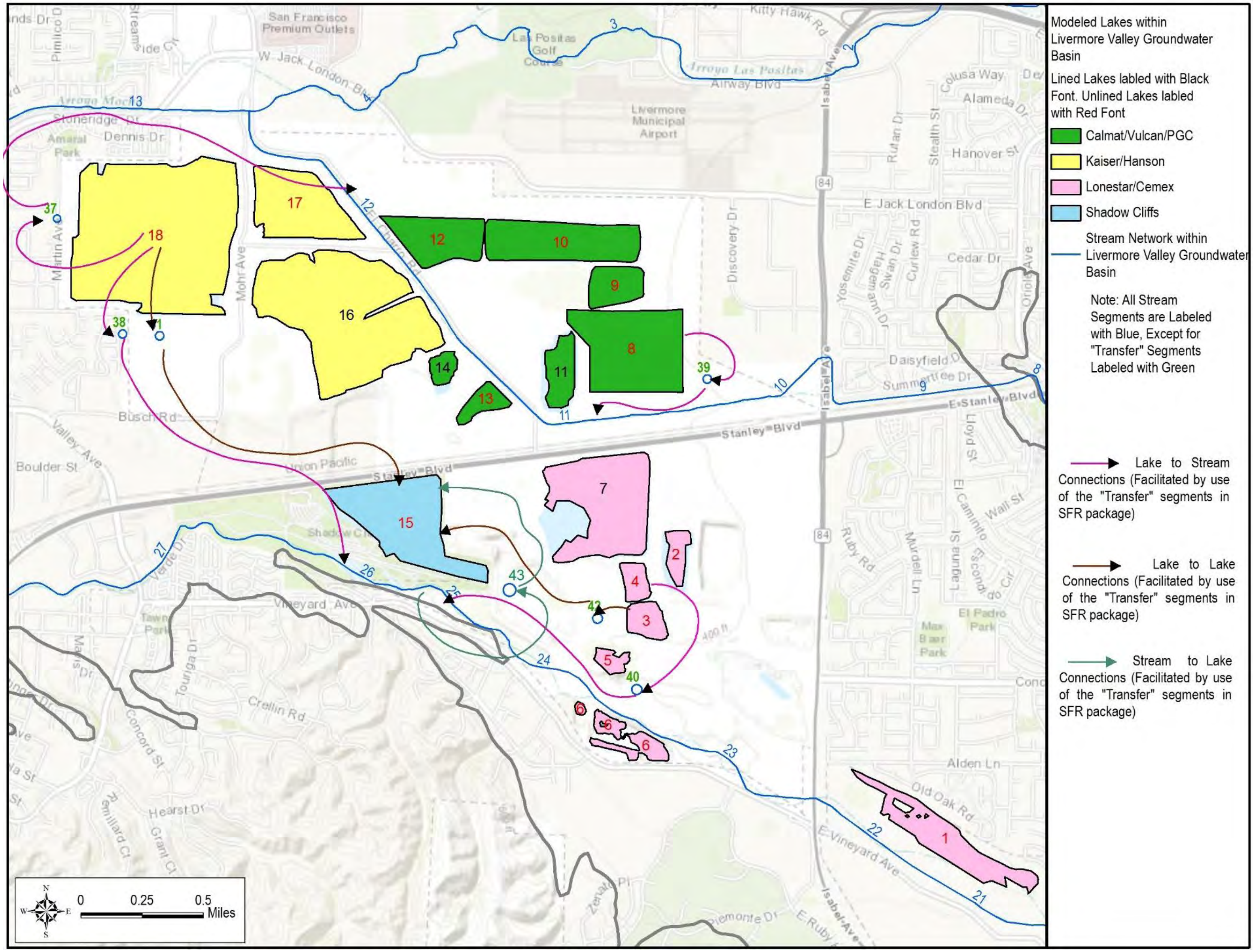

Figure 18: Location of Major Lakes in the Livermore Valley Groundwater Basin, with Lake to Lake, Stream to Lake and Lake to Stream Connections

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SECTION 3
TRANSPORT MODEL CONSTRUCTION

The fate and transport of salts or minerals, as represented by Total Dissolved Solids (TDS) within the Livermore Valley Groundwater Basin is modeled using MT3D along with two recently developed packages to model transport in streams (SFT) and lakes (LKT) and transport between surface water and groundwater. The SFT and LKT transport packages use flow results from the corresponding MODFLOW packages for streams (SFR) and lakes (LAK). Zone 7 funded development of these recently developed packages that will be included in the upcoming public release of MT3D-USGS by the US Geological Survey (Bedekar et al., 2016). In this section, the setup of MT3D and the two surface water packages (SFT and LKT) applied to model the fate and transport of salt within the Livermore Valley Groundwater Basin and its interaction with the surface water is explained in detail.

Version 1.0 of MT3D-USGS is used in conjunction with version 1.0.9 of MF-NWT that creates the flow-transport link (FTL) file that includes surface water flows needed to simulate surface water transport with the new package.

3.1 BOUNDARY CONDITIONS

The boundary conditions for the groundwater transport model are no-mass flux for all model boundaries except for the boundary at the top of the basin, which is a specified mass flux. The mass flux is determined internally in the model by the specified rate of areal recharge inflow and the concentration of the areal recharge. Figure 19 shows the average TDS concentration in the areal recharge for the period of 1974-2014 in the Livermore Valley Groundwater Basin.

3.2 INITIAL CONDITIONS

The initial conditions representing salt concentrations in 1974 are based on initial concentrations used for the three layers of version 2.0 of the model. Concentrations from layer 1 in model version 2.0 are used for updated layers 1-4. Concentrations from layer 2 in model version 2.0 are used for updated layer 5. Concentrations from layer 3 in model version 2.0 are used for updated layers 6-10. Zone 7 previously created the initial concentrations used in version 2.0 of the model based on data contouring. Figure 20 through Figure 22 show the initial salt concentrations in top (layers 1-4), middle (layer 5) and bottom layers (layers 6-10).

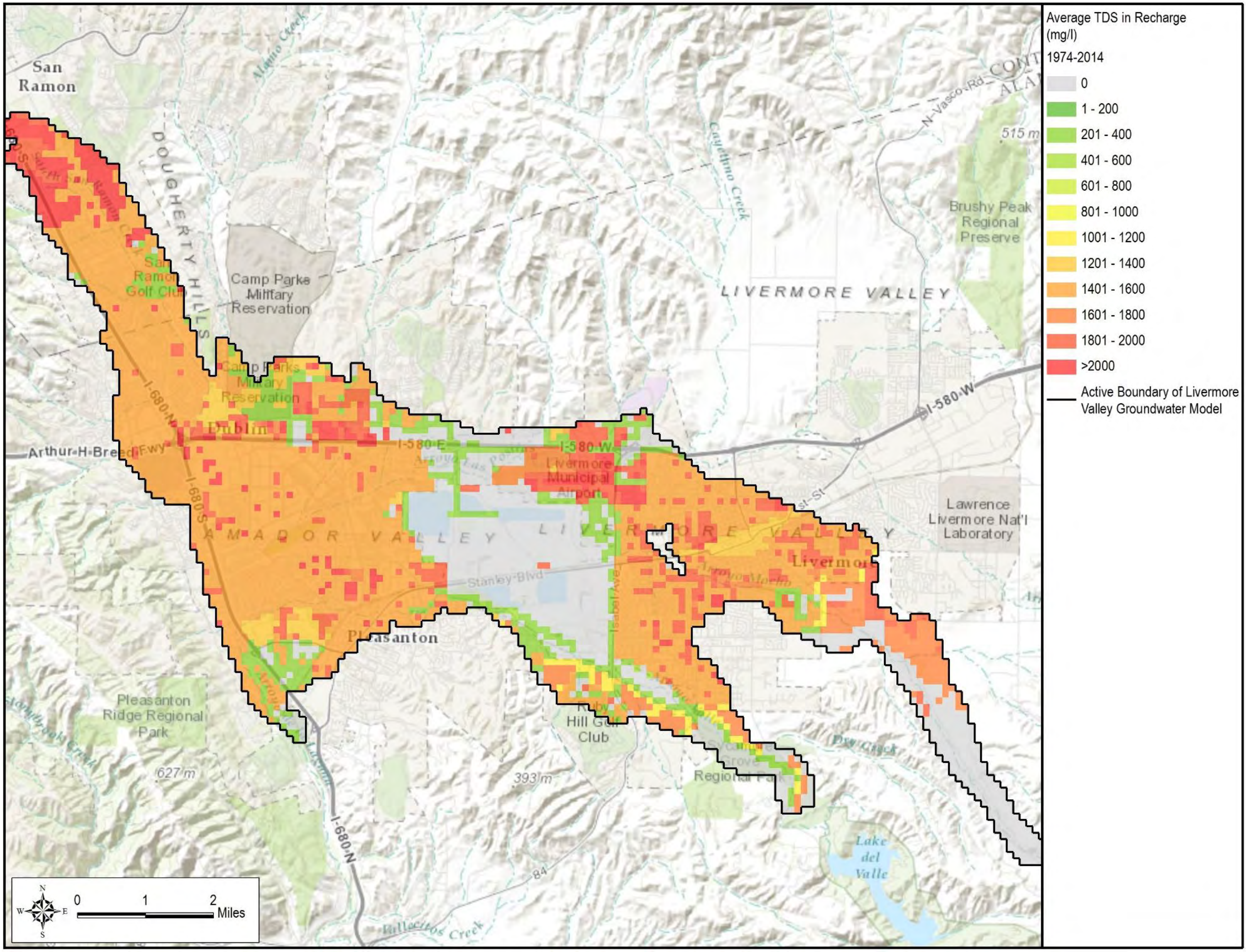


Figure 19: Average TDS Concentration in Areal Recharge (mg/l) in Livermore Valley Groundwater Basin

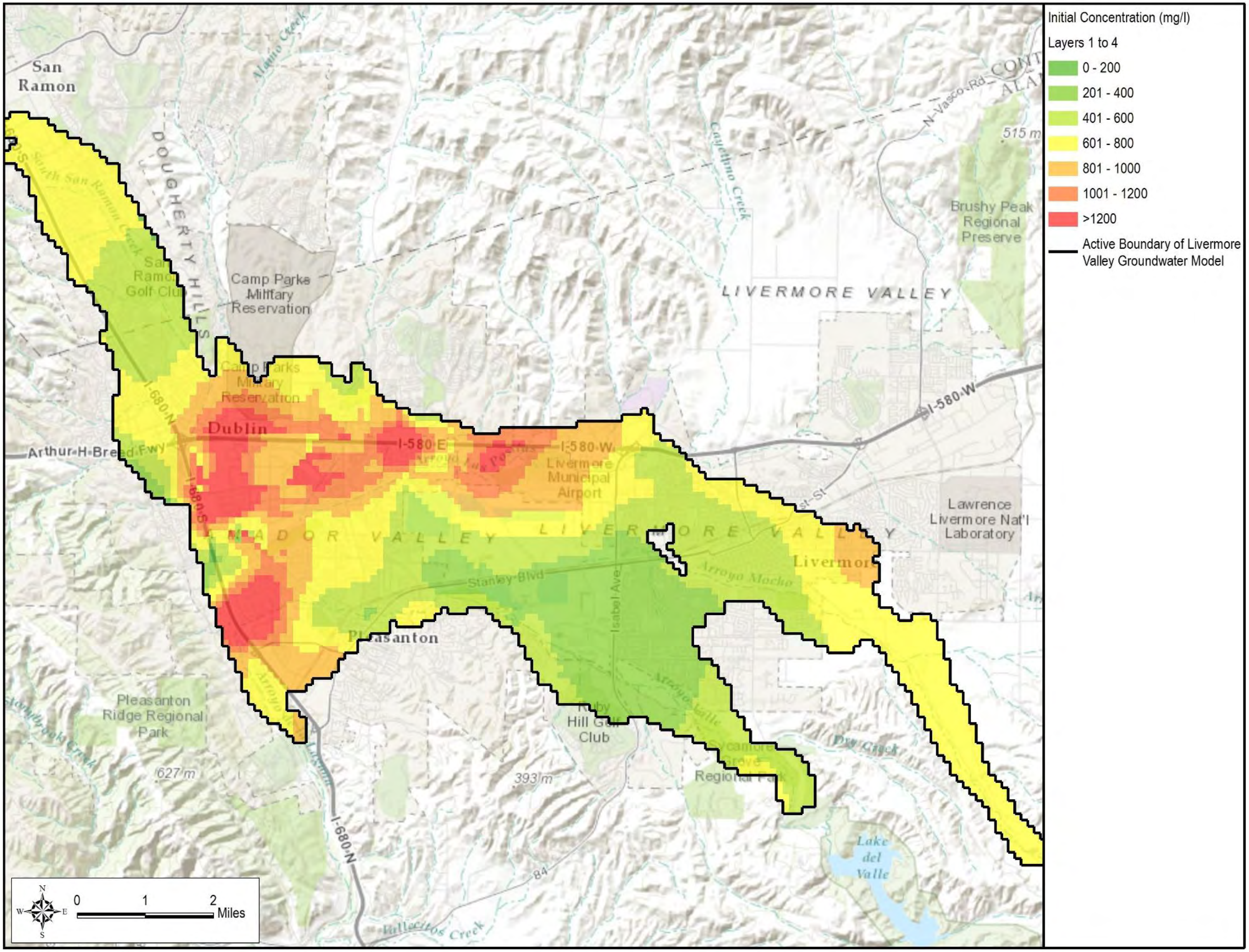


Figure 20: Initial Concentration in Layers 1 through 4 in the Livermore Valley Groundwater Basin

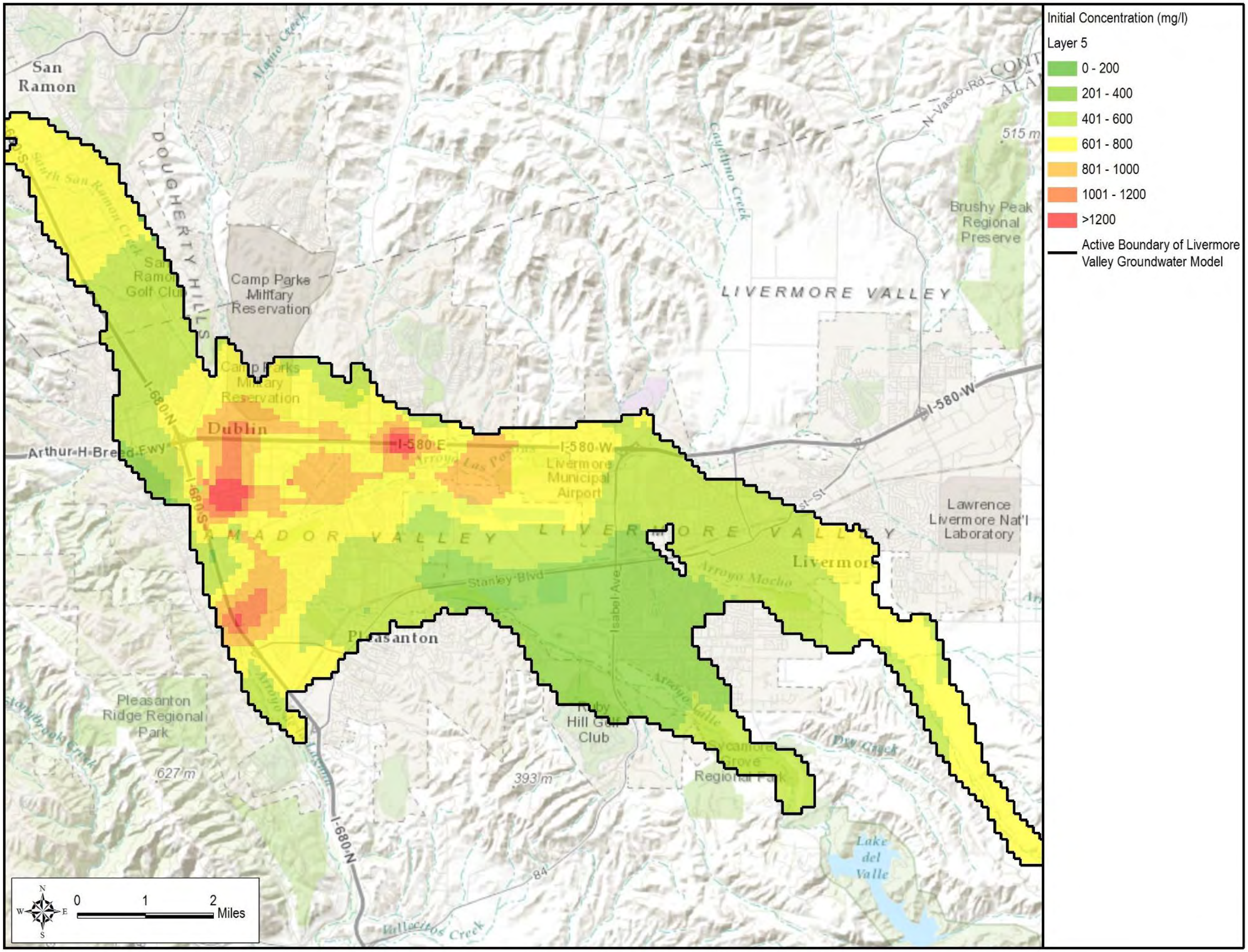


Figure 21: Initial Concentration in Layers 5 in the Livermore Valley Groundwater Basin

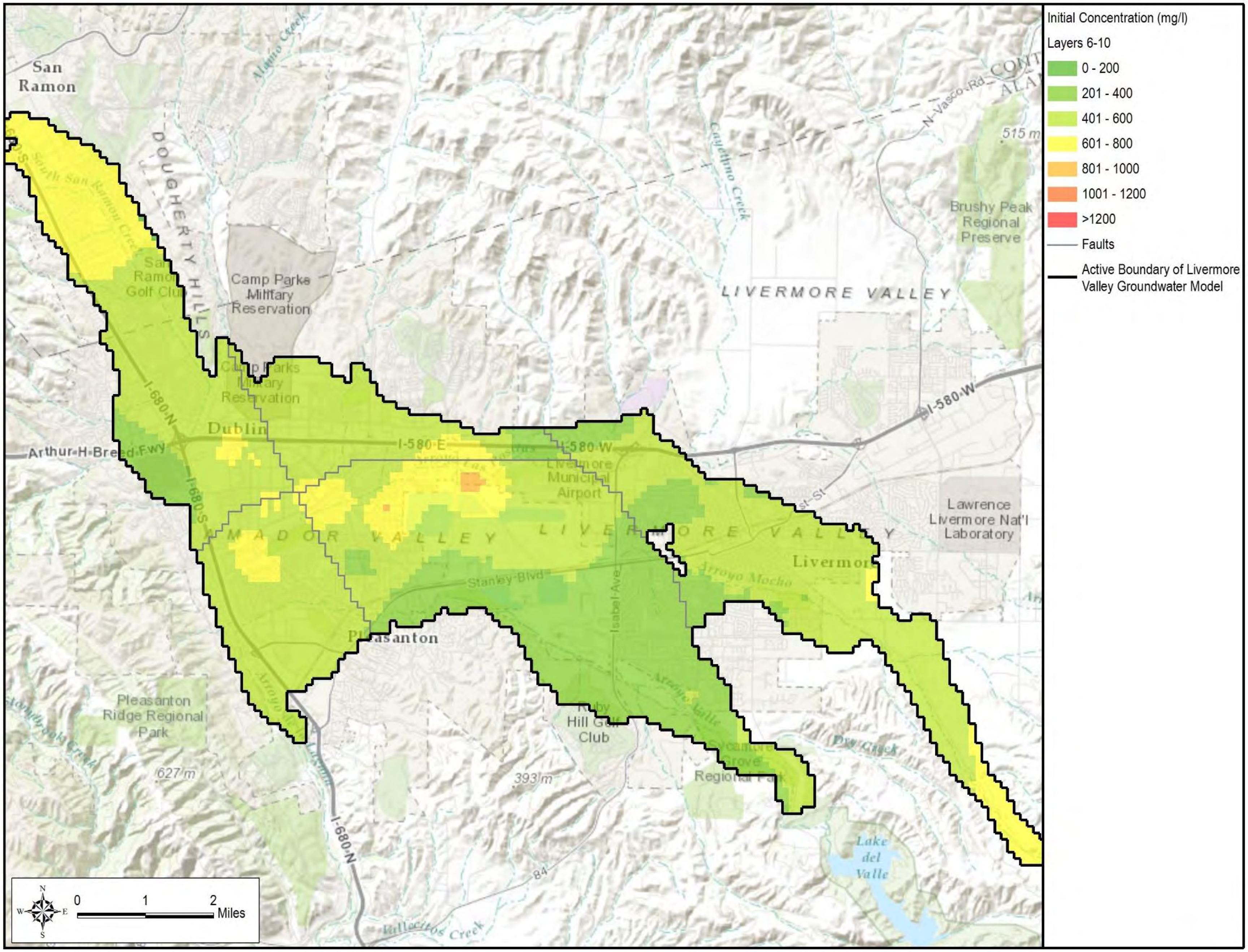


Figure 22: Initial Concentration in Layers 6 through 10 in the Livermore Valley Groundwater Basin

3.3 Transport Solution Options

The Finite Difference Method is used to solve the transport model. The transport model is set up such that the MT3DMS uses a general-purpose iterative solver called Generalized Conjugate Gradient (GCG) Package to implicitly solve the transport equation. Solver settings were chosen for increased run efficiency while consistently arriving at a stable solution. Table 6 provides a summary of the solution settings used for modeling transport of salt within the Livermore Valley Groundwater Basin and Livermore Valley surface water network.

3.4 Groundwater Transport Parameters

The primary groundwater transport parameter that is calibrated is effective porosity. Porosity is calibrated in conjunction with specific yield to ensure porosity is greater than or equal to specific yield. Effective porosity affects mass travel time.

Dispersion and diffusion are assumed to have negligible effect on the transport of the salts and minerals in the Livermore Valley Groundwater Basin and thus the Dispersion Package is not used in the transport modeling. Accounting for dispersion and diffusion would be unlikely to affect basin management of salts. Furthermore, the transport process is assumed to be free of any chemical reaction. Thus, advection is assumed to be the only process that governs the fate and transport of the salt in the groundwater basin.

Table 6: Summary of the Groundwater and Surface Water Transport Solution Settings

Package	Option	Value	Description	Notes
Advection (ADV)	MIXELM	0	Standard Finite Difference Method	
	PERCEL	0.5	Courant Number	Max Courant Number = 1 for accuracy purposes
Solver: Generalized Conjugate Gradient (GCG)	ISOLVE	3	Preconditioner: Modified Incomplete Cholesky Acceleration Scheme : Lanczos/ORTHOMIN	
	MXITER	5	Maximum Number of Outer Iterations	High to Handle Non-Linearity Introduced by Explicitly Coupled Lake (LKT) and Stream (SFT)Packages
	IITER	50	Maximum Number of Inner Iterations	
	CCLOSE	10^{-4}	Convergence criterion in terms of relative concentration	
Basin Transport (BTN)	DT0	0	Initial transport stepsize	Setting DT0 at zero forces the code to use the Courant number to calculate value of the appropriate initial transport stepsize
	TTSMULT	1	Transport stepsize multiplier	
	MXSTRN	5000	Maximum number of transport steps allowed within one time step of the flow solution	
Stream Transport (SFT)	ISFSOLV	1	Transport problem solver in the surface water network	This is the only option allowed with the current version
	WIMP	1	Stream solver time weighting factor	0=Explicit, 1= Crank-Nicolson, 1 = Fully Implicit
	WUPS	1	Stream solver space weighting factor	0=Explicit, 1= Crank-Nicolson, 1 = Fully Implicit
	CCLOSESF	0.001	Closure Criteria for the SFT solver	
	CRNTSF	0.5	Courant number used for the SFT time step	
	DISPSF	0	Dispersion Coefficient for Stream Network	No Dispersion is modeled within the stream network
Lake Transport (LKT)	NA	NA	NA	LKT assumes instantaneous mixing within the entire body of each lake. It only acts like a boundary condition to the groundwater system. The LKT equations are solved as a mass balance calculation and then coupled with the groundwater equations explicitly, hence, a separate solver is not needed for the solution of transport within lakes.

3.5 STREAM-FLOW TRANSPORT (SFT)

The stream-flow transport (SFT) package simulates solute transport within the surface water network and the mass transfer between streams, lakes and groundwater based on flow results calculated by the MODFLOW SFR package. The salt transport in the stream network and the mass transfer between the groundwater and surface water within the Livermore Valley Groundwater Basin is also simulated with the application of the SFT package, a recently developed package for MT3D-USGS (Bedekar et al., 2016). A summary of the setup of the SFT package used to model fate and transport of salt in the Livermore Valley Groundwater Basin stream network is provided in this section.

3.5.1 SOLVER OPTIONS

Finite Difference is the numerical technique that will be used to solve the transport problem in the surface water network (ISFSOLV = 1). The current release of MT3D-USGS (version 1.0) only allows for a finite-difference formulation for stream transport. The stream solver temporal and spatial weighting options are set so that the transport problem in the surface water is solved by employing an upstream weighted, fully implicit finite difference solution (WIMP =1, WUPS = 1). With these settings the stream transport solution is unconditionally stable. In this study it is assumed that the salt transport within the stream network is fully governed by the advection processes and no dispersion is simulated within the stream network (DISPSF = 0).

3.5.2 INITIAL CONDITIONS

A uniform concentration of 570 mg/liter was assigned as the initial concentration of the salt within the entire stream network. The available historic data on the stream network salt content is very scarce prior to the model start time (10/01/1974), therefore the concentration assigned to the stream network initial state uses the average of the available data at all stream gage stations prior to the model start time (2/11/1948 - 10/1/1974).

3.5.3 BOUNDARY CONDITIONS

As streams enter the boundary of Livermore Valley Groundwater Basin (e.g., “Headwater” segments for Arroyo Mocho, Arroyo Valle, Aroyo Las Positas and Alamo Creek), they introduce additional loads of salt to the stream network and the groundwater basin. This salt load is simulated with the application of the headwater boundary condition in the SFT package. It is assumed that no salt mass will exit or enter the surface-water network as a result of direct evaporation or precipitation on the stream channels. Salt transfer between the lakes and streams are considered as internal sources and sinks based on surface water connections specified in the MODFLOW SFR package and are not modeled as a boundary condition.

A summary of available TDS data for the headwater stations (ALPL for Arroyo Las Positas, AMNL for Arroyo Valle, AVNL for Arroyo Valle and AC_NP for Alamo Creek on Figure 11) is presented in Table 7. As it can be noted, the available TDS data for the headwater stations (and in general for the stream network in the Livermore Valley Groundwater Basin) is very irregular and exhibits major gaps between available data points (Table 7 and Figure 23 - Figure 26). The TDS data for the headwater stations is missing for 79% to 93% of the entire modeling period. TDS values for the headwater stations are required at all stress periods by the SFT package to accurately represent solute flowing into the model from the headwater station. For each headwater station, different strategies (e.g. monthly average, annual average, etc.) were evaluated to provide the model with an estimated concentration value for the data gap. Based on the evaluation the available concentration data were correlated to the flow rate data such that high concentrations were observed at low flows and vice versa (Figure 27 - Figure 30). The available stream TDS data does not provide a sufficient support for developing a one to one correlation equation. Hence, average concentration for events of high and low flows were calculated from available TDS data at each headwater station and used as model input for high and low flow periods. The high and low flow events are classified based on the monthly streamflow data and whether it is greater than or less than the median value of the entire population of the monthly streamflow for each headwater station. The value of the median streamflow for each headwater station is listed in Table 7 as well as the assigned concentration value for events of high and low streamflow with missing concentration data.

It should be noted that the TDS data at the AC_NP gage was used to represent the transient salt content that enters the model boundaries through Alamo Canal (headwater segment). AC_NP is about 5 miles downstream of the Alamo Canal entrance to the model domain and is the only station on the Alamo Canal with considerable stream TDS data.

It should be noted that although Tassajara Creek and Dublin Creek are considered headwater stations, as discussed in the flow section their inflow rates are set to zero and consequently cannot add additional load of salt to the Livermore Valley Groundwater Basin.

Table 7: Available TDS Data Summary for Modeling Headwater Boundary Segments within the Livermore Valley Groundwater Basin

Stream	Station Name	# of Records	First Record	Last Record	Average TDS (mg/l)	Concentration used for High Flow Events (mg/l)	Concentration used for Low Flow Events (mg/l)	Median Streamflow (cuft/d)	Remarks
Alamo Canal	AC_NP	101	10/1/1974	2/15/2000	807.3	567	846	773	
Arroyo Las Positas	ALPL	33	2/28/1983	7/23/2013	964.7	840	1022	245	
Arroyo Mocho	AMNL	55	4/19/1978	5/2/2013	465.3	451	675	26	
Arroyo Valle	AVNL	92	1/15/1974	11/14/2013	461.1	332	734	117	
Dublin Creek	DUBC	7	2/20/1975	5/19/1997	399.6	NA	NA	NA	Data not used
Tassajara Creek	TCNP	18	1/11/1979	6/8/1983	502.5	NA	NA	NA	Data not used

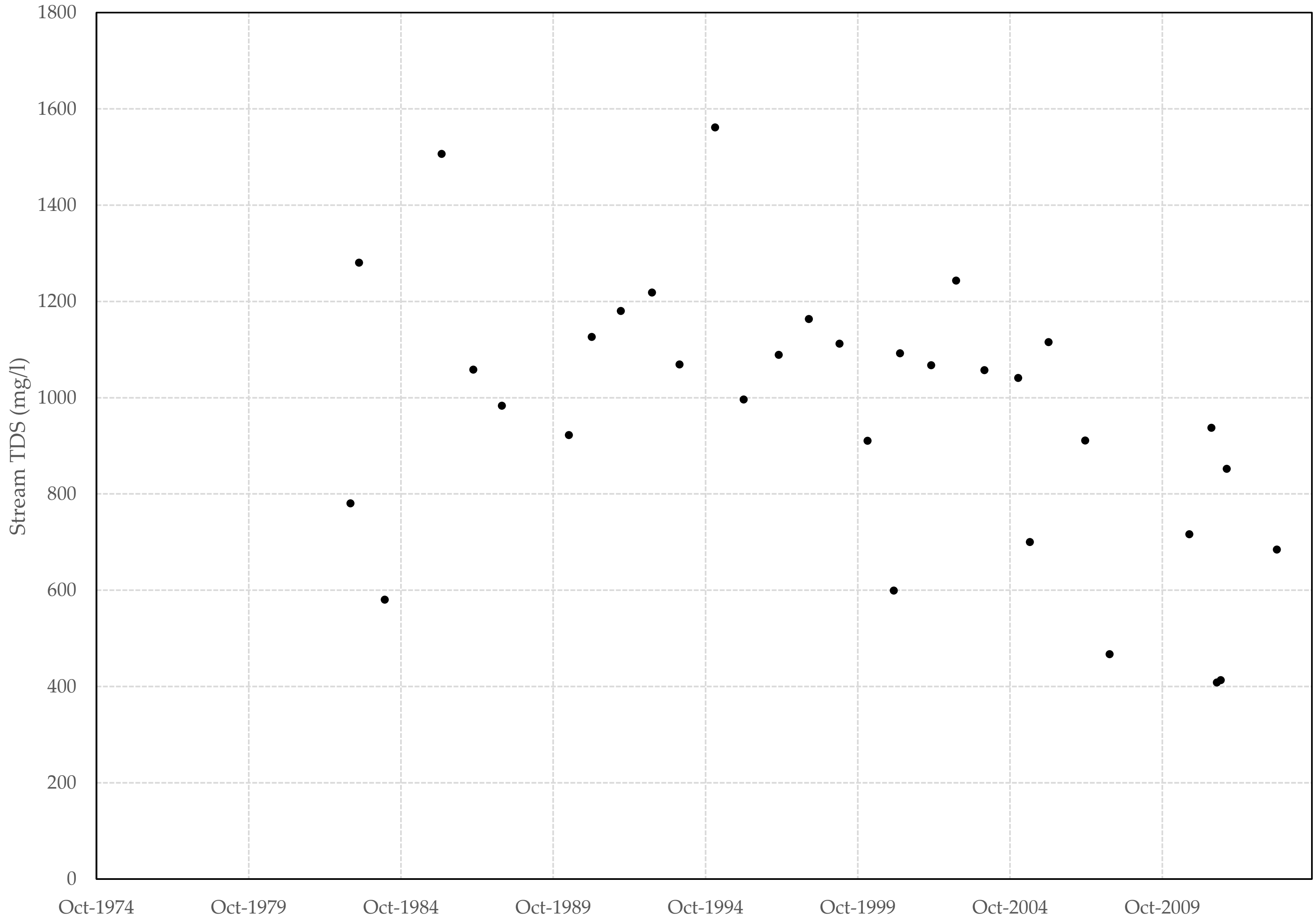


Figure 23: Available Stream TDS Data for Arroyo Las Positas Headwater Segment (ALPL) from Water Year 1974 to 2014

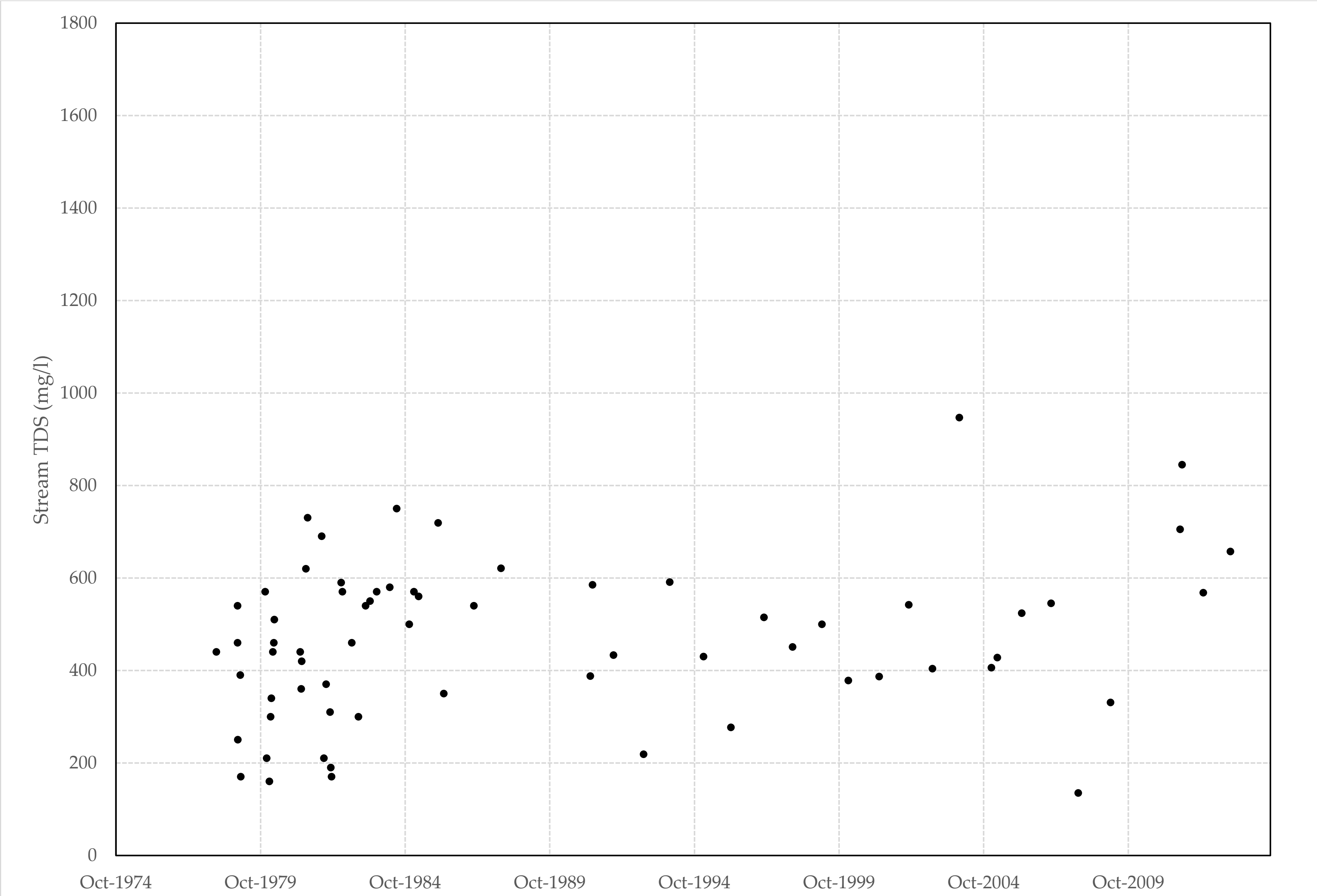


Figure 24: Available Stream TDS Data for Arroyo Mocho Headwater Segment (AMNL) from Water Year 1974 to 2014

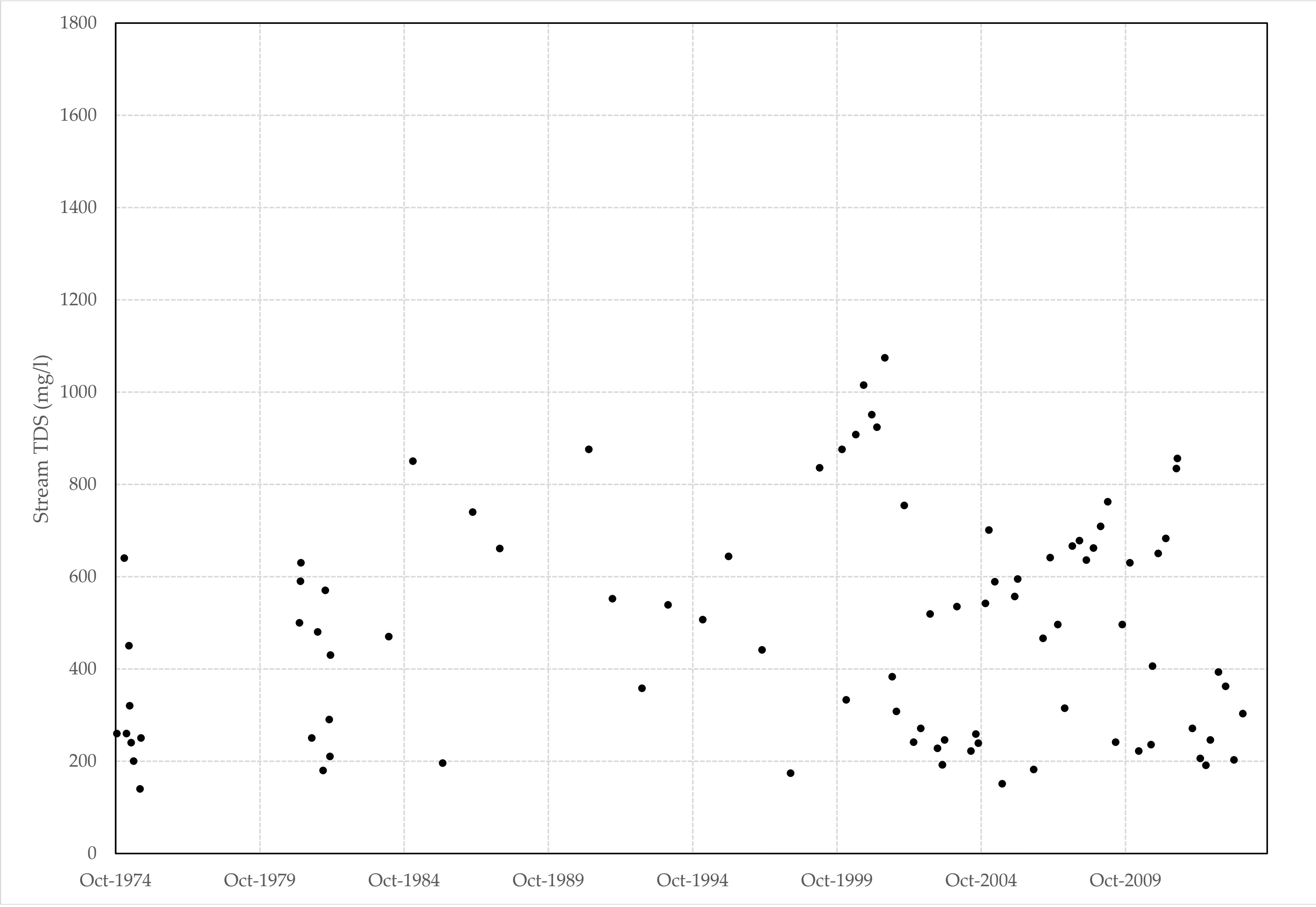


Figure 25: Available Stream TDS Data for Arroyo Valle Headwater Segment (AVNL) from Water Year 1974 to 2014

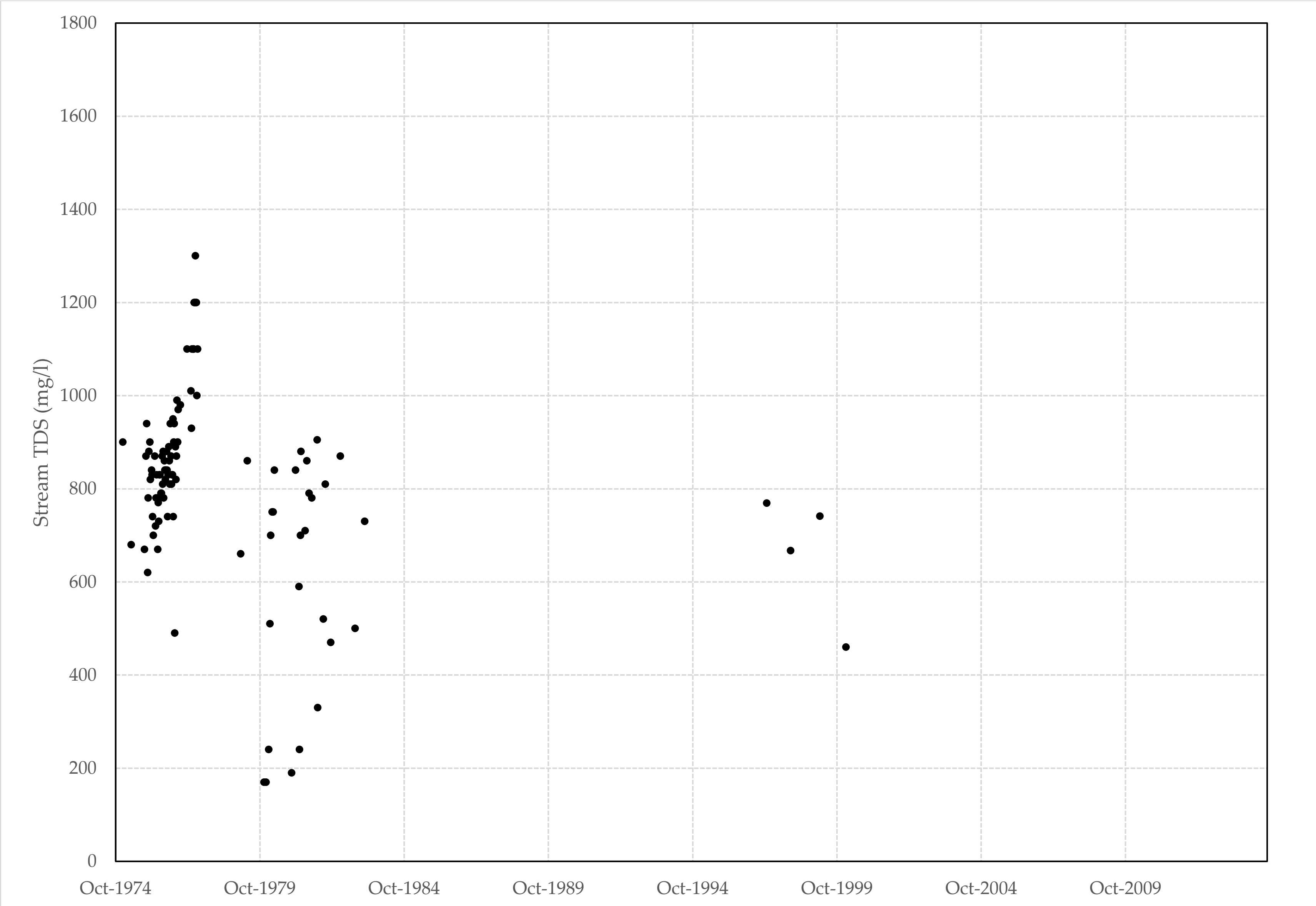


Figure 26: Available Stream TDS Data for Alamo Canal (AC_NP) from Water Year 1974 to 2014

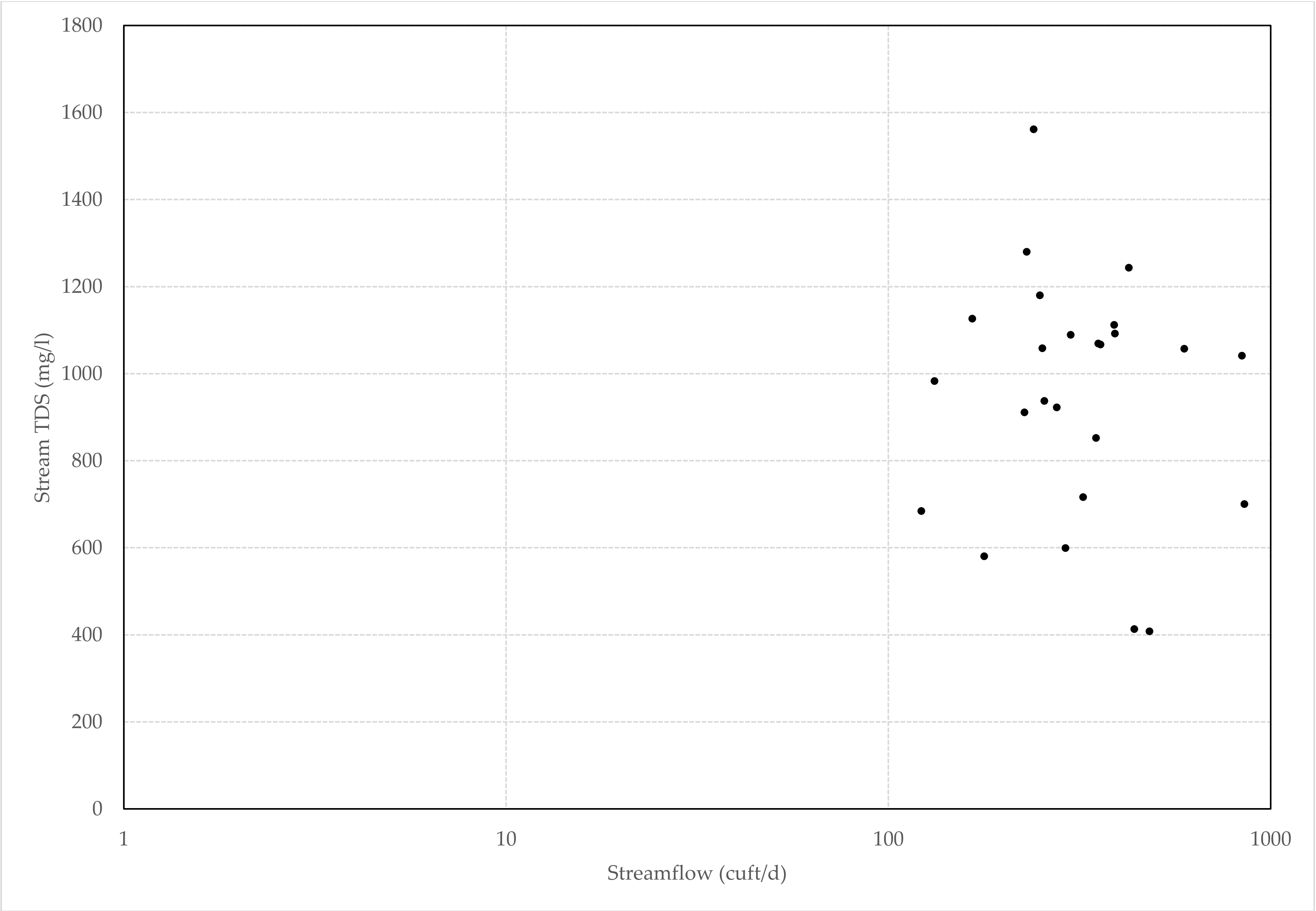


Figure 27: Stream TDS vs. Streamflow for Arroyo La Positas Headwater Segment (ALPL) from Water Year 1974 to 2014

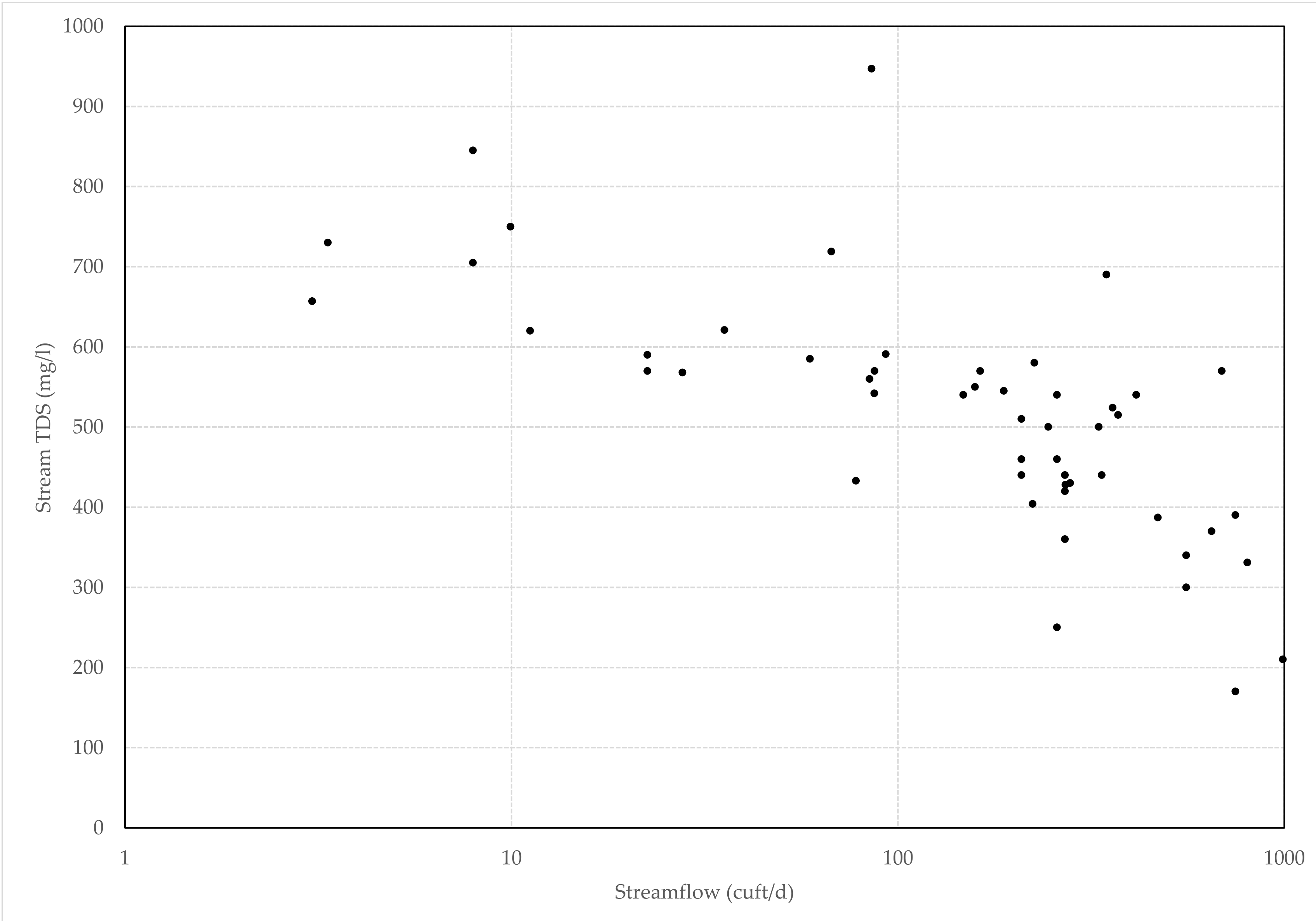


Figure 28: Stream TDS vs. Streamflow for Arroyo Mocho Headwater Segment (AMNL) from Water Year 1974 to 2014

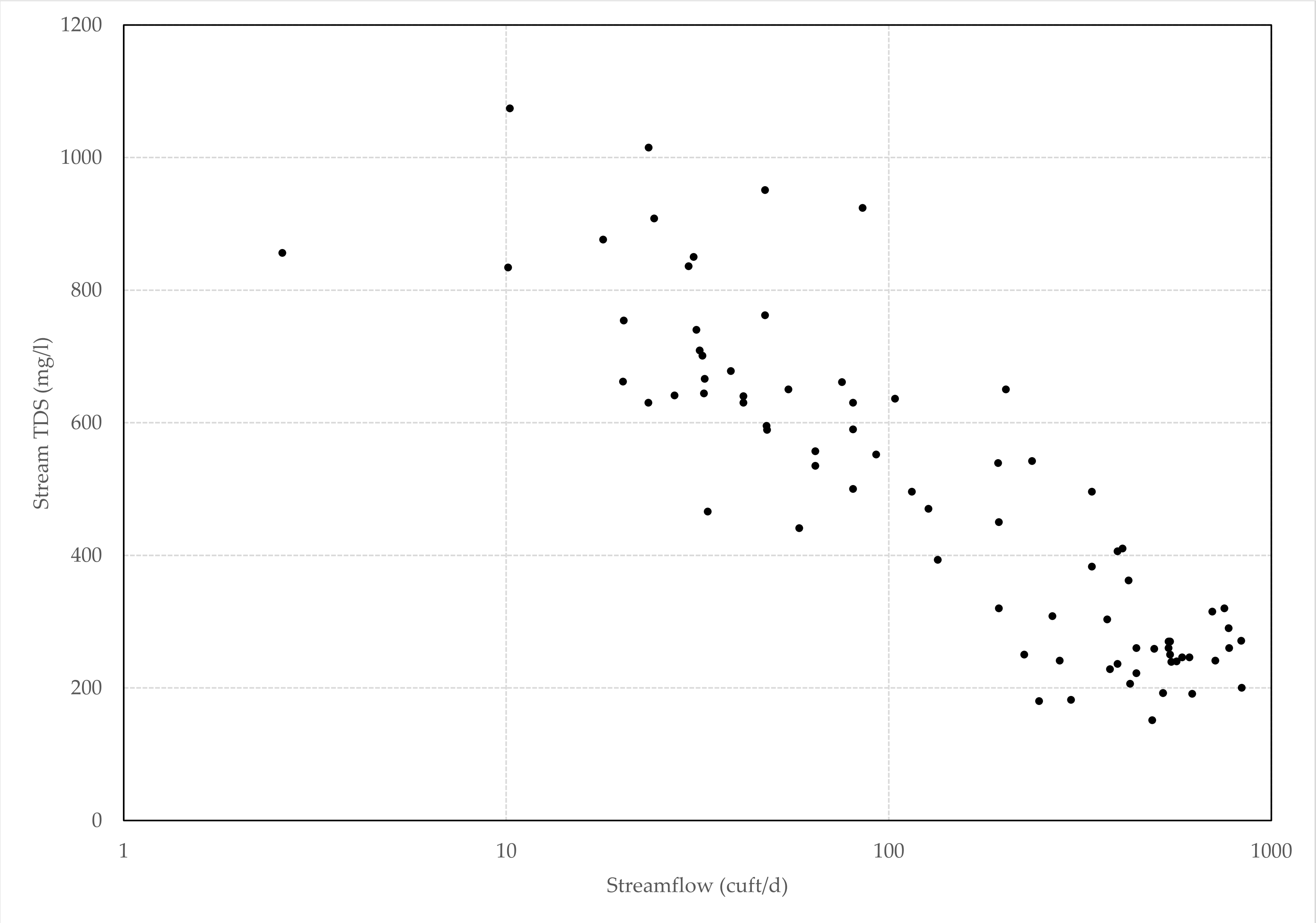


Figure 29: Stream TDS vs. Streamflow for Arroyo Valle Headwater Segment (AVNL) from Water Year 1974 to 2014

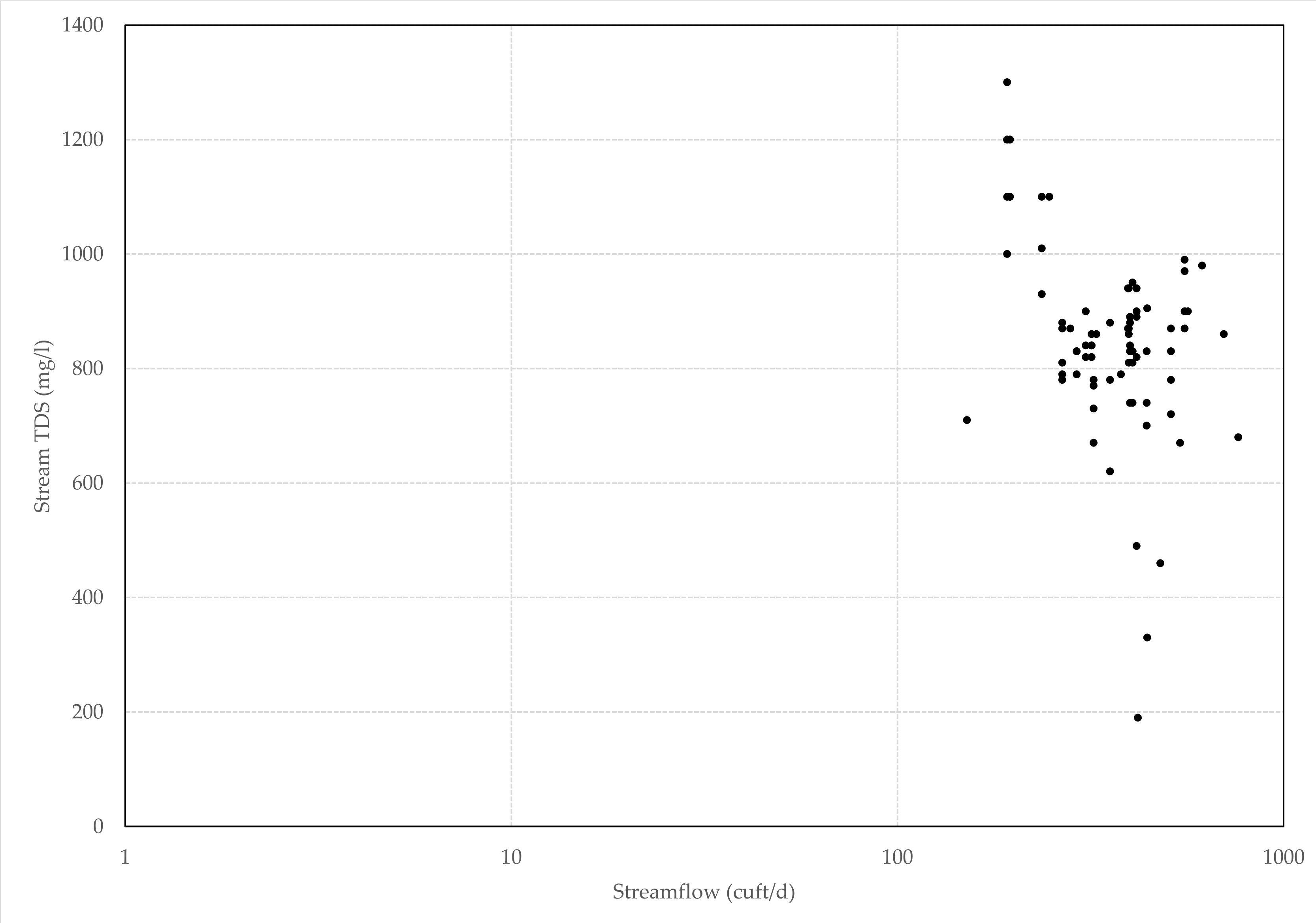


Figure 30: Stream TDS vs. Streamflow for Alamo Canal (AC_NP) from Water Year 1974 to 2014

3.5.4 LAKE TRANSPORT (LKT)

The salt transport within the lakes and the mass transfer between the lakes and groundwater in the Livermore Valley Groundwater Basin is simulated with the application of a recently developed lake transport (LKT) package for MT3D-USGS (Bedekar et al., 2016). The LKT package uses flow results calculated by the MODFLOW LAK package to simulate salt concentrations in lakes and salt transport between lakes and groundwater. A summary of the setup of the LKT package used to model fate and transport of salt in the Livermore Valley Groundwater Basin lake network is provided in this section.

3.5.4.1 SOLVER OPTIONS

LKT assumes instantaneous mixing within the entire body of each lake. Because no routing is done within the lake, it only acts like a boundary condition to the groundwater system. Furthermore, no routing is performed within the individual lakes. The LKT equations are solved as a mass balance calculation and then coupled with the groundwater equations explicitly; hence, a separate solver is not needed for the solution of transport within lakes. Multiple outer iterations for the GCG solver used by MT3D-USGS is required to accommodate any non-linearity introduced by the explicit coupling of the lake and groundwater transport equations so the model is run with 5 outer interations (MXITER=5).

3.5.4.2 INITIAL CONDITIONS

The available historic data on the salt content of the lakes in the Livermore Valley Groundwater Basin is very scarce prior to the model start time; 10/01/1974 (Table 12). Shadow Cliffs (K-15) is the only lake that has old enough TDS data that can represent the initial salt condition of the lakes (Table 12). Hence, an initial concentration of 319 mg/l is used to represent the initial condition of all lakes based on the Shadow Cliffs available historic data.

3.5.4.3 BOUNDARY CONDITIONS

It is assumed that no salt mass will exit or enter the surface-water network as a result of direct evaporation or precipitation on the lakes within the Livermore Valley Groundwater Basin. Any augmentation or withdrawal of salt from the lakes are considered internal sources/sinks and are not modeled as boundary conditions (these salt transport processes are mainly modeled via the use of the SFT package rather than the LKT package as explained in the flow modeling section). Furthermore, no runoff is routed to the lakes in the flow model and no salt will exit or enter the lakes as the result of runoff processes. Based on the assumptions explained here, no salt mass is added to lakes from outside the model domain and no salt mass is removed from the model domain via the lakes so the LKT package is solved with no boundary condition.

SECTION 4
MODEL CALIBRATION USING PEST

4.1 APPROACH

Calibrating the Livermore Valley Basin groundwater model involved successive attempts to match model simulated results to measured data for the calibration period. Measured data included groundwater elevations, streamflows, lake stages, and TDS concentrations in groundwater, streams, and lakes. The model was considered calibrated when simulated results matched the measured data within an acceptable measure of accuracy, and when successive calibration attempts did not notably improve the calibration statistics. Calibration was conducted by varying relatively uncertain and sensitive parameters over a reasonable range of values. The following parameters were varied during model calibration using the parameter estimation software, PEST (Watermark, 2004):

- Horizontal hydraulic conductivity,
- Vertical hydraulic conductivity using vertical anisotropy,
- Specific yield,
- Specific storage,
- Porosity,
- Fault conductance,
- Streambed conductance, and
- Lakebed conductance

4.2 CALIBRATION PERIOD

The calibration period was the historical period of Water Years 1974-2014 simulated by the groundwater model as described in Section 2.1.

4.3 PILOT POINT METHOD FOR MODEL CALIBRATION

Similar to calibration of version 2.0 of the model, a pilot point approach, rather than a zoned conductivity approach, was used to distribute aquifer parameters during calibration. The pilot point approach results in smoothly varying hydraulic conductivity, storage parameter, and porosity fields. Doherty (2003) describes the methodology for the use of pilot points in groundwater model calibration. Using this method, the values of aquifer hydraulic properties are estimated at the locations of a number of points spread throughout the model domain. Hydraulic properties are then assigned to the model grid through spatial interpolation from those points (Watermark, 2007). Spatial interpolation from pilot points to the finite difference grid defines a hydraulic property array on a cell-by-cell basis. Regularization, a geostatistical method that constrains heterogeneity, is also used. Using pilot points with regularization eliminates the need to guess where unmapped heterogeneity might exist: the calibration process informs where heterogeneity exists.

Pilot points had been placed manually for version 2.0 of the model based on following criteria (Watermark, 2002):

1) More pilot points were placed where there are more data;
2) Pilot points were placed between data points in order to calibrate to head differences between wells;
3) Pilot points were placed in between wells and outflow boundaries.
4) Pilot points were placed to eliminate big gaps between adjacent pilot points;

Pilot points used for version 2.0 layers 1, 2, and 3 were assigned to updated model layers 1-4, 5, and 6-10, respectively, then modified. Four sets of pilot points are used for the following groups of layers: layer 1, layers 2-4, layer 5, and layers 6-10 (Figure 31 through Figure 34). The same pilot point locations were used for all five pilot point based parameters.

4.3.1 Interpolation in Sub-Basins Defined by Faults

Faults are simulated below aquitard layer 5. These faults define sub-basins in layers 6-10 that may be geologically separated by the faults. Therefore, spatial interpolation of all parameters is conducted by sub-basin for layers 6-10 (Figure 34).

4.3.2 Hydraulic Conductivity for Aquitard Layers

The use of pilot point methodology results in approximately 2,500 parameter values that could be varied in the calibration. One strategy used to reduce the number of values to calibrate was to fix horizontal hydraulic conductivity in aquitard layers 3, 5, 7, and 9 and only vary vertical anisotropy for those aquitard layers. This recognizes that the aquitard layers are included to control vertical flow, particularly for salt transport, and will not be substantial pathways for horizontal flow.

Horizontal hydraulic conductivity values for nearly all the pilot points in these aquitard layers were fixed at 1.0 feet/day. Therefore, vertical anisotropy that was varied is equivalent to the inverse of vertical hydraulic conductivity.

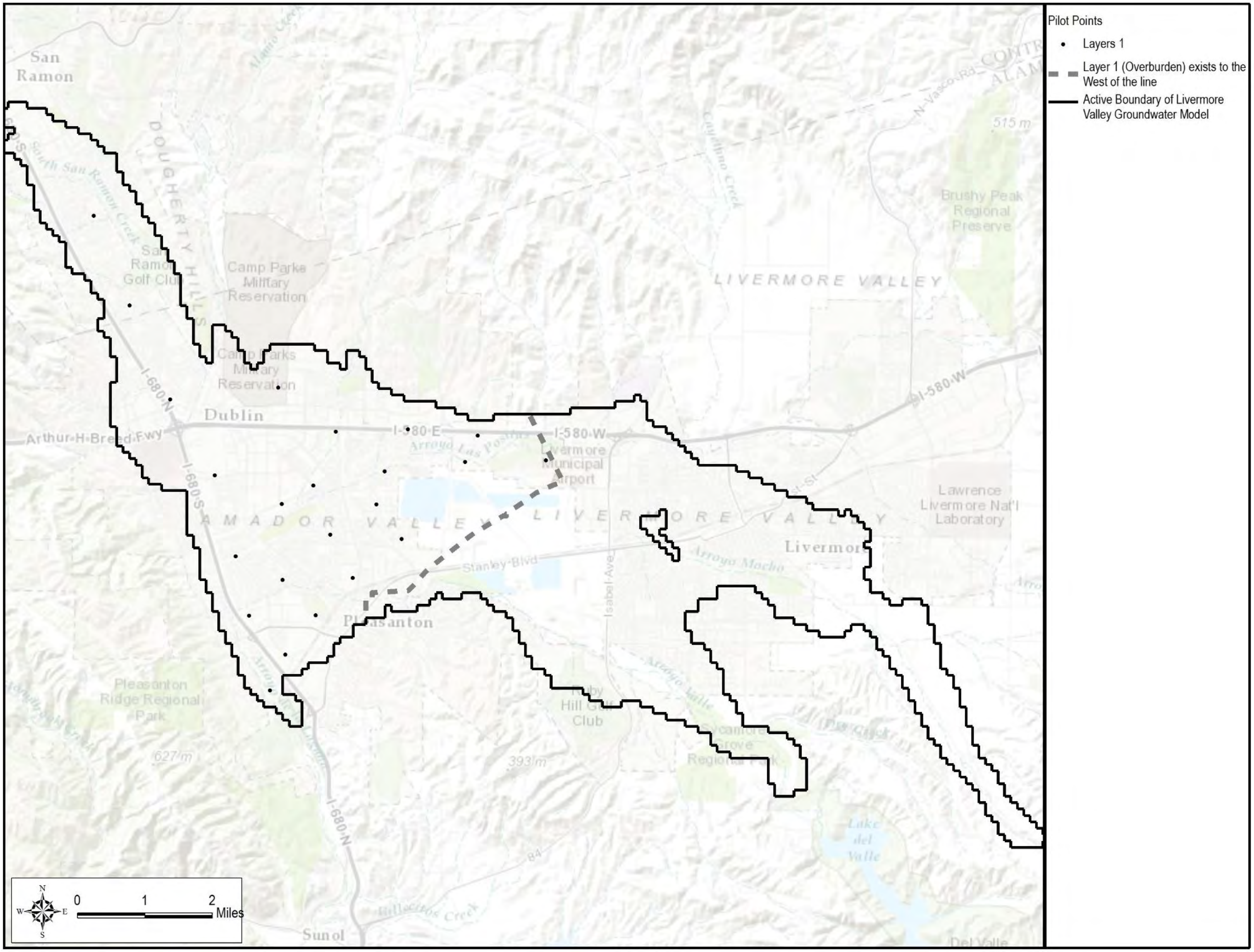


Figure 31: Pilot Points for Layer 1

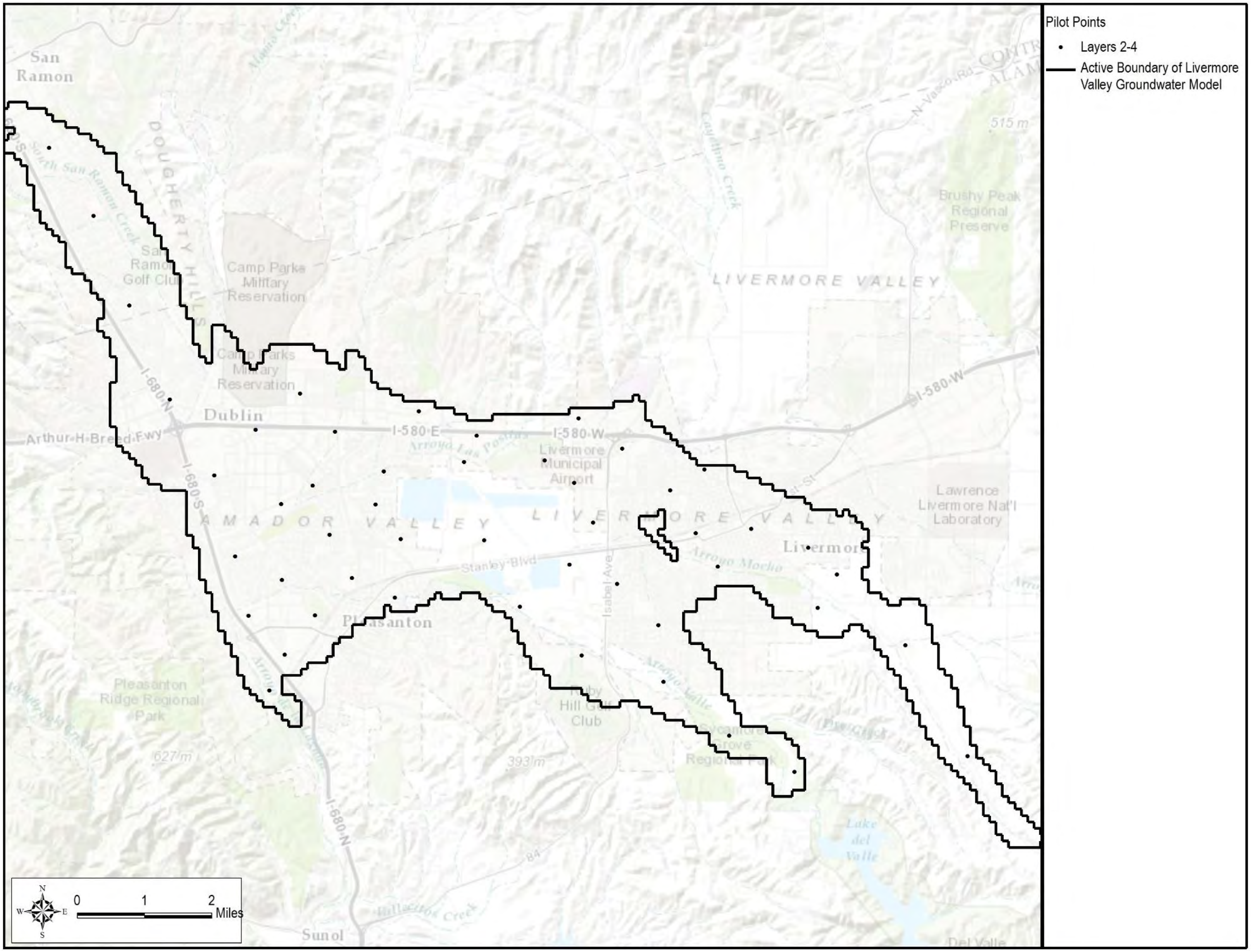


Figure 32: Pilot Points for Layers 2-4

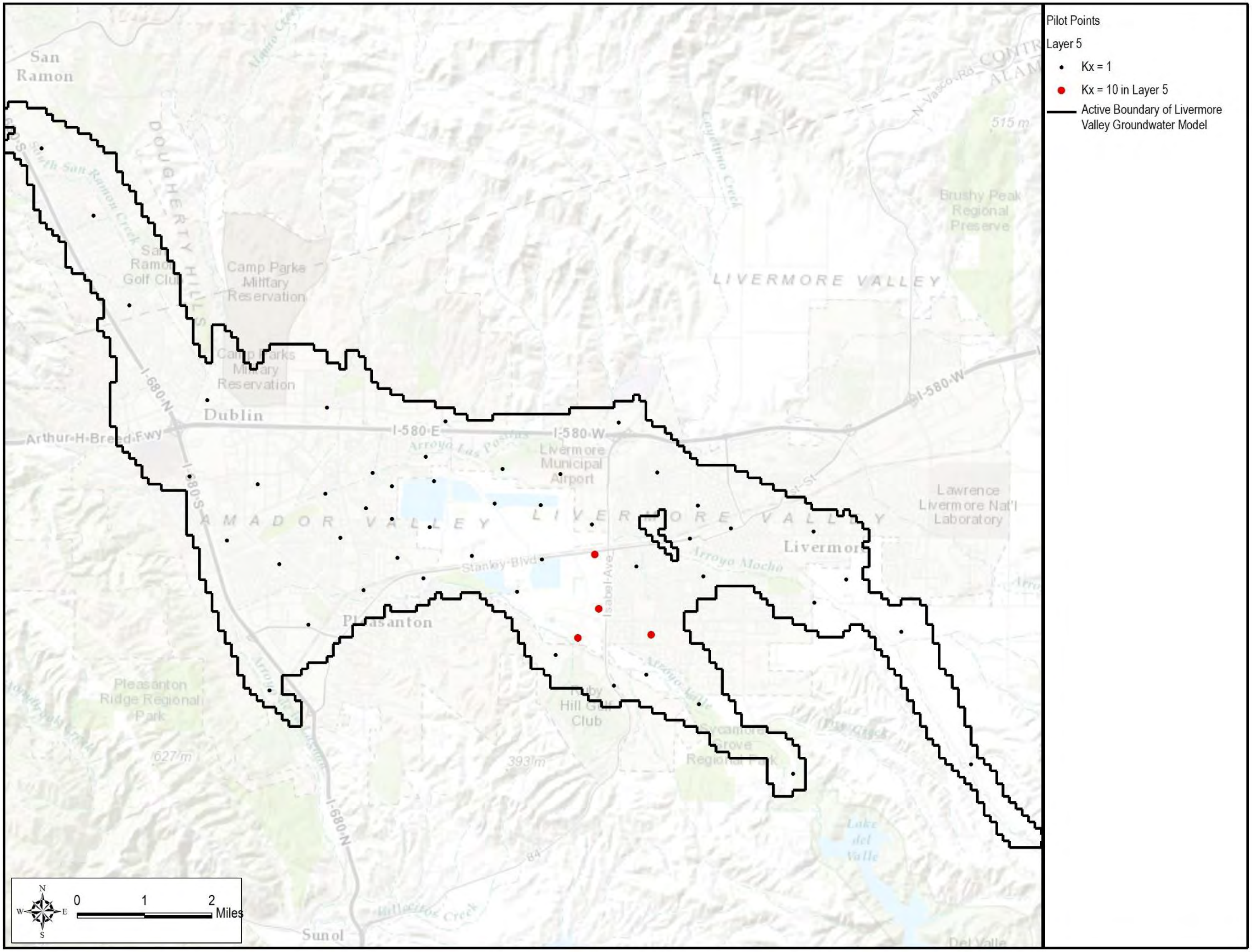


Figure 33: Pilot Points for Layer 5

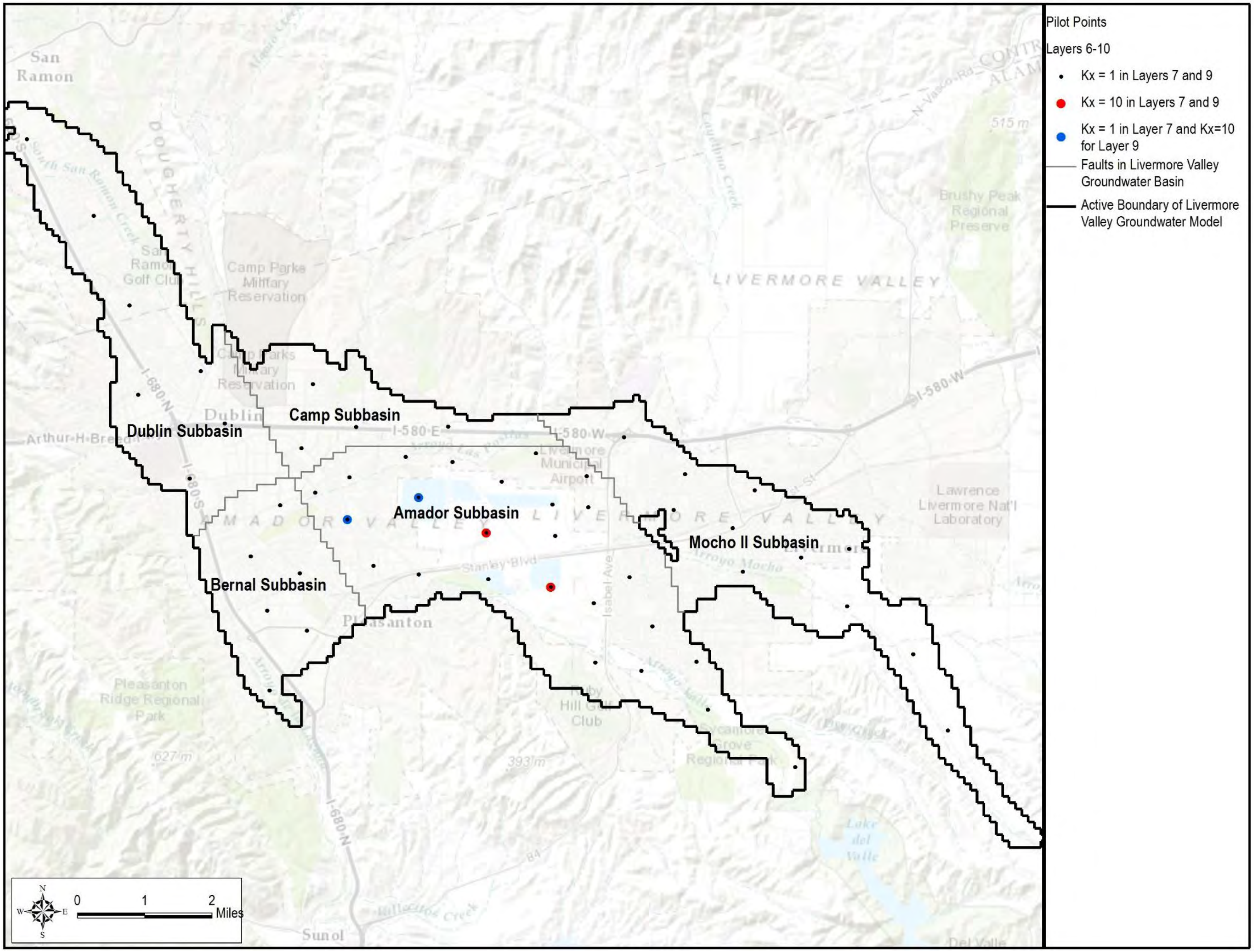


Figure 34: Pilot Points for Layers 6-10

There were several areas in the Amador Sub-basin where horizontal hydraulic conductivity values for aquitard layers 5, 7, and 9 were fixed at 10.0 feet/day because spatially grouped e-log results for those areas indicated higher hydraulic conductivities (Figure 33 and Figure 34).

4.3.3 Tied Parameter Fields by Layer

To further reduce the number of parameter values to be varied, another strategy used was to tie pilot point values for parameters for sets of layers. The three sets of tied layers are aquifer layers 2 and 4, aquifer layers 6, 8, and 10, and aquitard layers 7 and 9. Parameter fields are identical within these sets of tied layers with the exception of the areas in aquitard layers 7 and 9 with higher conductivity discussed above. Overburden layer 1 and aquitard layers 3 and 5 are not tied. The tied layers reflect the conceptual model that there is an upper and lower aquifer that provide groundwater supply above and below aquitard layer 5, so approximating the aquifer and aquitard layers within those aquifers as equivalent is appropriate. This still allows simulation of intervening aquitard layers 3, 7, and 9 that are lower conductivity units that affect salt transport.

4.3.4 Porosity Based on Specific Yield

Porosity is the calibration parameter specific to the transport model. Porosity physically cannot be less than specific yield. Porosity is calibrated by assigning a value to be added to the specific yield value to ensure that porosity is at least as large as specific yield.

4.4 Calibrated Parameters

4.4.1 Pilot Point Based Parameter Fields

Model parameters were adjusted during model calibration to improve the model's ability to simulate known conditions. Calibration of the model consisted of modifying the distribution and magnitude of horizontal hydraulic conductivity, vertical anisotropy for vertical hydraulic conductivity, specific yield, and specific storage values using the pilot point method discussed above. The final distributions of the aquifer parameter values are shown for relevant model layers in Figure 35 through Figure 41 and APPENDIX C:. These parameter distributions do not necessarily match estimated parameter values from e-log analysis by Zone 7. Most of the e-log results could not be spatially grouped to indicate that they are representative of parameters affecting regional flow, although there were several areas of higher hydraulic conductivity in the Amador Sub-basin for aquitards that were modeled (see Section 4.3.2).

A map of vertical hydraulic conductivity for layers 2 and 4 are not presented because calibrated anisotropy did not show much variation. Anisotropy of horizontal hydraulic conductivity to vertical hydraulic conductivity ranged from 9.5 to 10.9 in layers 2 and 4 so the distribution of vertical hydraulic conductivity is similar to the distribution of horizontal hydraulic conductivity shown in Figure 35.

Similarly, maps of specific storage for those layers are not presented because calibrated ranges for specific storage in those layers do not show much variation although there are areas in layers 2-5 that are confined. Table 8 shows the ranges of specific storage for layers 2-5.

Table 8: Range of Specific Storage (Ss) for Layers 2-5

Layer	Minimum Ss (1/feet)	Maximum Ss (1/feet)
Aquifer Layers 2 and 4	9.2×10^{-7}	1.1×10^{-6}
Aquitard Layer 3	9.9×10^{-7}	1.0×10^{-6}
Aquitard Layer 5	9.8×10^{-7}	1.1×10^{-6}

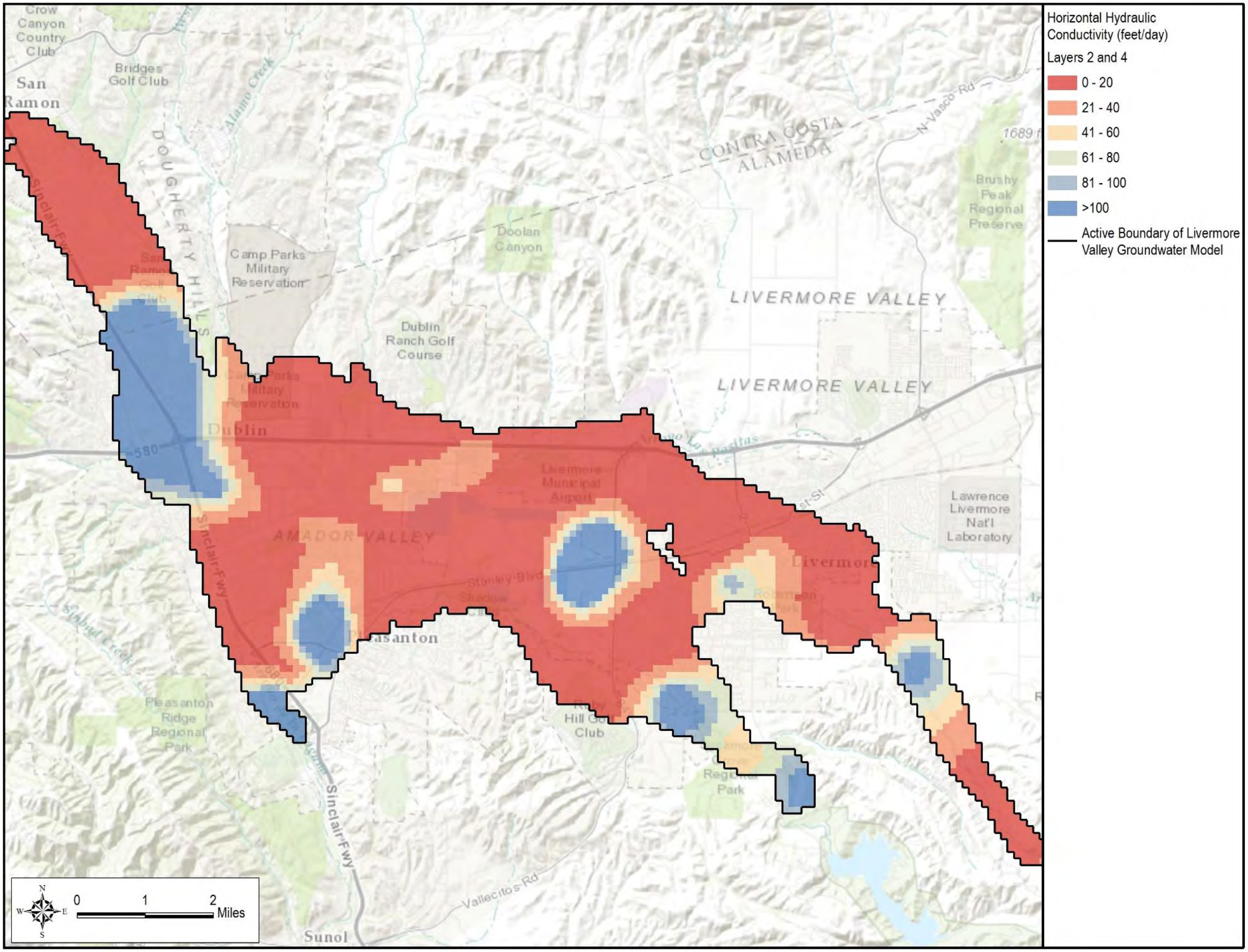


Figure 35: Horizontal Hydraulic Conductivity Aquifer Layers 2 and 4

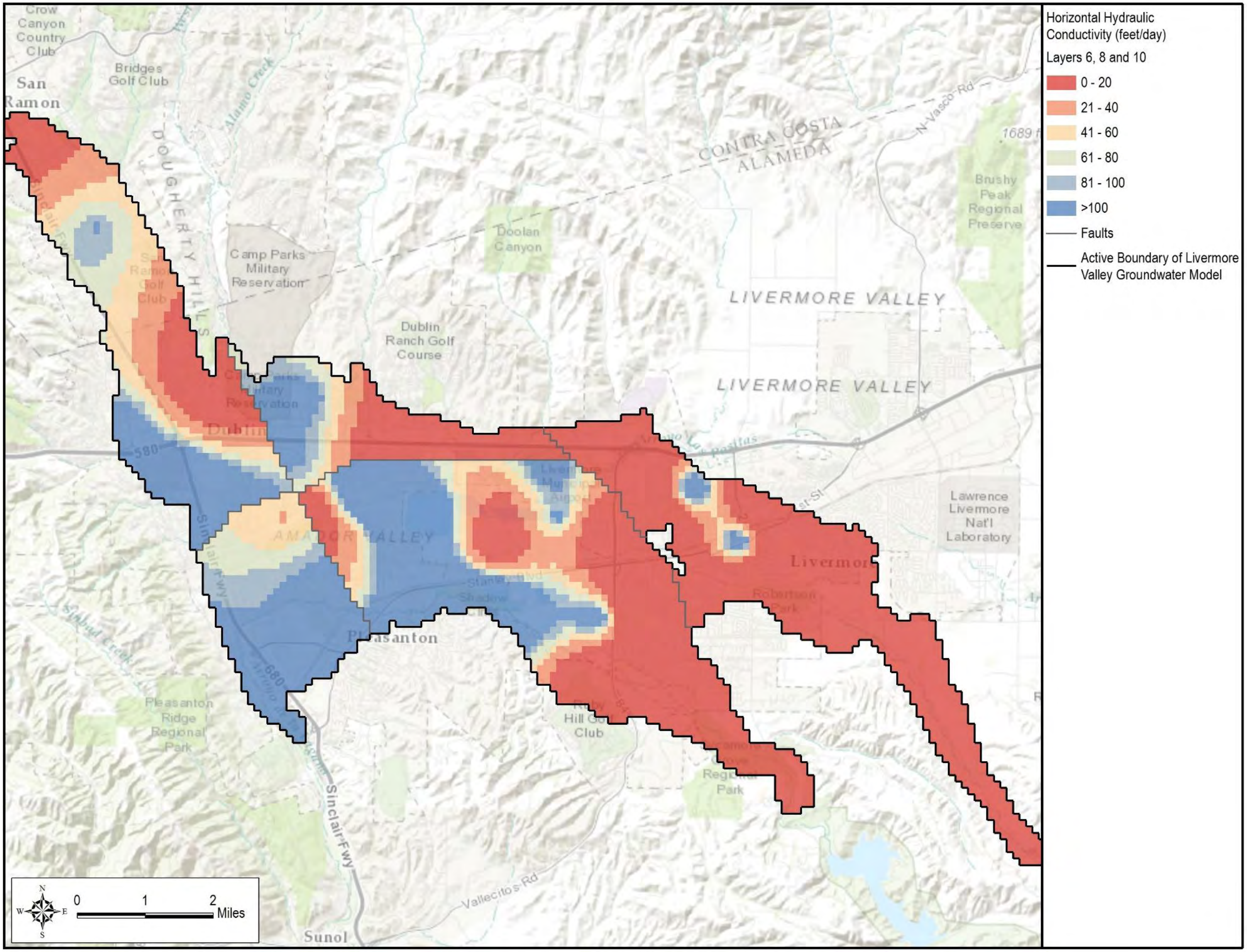


Figure 36: Horizontal Hydraulic Conductivity Aquifer Layers 6, 8, and 10

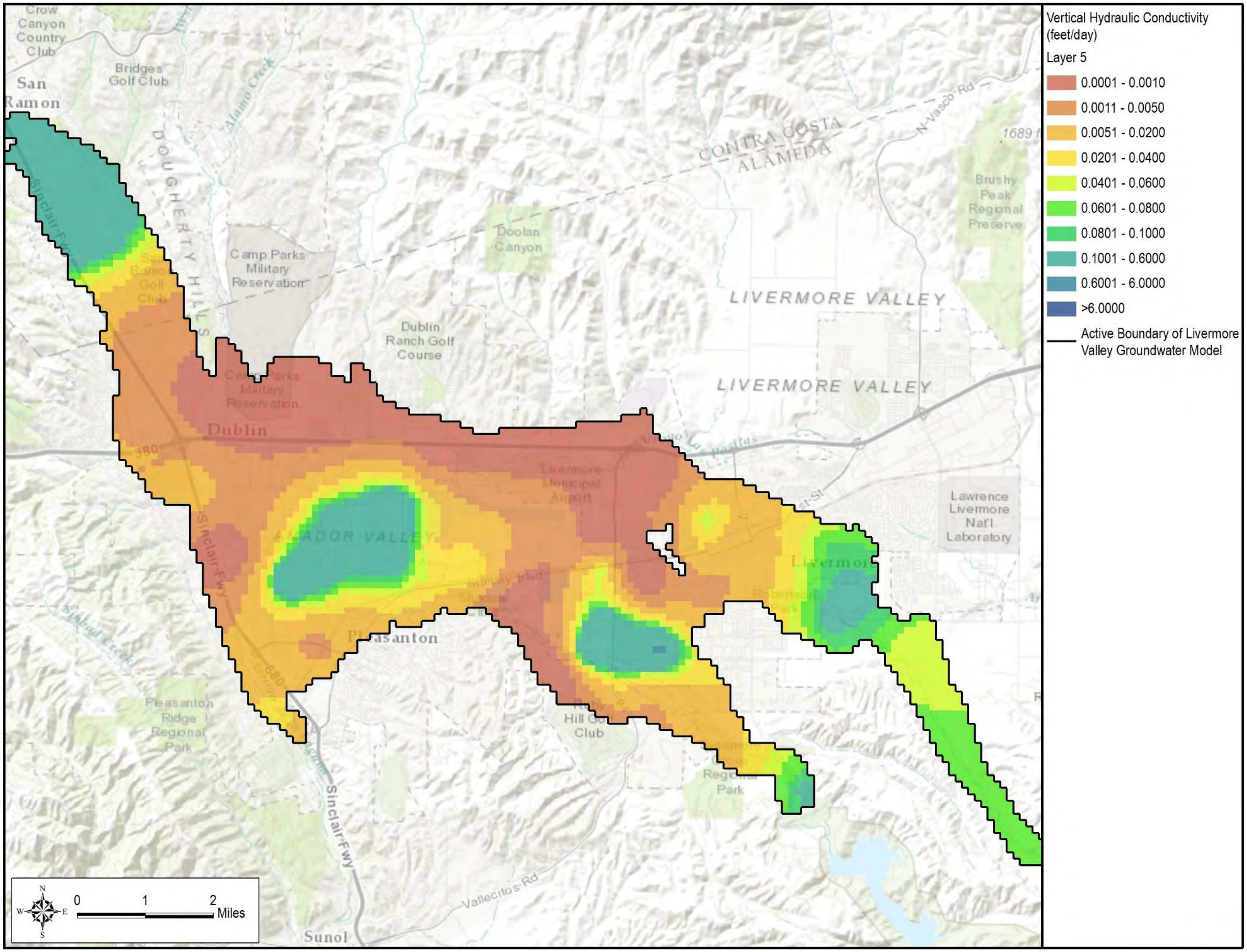


Figure 37: Vertical Hydraulic Conductivity Aquitard Layer 5

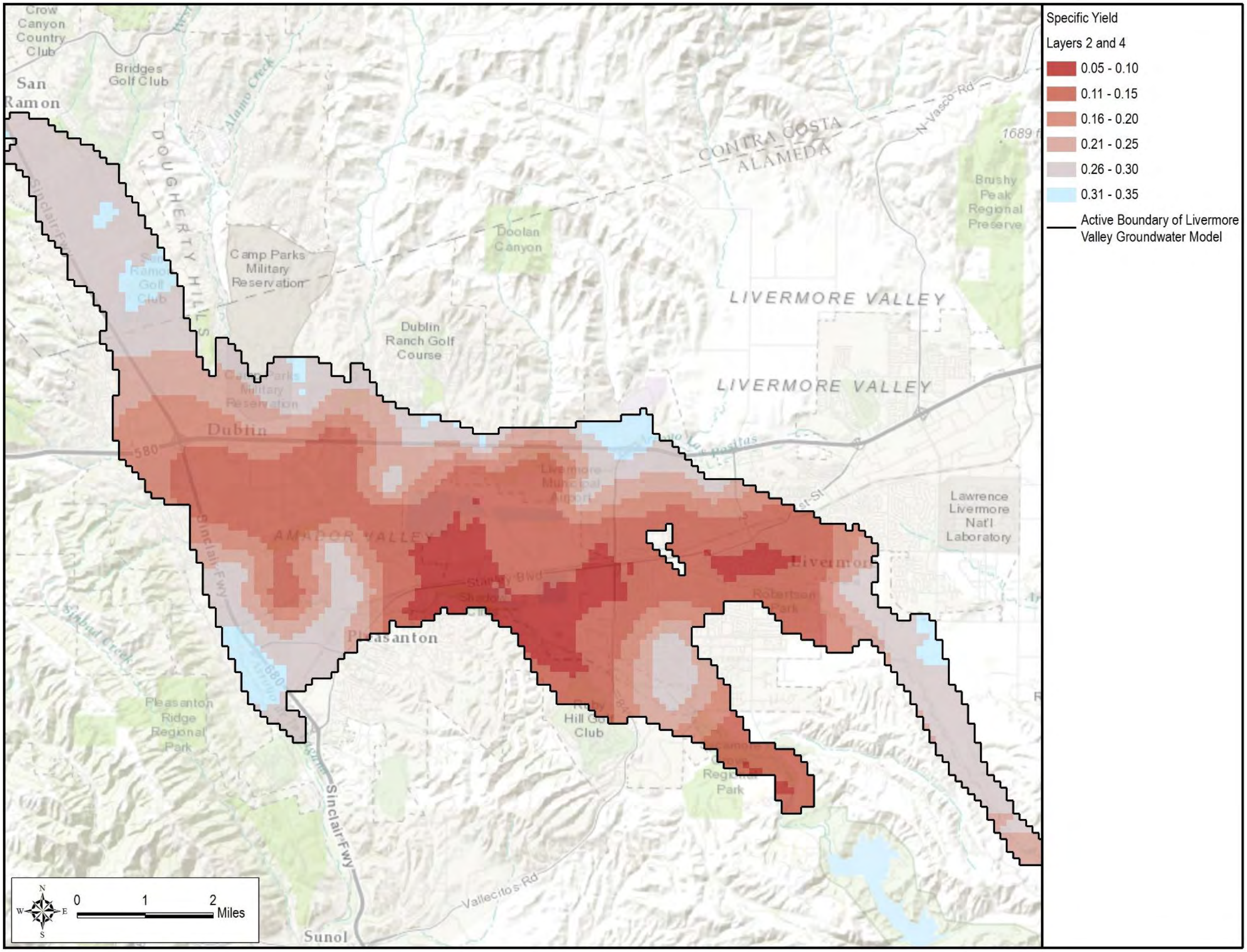


Figure 38: Specific Yield Aquifer Layers 2 and 4

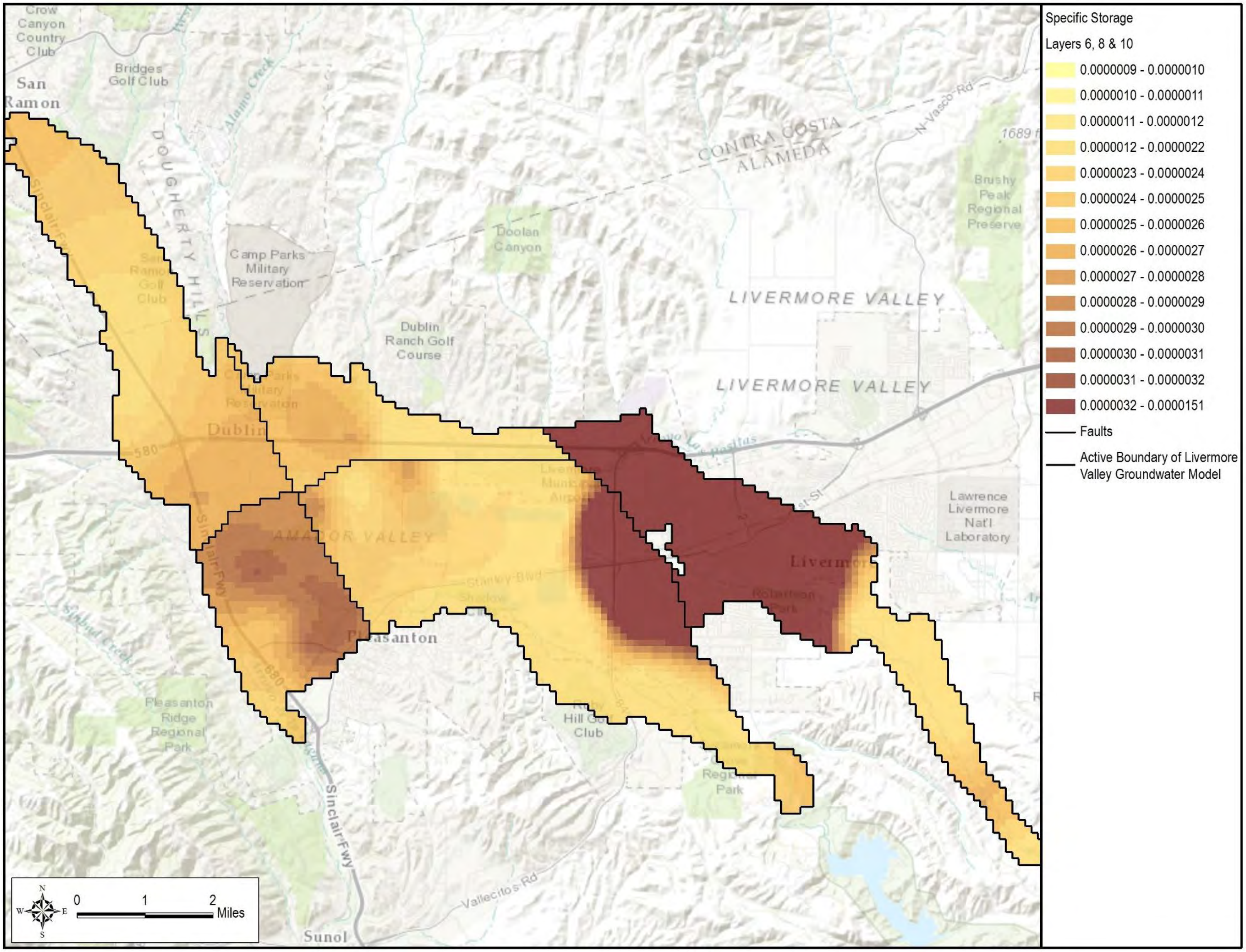


Figure 39: Specific Storage Aquifer Layers 6, 8, and 10

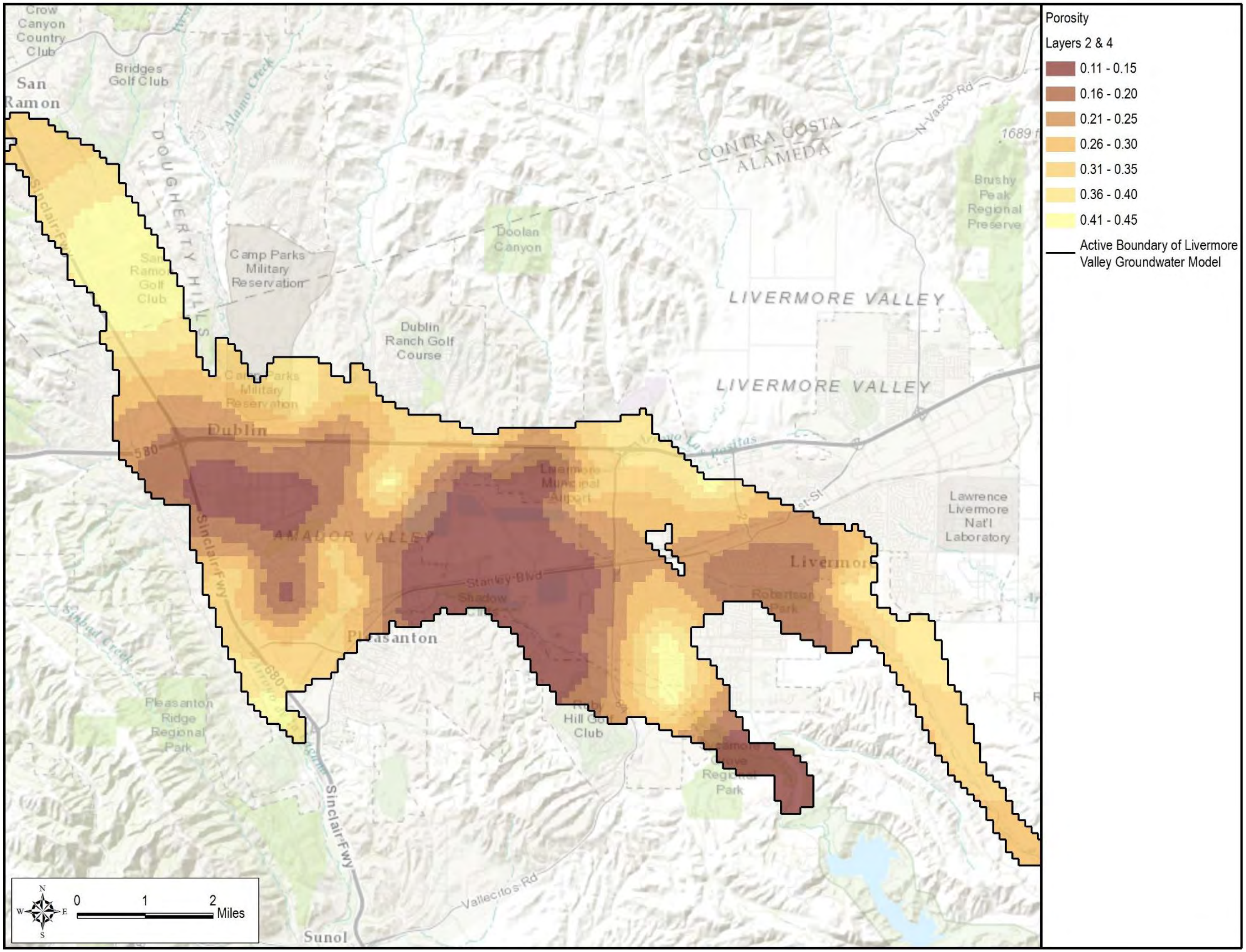


Figure 40: Porosity Aquifer Layers 2 and 4

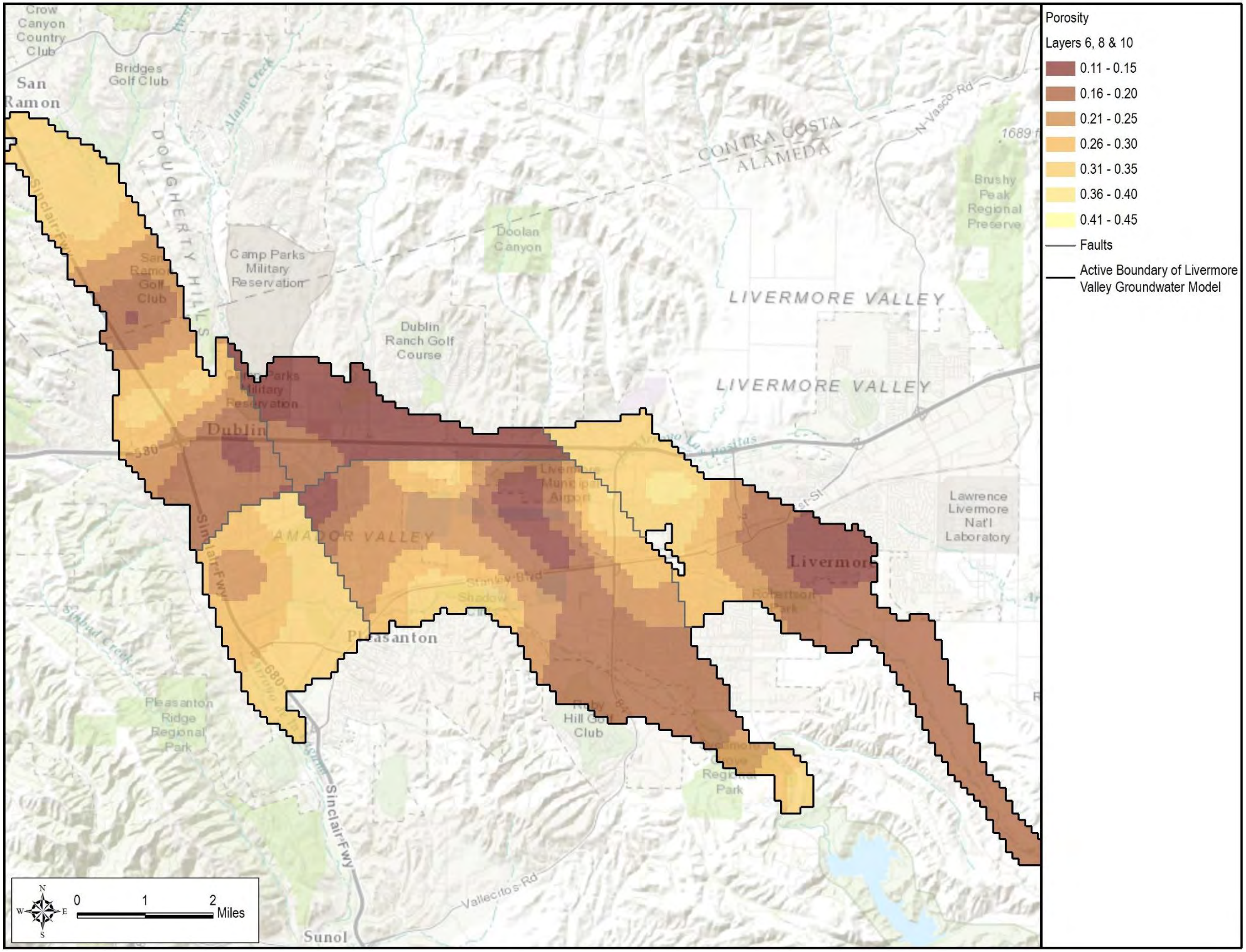


Figure 41: Porosity Aquifer Layers 6, 8, and 10

4.4.2 Fault Leakance

The faults in layers 6-10 are represented by the Horizontal Flow Barrier (HFB) package. The calibrated parameter for the faults is the HFB hydraulic characteristic or leakance which is equivalent to the fault hydraulic conductivity divided by fault width that represents the fault's ability to transmit flow. Six fault segments are defined based on segments between sub-basins. The leakance values are varied by segment, but uniform across all segment layers. Figure 42 shows the calibrated fault leakances.

4.4.3 Stream Leakance

The streambed conductance (KwL/b) in the SFR package relates the stream and aquifer head difference (h_s-h_a) to the transient leakage (Q_L) across the streambed based on Darcy's Law: Q_L=KwL/b(h_s-h_a) (Niswonger et al., 2005). The length L of each stream reach is defined based on the intersection of the streams with the model grid. The width w is defined as constant if stage is defined by a constant value and assigned as constant as part of a rating table (ICALC in Table 2). The streambed leakance (K/b) is the calibrated parameter to represent the streambed's ability to transmit flow and is calibrated by fixing streambed thickness b at 1 foot and varying hydraulic conductivity K. The leakances of segments 37-42 are not calibrated and are assumed to stay constant at zero at all times as discussed in Section 2.10. Figure 43 shows the calibrated stream leakances.

4.4.4 Lake Leakance

The lakebed leakance in the LAK package is used in a formula with aquifer hydraulic conductivity and cell spacing to calculate the conductance that relates the lake and aquifer head difference (h_l-h_a) to the transient lake leakage rate (q) across the lakebed (Merritt et al., 2000). The lakebed leakance (K/b), equivalent to the lakebed hydraulic conductivity (K) divided by the lakebed thickness (b) and representing the lakebed's ability to transmit flow, is defined for each model cell at or adjacent to a lake in the lake package input file. The lakebed leakance is therefore defined for both the lake bottoms and the sides of the lake. Leakance values are calibrated for each unlined lake with the same value for lateral and vertical leakance. However, since sidewall leakance is defined at the aquifer cell adjacent to the lake, some lake leakance values are applied to two lakes so each lake may not have a completely uniform leakance value. Figure 43 shows the calibrated lakebed leakances.

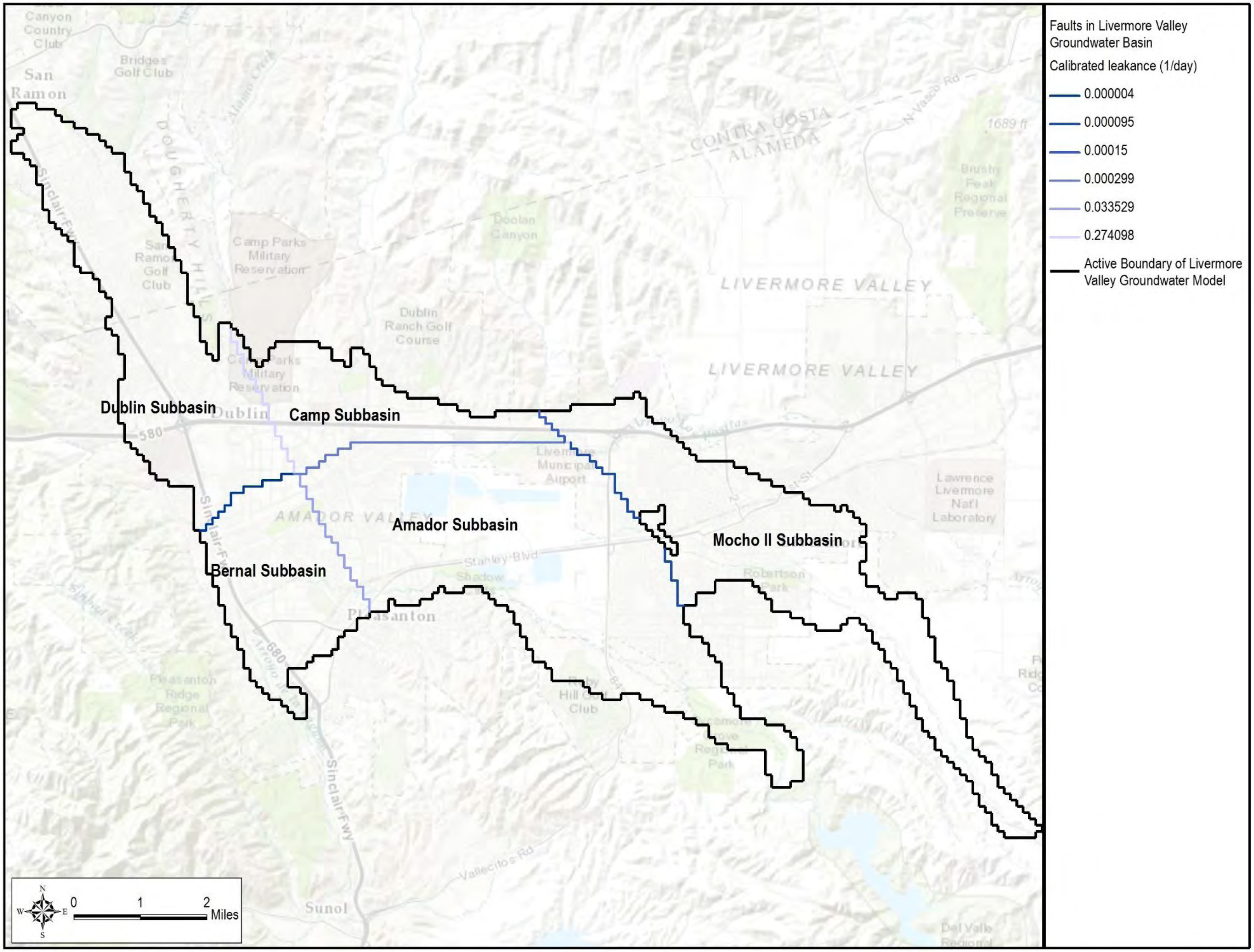


Figure 42: Calibrated Leakance Values for Faults

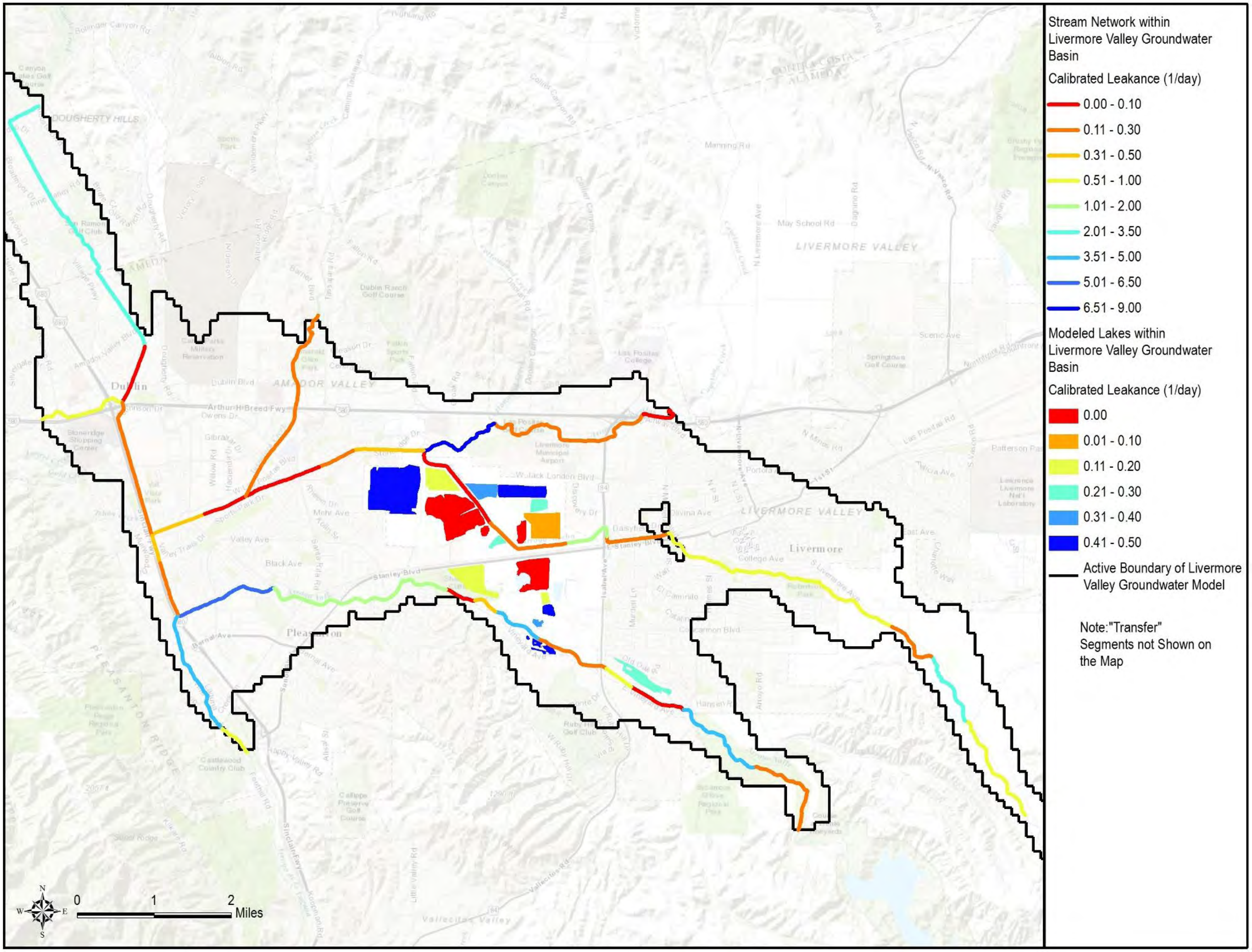


Figure 43: Calibrated Leakance Values for Streams and Lakes

4.5 Calibration Results

As introduced above, results simulated by the model for the calibration period of Water Year 1974-2014 were compared to measured groundwater elevations, streamflows, lake stages, and TDS concentrations in groundwater, streams, and lakes when adjusting parameters to calibrate the model.

4.5.1 Groundwater Elevations

Flow model calibration is commonly evaluated by comparing simulated water elevations with observed groundwater elevations from monitoring and production wells. Hydrographs of simulated groundwater elevations should generally match the trends and fluctuations observed in measured hydrographs. Furthermore, the average errors between observed and simulated groundwater elevations should be relatively small and unbiased. The target well locations used for calibration of the model to groundwater elevations are shown in Figure 44. The target wells were selected based on data availability for both groundwater levels and screen intervals. Wells were selected as representative of regional flow conditions for an area and in different model layers.

For comparison to observations, simulated groundwater levels were interpolated to the well location from results for the model grid and the measurement time from the results simulated at the end of each month using the groundwater data utility MOD2OBS (Watermark, 2008). For wells screened over multiple model layers, simulated groundwater levels in each of the layers are weighted by layer transmissivity and averaged before comparing with measured data.

Example maps of simulated piezometric surfaces are displayed on Figure 45 through Figure 48. The maps show end of water year (September) results from 1991, with relatively low groundwater elevations, and 1995, with relatively high groundwater elevations. APPENDIX D: includes maps for 1974, the first year of the simulation, and 2014, the last year of the simulation. The maps show results from model layers 2 and 6, representing the top aquifer units in the upper and lower aquifers.

Hydrographs showing both observed and simulated groundwater elevations are shown in Figure 49 through Figure 59. These example hydrographs were chosen to demonstrate the model's accuracy in various parts of the sub-basins. The hydrographs show that the model accurately simulates the general groundwater levels in the basins and trends observed in monitoring well data. This indicates that the groundwater system is well represented by the model structural upgrades to refine layers and simulate surface water features. However, a number of wells have larger fluctuations in groundwater levels than simulated by the model, indicating further evaluation of the water budget fluctuations over time may be warranted. APPENDIX E: includes hydrographs for all groundwater elevation targets used in the calibration.

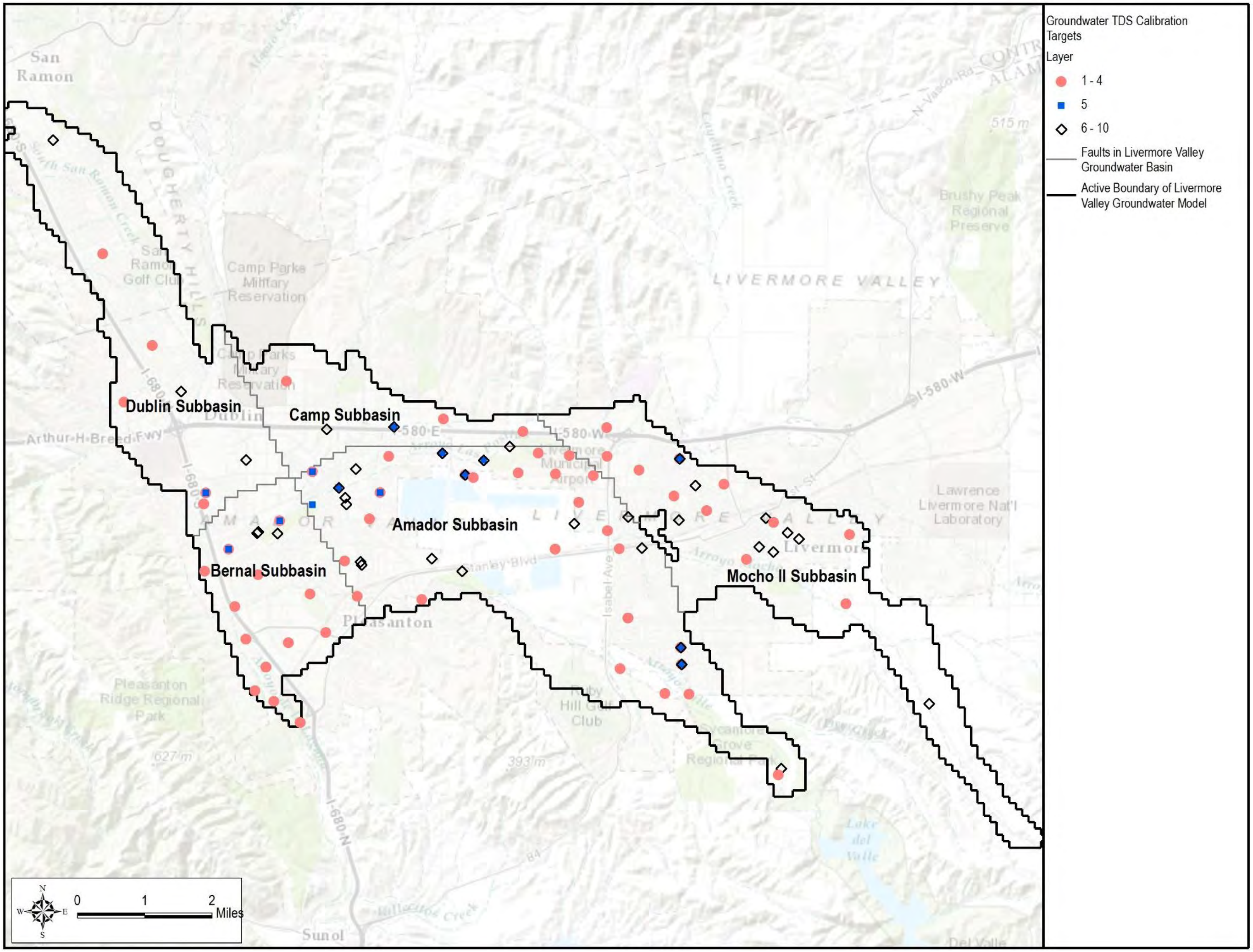


Figure 44: Groundwater Elevation Target Locations

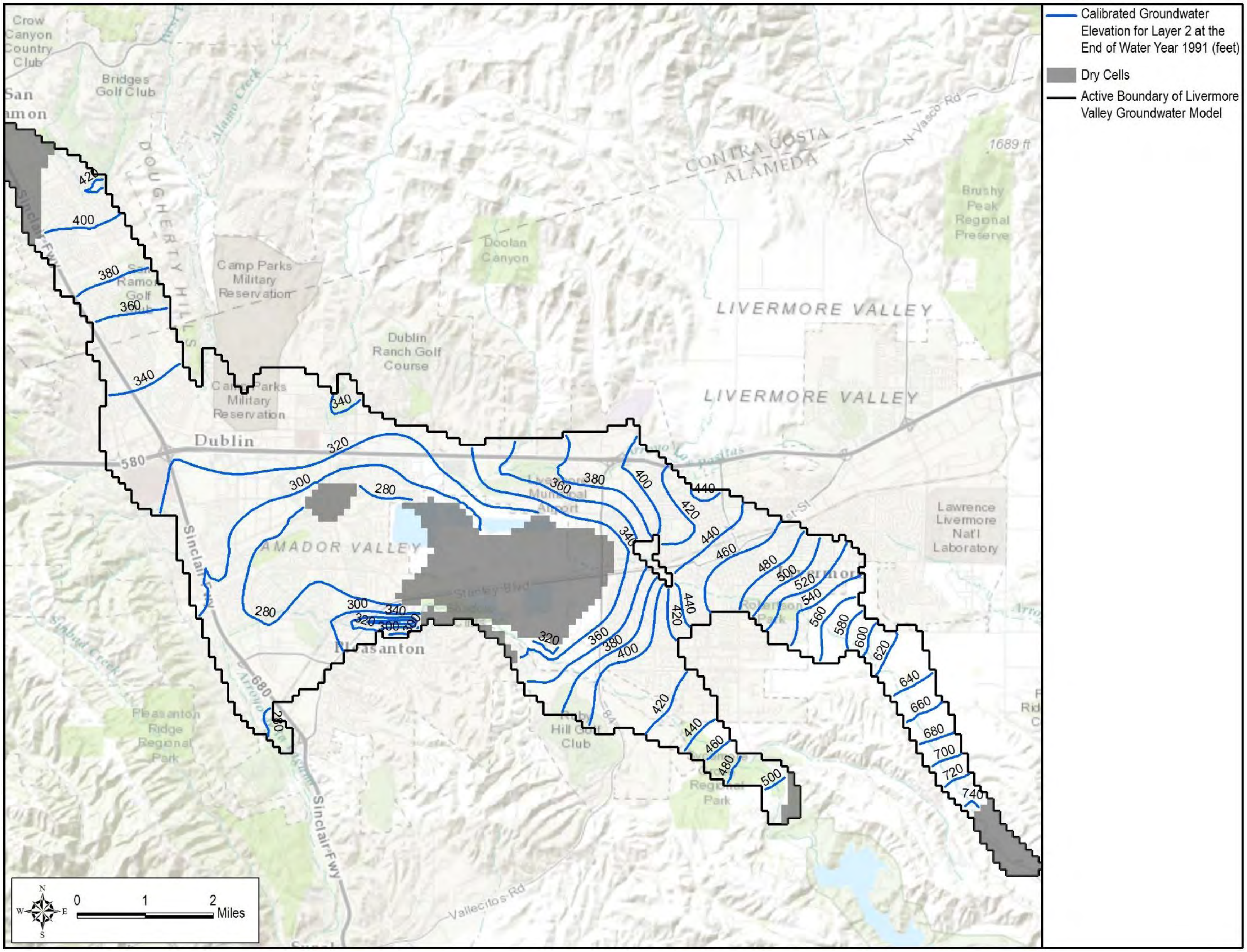


Figure 45: Simulated Groundwater Elevations for Layer 2 at the end of Water Year 1991

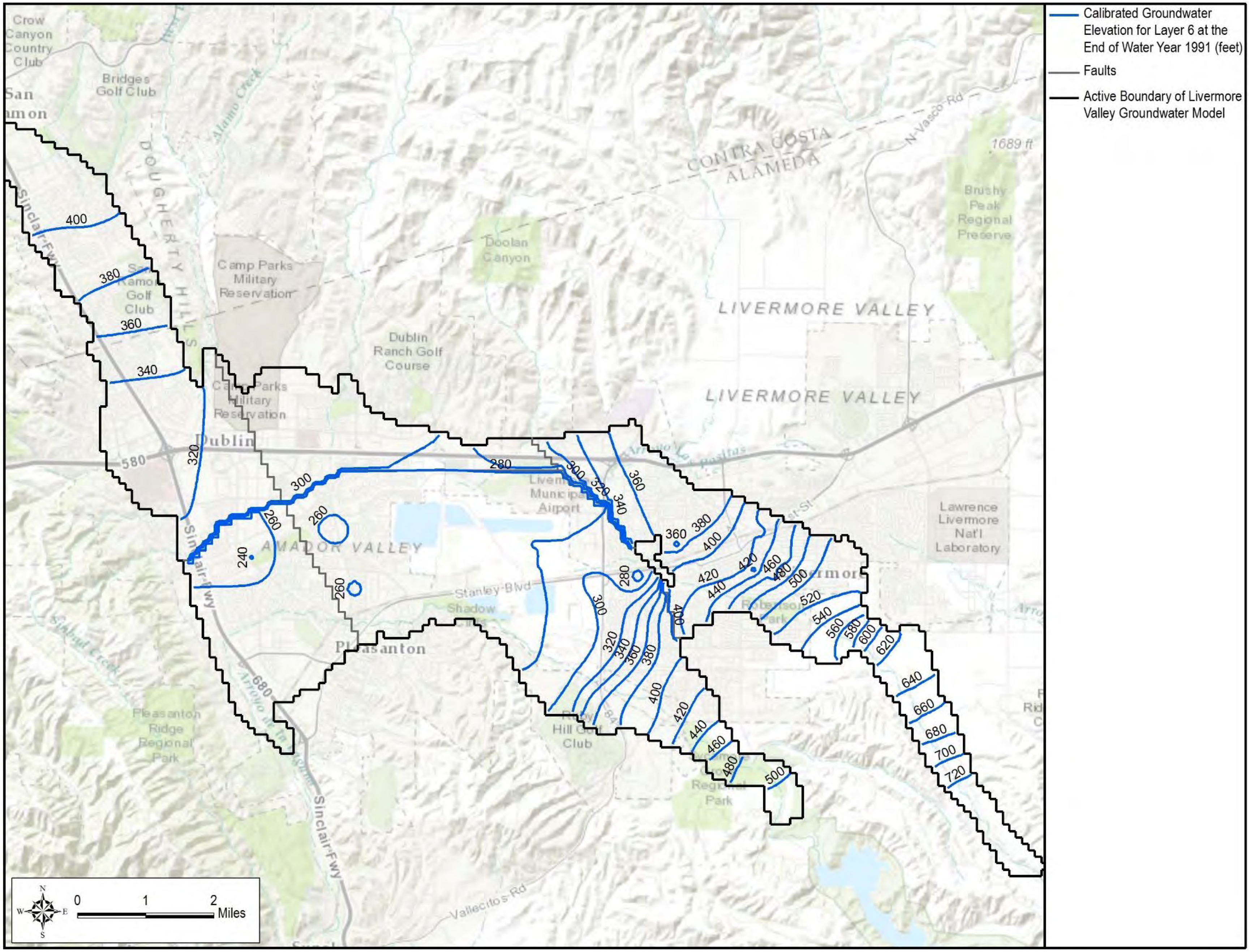


Figure 46: Simulated Groundwater Elevations for Layer 6 at the end of Water Year 1991

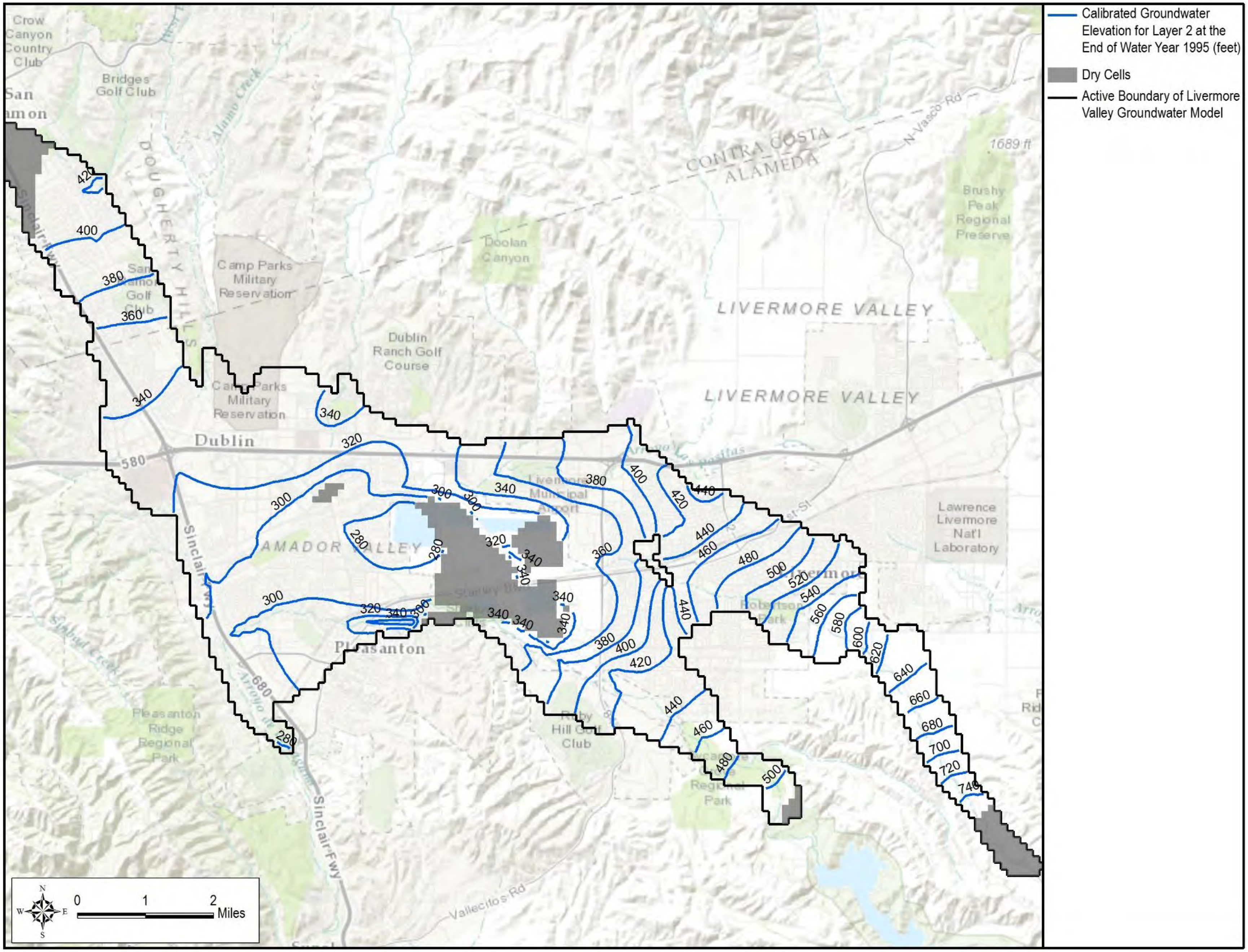


Figure 47: Simulated Groundwater Elevations for Layer 2 at the end of Water Year 1995

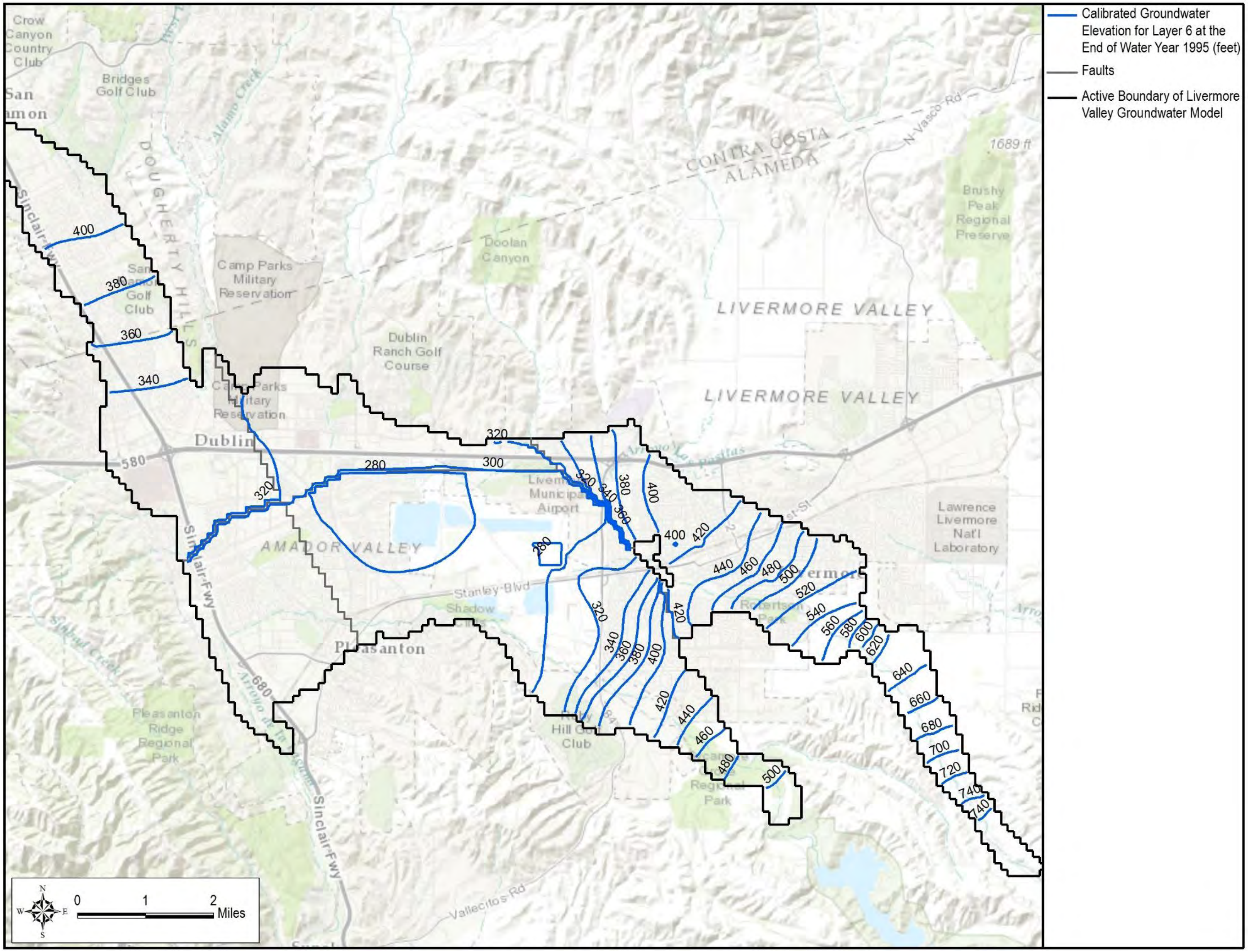


Figure 48: Simulated Groundwater Elevations for Layer 6 at the end of Water Year 1995

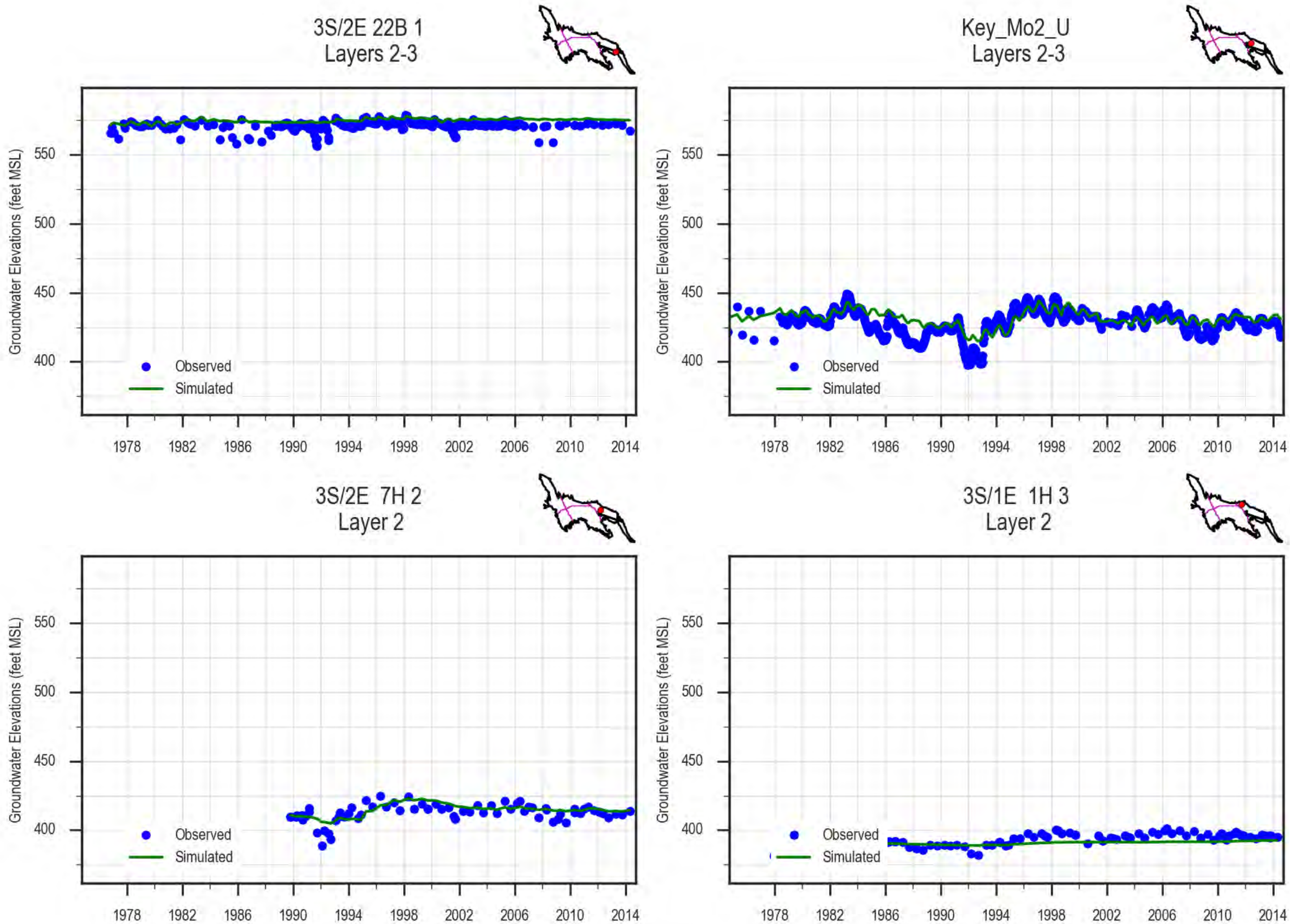


Figure 49: Example Groundwater Elevation Hydrographs for Mocho II Sub-basin Layers 2-4

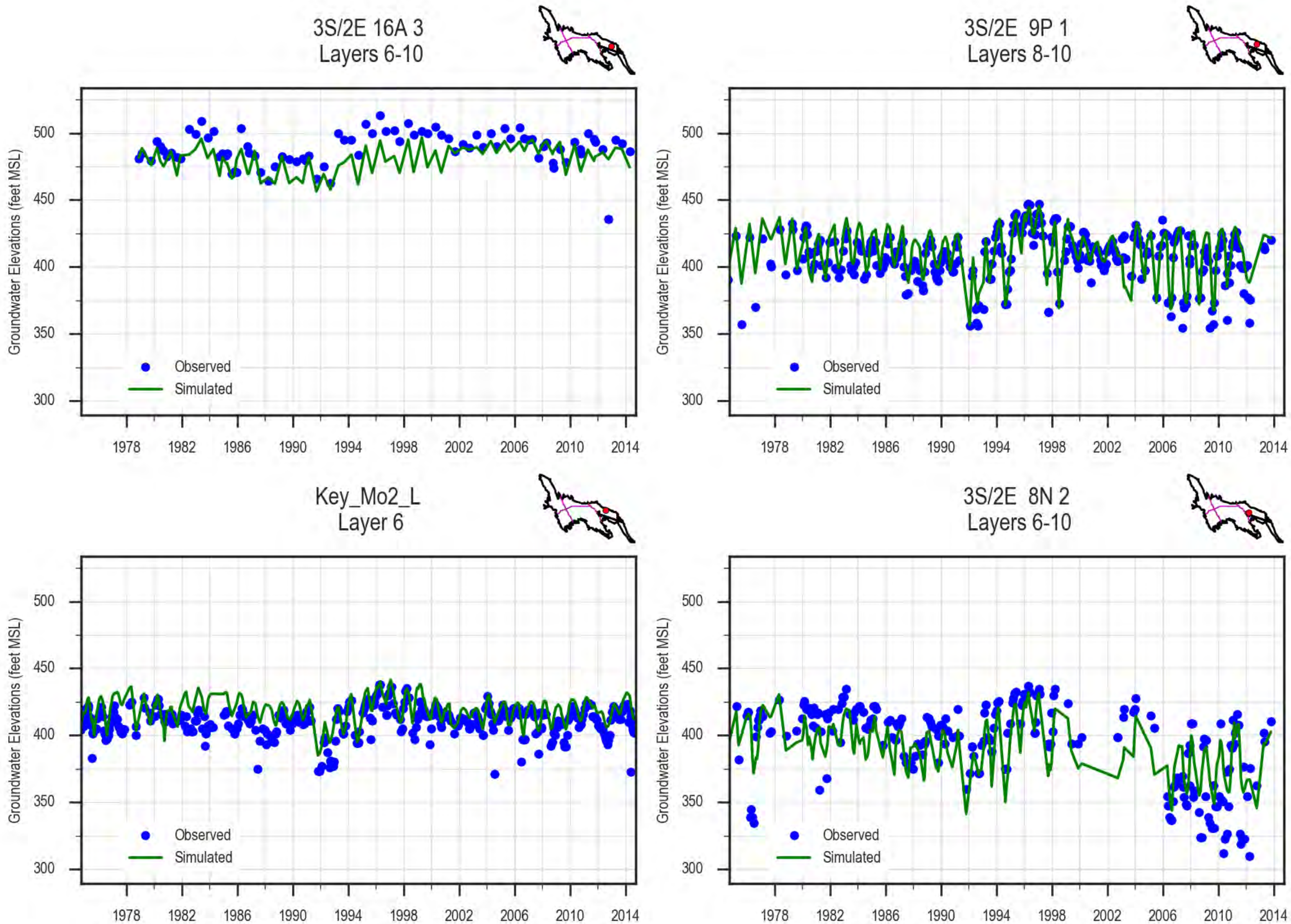


Figure 50: Example Groundwater Elevation Hydrographs for Mocho II Sub-basin Layers 6-10

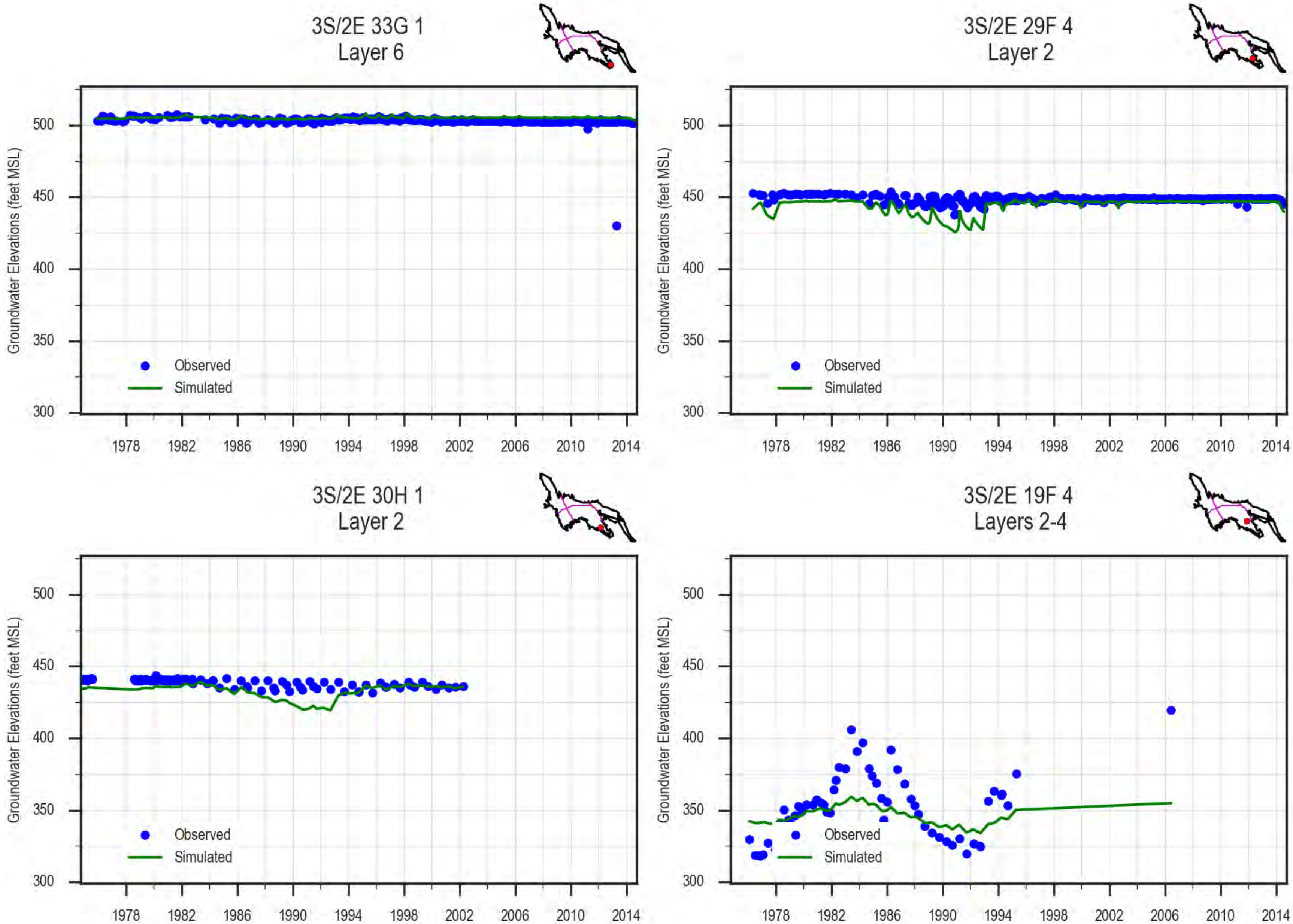


Figure 51: Example Groundwater Elevation Hydrographs for Amador Sub-basin Upstream Area

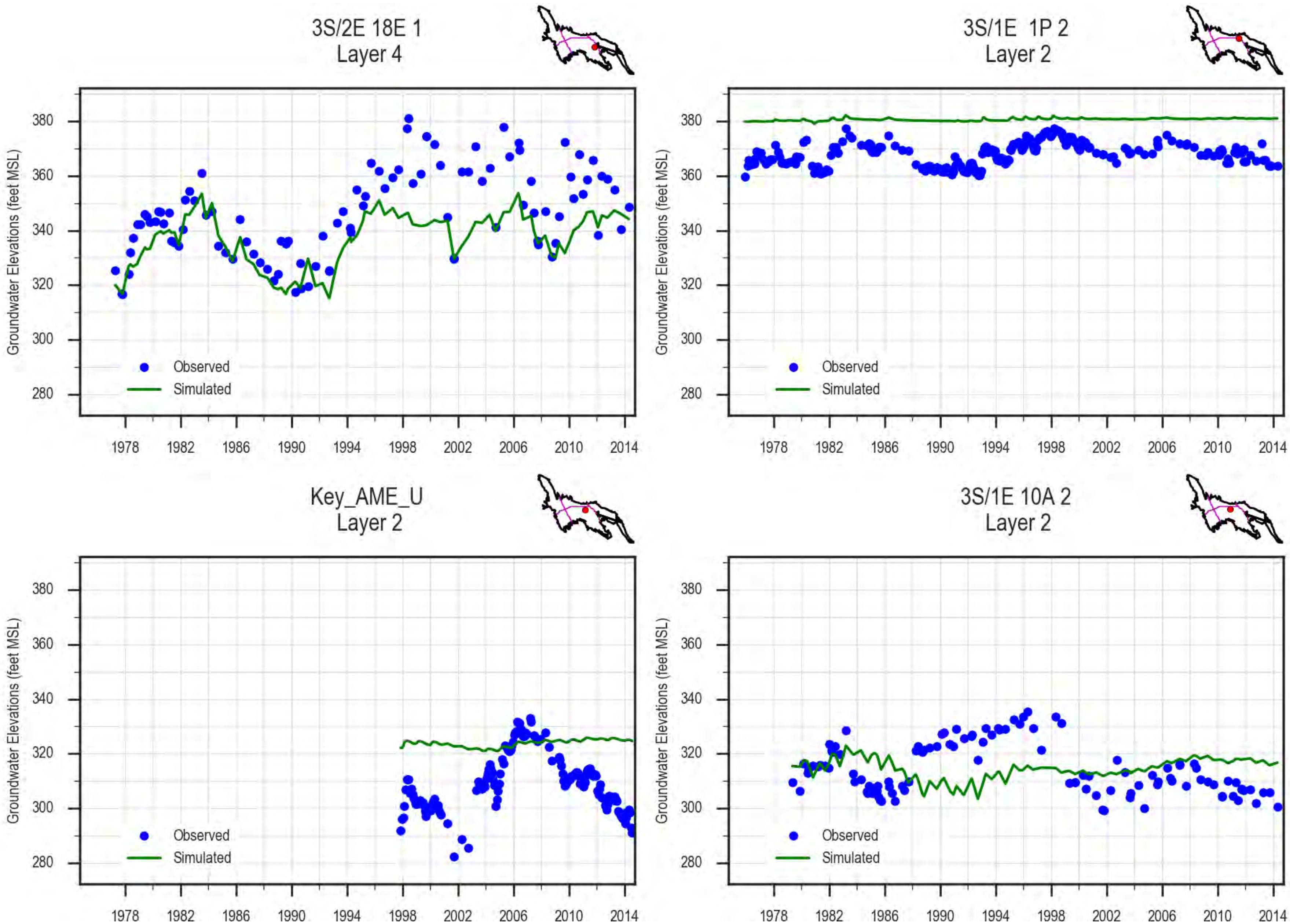


Figure 52: Example Groundwater Elevation Hydrographs for Amador Sub-basin East Area Layers 2-4

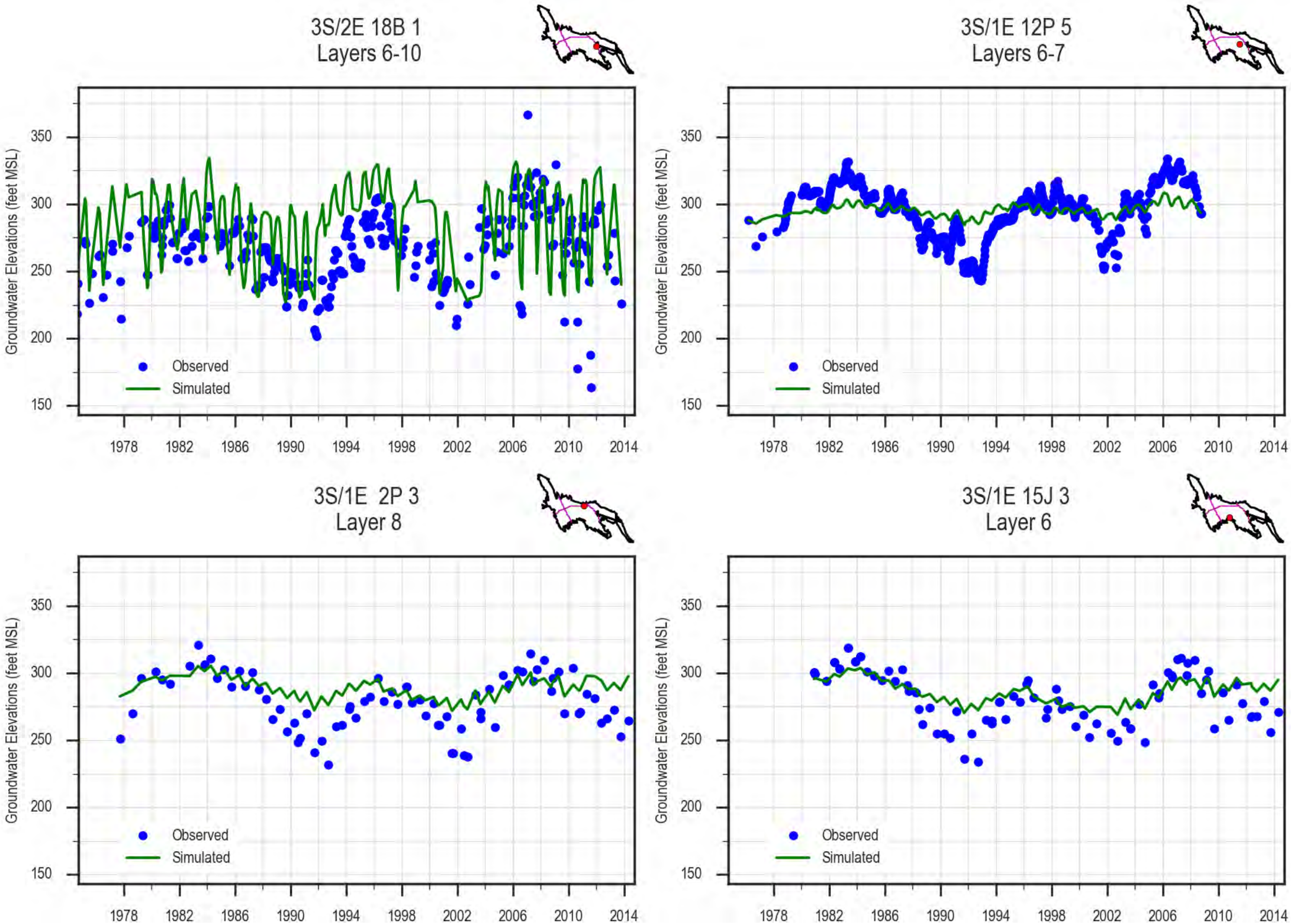


Figure 53: Example Groundwater Elevation Hydrographs for Amador Sub-basin East Area Layers 6-10

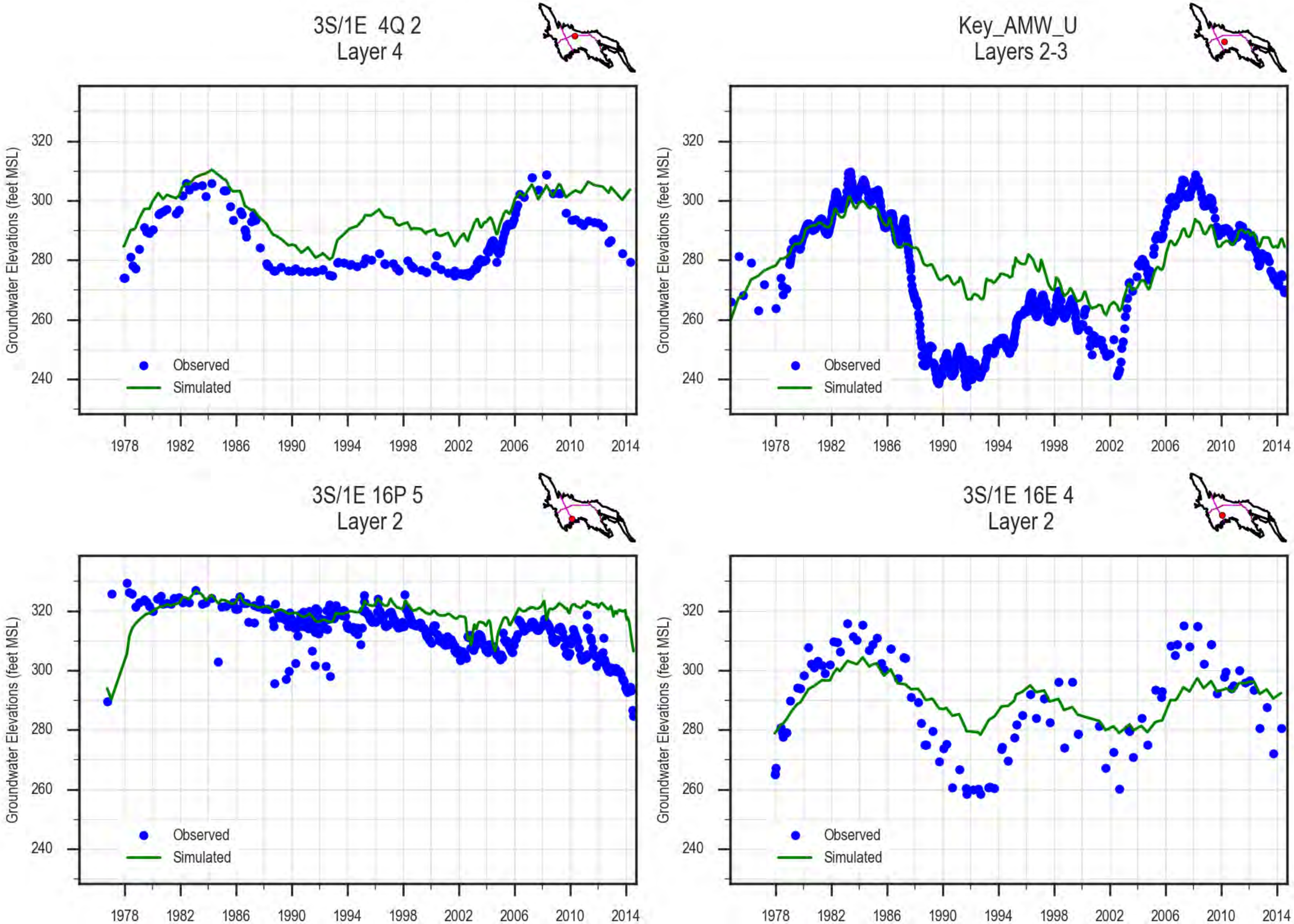


Figure 54: Example Groundwater Elevation Hydrographs for Amador Sub-basin West Area Layers 2-4

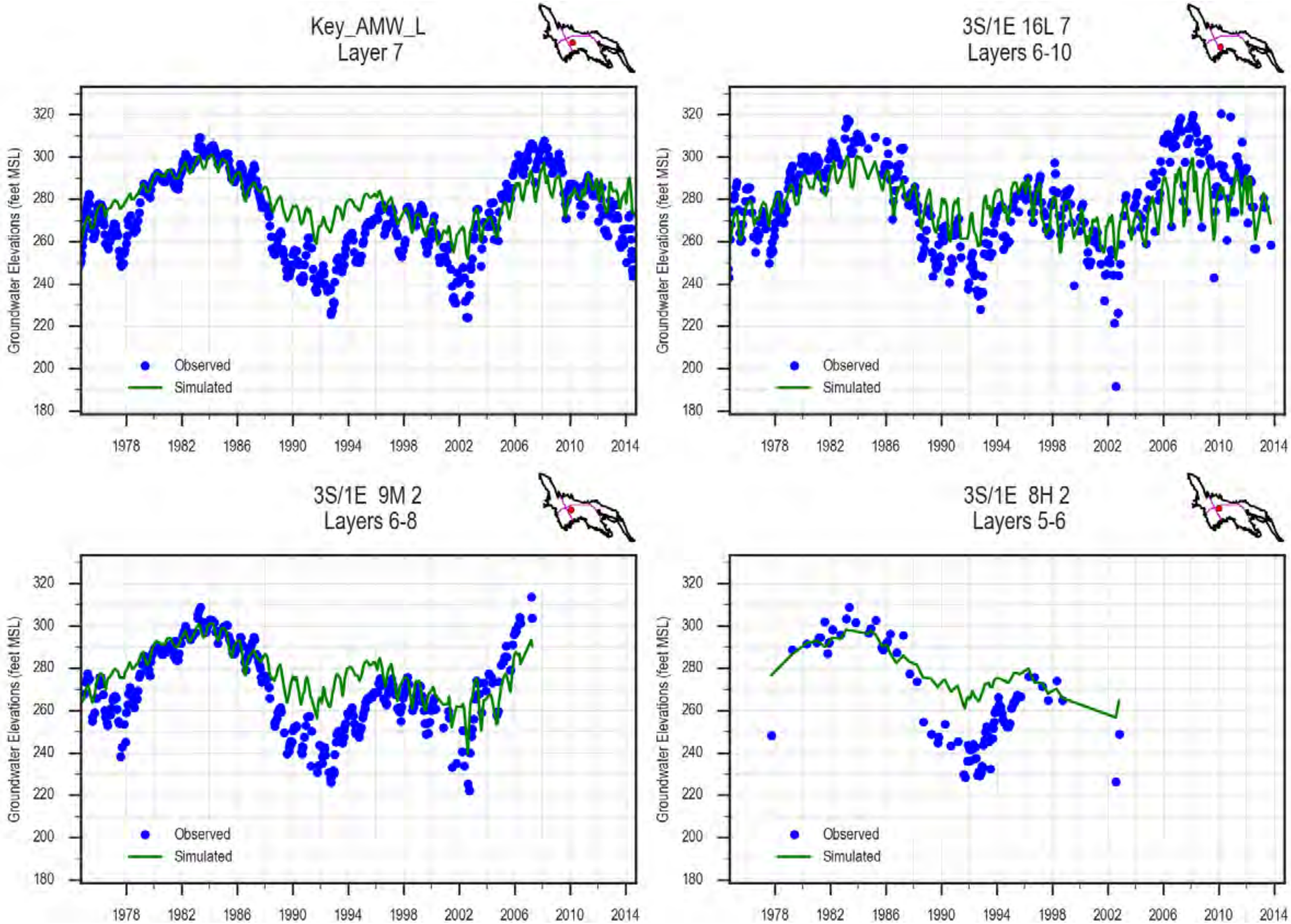


Figure 55: Example Groundwater Elevation Hydrographs for Amador Sub-basin West Area Layers 6-10

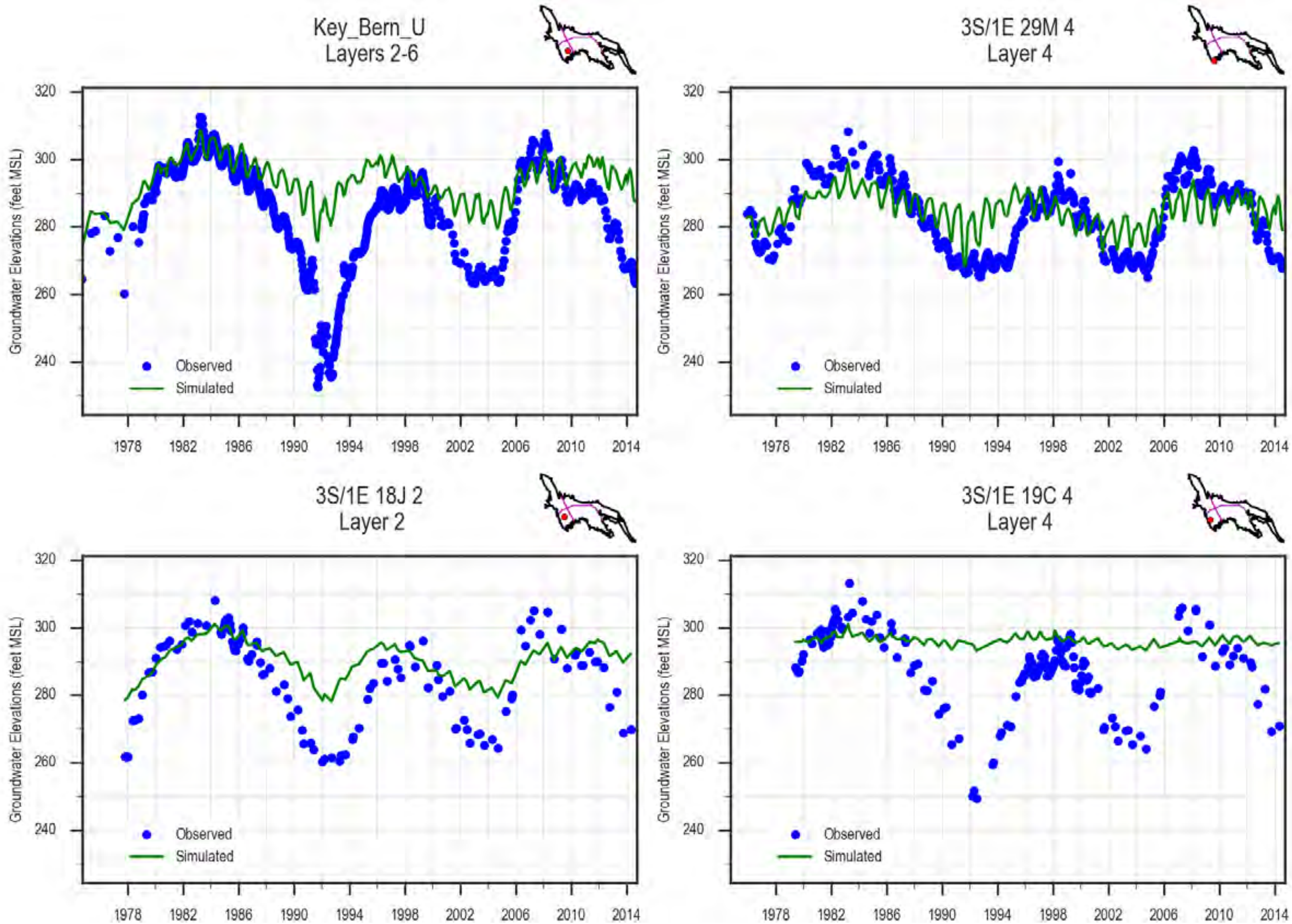


Figure 56: Example Groundwater Elevation Hydrographs for Bernal Sub-basin Layers 2-4

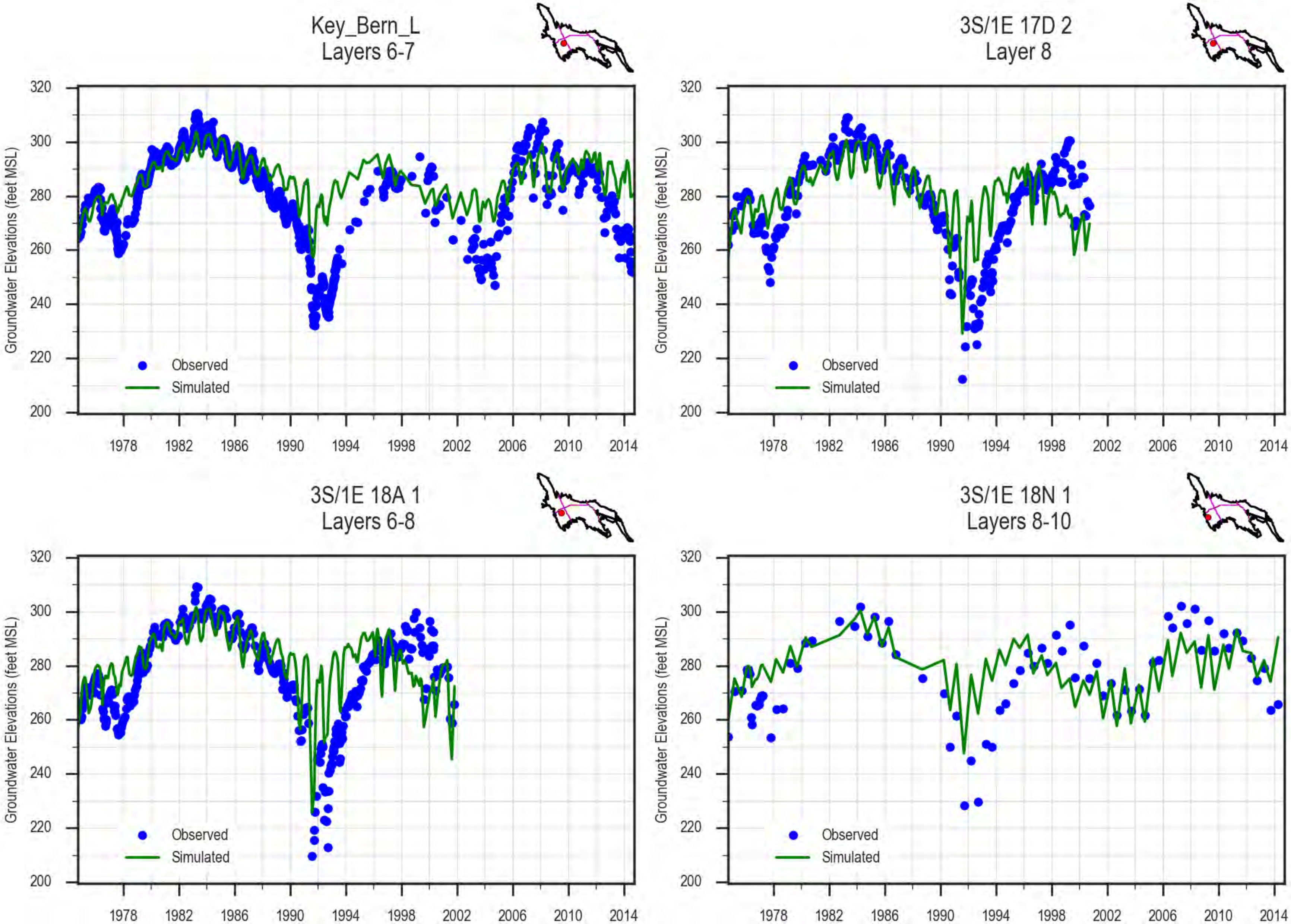


Figure 57: Example Groundwater Elevation Hydrographs for Bernal Sub-basin Layers 6-10

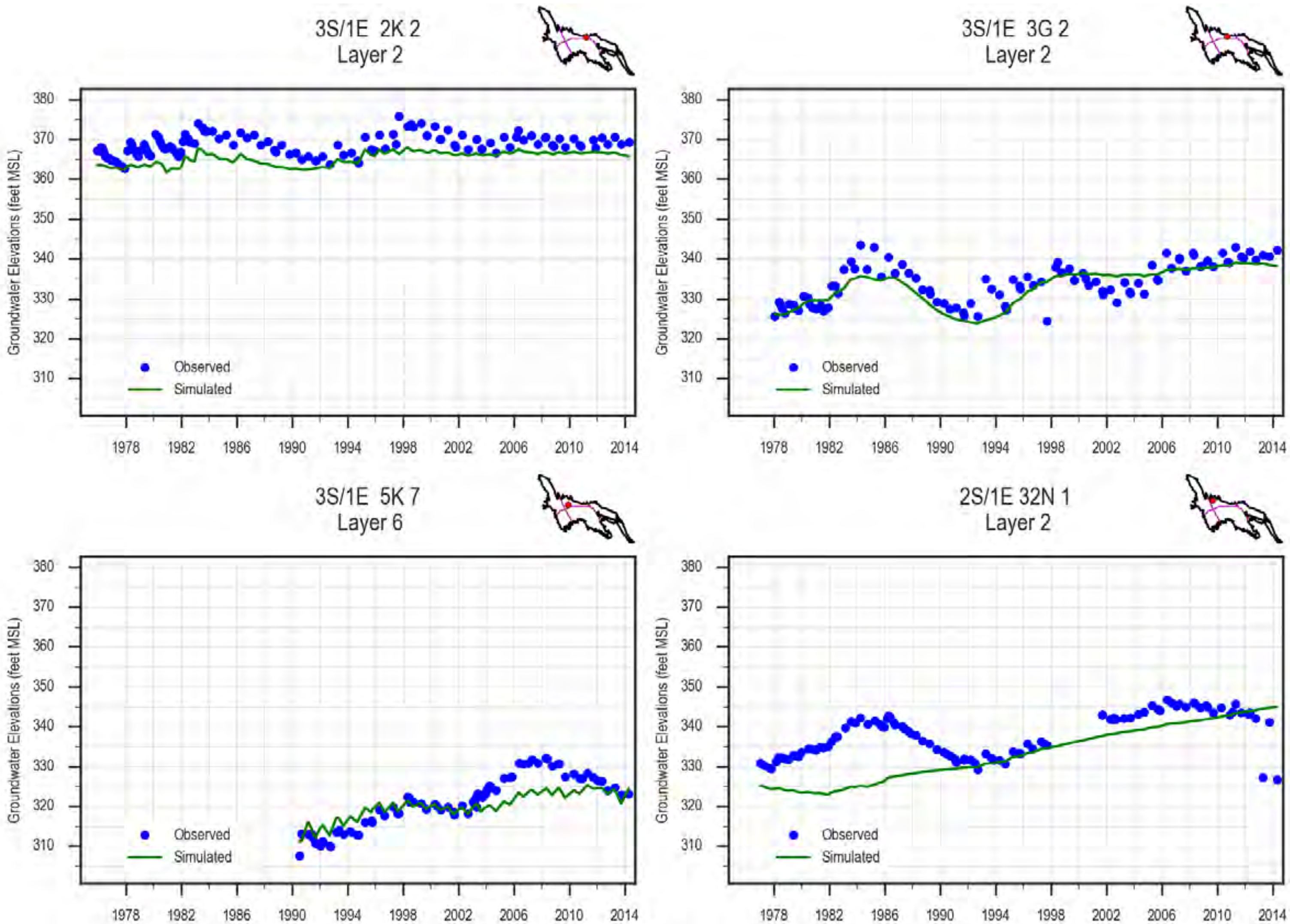


Figure 58: Example Groundwater Elevation Hydrographs for Camp Sub-basin

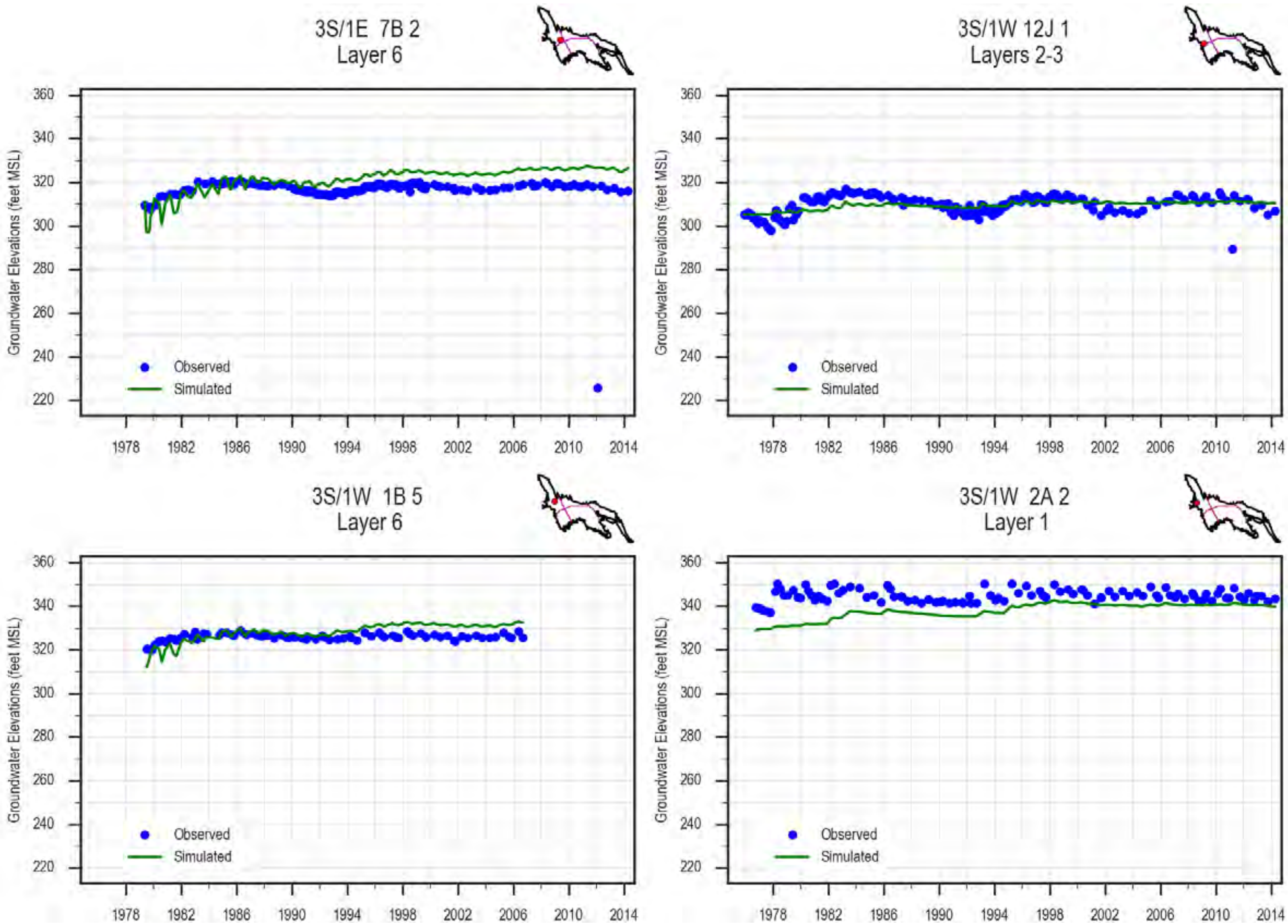


Figure 59: Example Groundwater Elevation Hydrographs for Dublin Sub-basin

Various graphical and statistical methods can be used to demonstrate the magnitude and potential bias of the calibration errors. Figure 60 shows simulated groundwater elevations plotted against observed groundwater elevations for the entire calibration period. Results from an unbiased model will scatter around a 45º line on this graph. If the model has a bias such as exaggerating or underestimating groundwater level differences, the results will diverge from this 45º line. The line drawn on Figure 60 demonstrates that the results lie close to a 45º line, suggesting that the model results are not biased towards overestimating or underestimating average groundwater level differences.

Figure 60 also includes various statistical measures of calibration accuracy. The four statistical measures used to evaluate calibration are the mean error (ME), the mean absolute error (MAE), the standard deviation of the errors (STD), and the root mean squared error (RMSE). The mean error is the average error between measured and simulated groundwater elevations for all data on Figure 60,

$$ME = \frac{1}{n}\sum_{i=1}^{n}(h_m - h_s)_i$$

Where h_m is the measured groundwater elevation, h_s is the simulated groundwater elevation, and n is the number of observations.

The mean absolute error is the average of the absolute differences between measured and simulated groundwater elevations.

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|h_m - h_s|_i$$

The standard deviation of the errors is one measure of the spread of the errors around the 45º line in Figure 60. The population standard deviation is used for these calculations.

$$STD = \sqrt{\frac{n\sum_{i=1}^{n}(h_m - h_s)_i^2 - \left(\sum_{i=1}^{n}(h_m - h_s)\right)_i^2}{n^2}}$$

The RMSE is similar to the standard deviation of the error. It also measures the spread of the errors around the 45º line in Figure 60, and is calculated as the square root of the average squared errors.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(h_m - h_s\right)_i^2}$$

As a measure of successful model calibration, Anderson and Woessner (1992) state that the ratio of the spread of the errors to the total head range in the system should be small to ensure that the errors are only a small part of the overall model response. As a general rule, the RMSE should be less than 10% of the total head range in the model. The RMSE of 13.0 feet is approximately 2.3% of the total head range of 555 feet. A second general rule that is occasionally used is that the mean absolute error should be less than 5% of the total head range in the model. The mean absolute error of 9.2 feet is approximately 1.6% of the total head range. Therefore, on average, the model errors are within an acceptable range.

A second graph used to evaluate bias in model results is shown on Figure 61. This figure is a graph of observed groundwater elevations versus model residual (simulated elevation minus observed elevation). Results from a non-biased simulation will appear as a cloud of data points clustered around the zero model residual line. Results that do not cluster around the zero residual line show potential model bias. Results that display a trend instead of a random cloud of points may suggest additional model bias. The results plotted on Figure 61 show that the calibrated model results are generally unbiased.

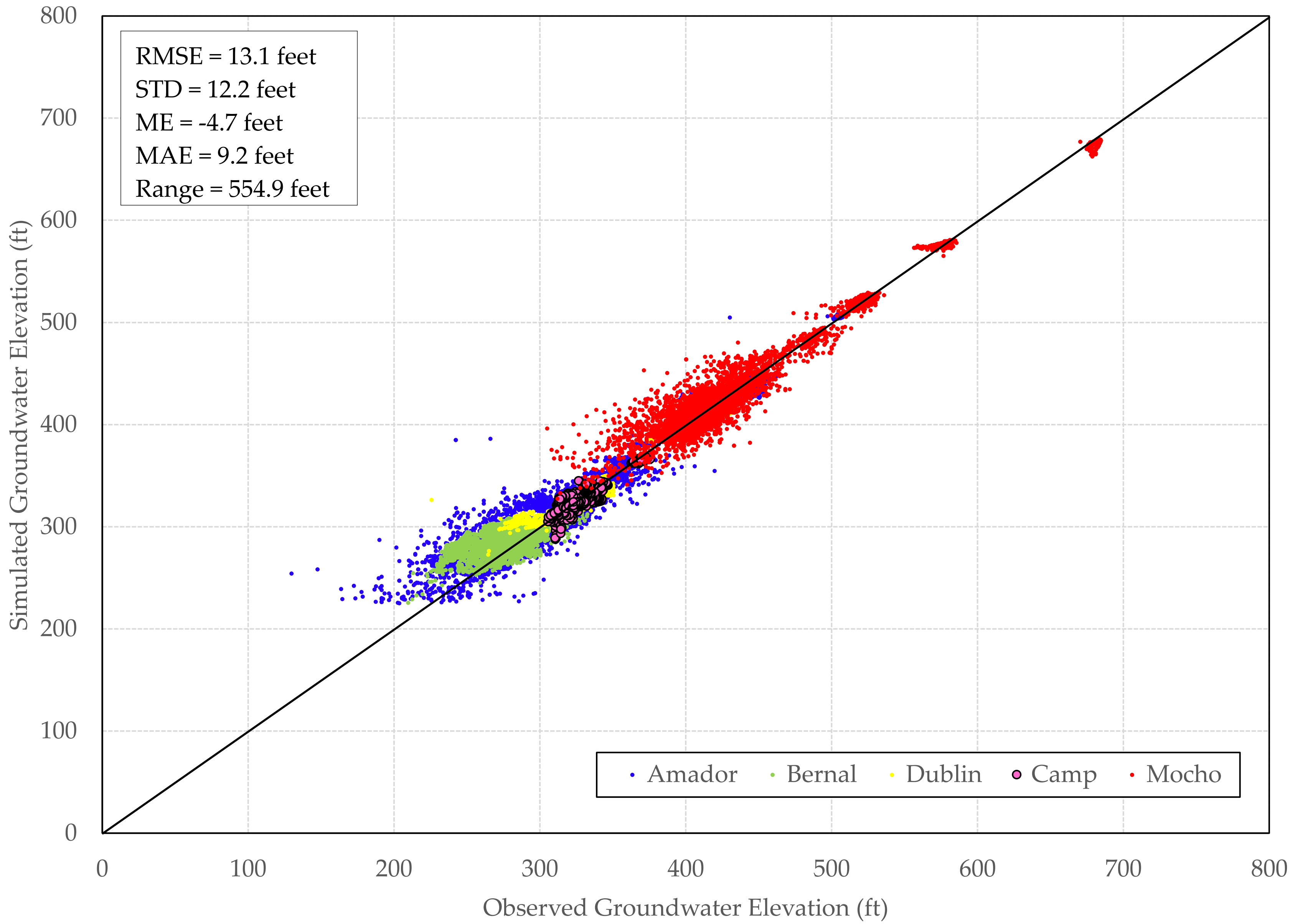


Figure 60: Simulated versus Observed Groundwater Elevations

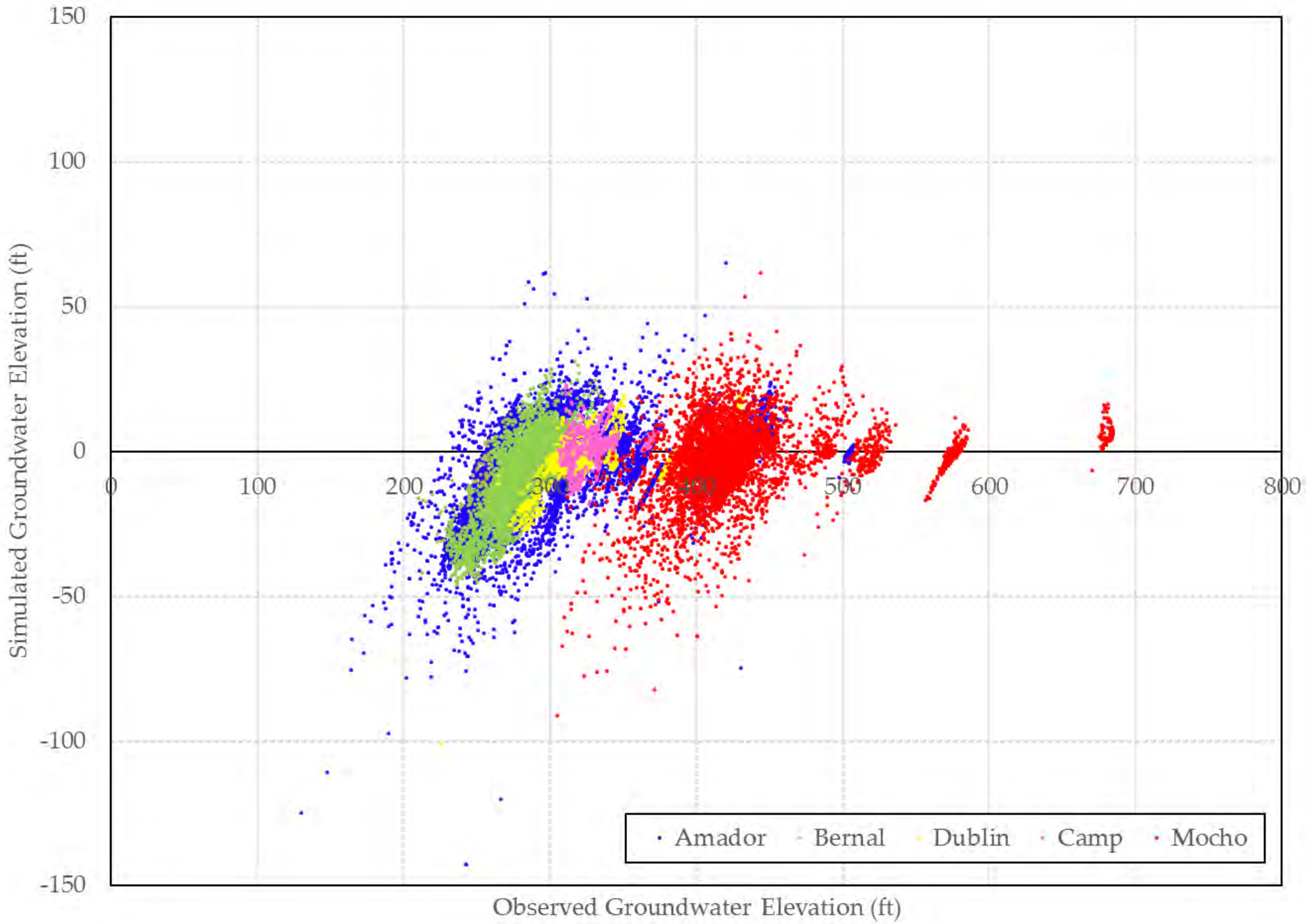


Figure 61: Model Residual versus Observed Groundwater Elevations

4.5.2 STREAMFLOW

Streamflows simulated by the model were calibrated to the available transient flow data in the internal stream gaging stations. Figure 62 portrays the location of the stream gaging stations with monthly streamflow data used to calibrate the leakance term in the SFR model calibration. Note that there is no station available at the Tassajara and Dublin Creeks. Table 9 provides a summary of the streamflow data available at each of the stream gaging stations.

The transient flow data at the headwater segments were not used here as calibration targets, because they were used to define the amount of the water entered to the system at the headwater segments. It should be noted that the transient flow data at ADLL gaging station is both used as a calibration target and to estimate the inflow at Alamo Creek (Table 4 and Table 9). Two reasons justify this selection:

1. ADLL is the only station on the Arroyo De La Laguna, the only outlet of the streamflow from the system. If no gaging station data is used as calibration target to constrain the stream outflow from the system, the stream model will likely suffer from non-uniqueness issues.
2. The transient flow data of the ADLL gaging station was not used directly to represent a Headwater segment but rather was used as part of a mass balance calculation to estimate the inflow at the Alamo Creek.

Transient flow data were processed to calculate total streamflow passing the gauge each month to compare with simulated values. Monthly volumes simulated by the model were calculated based on interpolation of flow results output by the MODFLOW GAGE package from the end of the previous month and the current month using surface water processing software TSPROC (Westenbroek, et al., 2012).

Figure 63 through Figure 65 show hydrographs for log-transformed simulated versus observed monthly flows. The hydrographs show that simulated values follow the pattern of observed data well, but for low flows, the model predicts no flow when there is flow recorded for the month. The model simulates all streamflow as groundwater recharge during these low flow periods while the data indicate that not all of the flow recharges groundwater. Lower recharge during low flow periods may result in the larger drops in observed groundwater levels than simulated during these periods.

Figure 66 shows simulated monthly flows plotted against observed monthly flows for the entire calibration period. Figure 66 also includes various statistical measures of calibration accuracy.

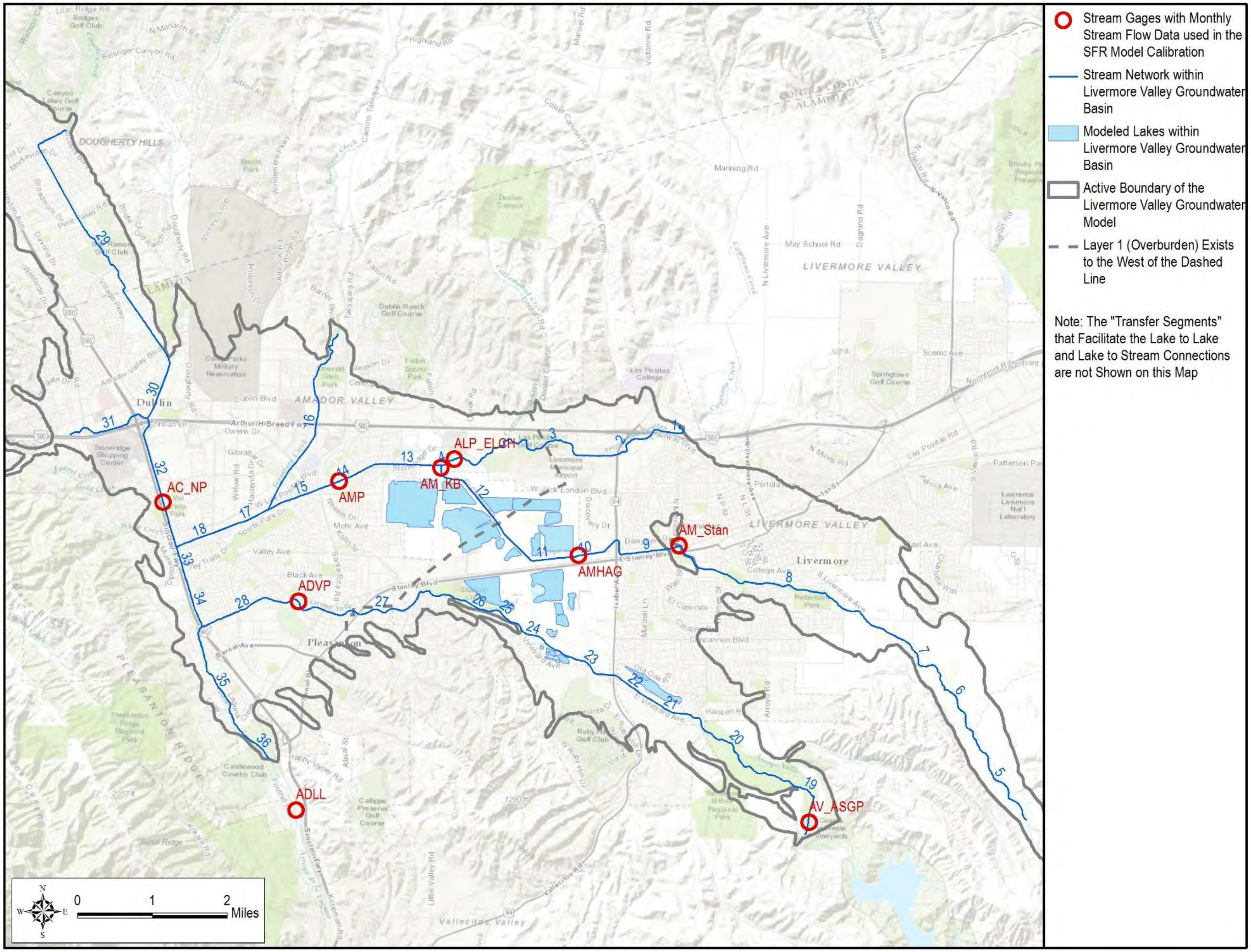


Figure 62: Location of the Stream Gaging Stations with Transient Stream Flow Data used in the SFR Model Calibration

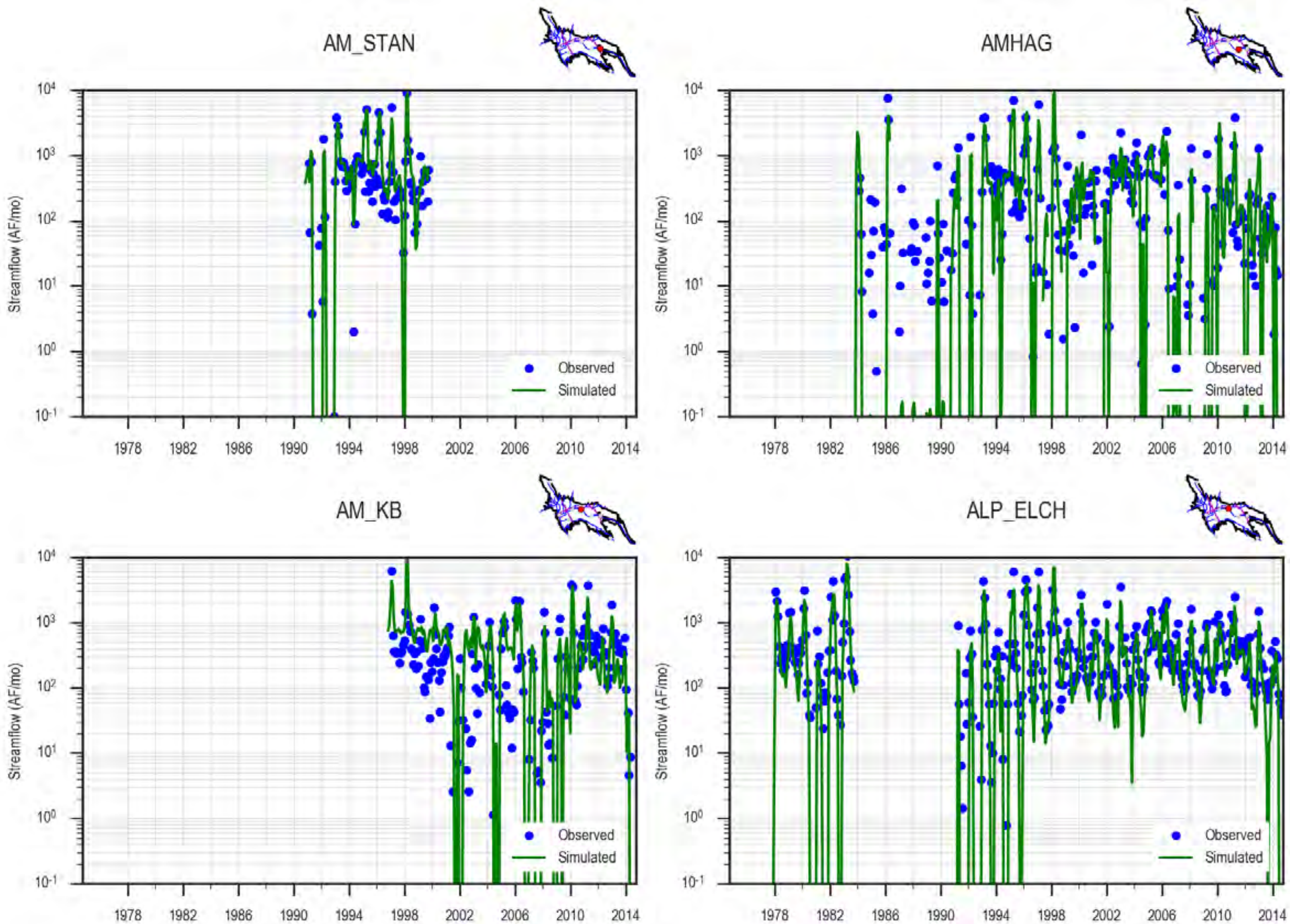


Figure 63: Hydrographs of Monthly Streamflow at Arroyo Mocho and Arroyo Las Positas Gauges Upstream of Confluence

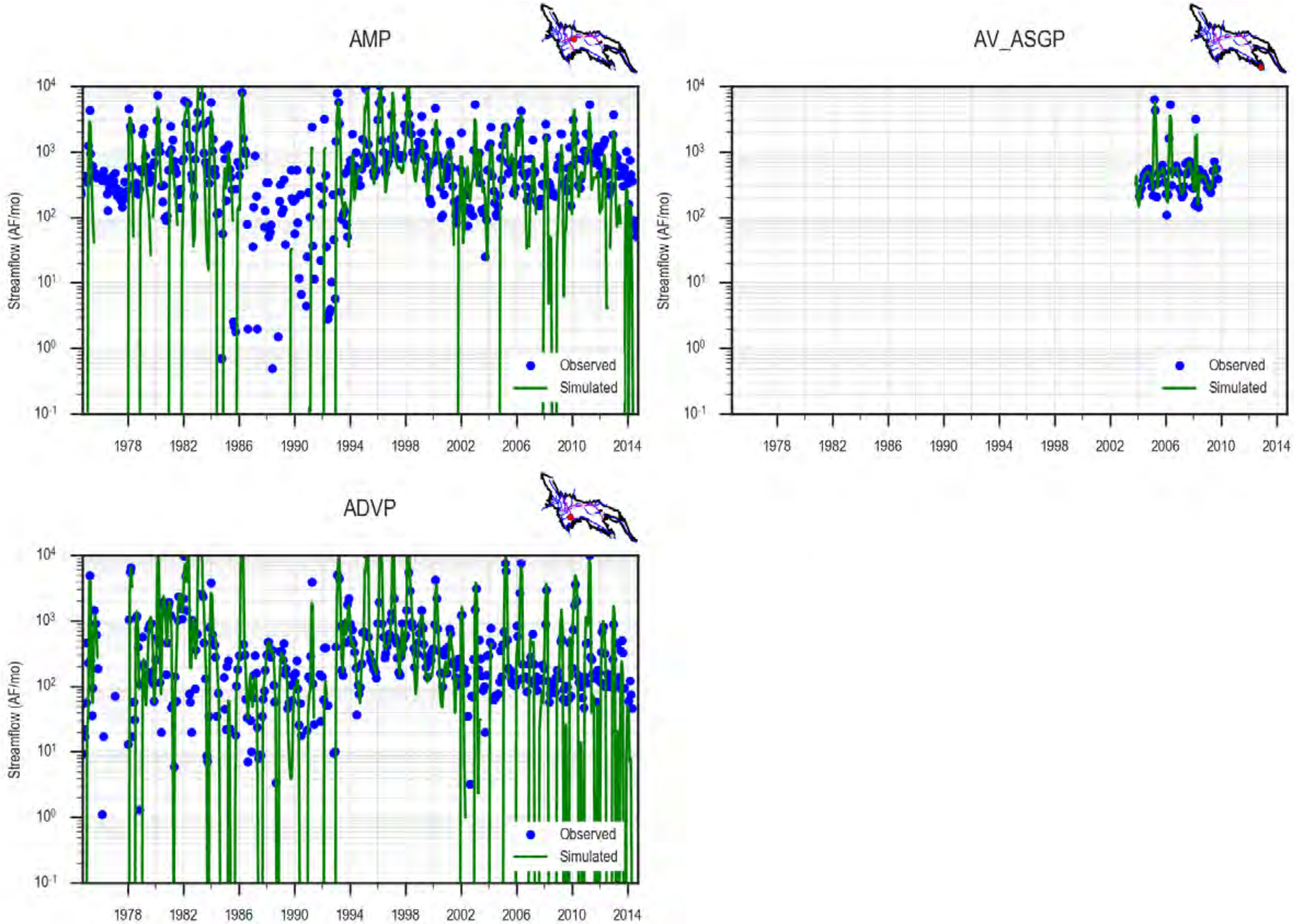
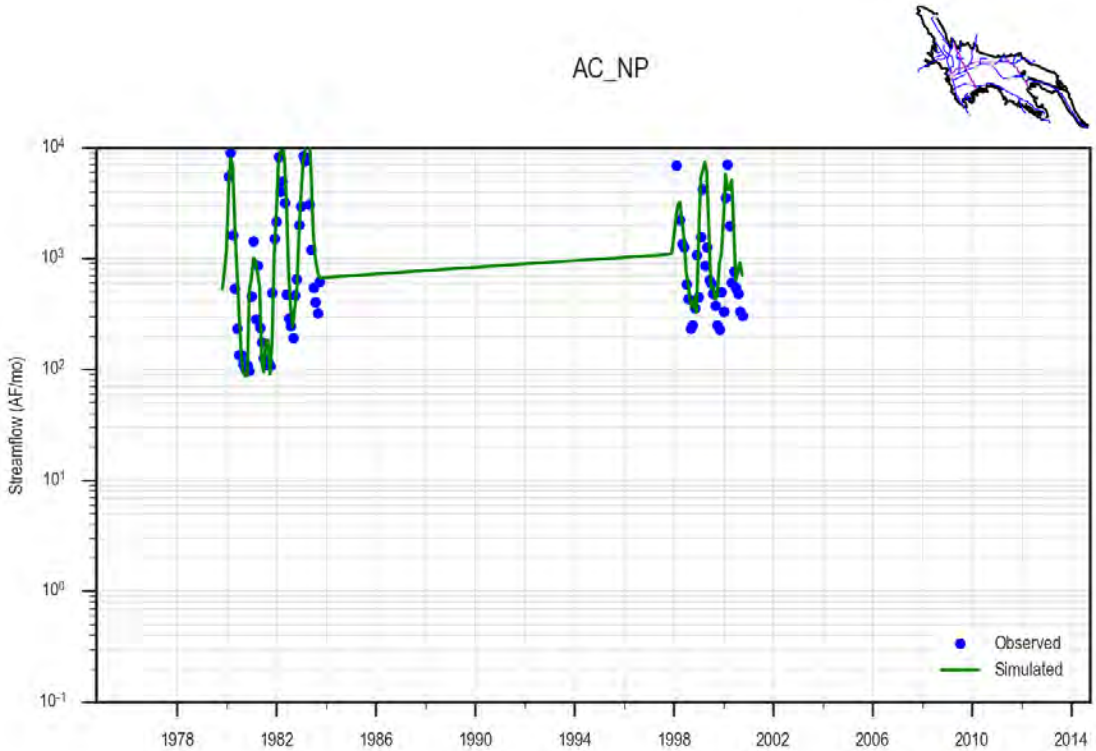


Figure 64: Hydrographs of Monthly Streamflow at Arroyo Mocho Gauge Downstream of Confluence and Arroyo Valle Gauges



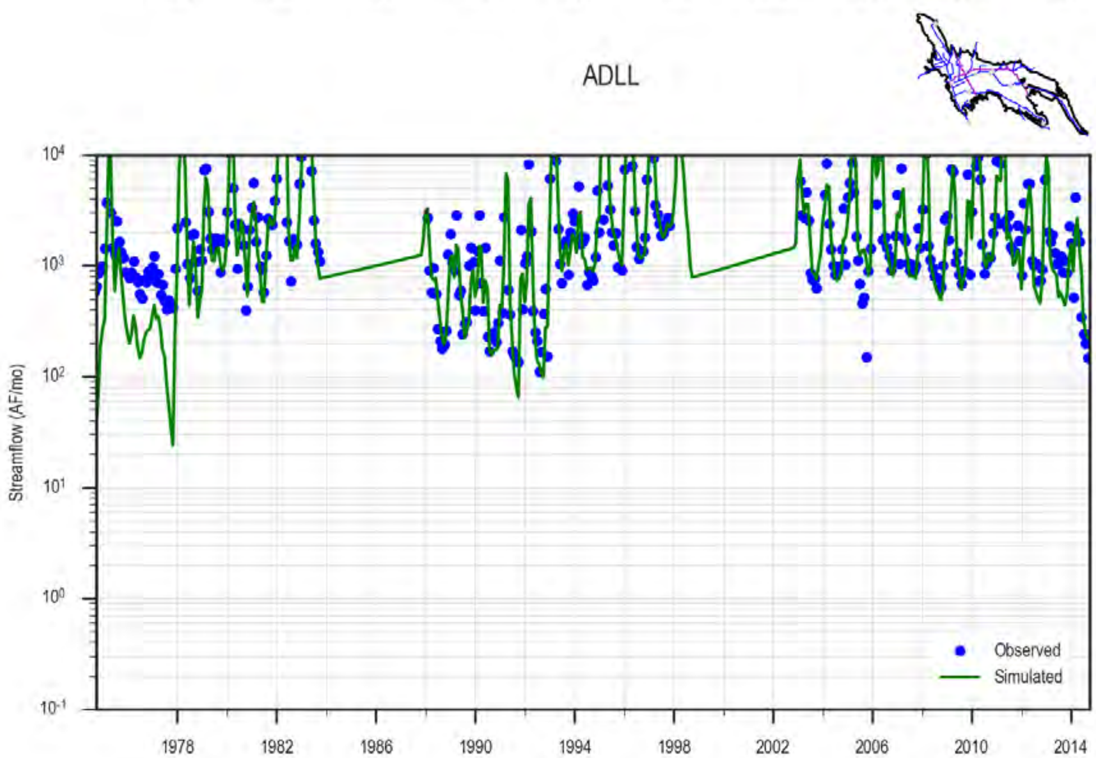


Figure 65: Hydrographs of Monthly Streamflow at Alamo Canal and Arroyo de la Laguna Gauges

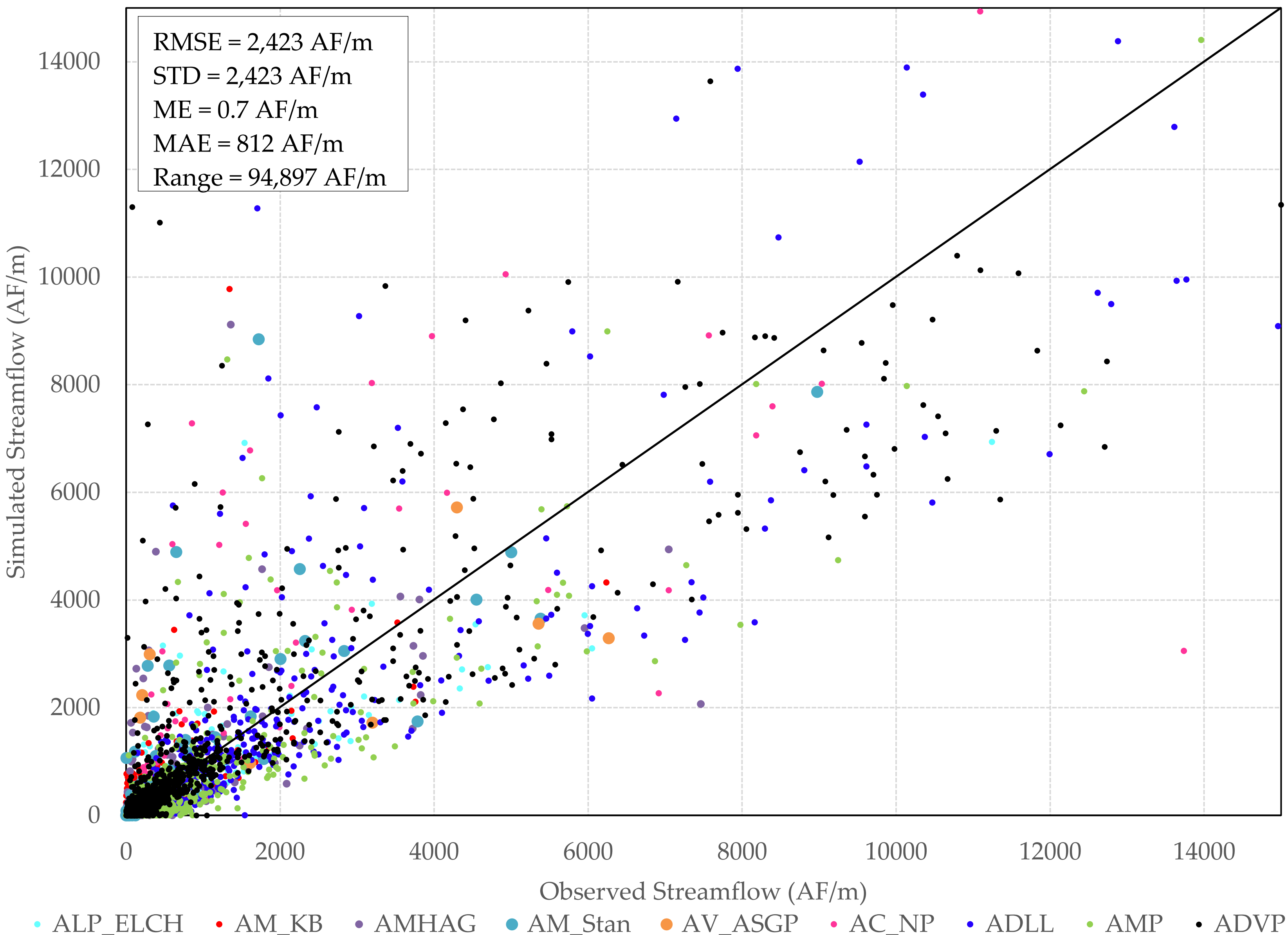


Figure 66: Simulated versus Observed Monthly Streamflows

Table 9: Summary of the Transient Stream Flow Data used in SFR Model Calibration

Stream Name	Station Name	Period of Record (WY)	Missing Years
Arroyo Las Positas	ALP_ELCH	1978-2014	Oct/73-Jan/78 Oct/84-Mar/91
Arroyo Mocho	AMHAG	1984-2014	Oct/73-Dec/83
Arroyo Mocho	AM_KB	1997-2014	
Arroyo Mocho	AMP	1974-2014	
Arroyo Mocho	AM_STAN	1991-1999	
Alamo Canal	AC_NP	1980-2000	Oct/79-Dec/79 Oct/83-Dec/97
Arroyo Valle	AV_ASGP	2004-2009	
Arroyo Valle	ADVP	1974-2014	
Arroyo De La Laguna	ADLL	1974-2014	Oct/84-Dec/87 Nov/97-Dec/02 Oct/03-Dec/03

4.5.3 Lake Stage

Stages simulated by the model for the unlined lakes were calibrated to the available lake stage data. Data from lined lakes are not included in the calibration. Simulated lake stages output by the MODFLOW GAGE package were interpolated to observation times using surface water processing software TSPROC (Westenbroek, et al., 2012). Table 10 provides a summary of the lake stage data available for this model. Figure 67 repeats the map of lakes with stage data.

Figure 68 through Figure 72 show hydrographs of simulated versus observed lake stages. A few wells simulate lake levels similar to the observations, but a number of wells show calibration error. . Calibrating lake stages were not a priority due to the unknown operations of water transfers between individual lakes. The model implements transfers between lakes using representative lakes for each lake group as opposed to modeling transfers between all lakes (Section 2.10).

Figure 72 shows simulated lake stages plotted against observed lake stages for the entire calibration period. Figure 72 also includes various statistical measures of calibration accuracy.

Table 10: Data Summary Used for Modeling and Calibration of Lakes within the Livermore Valley Groundwater Basin using the MODFLOW Lake Package

Lake #	Lake ID	Status	Lake Group	First Record	Last Record	# of Records	Average Lake Stage (ft)	Deepest Mined Depth (ft)	Discharge to Arroyo (Segment)	Discharge to Lake (#)
1	P-41	Unlined	LoneStar/Cemex	1/24/03	4/24/14	70	401	370	NA	NA
2	P-27	Unlined	LoneStar/Cemex	5/28/91	4/24/14	59	277	250	NA	NA
3	P-45	Unlined	LoneStar/Cemex	5/3/07	9/15/09	7	323	310	NA	Shadow Cliff (15)
4	P-44	Unlined	LoneStar/Cemex	5/6/04	4/24/14	56	323	250	NA	NA
5	P-42	Unlined	LoneStar/Cemex	11/23/04	4/24/14	56	279	270	Valle (25)	NA
6	P-10	Unlined	LoneStar/Cemex	10/21/80	4/24/14	197	368	340	NA	NA
7	P-43	Lined	LoneStar/Cemex	7/27/04	4/24/14	12	344	240	NA	NA
8	R-24	Unlined	Calmat/Vulcan/PGC	5/11/00	5/12/10	69	301	200	Mocho (11)	NA
9	R-23	Unlined	Calmat/Vulcan/PGC	10/17/96	4/24/14	65	354	270	NA	NA
10	R-22	Unlined	Calmat/Vulcan/PGC	4/18/96	4/24/14	34	342	290	NA	NA
11	R-21	Lined	Calmat/Vulcan/PGC	4/23/93	9/25/08	146	321	280	NA	NA
12	R-8	Unlined	Calmat/Vulcan/PGC	2/5/81	4/24/14	146	311	260	NA	NA
13	R-4	Unlined	Calmat/Vulcan/PGC	4/23/80	4/24/14	242	309	240	NA	NA
14	R-3	Lined	Calmat/Vulcan/PGC	11/21/80	4/24/14	101	325	240	NA	NA
15	K-15	Unlined	Shadow Cliffs	3/9/79	4/24/14	421	332	265	NA	NA
16	K-30	Lined	Kaiser/Hanson	5/25/83	4/24/14	383	342	240	NA	NA
17	K-28-LkH	Unlined	Kaiser/Hanson	5/1/83	4/24/14	179	290	220	NA	NA
18	K-37-LkI	Unlined	Kaiser/Hanson	1/24/03	4/24/14	80	291	220	Valle (26)& Mocho (13)	Shadow Cliff (15)

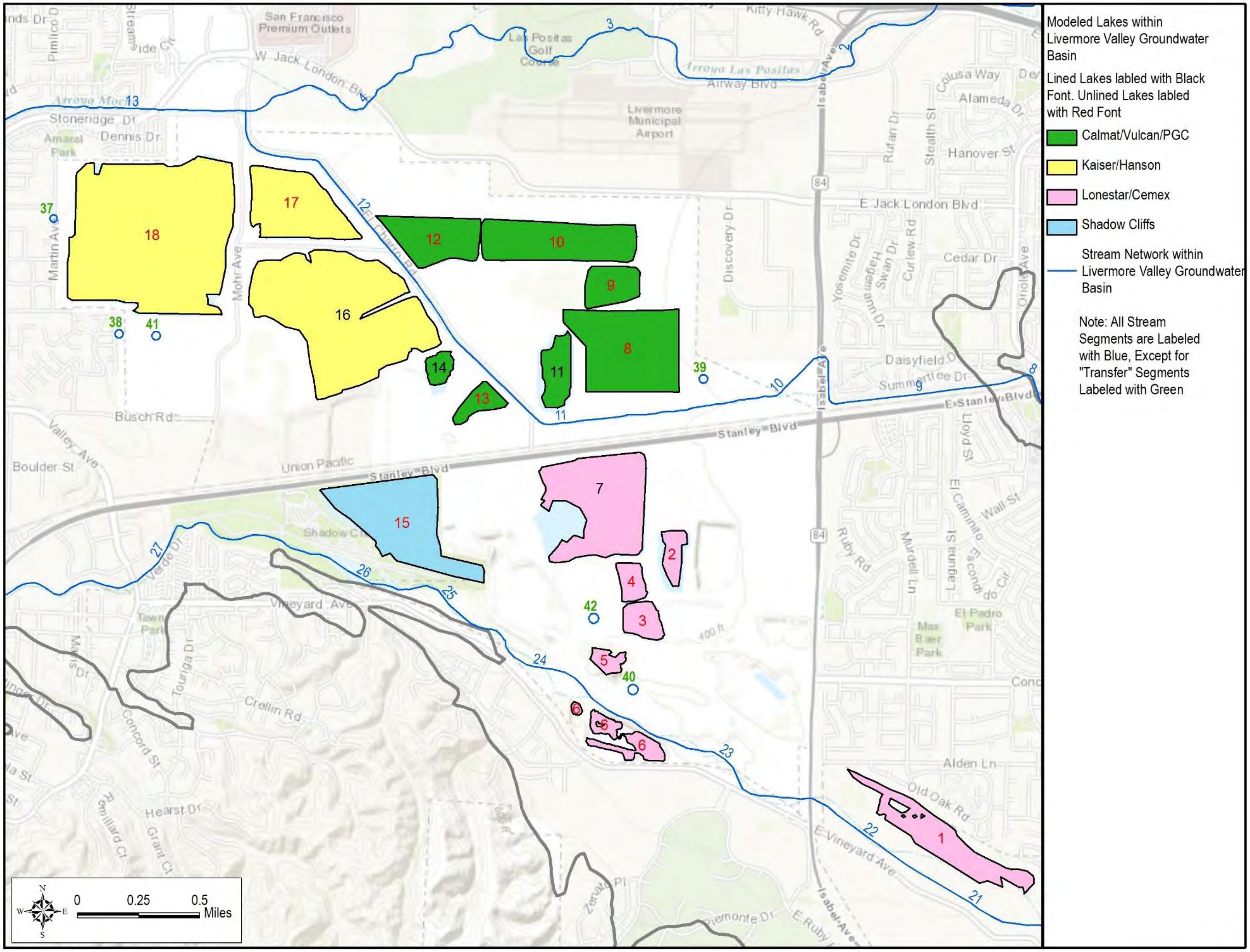


Figure 67: Map of Lakes with Stage and TDS Data

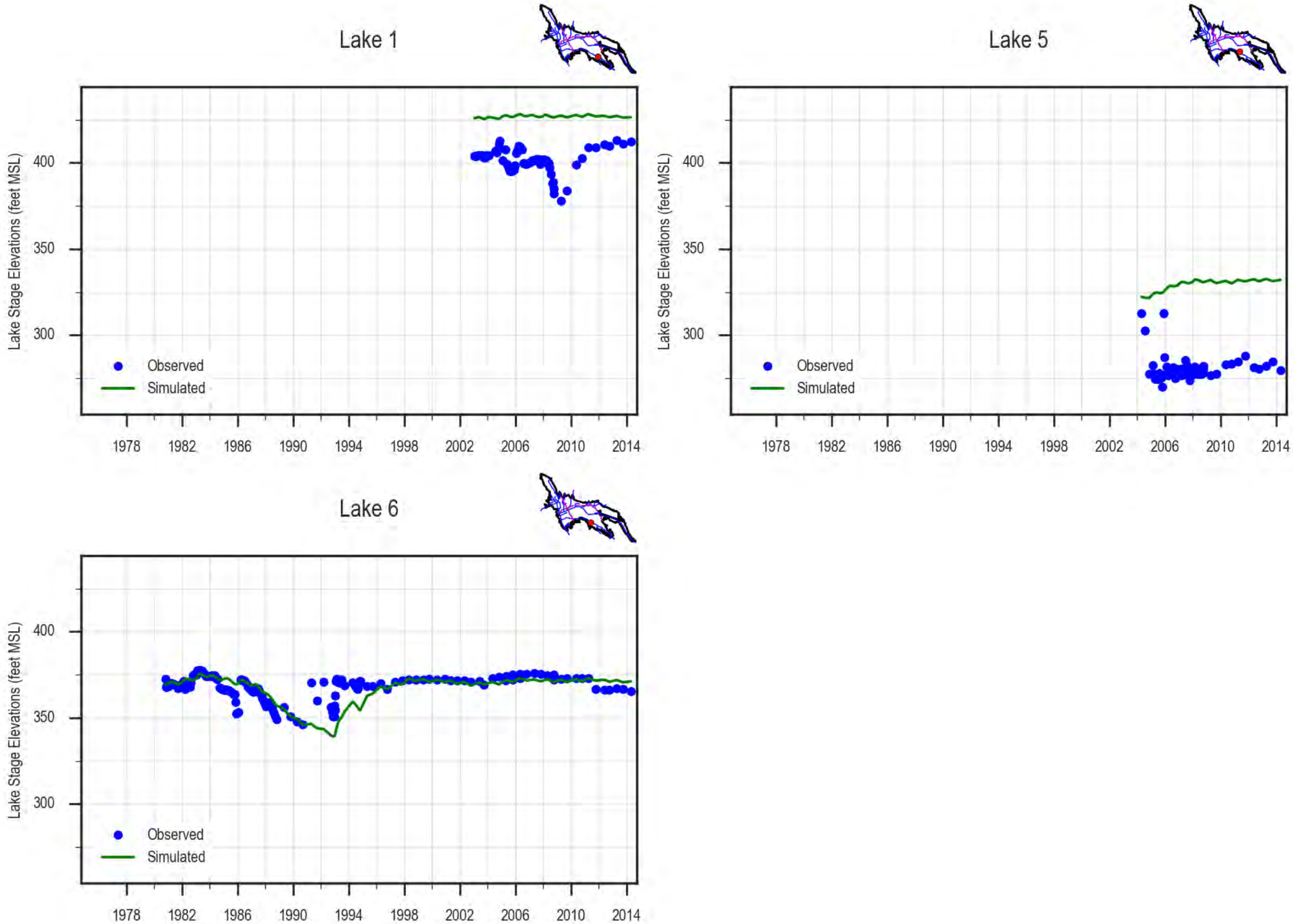


Figure 68: Hydrographs of Lake Stages for LoneSta/Cemex Group along Arroyo Valle

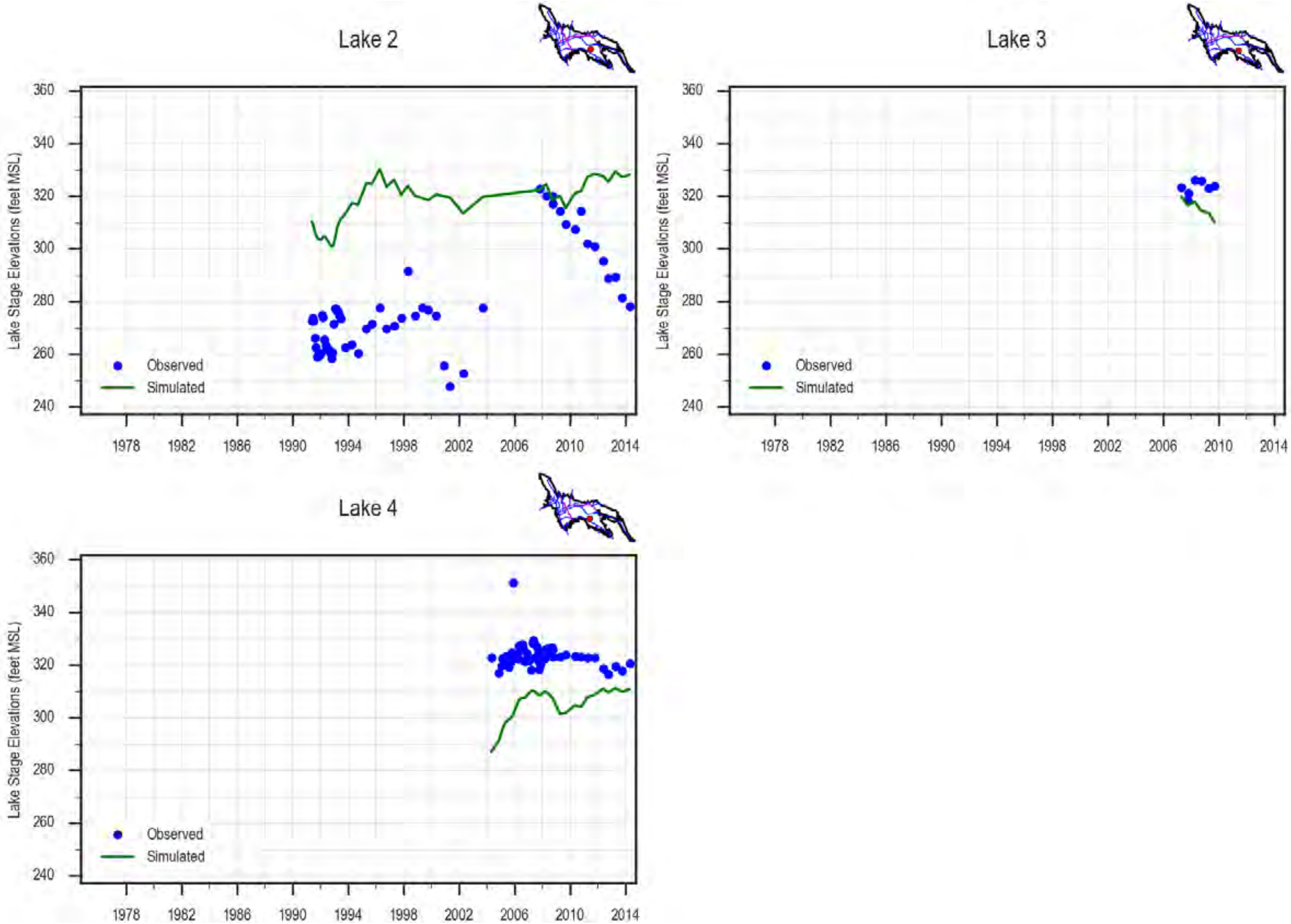


Figure 69: Hydrographs of Lake Stages for LoneStar Group between Arroyo Valle and Arroyo Mocho

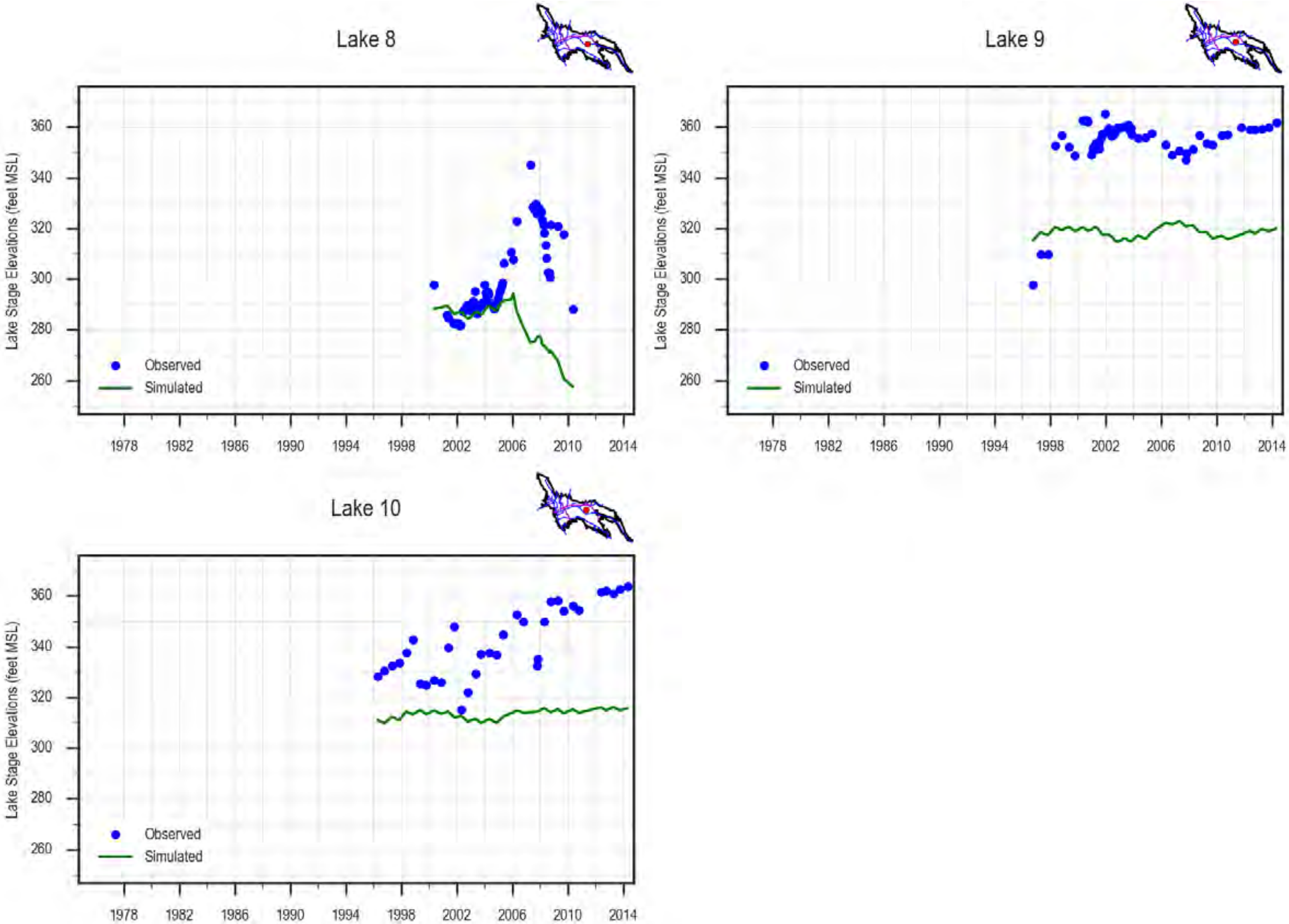
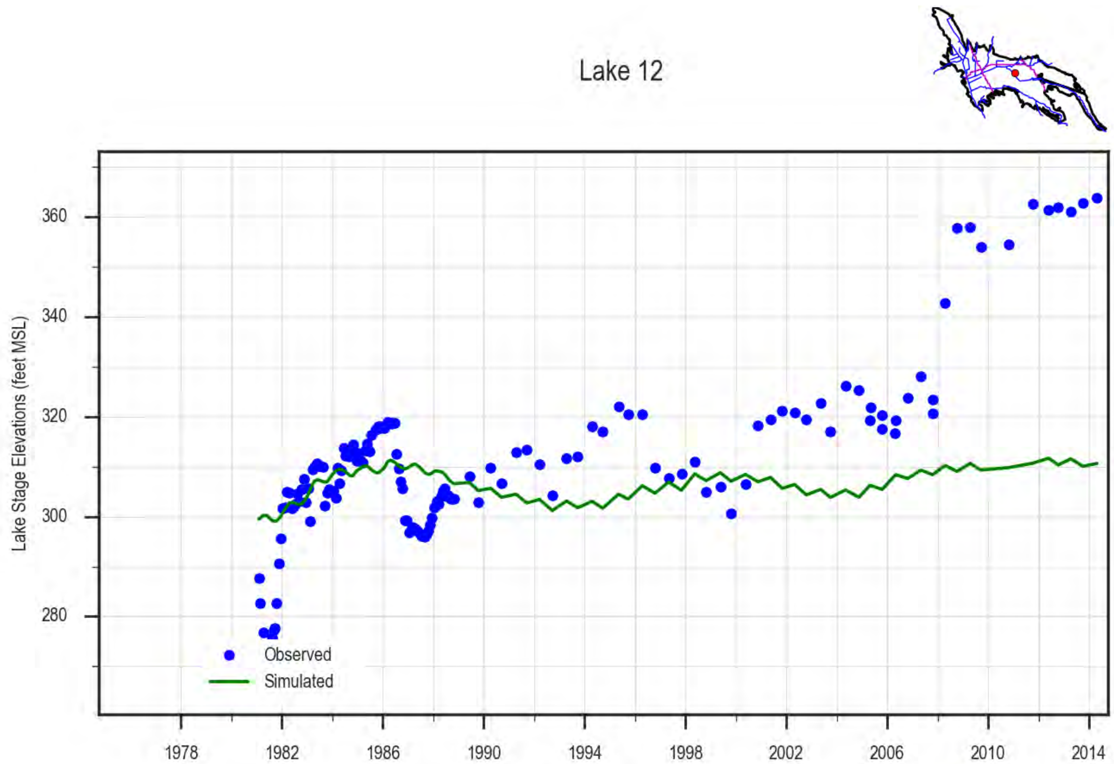


Figure 70: Hydrographs of Lake Stages for Calmat/Vulcan/PGC Group – East



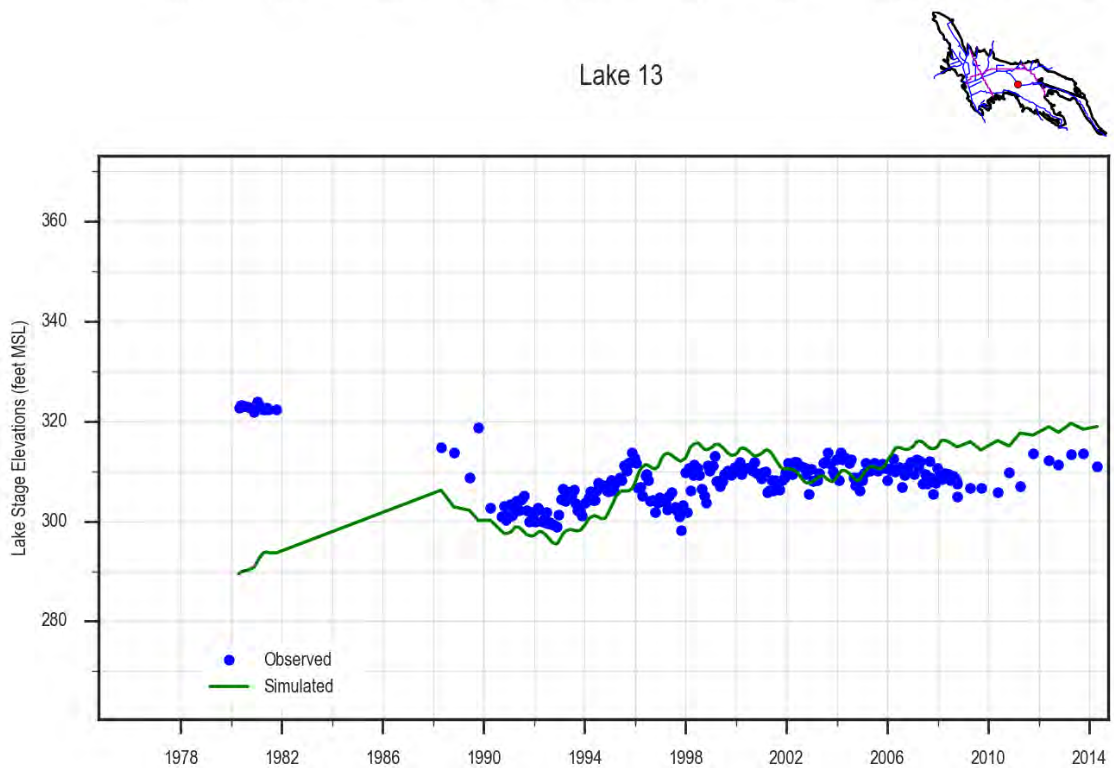


Figure 71: Hydrographs of Lake Stages for Calmat Group - West

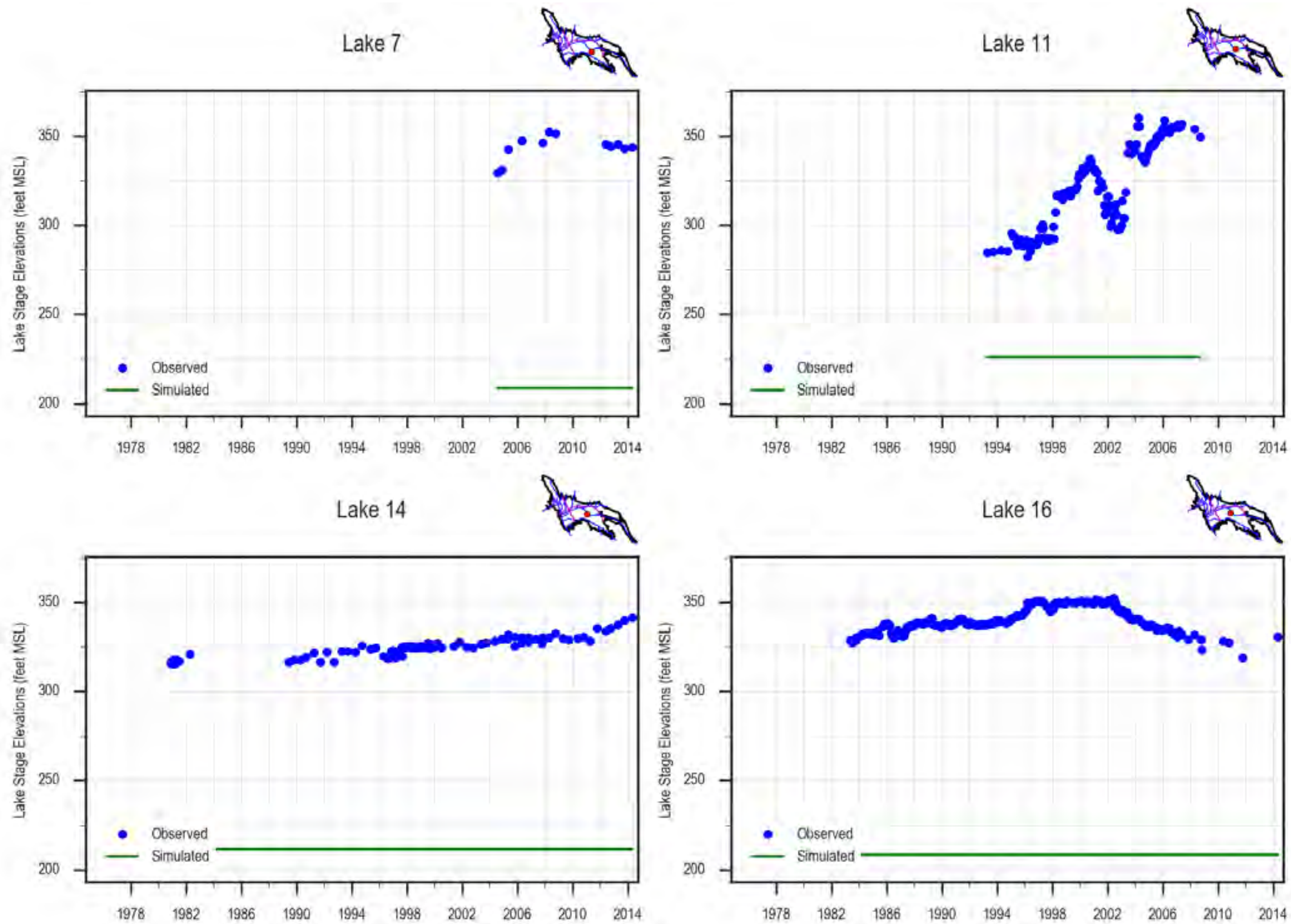


Figure 72: Hydrographs of Lake Stages for Kaiser Group and Shadow Cliffs

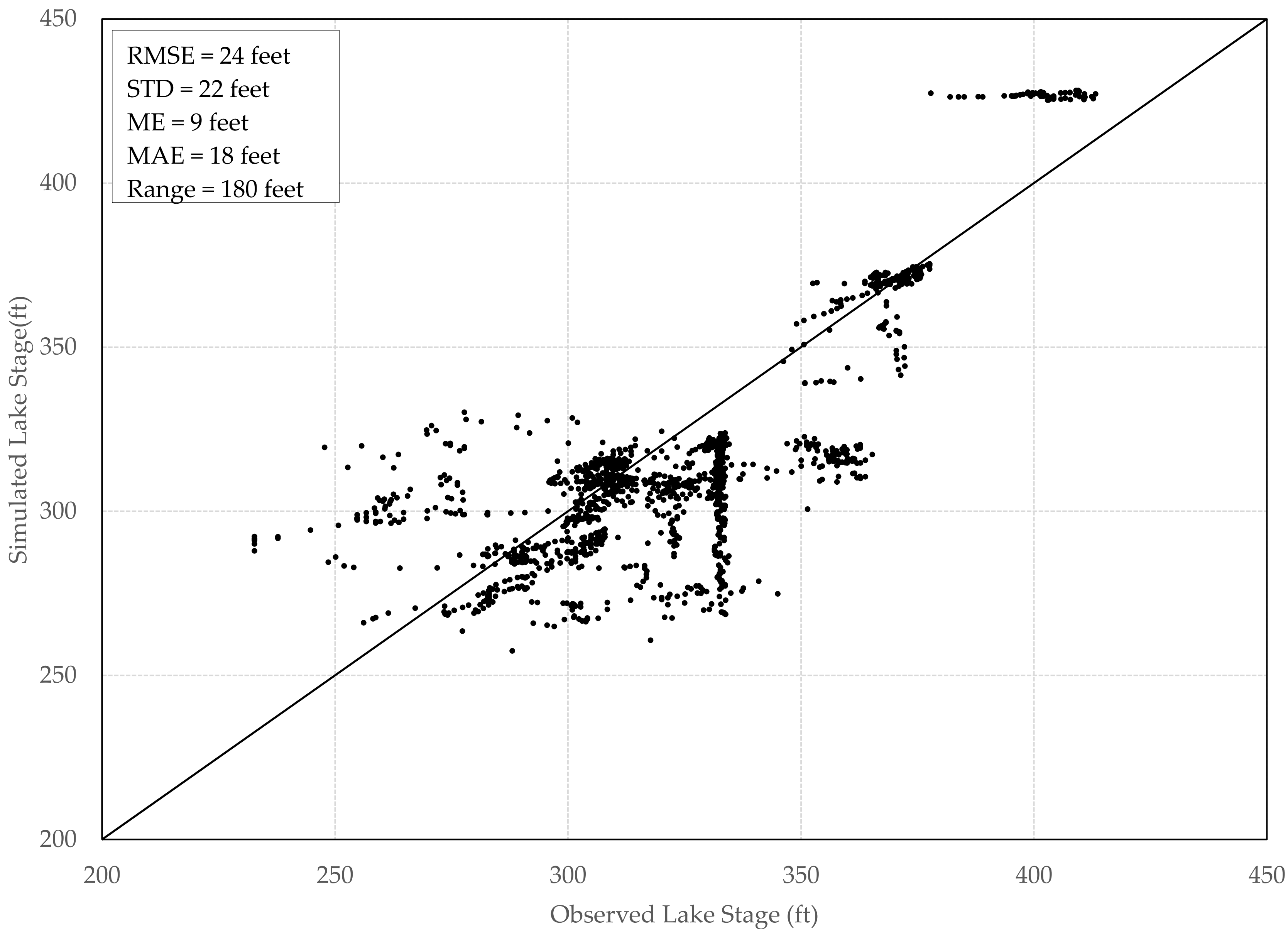


Figure 73: Simulated versus Observed Lake Stages

4.5.4 GROUNDWATER TDS CONCENTRATIONS

TDS concentrations in groundwater were calibrated to observed TDS concentrations at selected wells. The target well locations used for calibration of the model to groundwater TDS concentrations are shown in Figure 74. The target wells were selected based on data availability for both groundwater levels and screen intervals. Wells were selected as representative of regional salt water quality for an area and in different model layers. There were a few wells with very high concentrations (>20,000 mg/L) that were excluded from the calibration because the high concentrations indicate an ongoing local source of salt that is not simulated in the model.

As with groundwater levels, simulated groundwater concentrations were interpolated to the well location from results for the model grid and the measurement time from the results simulated at the end of each month using the groundwater data utility MOD2OBS (Watermark, 2008). For wells screened over multiple model layers, simulated groundwater levels in each of the layers are weighted by layer transmissivity and averaged before comparing with measured data.

Example maps of simulated TDS concentrations are displayed on Figure 75 through Figure 82. The maps show 1991, with relatively low groundwater elevations, 1995, with relatively high groundwater elevations, and 2014, the last year of the simulation. The maps show end of water year (September) results from model layers 2 and 6 representing top aquifer units of the Upper and Lower Aquifers, respectively. APPENDIX F: includes maps of simulated TDS concentrations for the end of the same three water years for aquifer model layers 4 and 8.

Chemographs showing both observed and simulated groundwater TDS concentrations are shown in Figure 83 through Figure 93. These example chemographs were chosen to demonstrate the model's accuracy in various parts of the sub-basins. The chemographs show that the model generally simulates concentration magnitudes and trends observed in monitoring well data. This level of calibration supports use of the model to evaluate salt balance and the calibration to wells in different layers supports evaluation of salt transport through layers. However, the model does not simulate the many fluctuations observed in the data; typically, basinwide transport models are unlikely to simulate local variations and fluctuations. APPENDIX G: includes chemographs for all target wells used in the calibration.

Figure 94 shows simulated TDS concentrations plotted against observed TDS concentrations for the entire calibration period.
Figure 94 also includes various statistical measures of calibration accuracy.

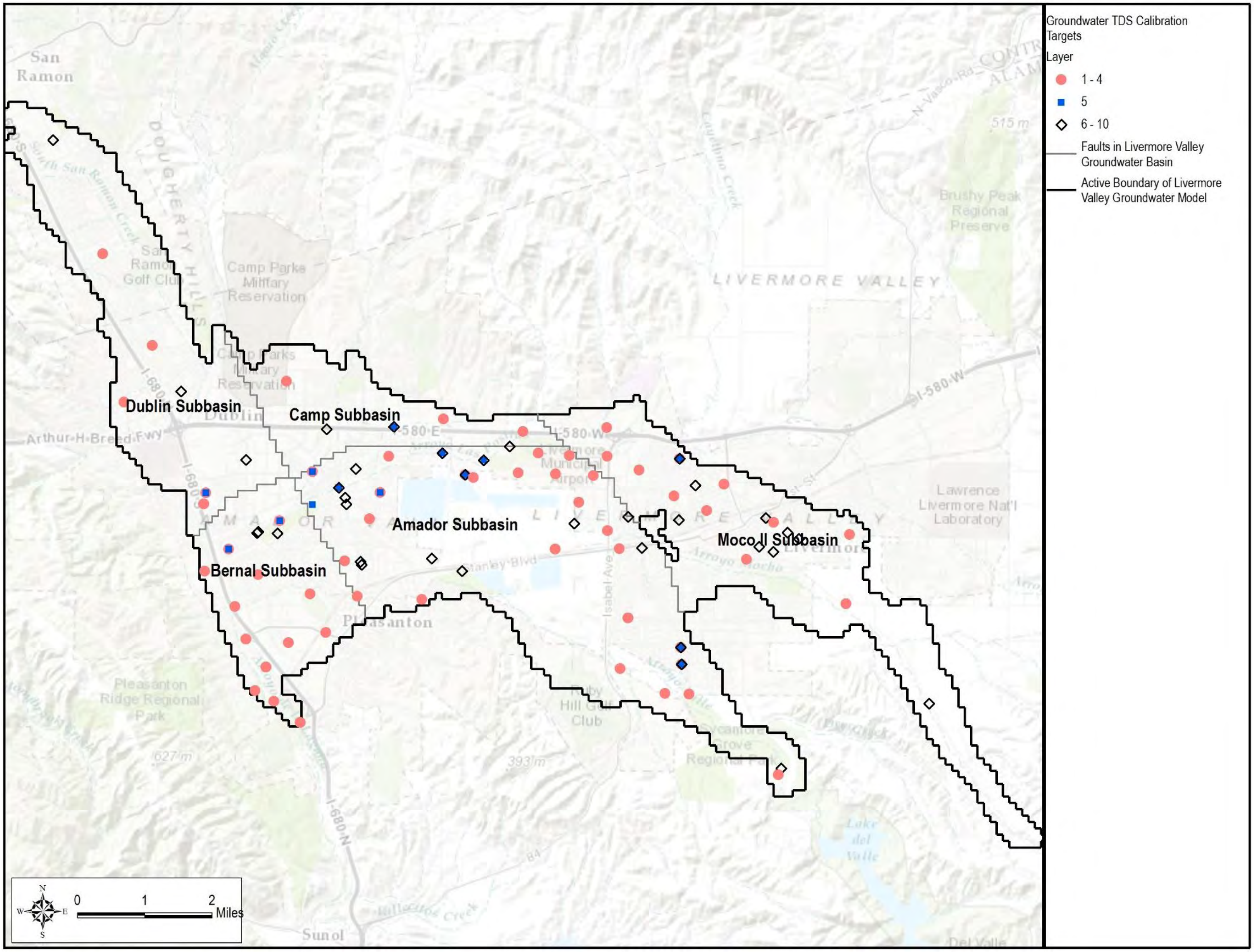


Figure 74: Groundwater TDS Concentration Target Locations

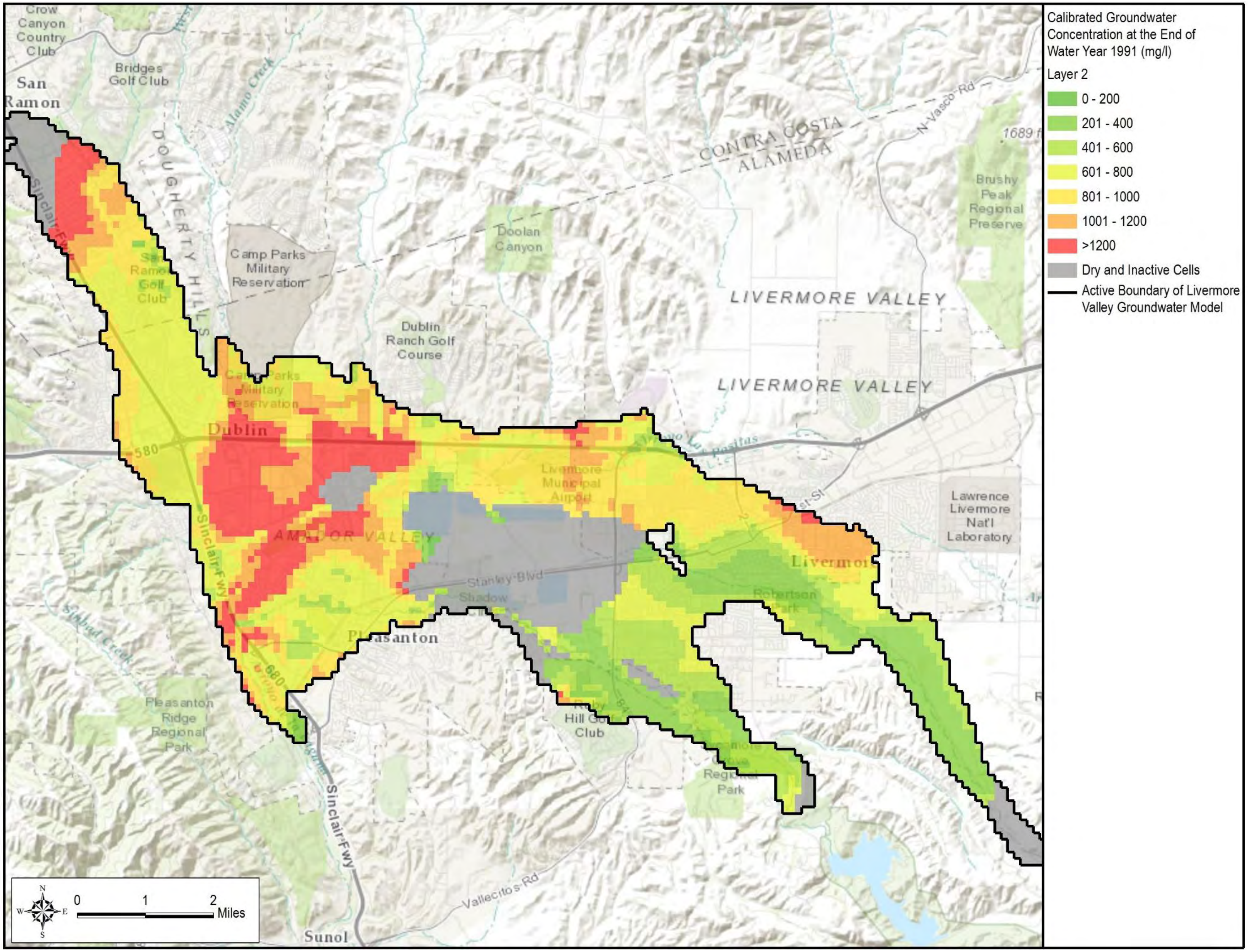


Figure 75: Simulated Groundwater TDS Concentrations for Layer 2 at the End of Water Year 1991

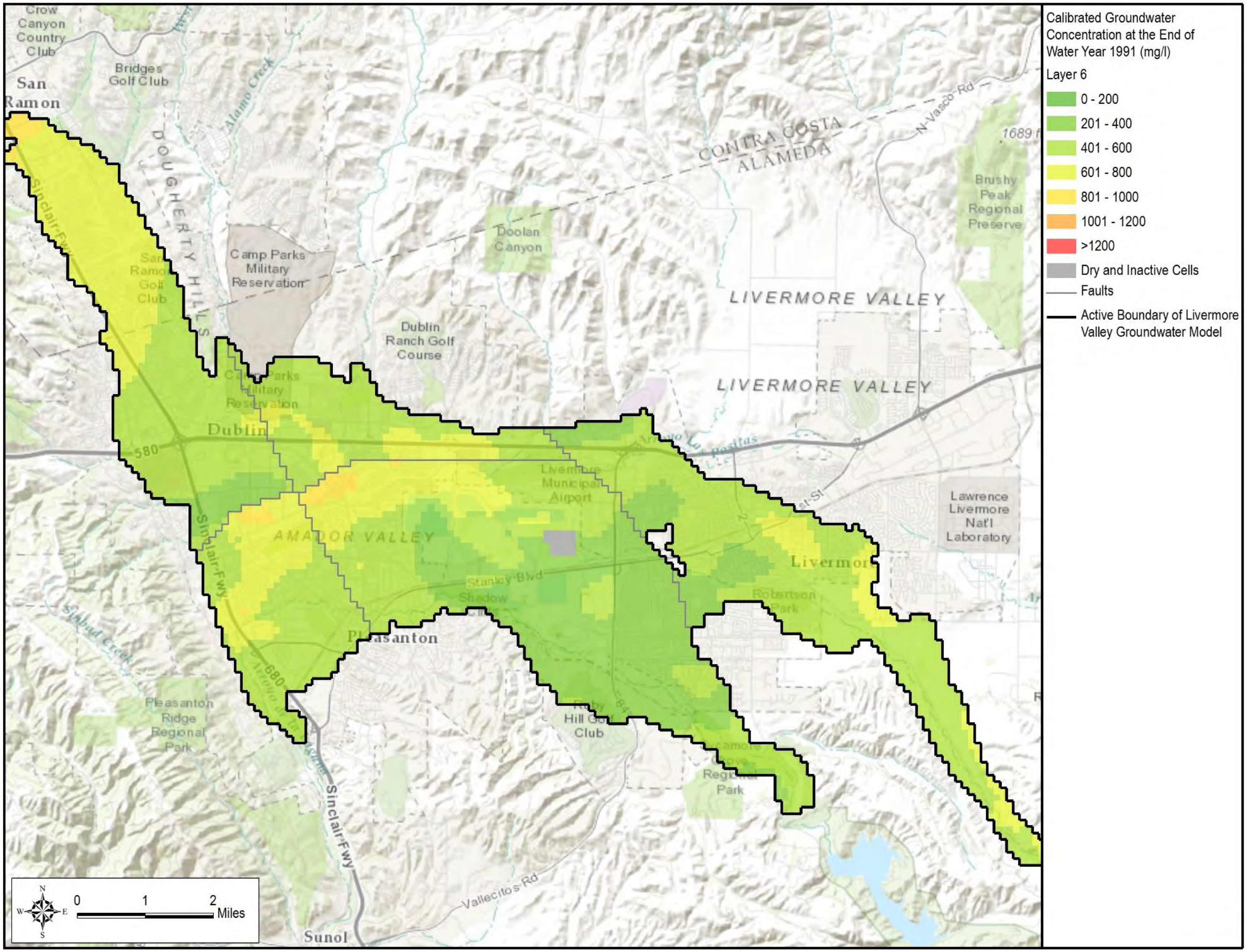


Figure 76: Simulated Groundwater TDS Concentrations for Layer 6 at the End of Water Year 1991

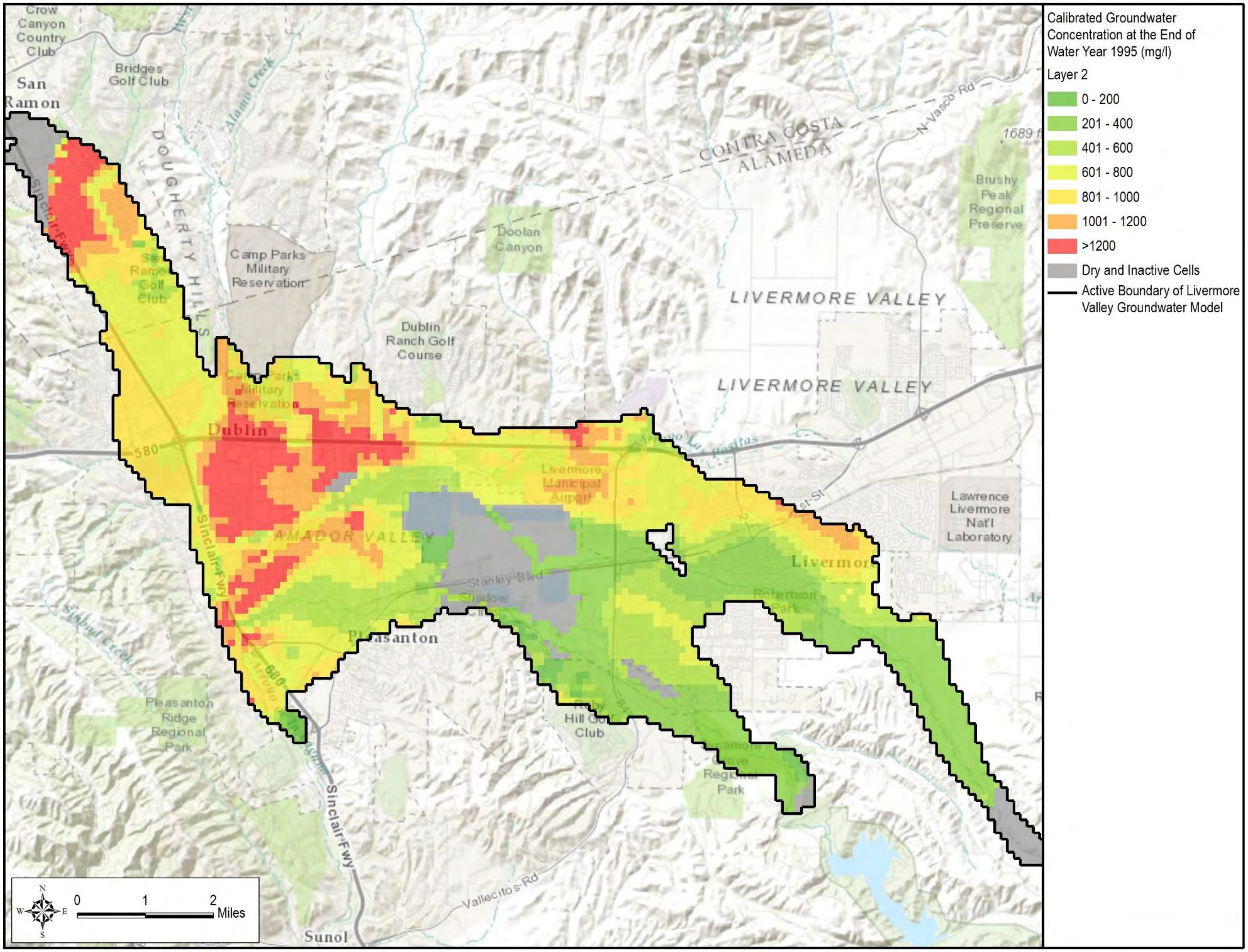


Figure 77: Simulated Groundwater TDS Concentrations for Layer 2 at the End of Water Year 1995

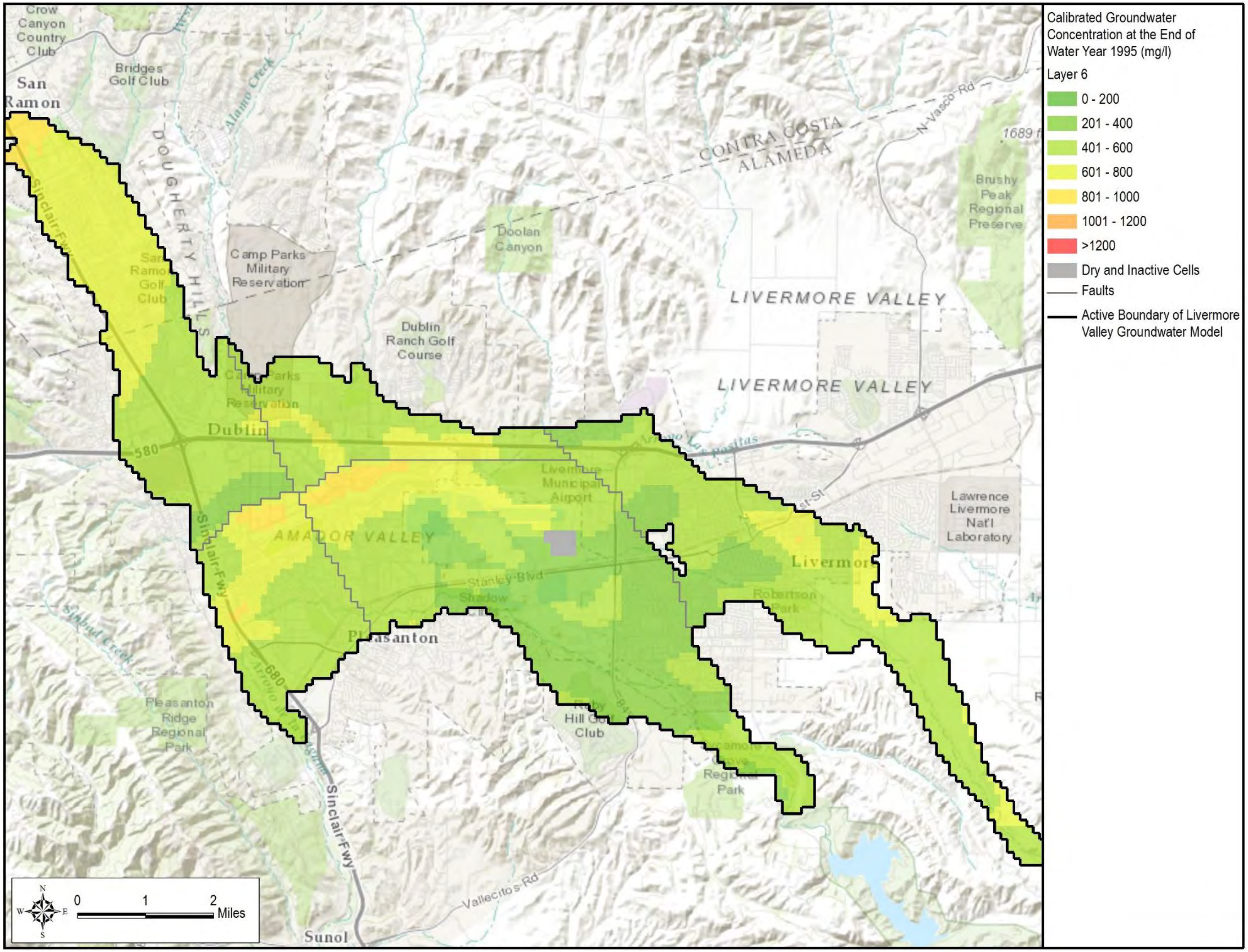


Figure 78: Simulated Groundwater TDS Concentrations for Layer 6 at the End of Water Year 1995

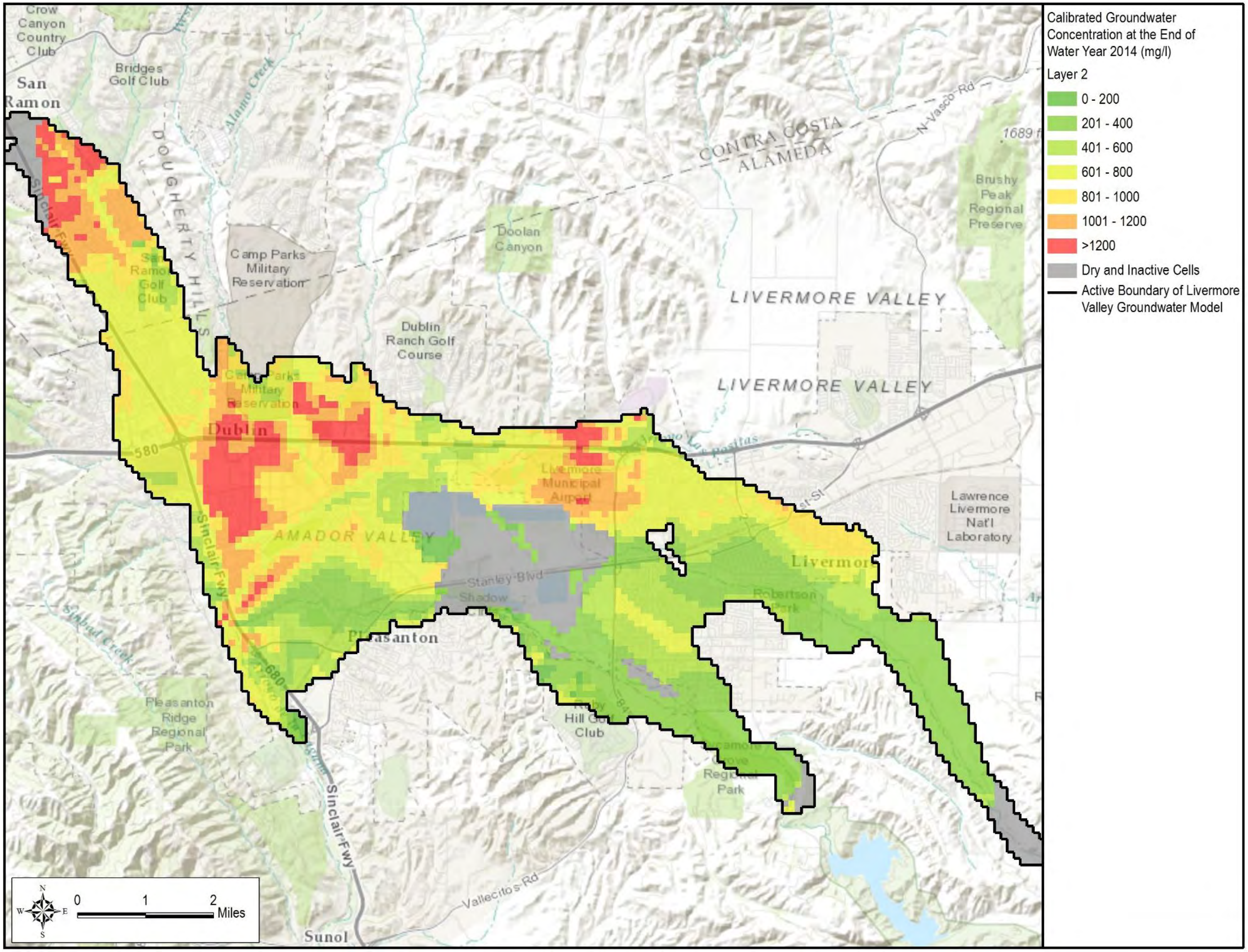


Figure 79: Simulated Groundwater TDS Concentrations for Layer 2 at the End of Water Year 2014

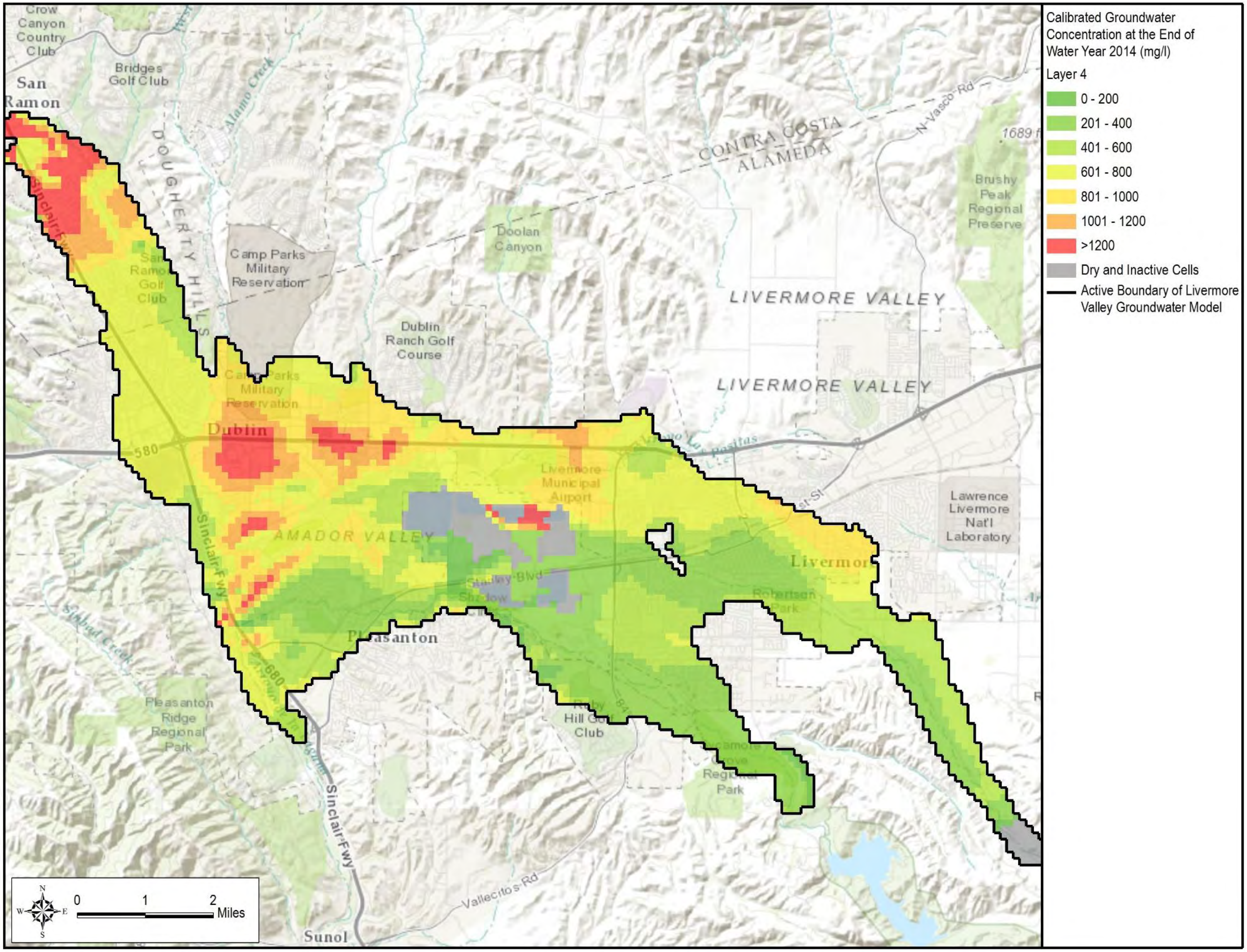


Figure 80: Simulated Groundwater TDS Concentrations for Layer 4 at the End of Water Year 2014

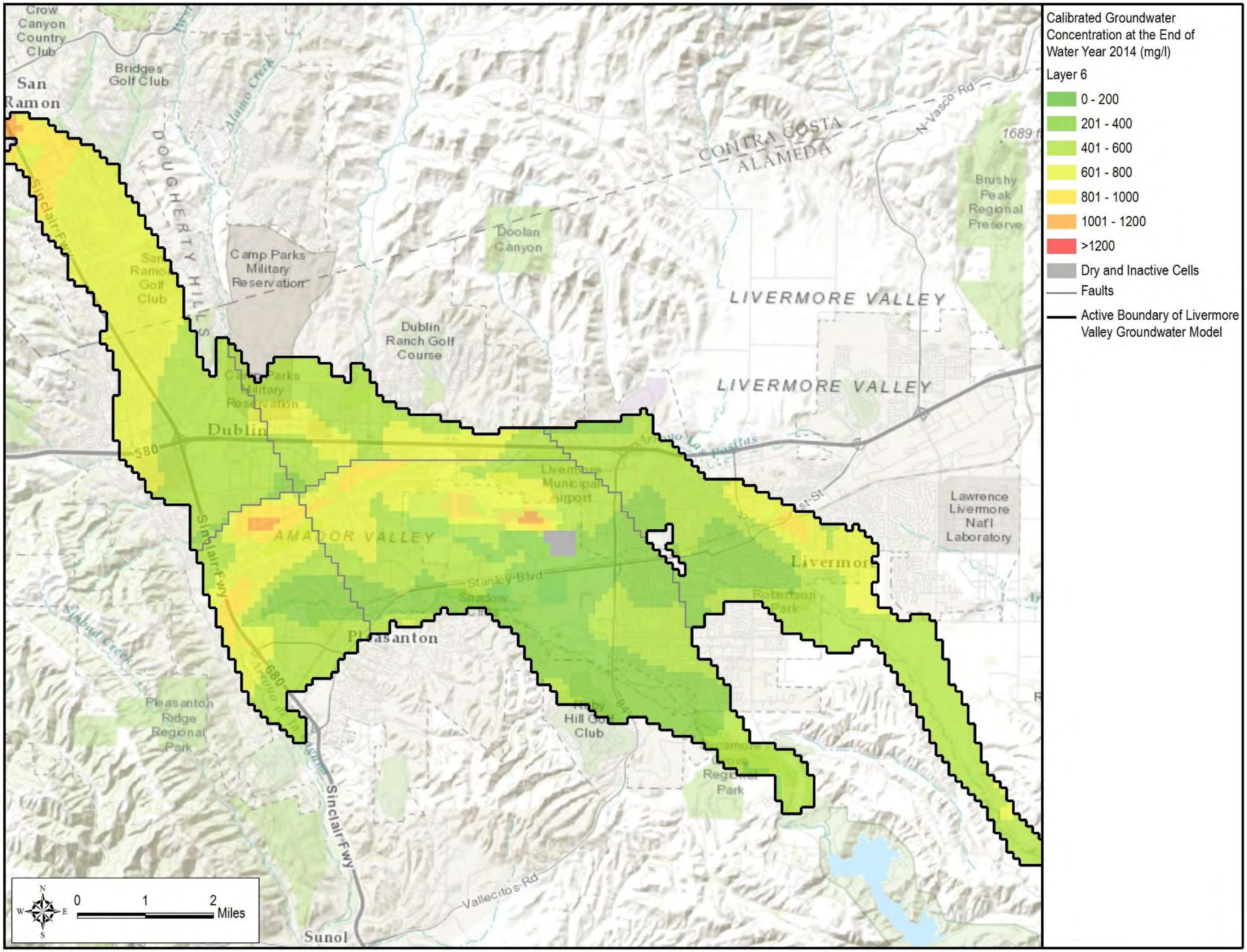


Figure 81: Simulated Groundwater TDS Concentrations for Layer 6 at the End of Water Year 2014

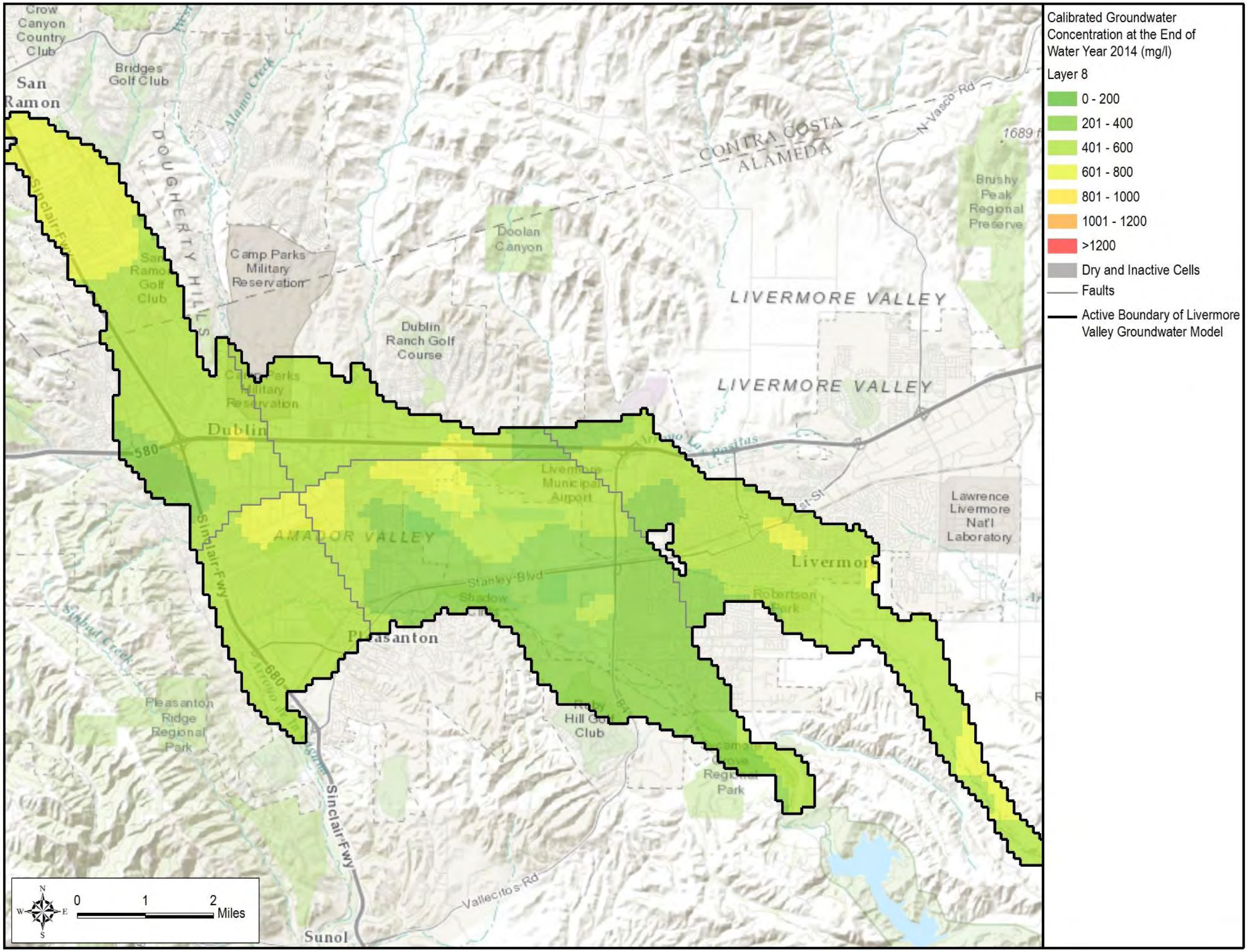


Figure 82: Simulated Groundwater TDS Concentrations for Layer 8 at the End of Water Year 2014

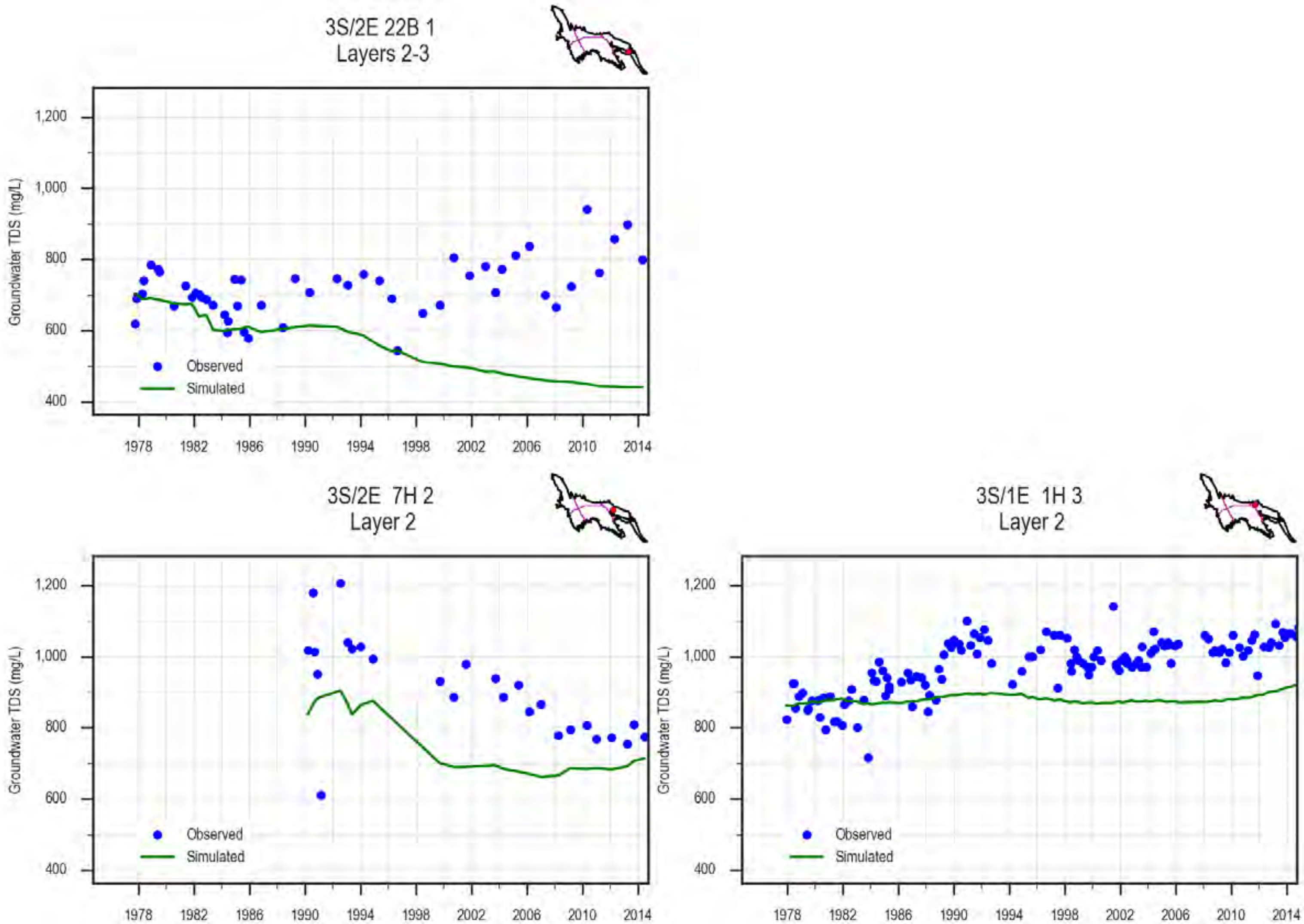


Figure 83: Example Groundwater TDS Chemographs for Mocho II Sub-basin Layers 2-4

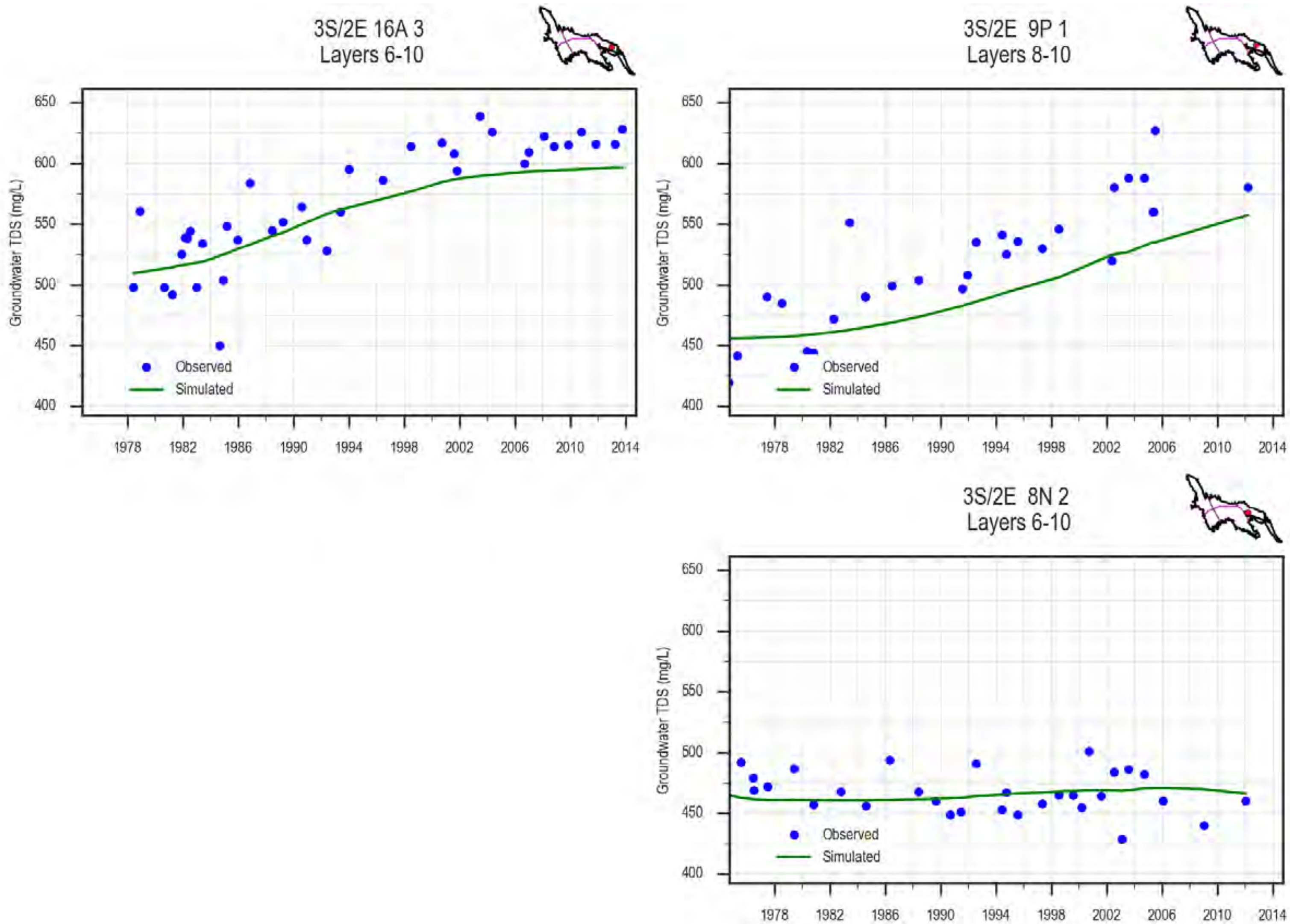


Figure 84: Example Groundwater TDS Chemographs for Mocho II Sub-basin Layers 6-10

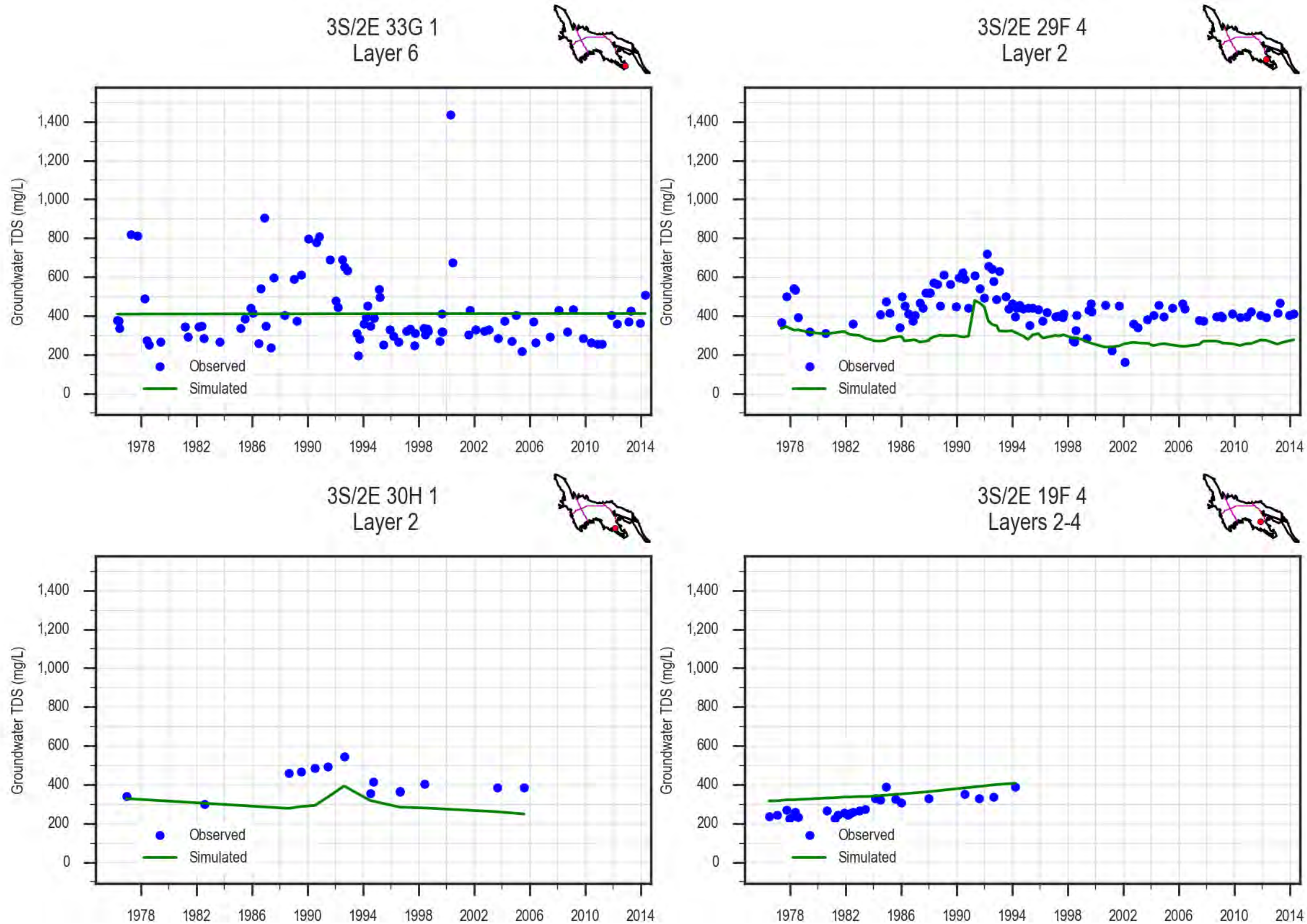


Figure 85: Example Groundwater TDS Chemographs for Amador Sub-basin Upstream Area

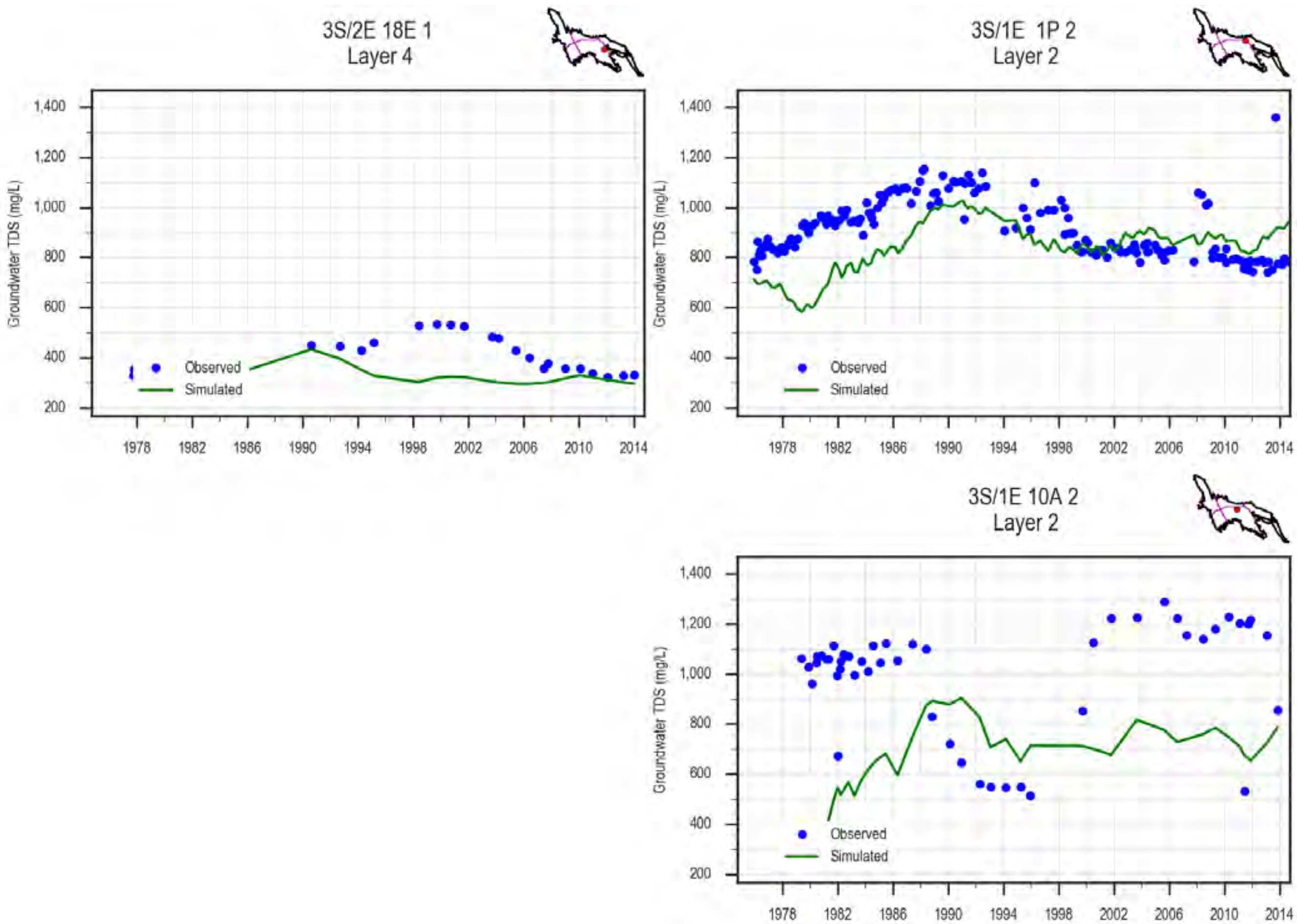


Figure 86: Example Groundwater TDS Chemographs for Amador Sub-basin East Area Layers 2-4

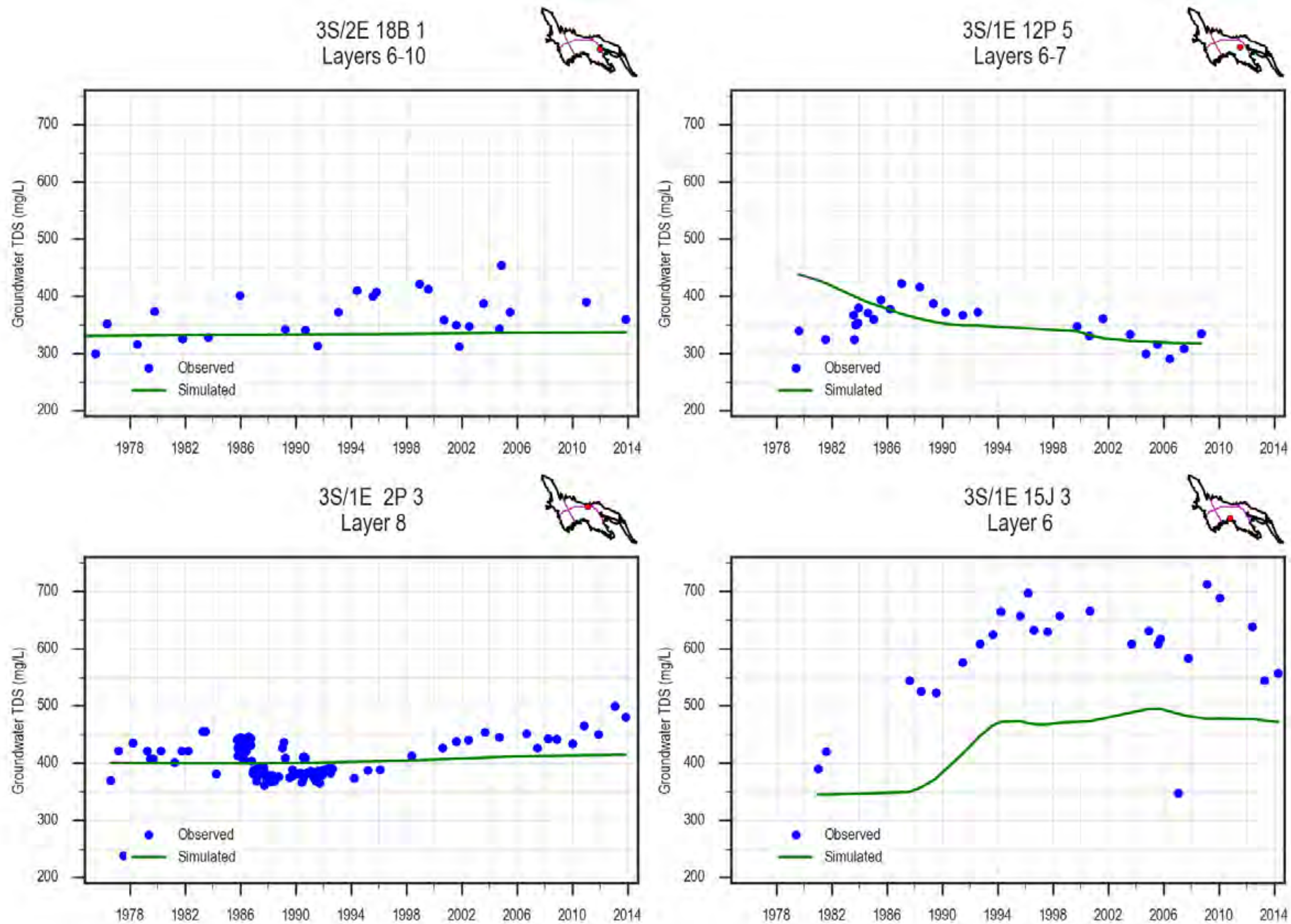


Figure 87: Example Groundwater TDS Chemographs for Amador Sub-basin East Area Layers 6-10

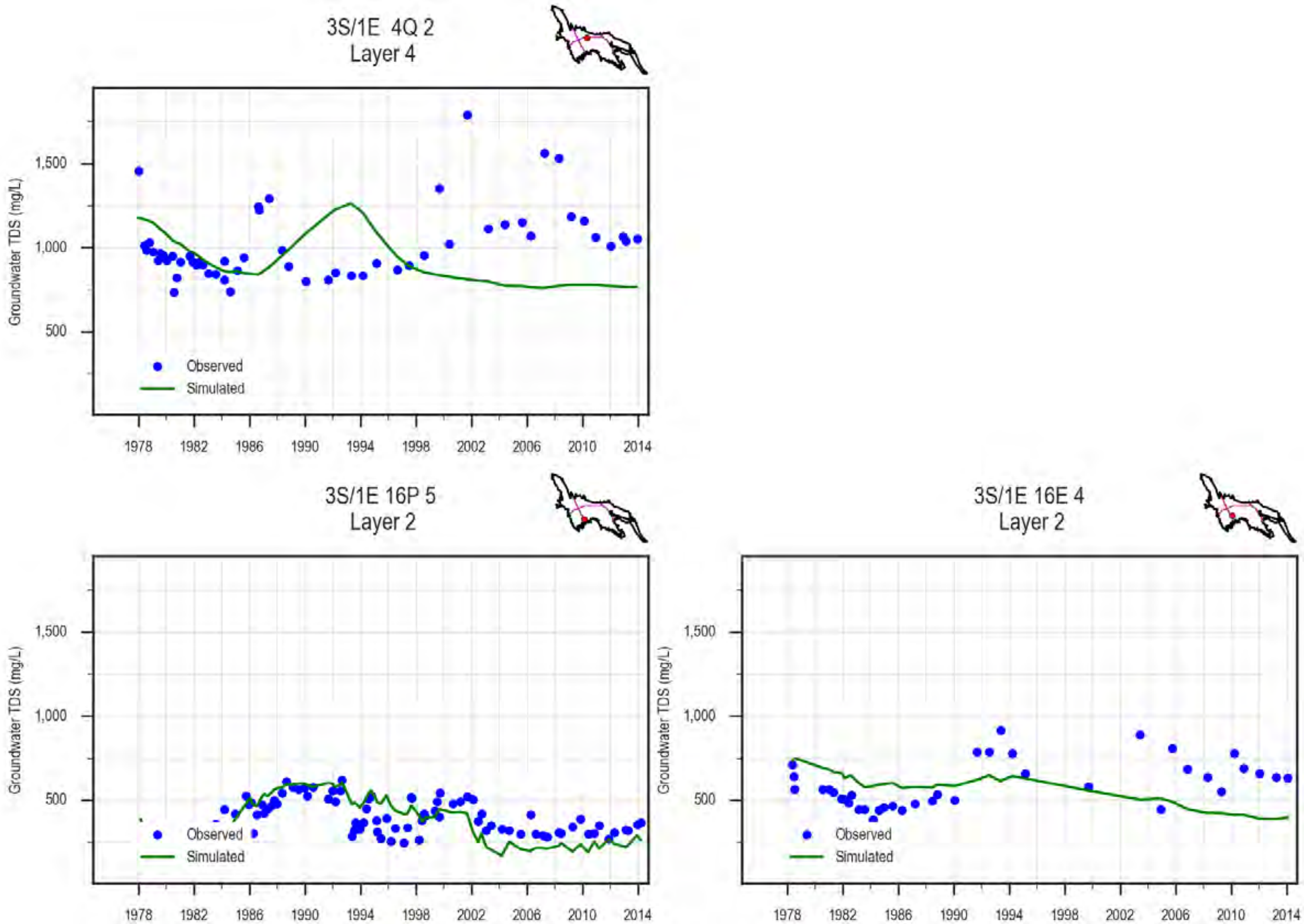


Figure 88: Example Groundwater TDS Chemographs for Amador Sub-basin West Area Layers 2-4

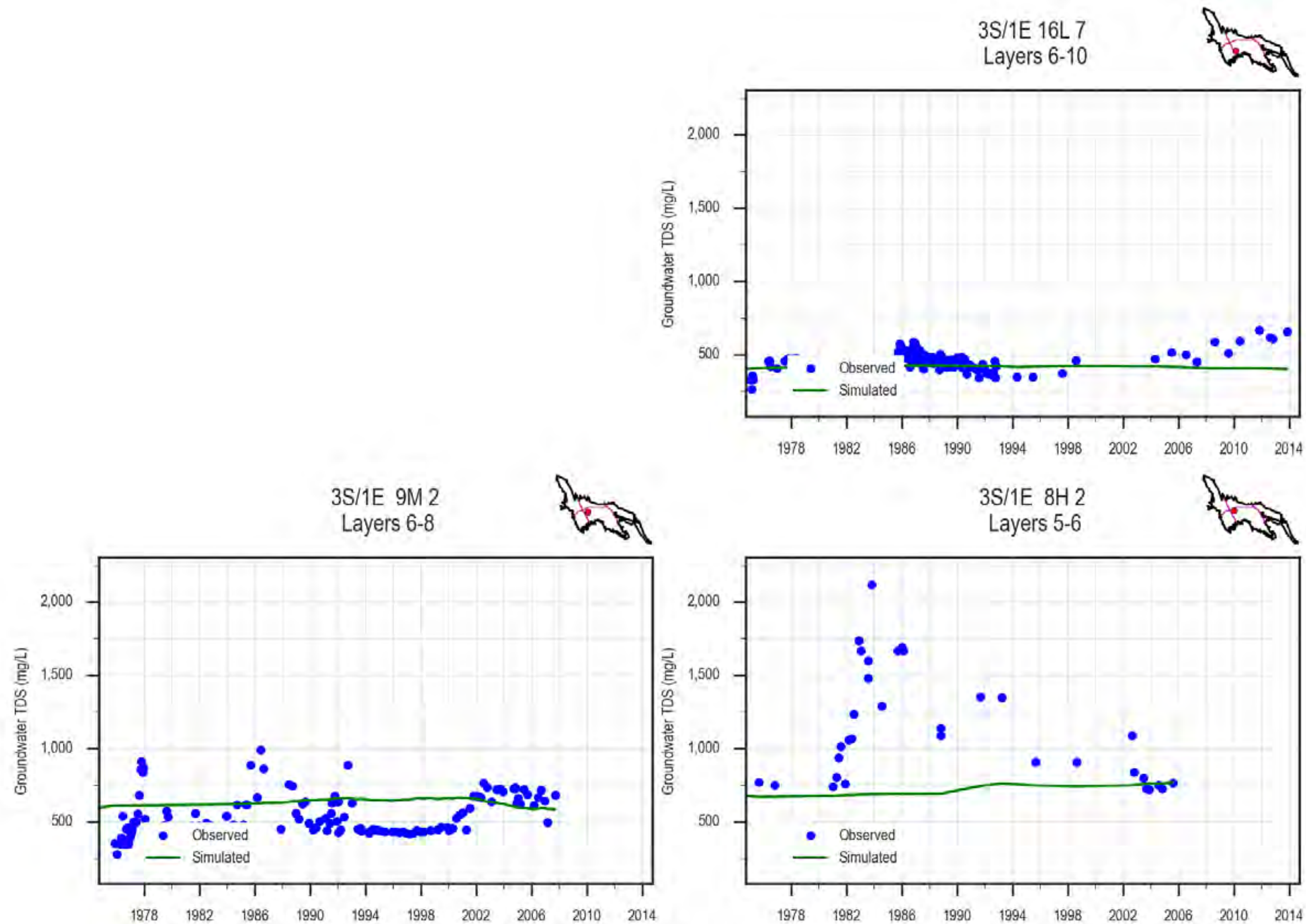


Figure 89: Example Groundwater TDS Chemographs for Amador Sub-basin West Area Layers 6-10

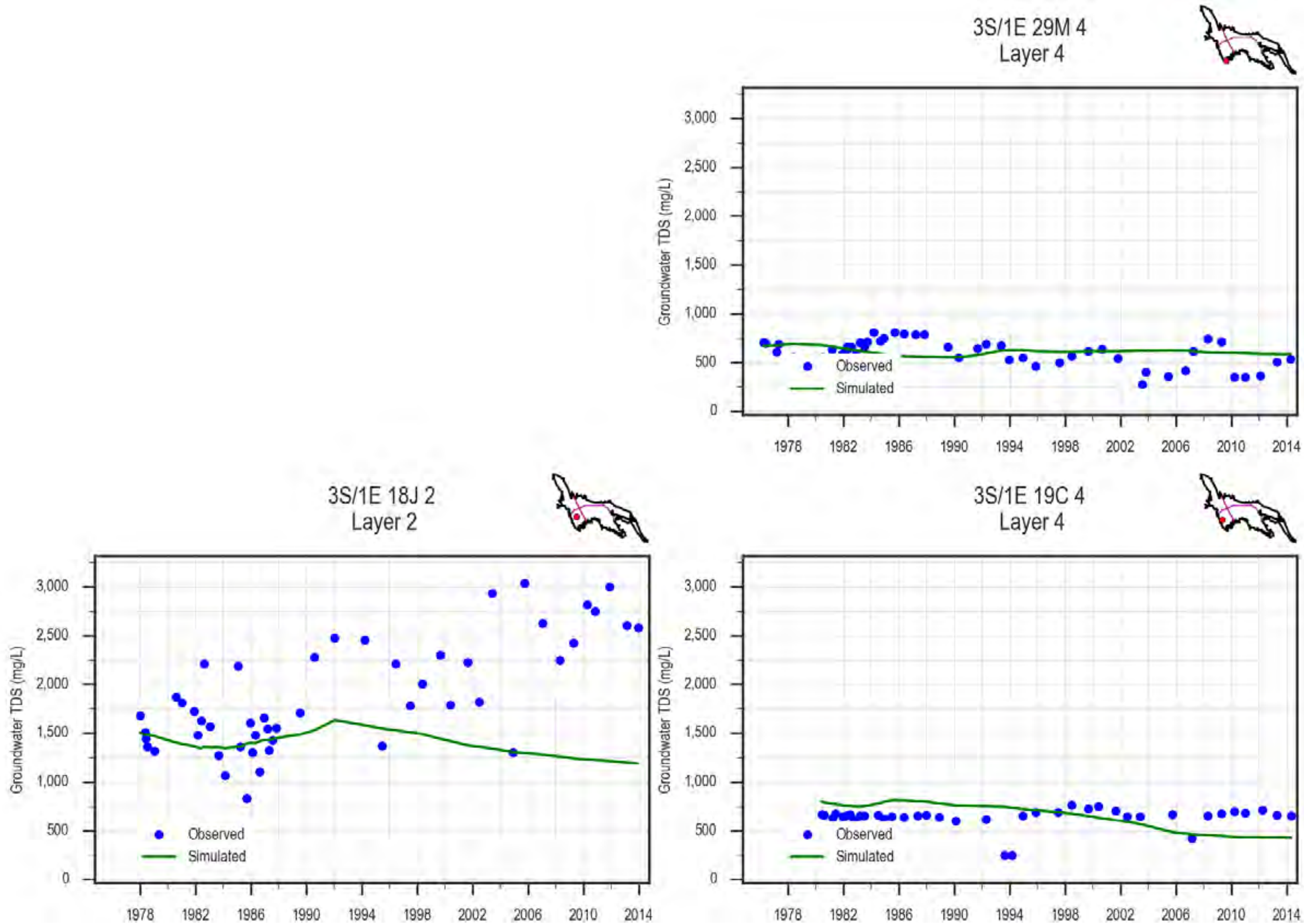


Figure 90: Example Groundwater TDS Chemographs for Bernal Sub-basin Layers 2-4

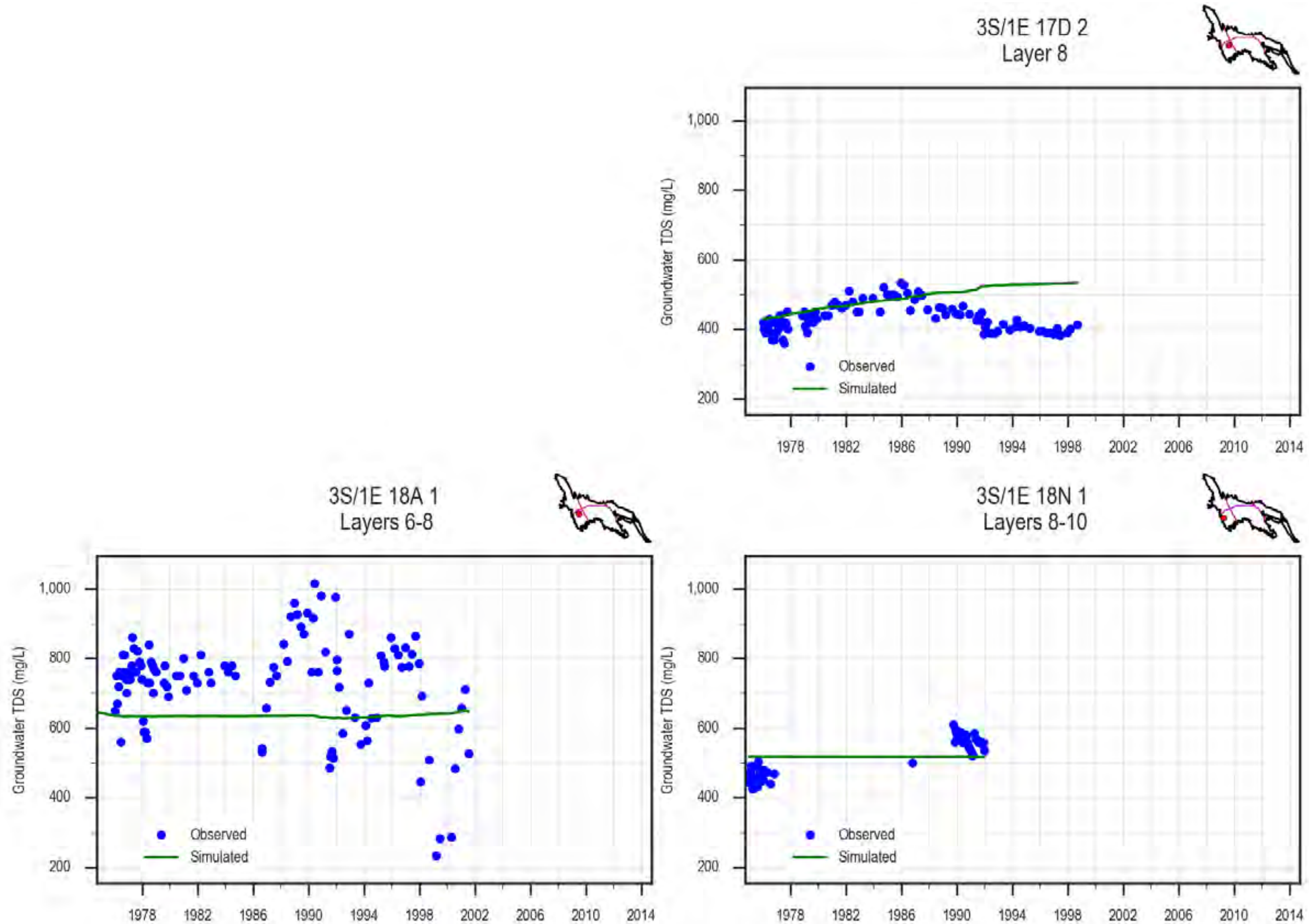


Figure 91: Example Groundwater TDS Chemographs for Bernal Sub-basin Layers 6-10

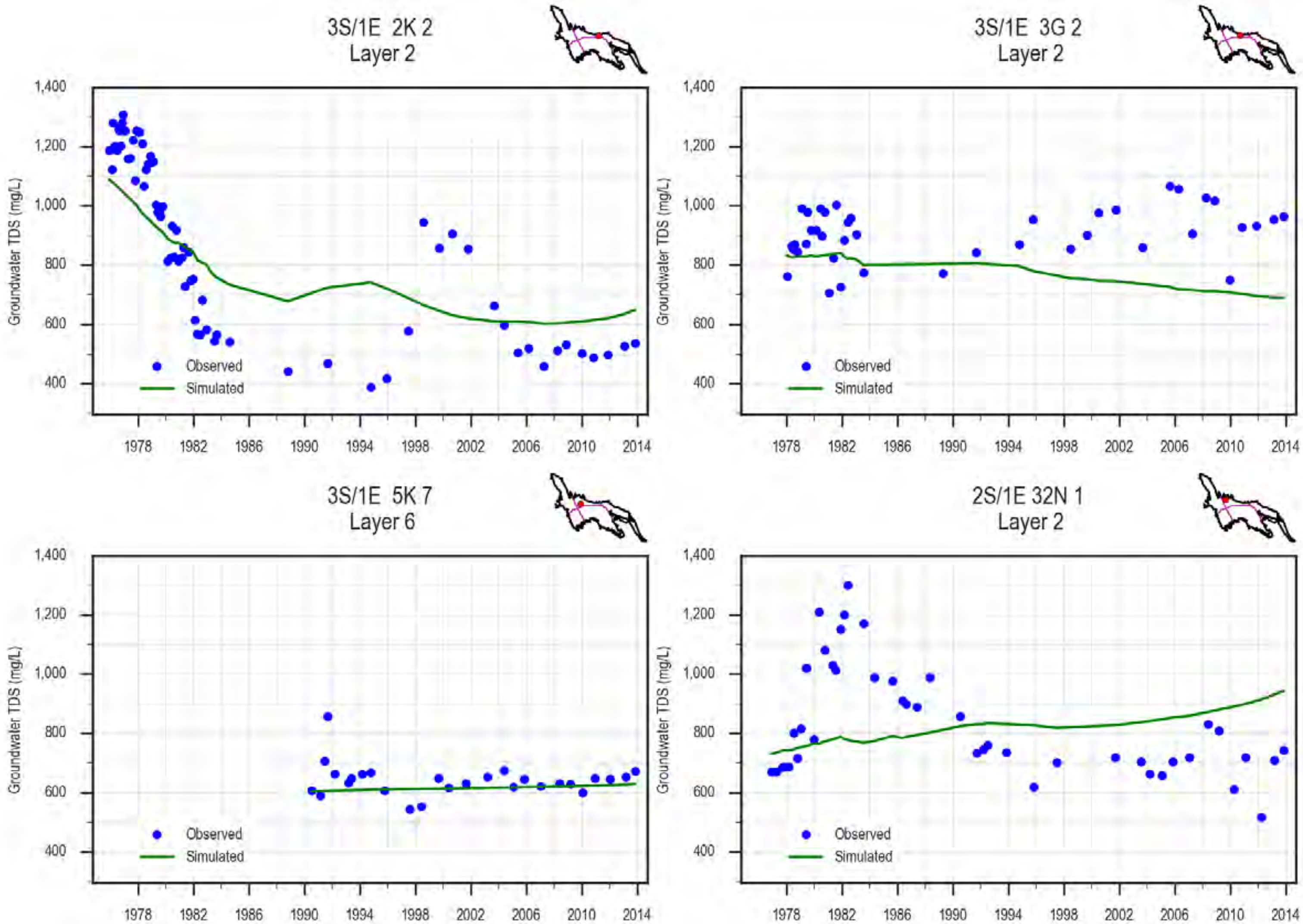


Figure 92: Example Groundwater TDS Chemographs for Camp Sub-basin

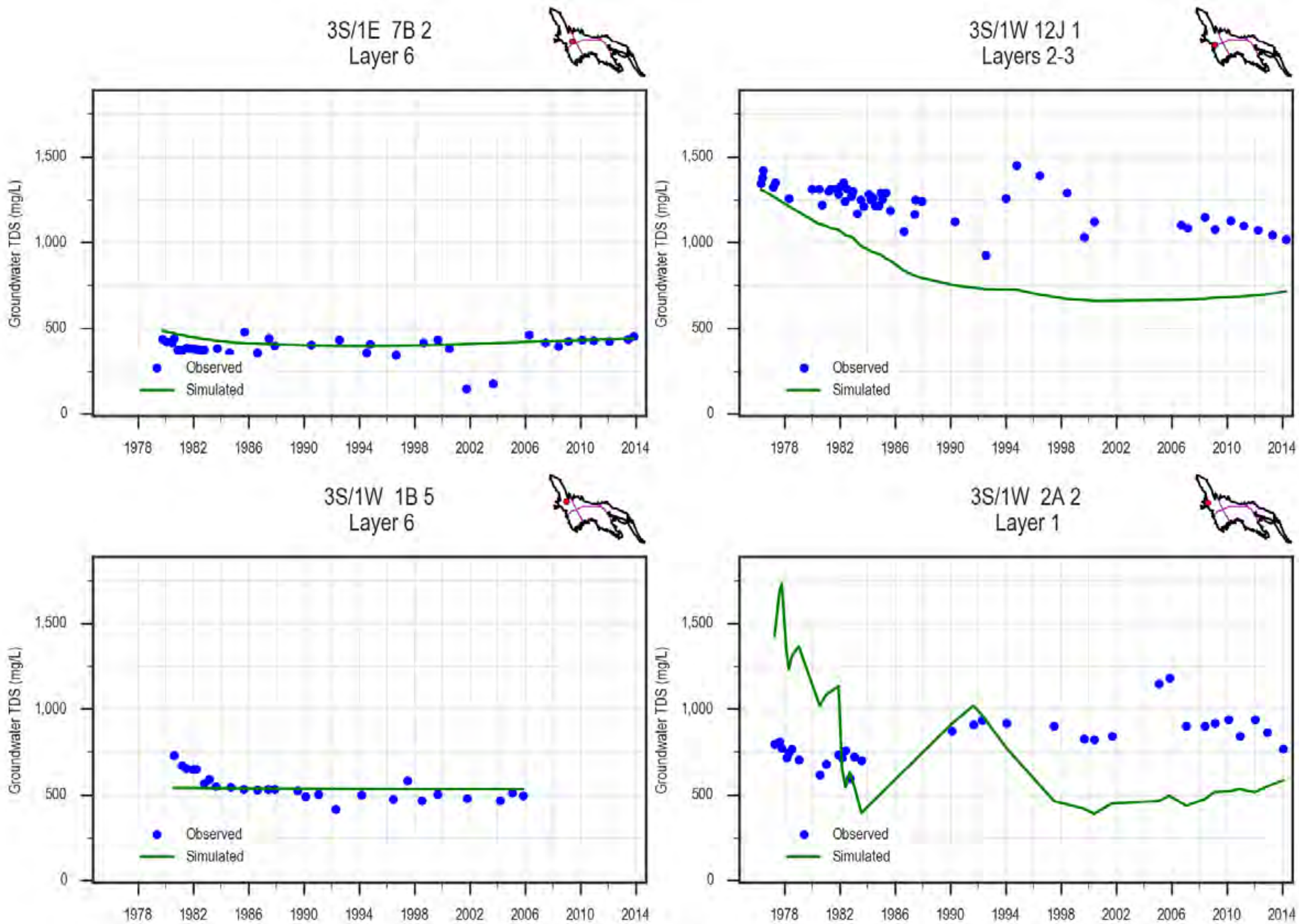


Figure 93: Example Groundwater TDS Chemographs for Dublin Sub-basi

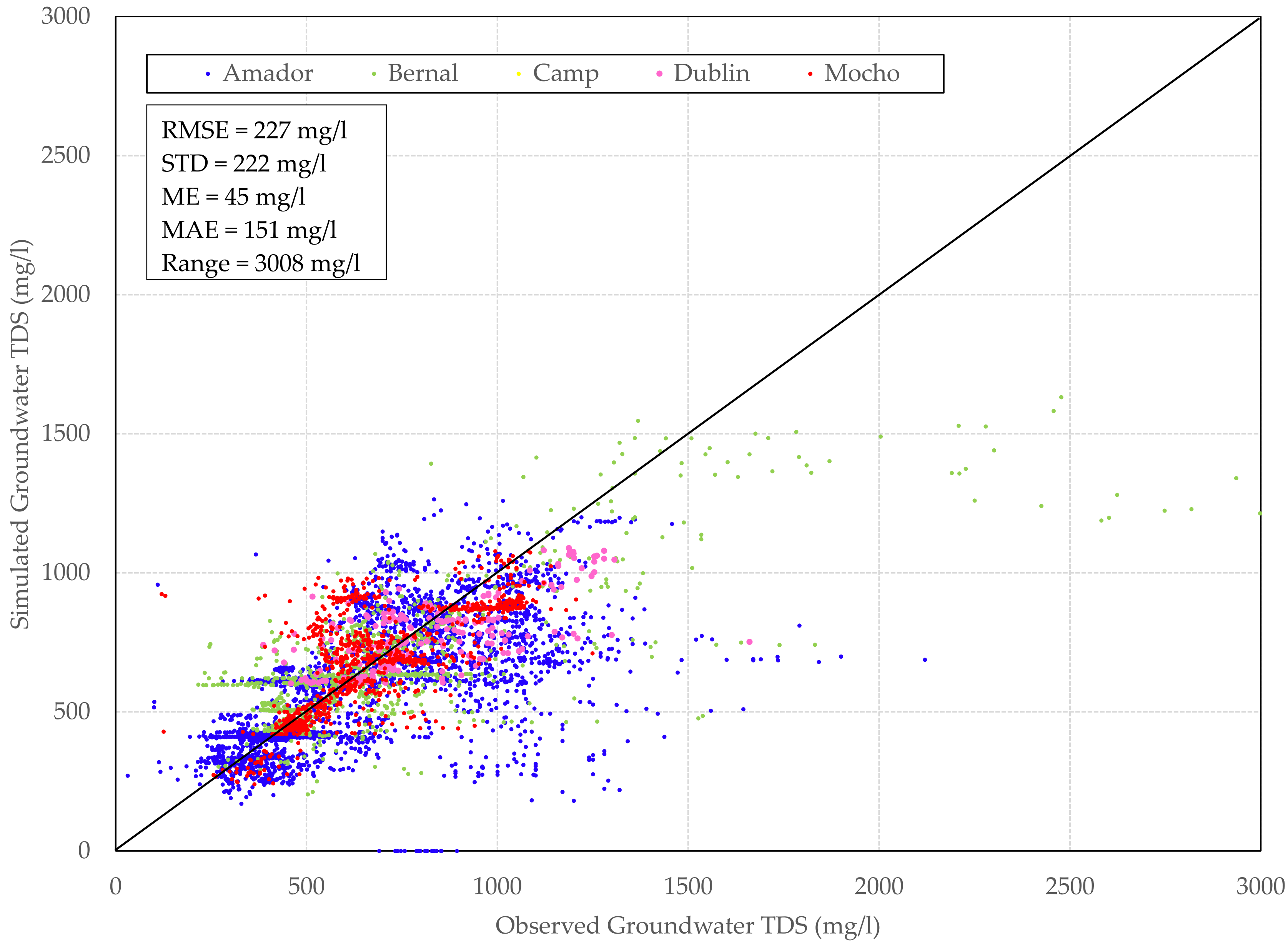


Figure 94: Simulated versus Observed Groundwater TDS Concentrations

4.5.5 STREAM TDS CONCENTRATIONS

Stream TDS concentrations simulated by the model were calibrated to the available transient TDS concentration data from the internal stream sampling stations. Simulated stream TDS concentrations output by the recently developed SFT package in MT3D-USGS (Bedekar, et al. 2016) were interpolated to observation times using surface water processing software TSPROC (Westenbroek, et al., 2012).

Figure 95 portrays the location of the stream gaging stations with stream TDS data used to calibrate. Note that there is no station available at the Tassajara and Dublin Creeks. Table 11 provides a summary of the stream TDS data available at each of the stream sampling stations.

Table 11: Summary of the Transient Stream TDS Data used in SFT Model Calibration

Stream Name	Station Name	# of Records	First Record	Last Record	Average TDS (mg/l)
Alamo Canal	AC_NP	108	10/1/1974	2/15/2000	807
Arroyo De Laguna	ADLL	54	7/24/1979	8/5/2014	565
Arroyo Valle	ADVP	182	1/24/1975	3/5/2014	300
Arroyo Las Positas	ALP_ELCH	70	10/16/1974	8/5/2014	779
Arroyo Mocho	AMHAG	25	3/28/1985	7/23/2013	303
Arroyo Mocho	AMP	31	3/16/1983	8/5/2014	641

The concentration data at the headwater segments are generally not used here as calibration targets, because they are used to define the amount of the water and salt entering the system at the headwater segments. The exception to this is at AC_NP station on Alamo Canal where transient TDS data at the station is used both to represent the amount of the salt entering the model domain through the Alamo Canal and also as a calibration target at its actual location 5 miles downstream of the Alamo Canal headwaters. Including this station's data in the calibration is used to check the assumption used to set the boundary condition that concentrations do not vary considerably between the headwaters.

Figure 96 through Figure 97 show hydrographs for simulated versus observed stream TDS concentrations. The chemographs show that the model generally simulates concentration magnitudes and trends observed in stream sampling data. This indicates that the use of the SFT package sufficiently simulates stream contribution to the basin salt balance. As with groundwater levels, the model is not able to simulate many of the local fluctuations observed in the concentration data.

Figure 98 shows simulated stream TDS concentrations plotted against observed TDS concentrations for the entire calibration period. Figure 98 also includes various statistical measures of calibration accuracy.

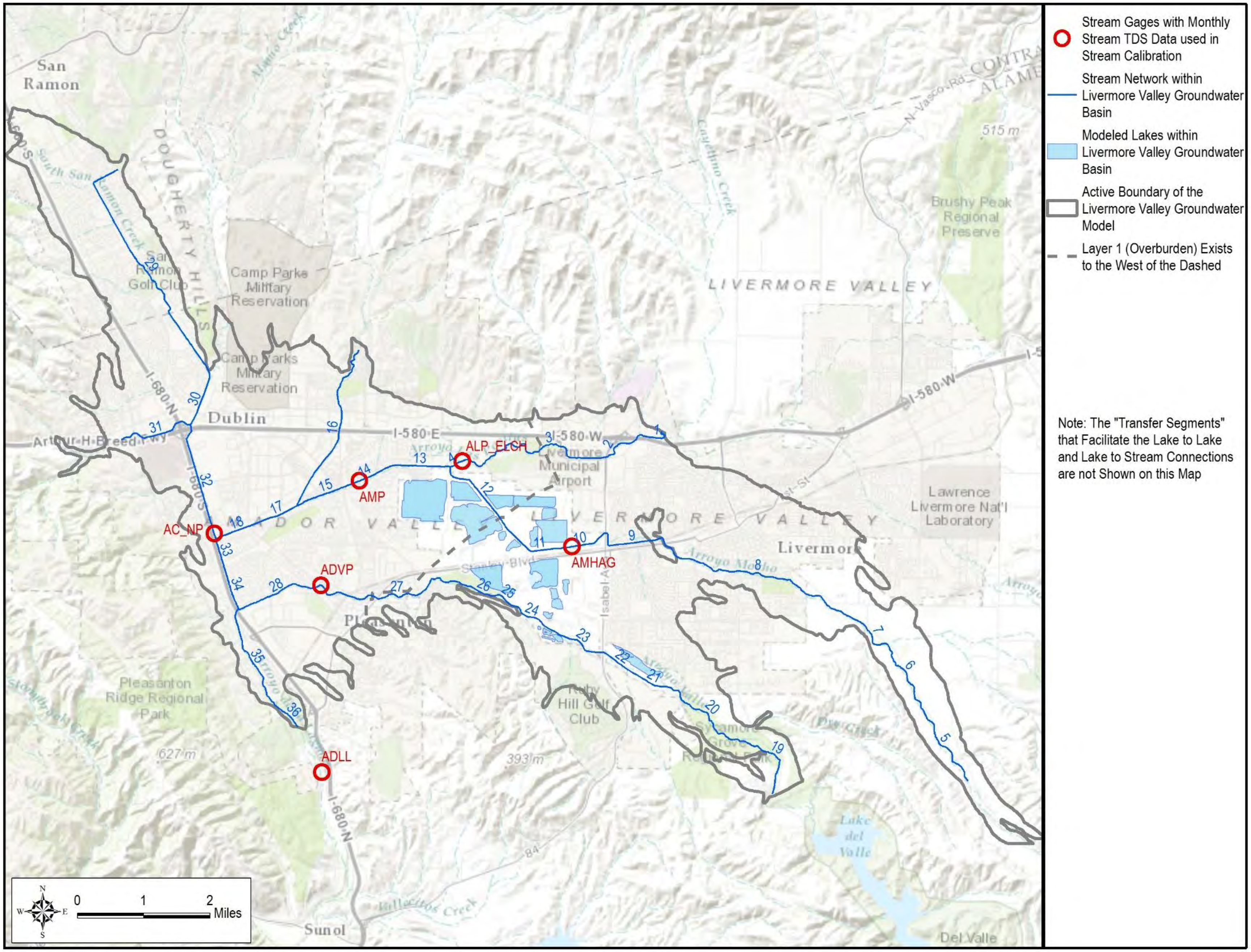


Figure 95: Location of the Stream Gaging Stations with Transient Stream TDS Data used in the Stream Calibration

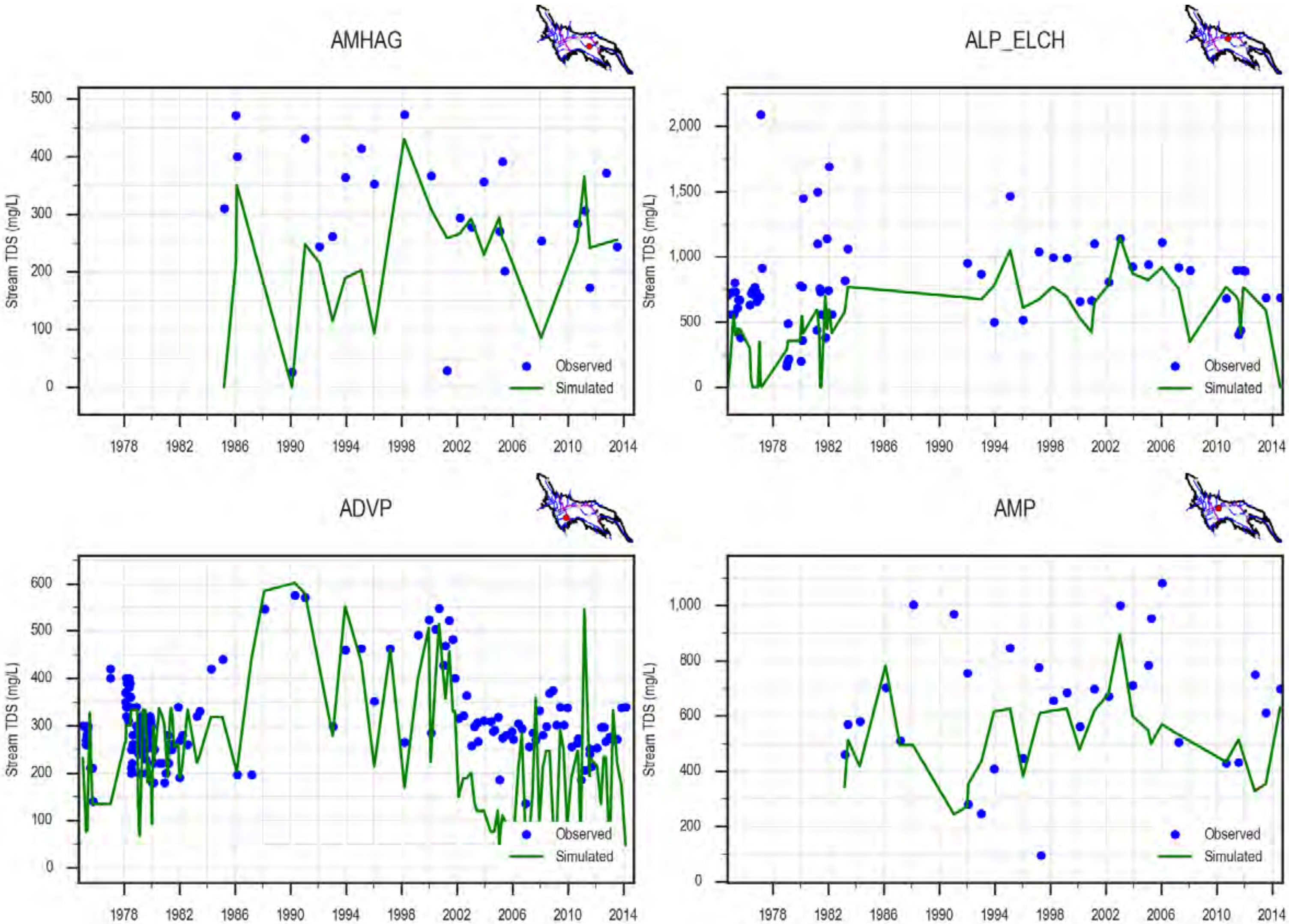


Figure 96: Stream TDS Chemographs for Arroyos Upstream of Confluences

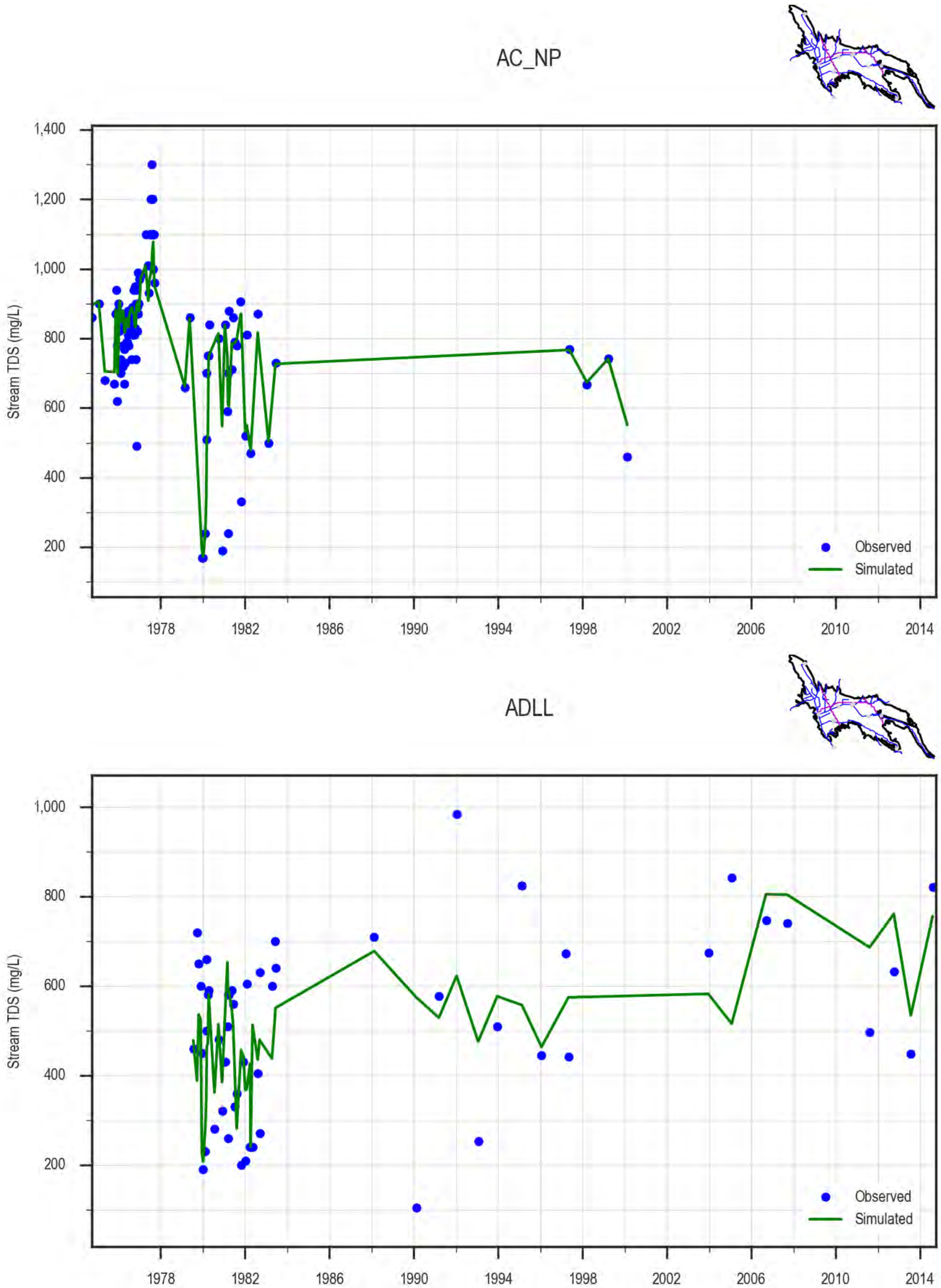


Figure 97: Stream TDS Chemographs for Arroyos Downstream of Confluence

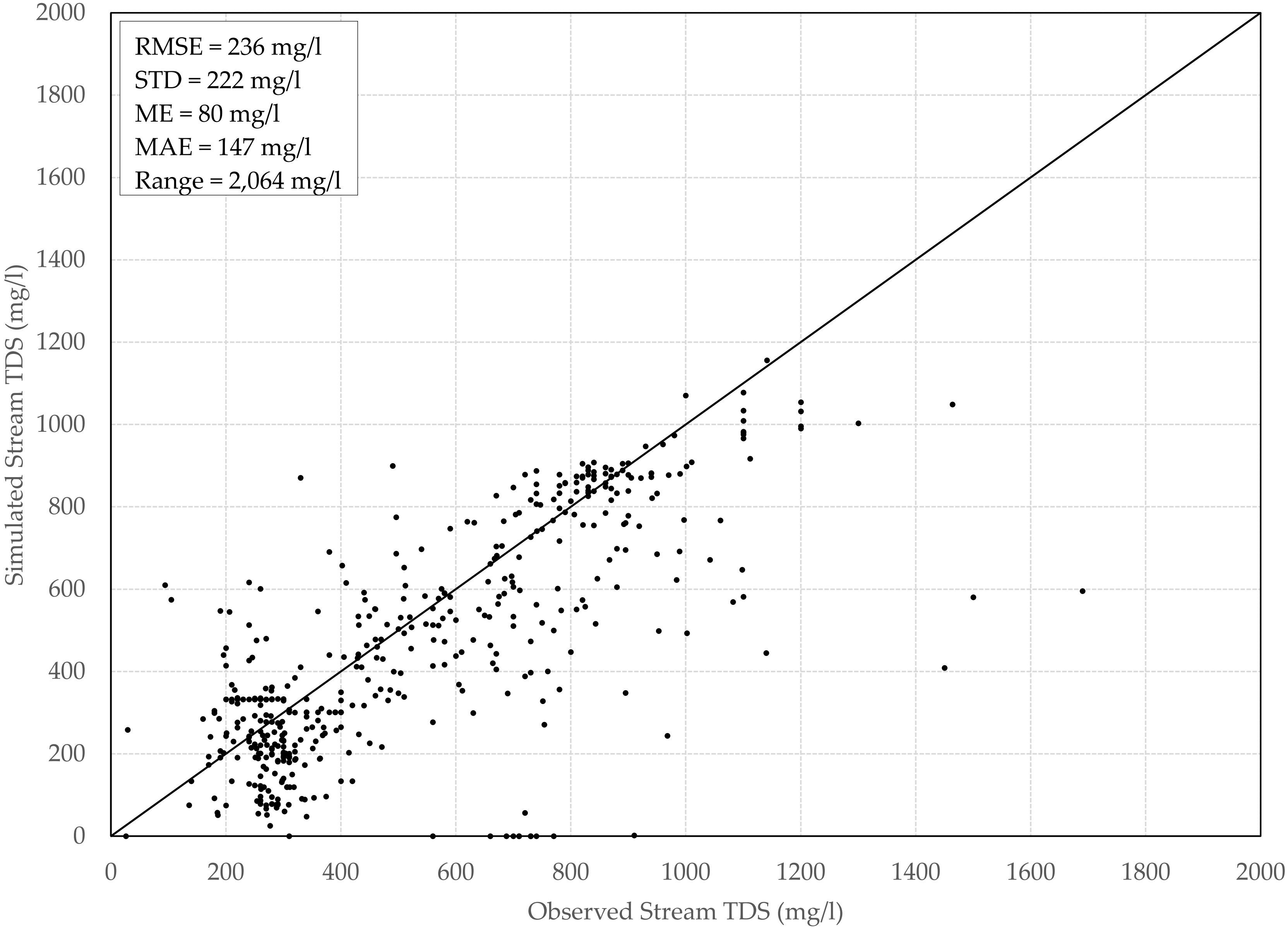


Figure 98: Simulated versus Observed Stream TDS Concentrations

4.5.6 Lake TDS Concentrations

Lake TDS concentrations simulated by the model were calibrated to the available transient TDS concentration data sampled from the lakes. Simulated lake TDS concentrations output by the recently developed LKT package in MT3D-USGS (Bedekar, et al. 2016) were interpolated to observation times using surface water processing software TSPROC (Westenbroek, et al., 2012).

Table 12 provides a summary of the lake TDS data available for this model. Data from lined lakes are not included in the calibration.

Table 12: TDS Data Summary Used for Calibration of Lakes within the Livermore Valley Groundwater Basin

Lake #	Lake Name	Status	# of Records	First Record	Last Record	TDS Range (mg/l)	Average TDS (mg/l)
1	P-41	Unlined	72	Jan-03	Sep-14	319-538	410
2	P-27	Unlined	52	May-91	Sep-14	64-446	280
3	P-45	Unlined	6	Sep-04	Apr-08	332-377	362
4	P-44	Unlined	57	May-04	Sep-14	276-401	366
5	P-42	Unlined	61	Apr-04	Sep-14	228-423	377
6	P-10	Unlined	155	Sep-78	Sep-14	206-721	350
7	P-43	Lined	12	Jul-04	Sep-14	328-390	361
8	R-24	Unlined	75	May-00	May-10	174-567	377
9	R-23	Unlined	59	Oct-96	Sep-14	364-899	492
10	R-22	Unlined	31	Apr-96	Sep-14	382-690	563
11	R-21	Lined	148	Apr-93	Apr-08	276-549	364
12	R-08	Unlined	157	Aug-79	May-12	391-767	515
13	R-04	Unlined	237	Jul-80	Sep-14	237-631	439
14	R-03	Lined	91	Apr-80	Sep-14	331-690	464
15	K-15	Unlined	382	Nov-75	Sep-14	319-747	480
16	K-30	Lined	299	Oct-82	Sep-14	400-1025	572
17	K-28	Unlined	176	Jul-83	Sep-14	356-663	494
18	K-37	Unlined	82	Jan-03	Sep-14	368-628	555

Figure 99 through Figure 103 show chemographs for simulated versus observed lake TDS concentrations. The chemographs show that the model simulates concentration magnitudes and trends observed in lake sampling data at most lakes, but at number of lakes, the model simulates concentrations that are too high compared to the data. Similar to calibrating lake stages, calibrating to lake TDS concentrations was not a priority due to the unknown operations of individual lakes that have changed the salt balance in those lakes, but are unlikely to have a large effect on the overall groundwater salt balance.

Figure 104 shows simulated lake TDS concentrations plotted against observed TDS concentrations for the entire calibration period.
Figure 104 also includes various statistical measures of calibration accuracy.

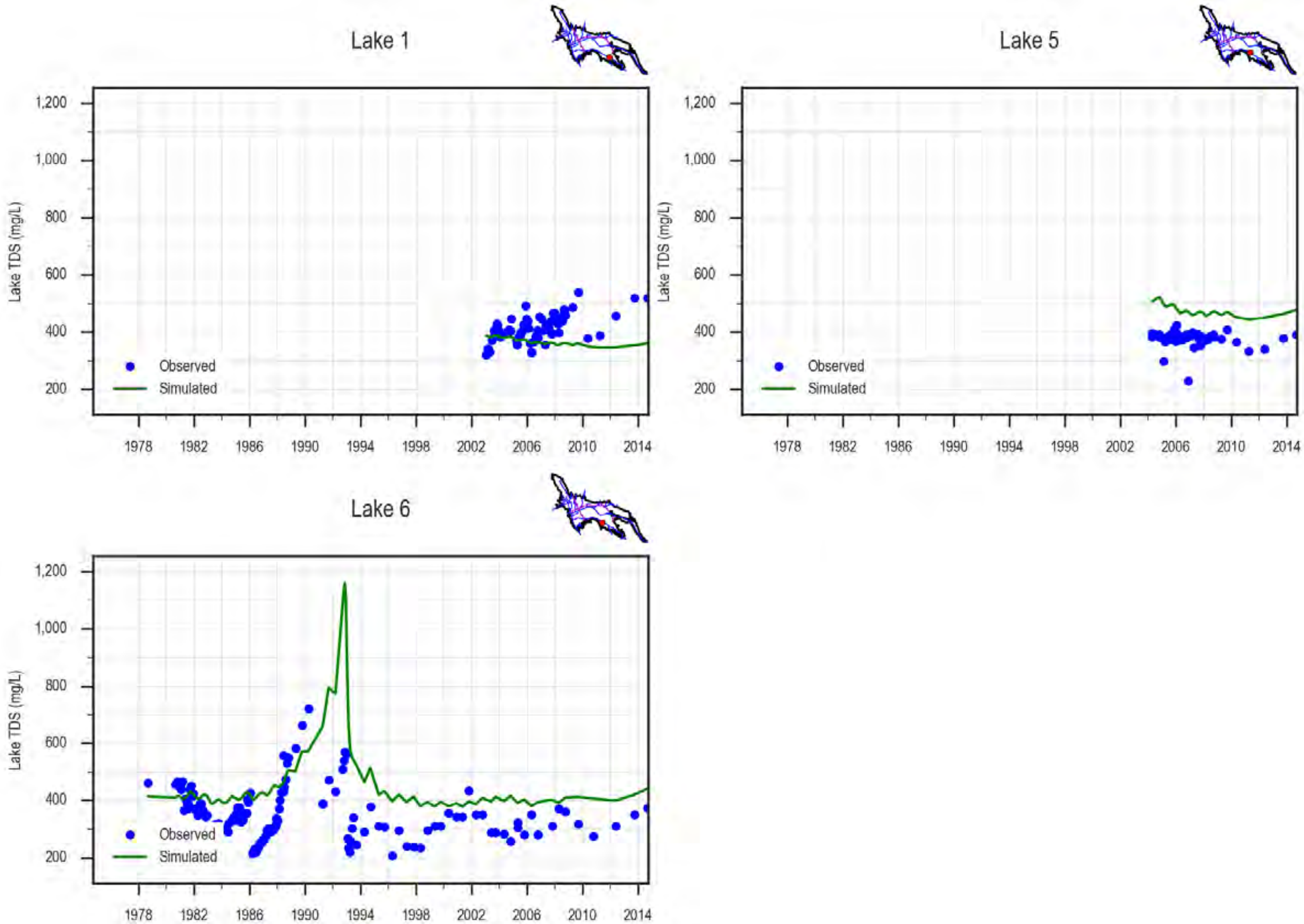


Figure 99: Chemographs of Lake TDS Concentrations for LoneStar/Cemex Group along Arroyo Valle

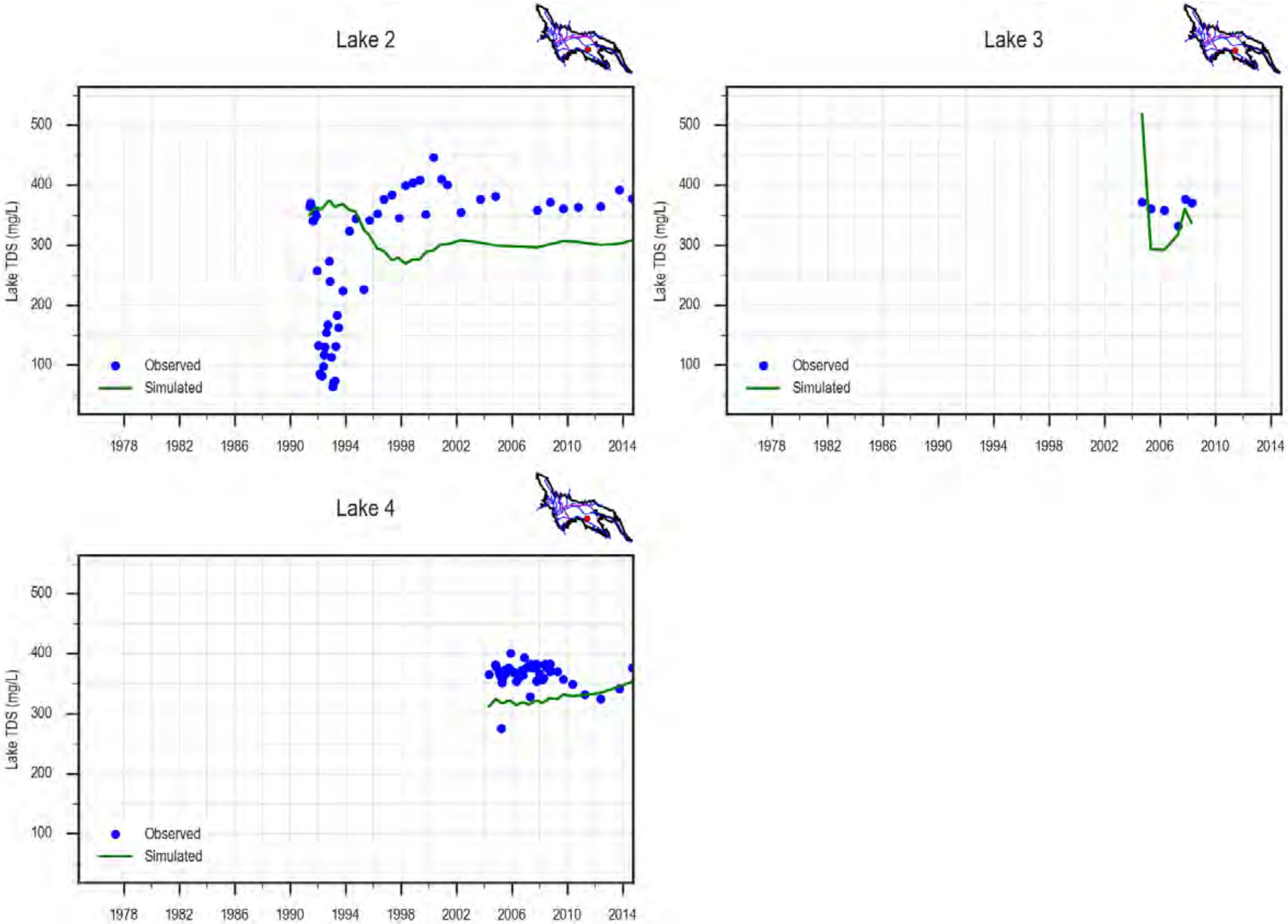


Figure 100: Chemographs of Lake TDS Concentrations for LoneStar/Cemex Group between Arroyo Valle and Arroyo Mocho

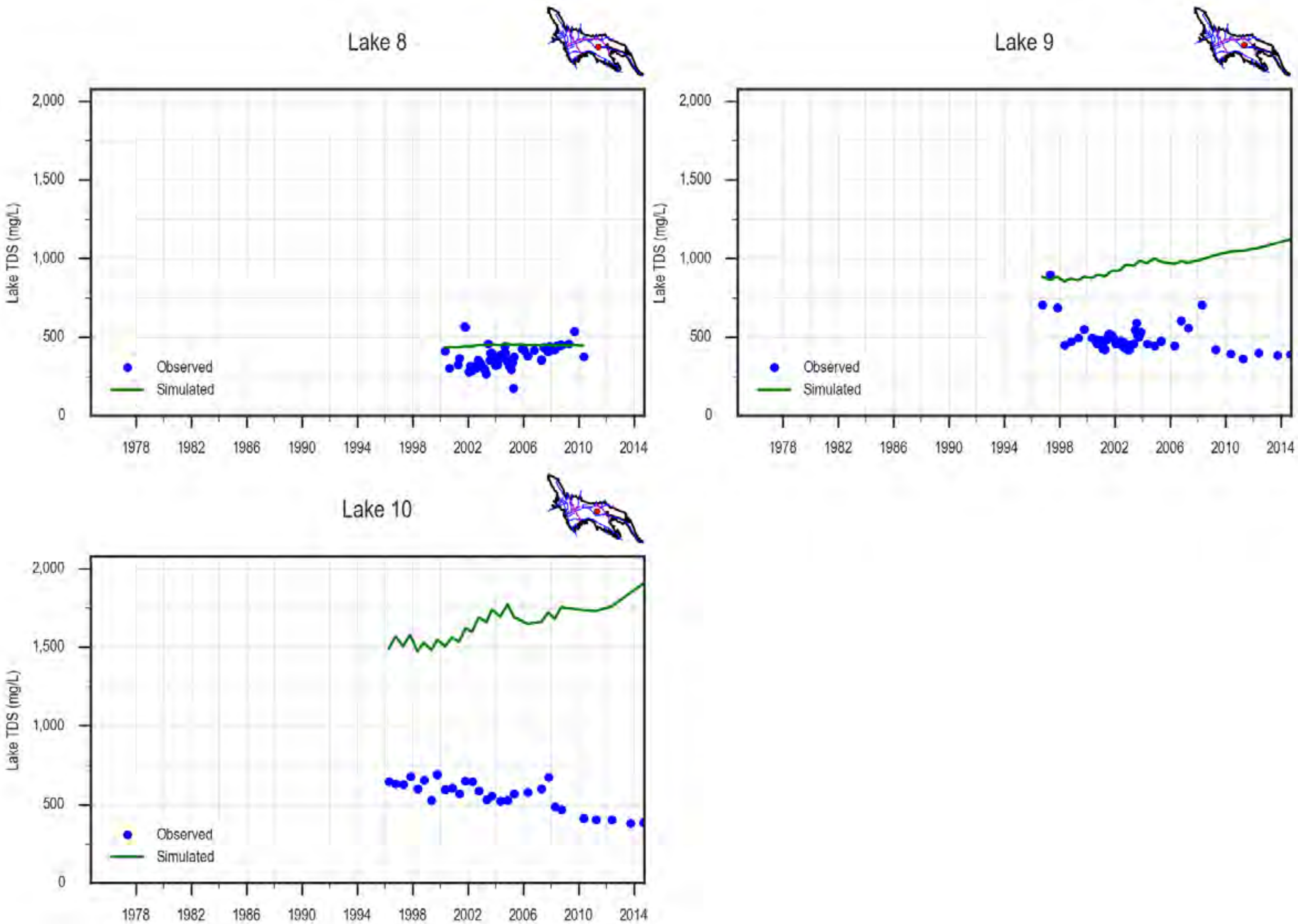


Figure 101: Chemographs of Lake TDS Concentrations for Calmat/Vulcan/PGC Group – East

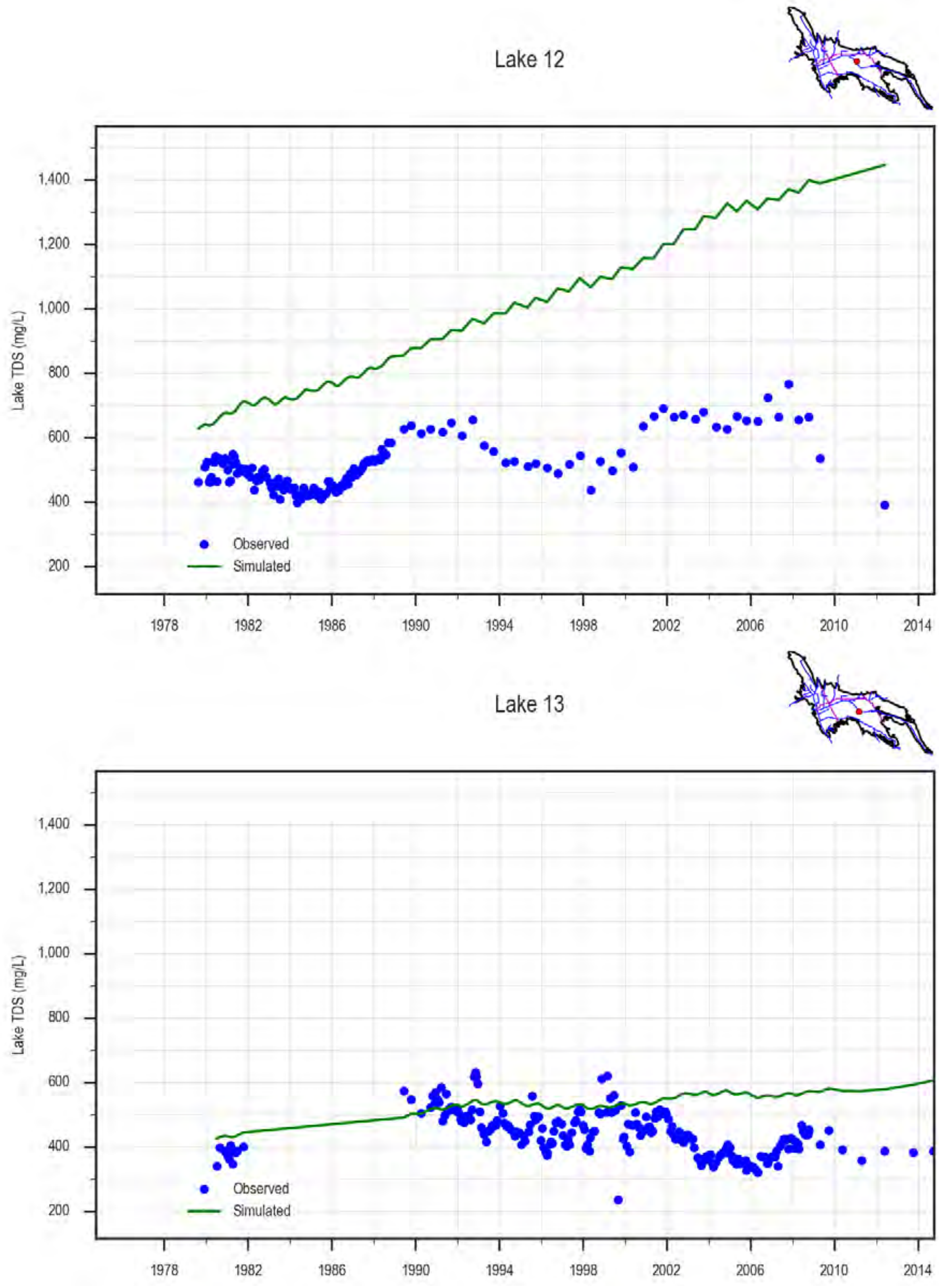


Figure 102: Chemographs of Lake TDS Concentrations for Calmat/Vulcan/PGC Group - West

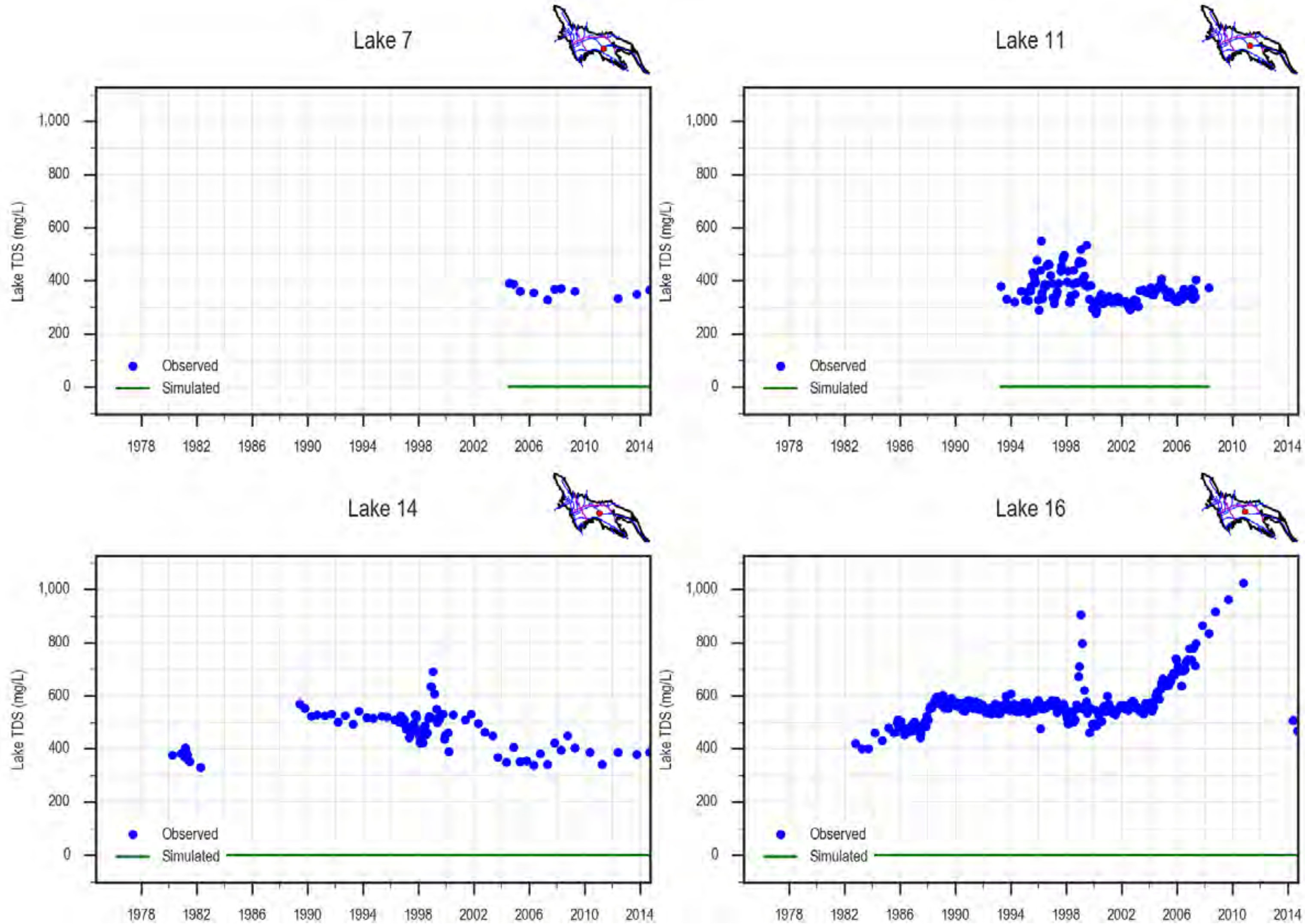


Figure 103: Chemographs of Lake TDS Concentrations for Kaiser/Hanson Group and Shadow Cliffs

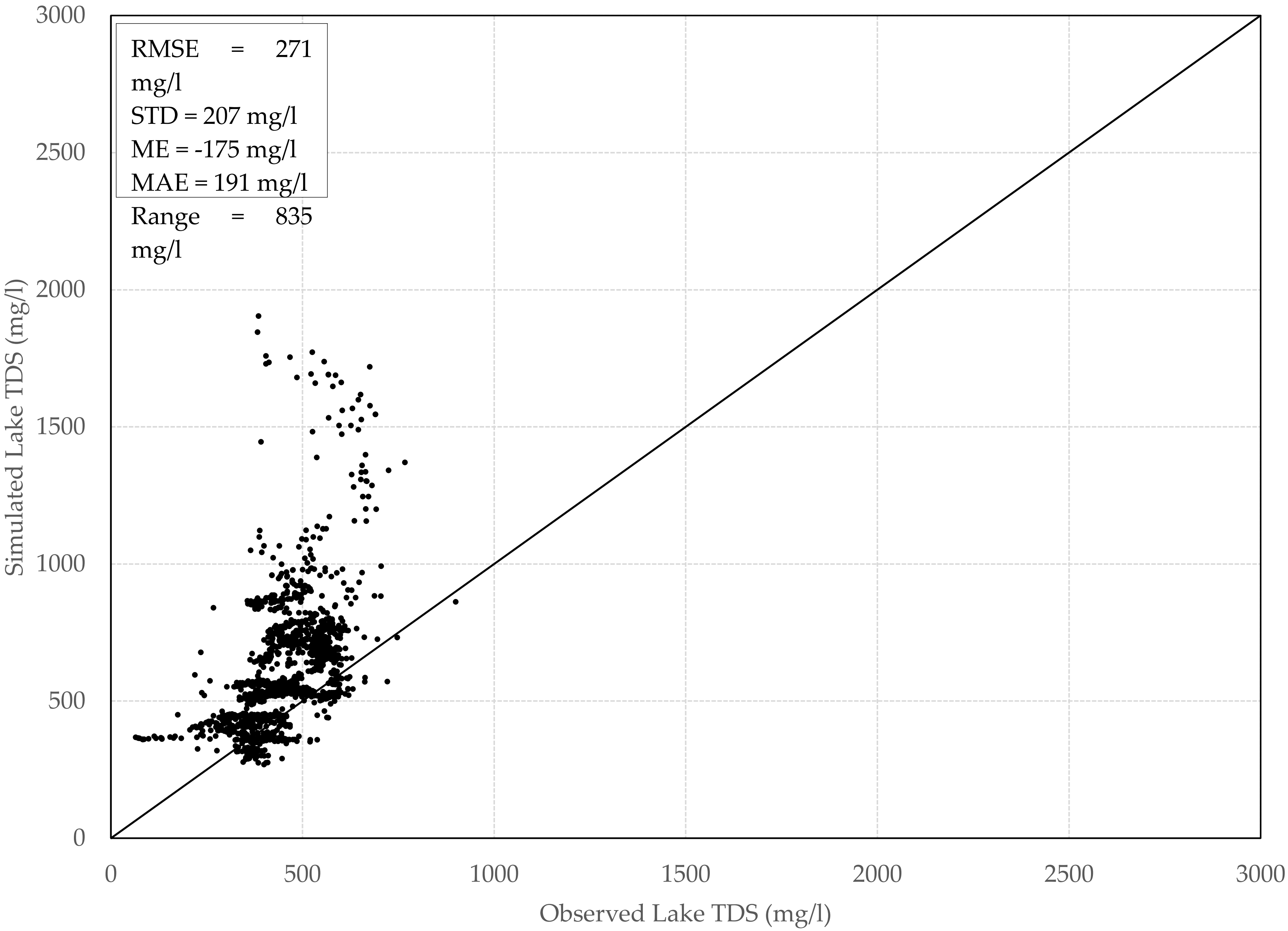


Figure 104: Simulated versus Observed Lake TDS Concentrations

4.6 SIMULATED WATER BUDGET FOR CALIBRATED MODEL

Water budget components simulated by the calibrated model were compared to Zone 7's hydrologic inventory. Table 13, and Figure 105 through Figure 109 show these comparisons of water budget by water year. Figure 105 and Figure 106 show the model simulates pumping and areal recharge that matches the hydrologic inventory.

Figure 107 and Figure 108 shows lake and stream water budgets with hydrologic inventory components for lakes and streams. However, the model simulates flows from lakes and to streams that are not included in the hydrologic inventory. These are transfers from lakes to streams that Zone 7 estimates as groundwater recharge in streams. These flows are not included in the hydrologic inventory because it is considered groundwater to groundwater transfer. The lake to stream transfer estimated to recharge groundwater are added to hydrologic inventory components to model results.

Upgrading the model to simulate lake levels allows for calculating lake losses based on groundwater levels. Figure 107 shows modeled lake losses generally follow the pattern of Zone 7 estimates, but are higher overall. However, the lake losses do not show the same variation observed in some hydrologic periods: most notably from 2002-2014. This reflects the model simulating smaller than observed groundwater level fluctuations in some areas of the basin.

Figure 108 also shows modeled stream recharge that follows the overall pattern of Zone 7 estimates but does not match the fluctuation range for a number of periods. In this basin, stream recharge is mostly independent of groundwater levels so increasing the fluctuation of stream recharge should be evaluated to better match the fluctuation of groundwater levels.

Figure 109 shows storage variations that are smaller in the model results than in the hydrologic inventory. This is likely related to less accuracy in groundwater level calibration discussed in Section 4.5.1. These differences may necessitate future assessment of assumptions for lake and stream water budgets and led to simplifying assumptions for lake and stream water budget in the simulations discussed in Section 5.

4.7 SIMULATED SALT BALANCE FOR CALIBRATED MODEL

Cumulative salt loading simulated by the calibrated model were compared to Zone 7's hydrologic inventory estimates of salt loading as shown in Figure 110. Figure 110 shows that simulated salt loading matches the trend of Zone 7's estimates while estimating higher mass in the system. This shows that the model is an appropriate tool for evaluating effects of salt management projects on salt mass in the basin.

Table 13. Modeled Water Budget Components Compared to Hydrologic Inventory

Acre Feet		1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Annual Change in Storage	Hydrologic Inventory	-452	5,535	-4,280	-5,917	11,983	6,440	8,154	-473	11,653	9,258	-4,133	-9,647	-1,602	-7,817	-9,011
	Model	3,261	5,394	-3,510	-4,879	11,329	5,662	6,099	1,007	9,028	7,913	-5,549	-7,119	11	-8,161	-6,912
Annual Total Pumping	Hydrologic Inventory	16,250	12,798	13,078	12,391	10,913	12,618	10,310	10,494	9,276	10,007	10,729	10,604	11,263	10,322	11,607
	Model	15,654	12,262	12,158	11,517	10,344	12,022	9,635	9,940	8,731	9,542	10,273	10,628	11,475	10,418	11,822
Annual Aerial Recharge	Hydrologic Inventory	5,825	5,064	3,233	3,109	7,294	5,159	6,750	3,206	12,952	17,890	5,480	3,363	11,163	2,423	2,696
	Model	4,784	3,820	2,337	2,334	6,338	3,943	5,411	3,036	12,908	17,581	5,205	3,058	10,556	2,419	2,709
Annual Stream Recharge	Hydrologic Inventory (HI)	11,340	15,400	6,910	3,820	16,330	16,110	16,480	15,040	16,420	17,158	9,486	4,747	9,045	3,565	4,549
	HI+ Recharged Lake Transfer to Stream	12,465	16,349	7,662	3,969	16,852	16,650	17,404	15,732	17,396	20,069	11,633	6,536	11,857	6,339	8,033
	Model	18,716	21,058	12,040	7,802	22,107	21,309	19,196	17,608	15,882	12,611	9,647	8,656	12,196	7,564	8,344
Annual Lake Net Loss	Hydrologic Inventory (HI)	-2,368	-3,131	-2,354	-2,245	-1,958	-3,051	-4,886	-8,305	-6,913	-13,253	-6,781	-6,702	-10,687	-3,653	-5,169
	HI - Recharged Lake Transfer to Stream	-3,493	-4,080	-3,107	-2,394	-2,480	-3,591	-5,810	-8,997	-7,889	-16,164	-8,928	-8,491	-13,498	-6,427	-8,653
	Model	-6,445	-8,580	-7,772	-5,808	-8,091	-8,808	-9,620	-10,265	-11,535	-13,270	-10,789	-9,070	-12,338	-9,159	-7,741

Acre Feet		1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Annual Change in Storage	Hydrologic Inventory	-4,873	-5,469	-8,451	-6,510	15,097	721	13,166	2,015	-1,242	2,015	-4,750	-3,506	-11,326	249	8,492
	Model	-2,187	-4,865	-6,214	-3,243	17,074	3,562	11,805	2,562	-180	-166	-2,681	-2,395	-6,760	279	2,404
Annual Total Pumping	Hydrologic Inventory	12,259	13,315	18,611	14,386	10,045	7,417	5,444	7,236	9,790	11,037	11,089	15,305	18,733	19,897	17,766
	Model	12,340	13,534	18,554	14,432	8,503	6,188	5,504	7,361	9,934	11,639	11,775	17,140	18,988	20,118	17,915
Annual Aerial Recharge	Hydrologic Inventory	2,230	2,172	2,800	3,910	12,609	3,296	15,182	10,669	11,369	12,943	7,855	8,486	6,263	7,035	7,540
	Model	2,213	2,070	2,876	3,963	12,626	3,306	15,609	10,776	11,735	12,766	7,885	8,561	6,321	7,238	7,711
Annual Stream Recharge	Hydrologic Inventory (HI)	7,880	7,026	8,347	5,247	14,714	11,838	13,058	11,109	12,284	13,603	10,813	12,842	8,768	16,205	21,483
	HI+ Recharged Lake Transfer to Stream	11,078	9,758	11,336	8,020	17,612	15,354	17,141	16,328	16,438	16,996	15,398	17,181	12,144	16,456	21,483
	Model	13,233	11,596	13,735	11,836	23,398	19,481	17,893	15,769	15,902	14,952	15,895	18,133	15,149	18,525	18,946
Annual Lake Net Loss	Hydrologic Inventory (HI)	-3,784	-2,612	-2,667	-2,851	-3,510	-8,086	-10,420	-12,681	-15,024	-13,555	-12,716	-10,310	-8,624	-4,094	-3,764
	HI - Recharged Lake Transfer to Stream	-6,983	-5,344	-5,656	-5,624	-6,409	-11,601	-14,503	-17,900	-19,178	-16,948	-17,301	-14,649	-12,000	-4,345	-3,764
	Model	-7,075	-6,740	-6,152	-6,439	-11,891	-14,341	-17,524	-18,005	-19,544	-18,148	-16,566	-13,949	-11,329	-7,442	-8,255

Acre Feet		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Annual Change in Storage	Hydrologic Inventory	-4,372	13,387	8,990	-3,433	-2,799	-4,779	4,515	7,124	-10,201	-5,299	-11,937
	Model	-1,725	6,612	5,858	-1,521	-875	-473	3,022	4,328	-4,308	-486	-8,131
Annual Total Pumping	Hydrologic Inventory	20,414	15,474	12,485	13,469	14,312	18,817	16,858	14,215	21,258	18,010	18,003
	Model	20,294	15,621	12,665	13,618	14,549	18,992	17,098	14,410	21,610	18,284	18,301
Annual Aerial Recharge	Hydrologic Inventory	6,081	9,190	9,742	5,050	7,022	6,629	7,463	8,950	4,945	5,944	3,849
	Model	6,190	9,305	9,967	5,126	7,183	6,718	7,598	9,118	5,107	6,111	4,508
Annual Stream Recharge	Hydrologic Inventory (HI)	12,885	21,025	13,418	9,154	8,448	11,249	17,144	17,595	12,734	13,457	5,819
	HI+ Recharged Lake Transfer to Stream	13,023	20,875	15,002	9,940	9,587	12,377	18,717	20,434	14,521	15,716	6,229
	Model	16,182	18,474	15,364	11,889	10,756	13,866	16,449	15,665	15,083	16,348	8,751
Annual Lake Net Loss	Hydrologic Inventory (HI)	-3,924	-2,355	-2,685	-4,247	-3,752	-4,646	-4,234	-6,206	-7,622	-7,691	-4,602
	HI - Recharged Lake Transfer to Stream	-4,062	-2,205	-4,268	-5,032	-4,891	-5,774	-5,807	-9,045	-9,409	-9,950	-5,012
	Model	-5,748	-7,322	-8,356	-6,403	-5,765	-3,658	-5,562	-7,562	-4,511	-6,288	-4,949

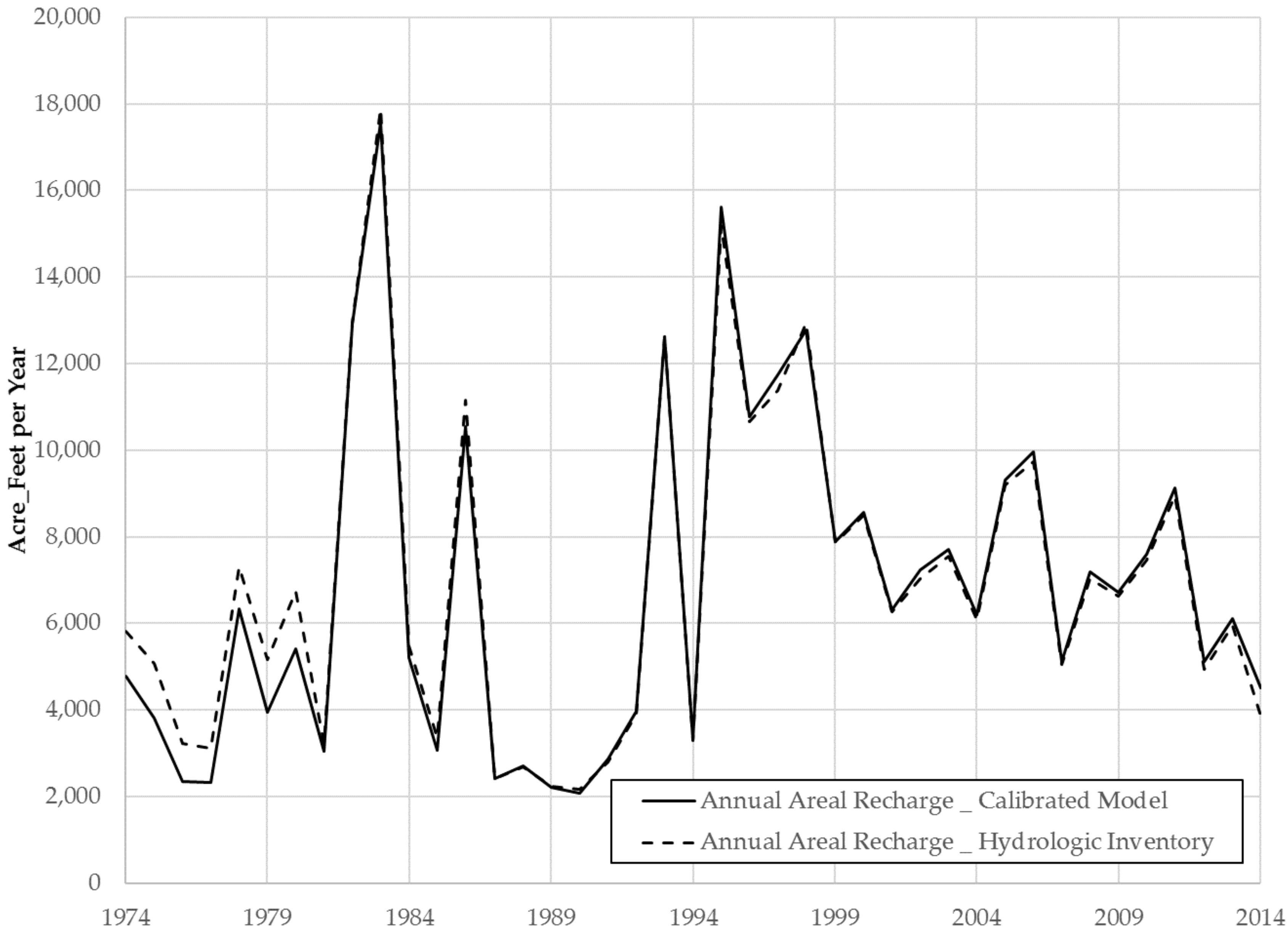


Figure 105: Model Water Budget and Hydrologic Inventory for Annual Areal Recharge

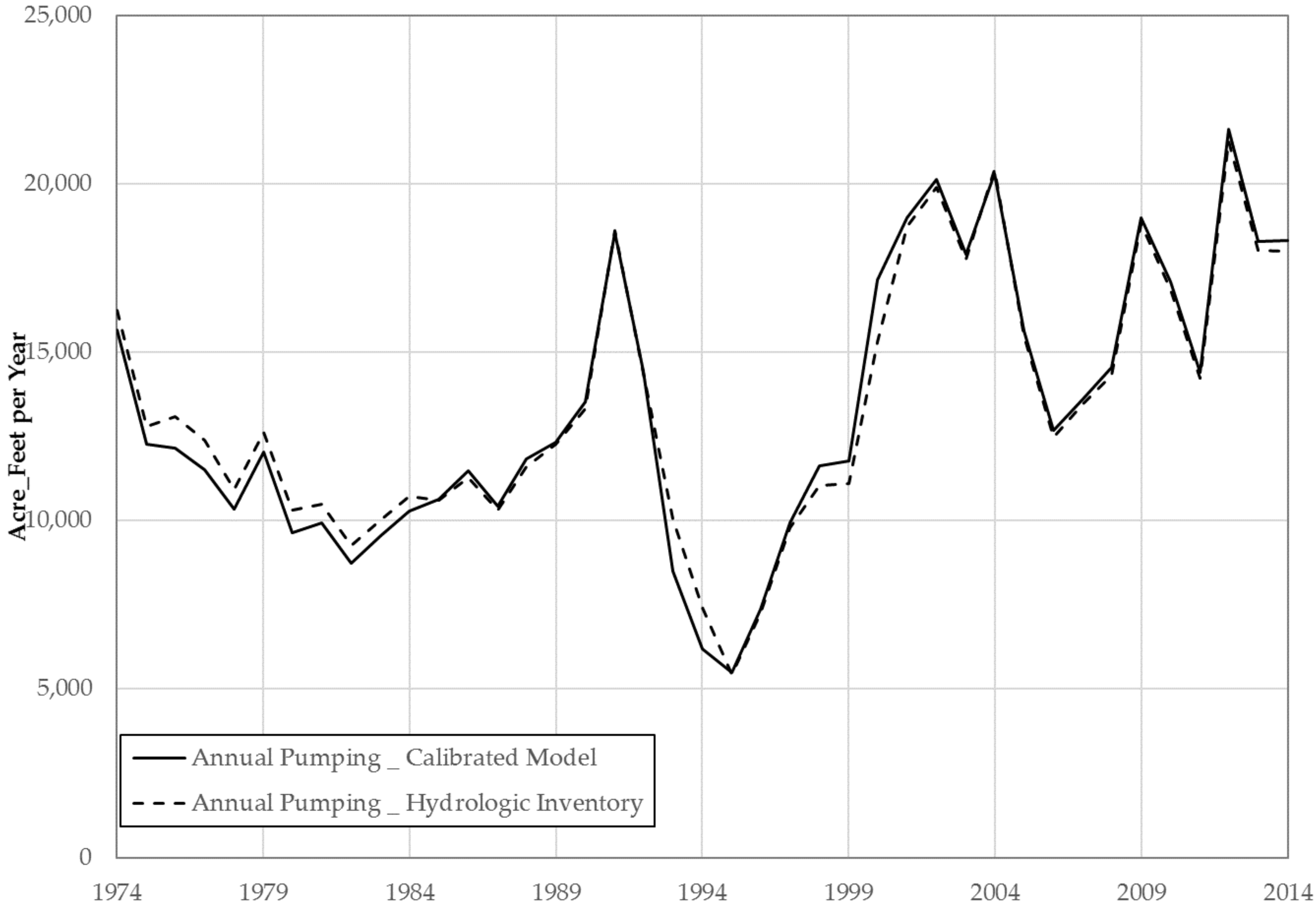


Figure 106: Model Water Budget and Hydrologic Inventory for Annual Pumping

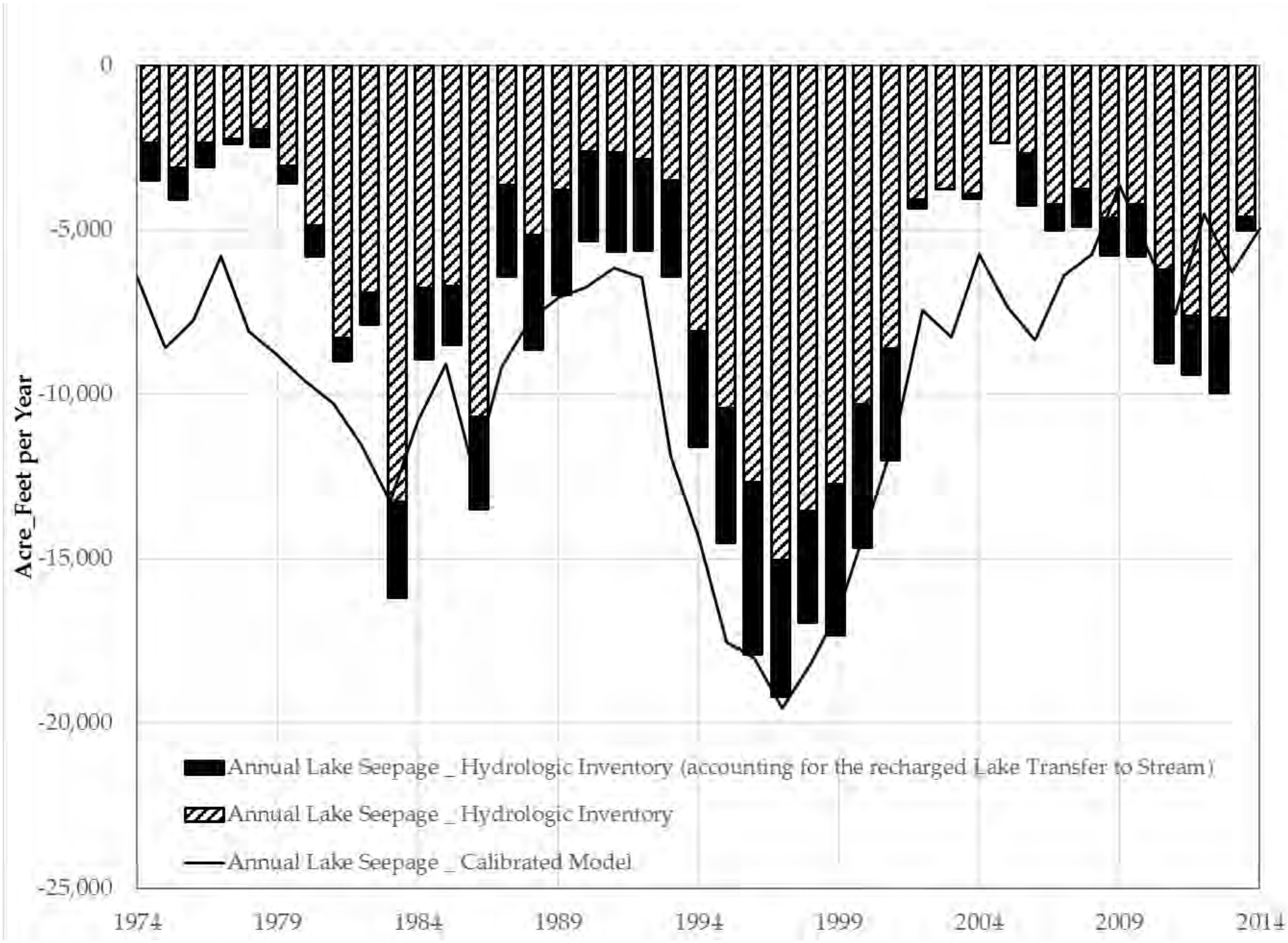


Figure 107: Model Water Budget for Annual Lake Seepage

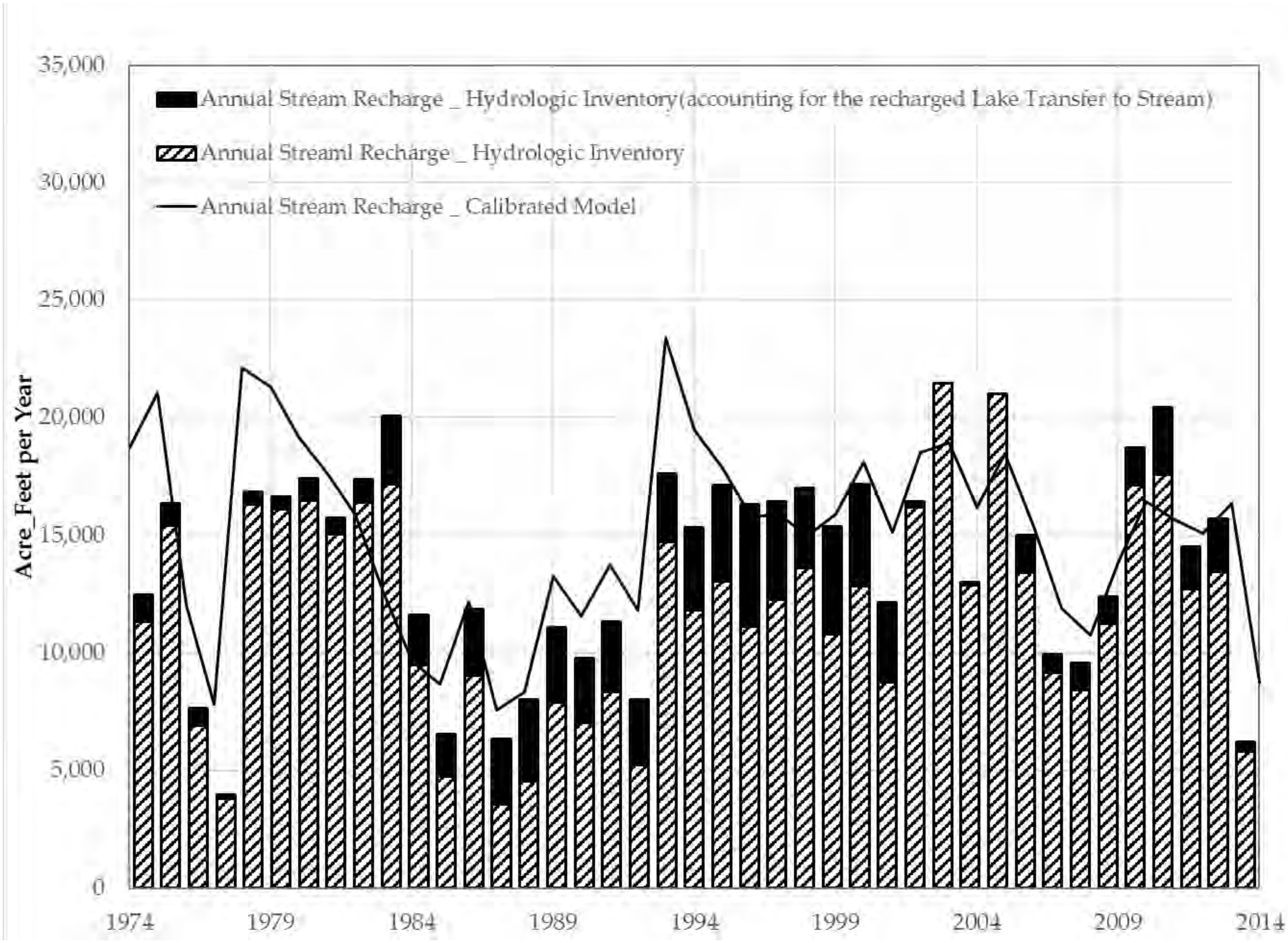


Figure 108: Model Water Budget and Hydrologic Inventory for Annual Stream Recharge

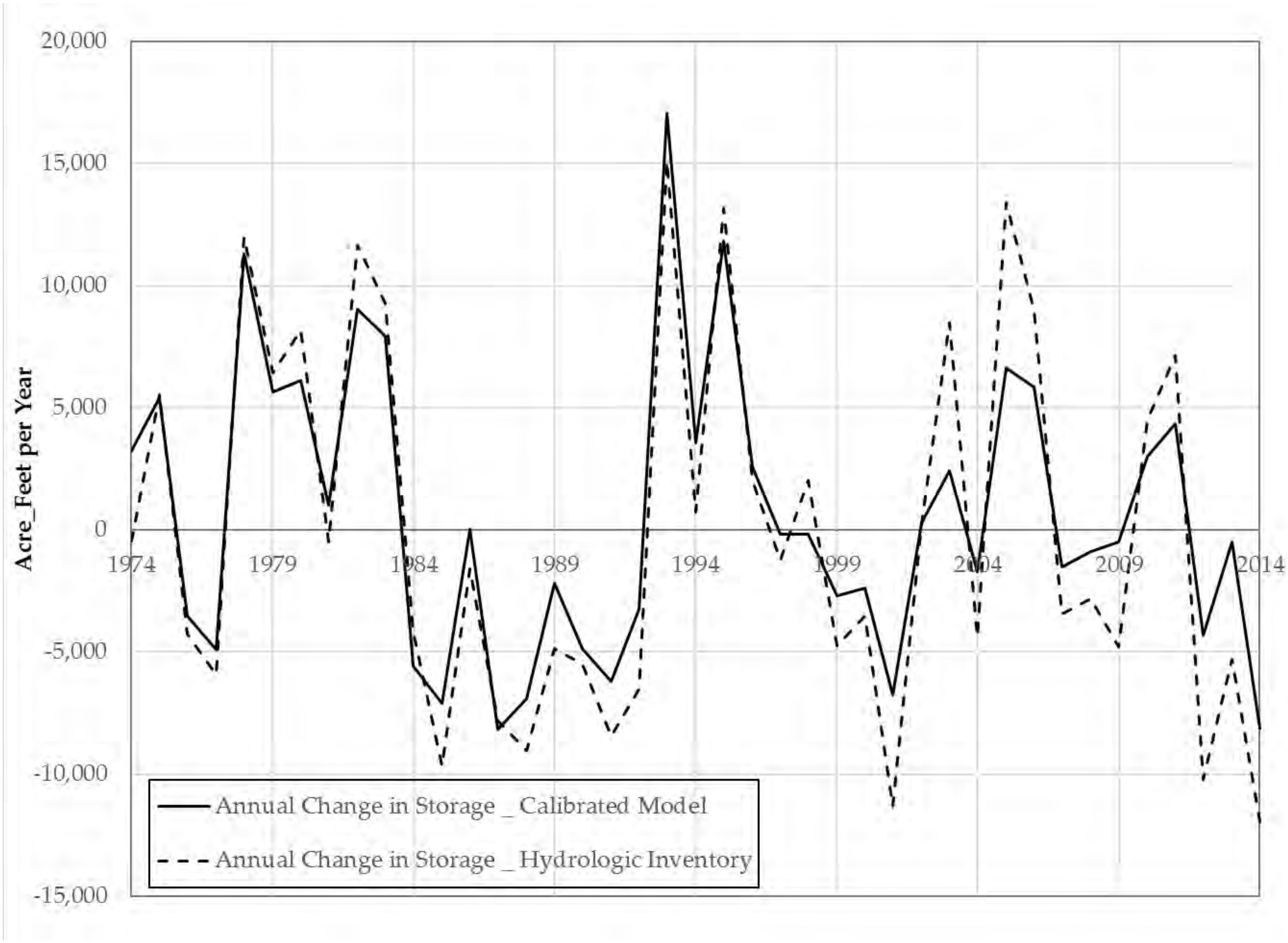


Figure 109: Model Water Budget and Hydrologic Inventory for Annual Storage

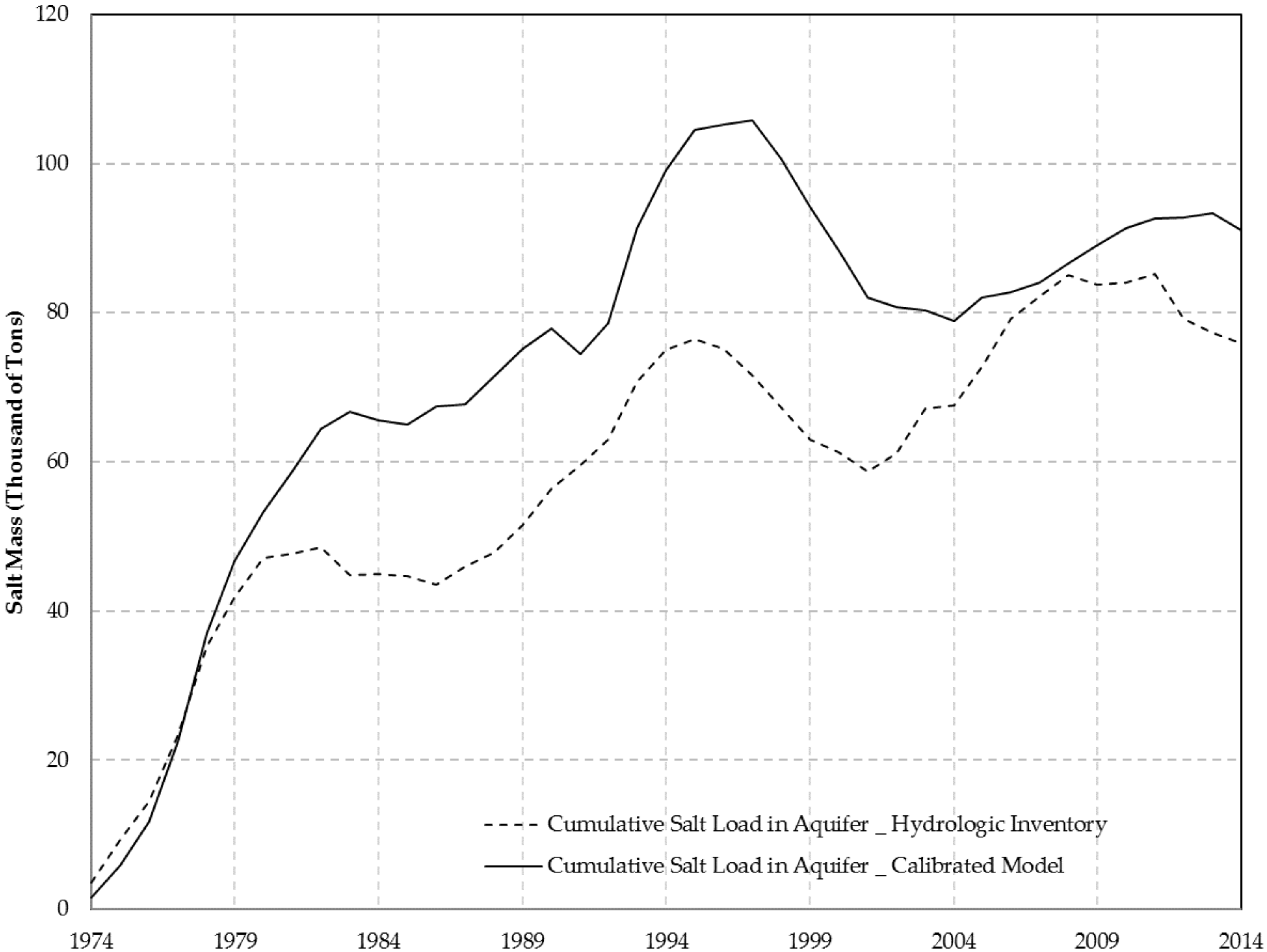


Figure 110: Model and Hydrologic Inventory Cumulative Salt Loading

4.8 MODEL RECOMMENDED USES AND LIMITATIONS

The Livermore Valley Groundwater Model is designed and calibrated to simulate the surface-water and groundwater interaction for the evaluation of groundwater conditions under various groundwater and salt management alternatives. The main use of flow model results is to evaluate groundwater levels throughout the Main Basin (Mocho II, Amador, and Bernal Sub-basins) for changes in hydrology affecting areal recharge and stream inflows as well as pumping. As discussed, the model does not simulate the range of fluctuations in groundwater levels in some areas of the basin. Therefore, evaluations of drought or wet period simulations should consider this calibration error.

The main use of the transport model is to evaluate salt balance and groundwater TDS concentration trends for whole sub-basins and vertically through identified hydrostratigraphic layers, for various and salt management alternatives. However, the transport model should not be used to predict produced groundwater TDS concentrations for specific wells. Localized sources of salt that are not included in the model, may result in actual concentrations being substantially different from model results.

Use of surface water results from the model should also be limited. Addition of the SFR stream and LAK lake packages allows the model to calculate groundwater head dependent flows from the surface water to groundwater, but assumptions for lake and stream water budget components may need to be re-evaluated as discussed in Section 4.9. Until that re-evaluation is performed, simplifying assumptions for these surface water budget components are recommended for groundwater and salt management simulations. In addition, the model should not be used to simulate more active usage of the lakes as recharge facilities than what has occurred historically until maximum lake stage is better defined as discussed in Section 2.9.

Model results for streamflows at specific locations or stages in specific lakes should not be used for management purposes. Similarly, the implementation of the newly developed SFT stream and LKT lake transport packages allow simulation of salt to be transported to various areas of the groundwater basin, but salt concentrations at specific stream and lake locations likely depend on localized conditions not simulated by the model.

The LAK and LKT packages were implemented with the plan to use the model to evaluate groundwater and salt management alternatives involving the planned Chain of Lakes. The model can be used to evaluate sub-basin scale effects of these alternatives, but operational planning for use of specific lakes will likely require additional calibration with data that better define transfers to and from specific lakes.

4.9 Suggestions for Additional Calibration

As discussed above, the groundwater model satisfactorily simulates the general groundwater levels in the basin, and trends observed in monitoring well data, indicating that groundwater system is well represented by the model's structural upgrades including layer refinements and addition of interactive surface water features. However, the model does not accurately simulate the full range of fluctuations in groundwater levels at a number of monitoring wells, which limits its use for predictions of short-term droughts or very wet period impacts.

One future refinement that may facilitate better simulation of groundwater level fluctuations over time is changing implementation of the MODFLOW stream (SFR1) package. Stream recharge is a major component of the basin's water budget that is relatively independent of groundwater levels and the model appears to simulate average stream recharge over time accurately; however, the model does not simulate the full range of stream recharge fluctuations estimated by the hydrologic inventory. This suggests that further calibration of stream recharge fluctuations, while generally maintaining stream recharge average may improve simulation of groundwater levels.

However, the model is currently limited in its ability to increase fluctuations of stream recharge. As a reflection of this limitation, the model simulates streams as drying out during times when low streamflows are observed. During these low flow periods, the model simulates that all streamflows become groundwater recharge, when in reality recharge may be reduced at these low flows such that some flow is maintained in the streams. The SFR1 package is set up in the model with constant stream widths across all stages and streamflows of the rating curve. Varying the stream widths with stages could reduce recharge during low flows and increase recharge during high flows, resulting in greater fluctuation of stream recharge.

Another calculation that may affect the ability of the model to increase streamflow fluctuation is the calculation of runoff. Runoff is calculated as a function of hydrologic inventory estimates for stream recharge (Section 2.8.4). Using a calculation of historical runoff independent of estimates of stream recharge would allow the model to provide independent estimates of stream recharge if the model is well calibrated to groundwater levels and streamflows.

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SECTION 5
GROUNDWATER AND SALT MANAGEMENT SIMULATIONS

The calibrated model was used to run four simulations that will help Zone 7 with setting groundwater resource planning criteria and managing the salt balance in the basin. Three alternative simulations are compared to a baseline scenario that simulates the average monthly conditions of the calibrated model (Water Years 1974-2014). The simulations are conducted for 10 years (Water Years 2016-2025) in monthly stress periods. The simulations are designed to be simple, relevant to current conditions, and evaluate both pumping plans and salt management. The four simulations are:

1. **Baseline Simulation**: This simulation simulates average monthly hydrologic conditions and will be used to assess medium-term sustainability of current pumping and for comparison with the alternative simulations below.

2. **1 Year Drought Optimization Simulations**: This simulation is designed to estimate the maximum volume Zone 7 can pump during a worst-case one year drought occurring in Water Year 2017. Multiple iterations of this simulation were run to maximize pumping provided that groundwater levels do not drop below historic lows in the Amador and Bernal Sub-basins. The results will be used in Zone 7's Water Supply Evaluation currently in progress.

3. **6 Year Drought Simulation**: This scenario is designed to evaluate Zone 7's pumping plans during a six year drought starting from Water Year 2017. The results will be used to plan for future extended drought.

4. **No Groundwater Demineralization Simulation:** This scenario is designed to evaluate the effectiveness of the Mocho Groundwater Demineralization Plant operations on the Basin's salt balance. This is implemented by increasing the TDS concentration of applied municipal water throughout the basin in a MT3D transport run based on the simulated baseline flow conditions.

Simulation assumptions are outlined in the following section followed by presentation of groundwater elevations and TDS concentration results for each simulation scenario. The simulations differ in assumed hydrology, pumping, and demineralization. Hydrology changes affect areal recharge and concentrations, headwater stream inflows and concentrations, runoff into streams, evaporation and rainfall at lakes. Demineralization changes are reflected in areal recharge concentrations unrelated to hydrology. Other model inputs such as initial conditions, land use, surface water transfers are the same across all simulations.

5.1 Simulation Assumptions

5.1.1 Initial Conditions

Initial heads are based on a steady-state flow simulation using specified heads representing Fall 2015 observed groundwater levels. As discussed for the calibration run in Section 2.4, this allows the transient run to start from heads that are consistent with the model as well as observations. Figure 111-Figure 112 show the groundwater levels used as specified heads in the steady state run to create initial conditions for all simulations as applied to the upper aquifer layers 2 and 4 and the lower aquifer layers 6, 8, and 10.

Initial TDS concentrations are based on a raster coverages of salt concentrations representing Fall 2015 provided by Zone 7 for the upper aquifer (Layers 1-4), and aquitard and lower aquifer (Layers 5-10). Figure 113 and Figure 114 show the initial TDS concentrations used for all simulations.

5.1.2 Land Use Assumed for Areal Recharge

In calculating areal recharge for all simulations, Zone 7 assumed 2015 land use is constant for the whole simulation period.

5.1.3 Surface Water Transfers

Unlike the calibration model where surface water transfers are simulated as discussed in Section 2.10, there are assumed to be no lake to lake or lake to stream transfers for all simulations.

5.1.4 Hydrology

Hydrology affects model inputs for areal recharge, headwater stream inflows, runoff into streams, and evaporation and rainfall at lakes. Headwater stream inflows include both natural streamflows and artificial streamflows provided by Zone 7.

- The Baseline Simulation assumes average monthly hydrology for the entire 10 year (Water Years 2016-2025) simulation period. Zone 7 estimated artificial streamflows as the amount needed to meet pumping demand.

- The 1 Year Drought Optimization Simulation assumes average monthly hydrology for year 1 (Water Year 2016) and years 3-10 (Water Years 2018-2025). Year 2 (Water Year 2017) is assumed to have drought hydrology based on Water Year 2014. Zone 7 estimated artificial streamflows based on worst-case estimates of artificial supply availability.
- The 6 Year Drought Simulation assumes average monthly hydrology for Year 1 (Water Year 2016) and Years 8-10 (Water Years 2023-2025). Years 2-7 (Water Years 2017-2022) are assumed to have drought hydrology identical to the 1 Year Drought Optimization Simulation.
- The No Groundwater Demineralization Simulation assumes the same hydrology as the Baseline Simulation

Figure 115 shows annual areal recharge for water years with average hydrology. *Figure 116* shows annual areal recharge for water years with drought hydrology.

Figure 117 shows monthly inflow at headwater segments for the three flow simulations. Figure 118 shows monthly runoff into streams for the three flow simulations.

Figure 119 and Figure 120 show the evaporation and rainfall rates assumed for all lakes for the three flow simulations.

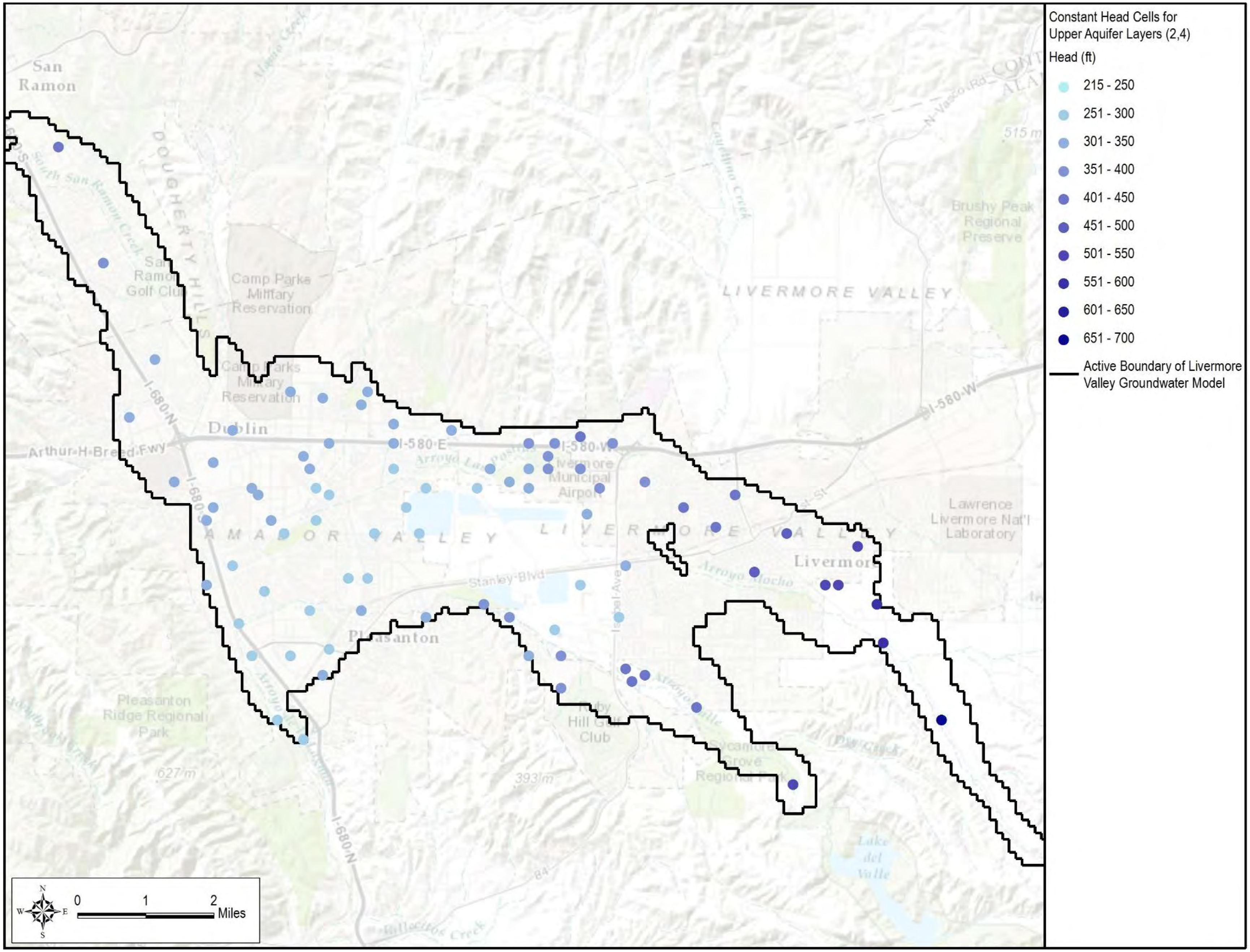

Figure 111: Constant Head Cells in Upper Aquifer Layers (2 &4)

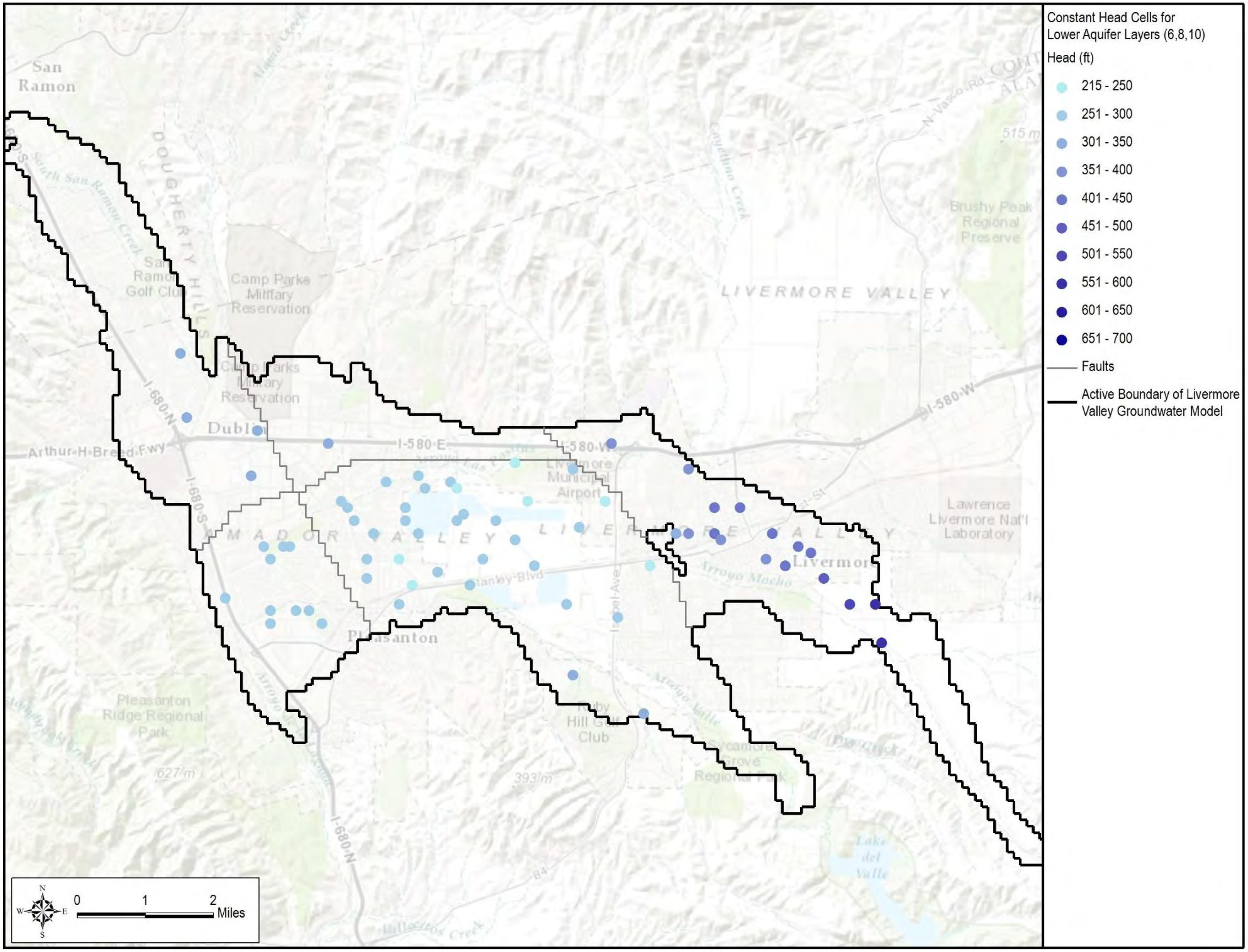

Figure 112: Constant Head Cells in Lower Aquifer Layers (6, 8 & 10)

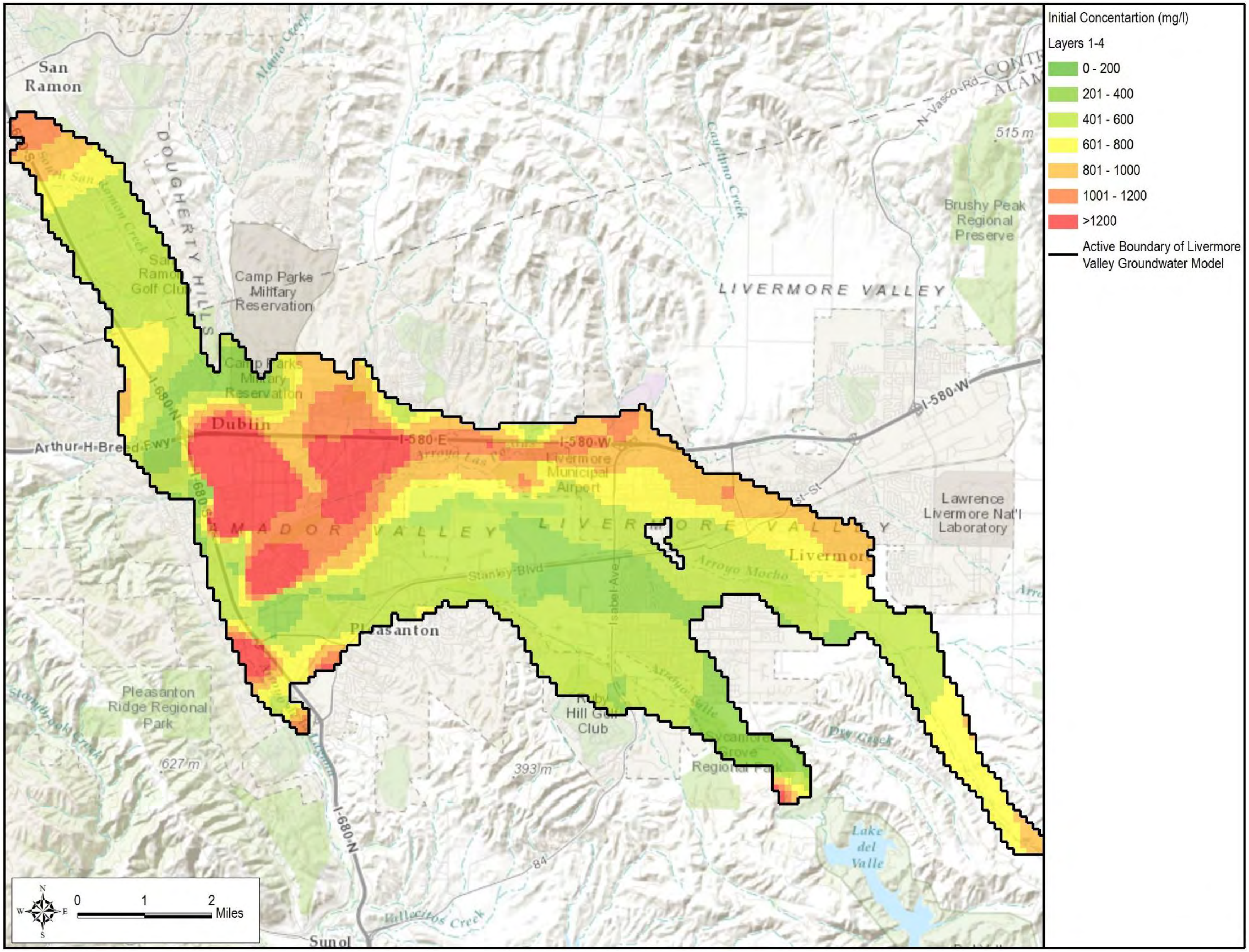

Figure 113: Initial Concentration in Layers 1 through 4 in the Livermore Valley Groundwater Basin

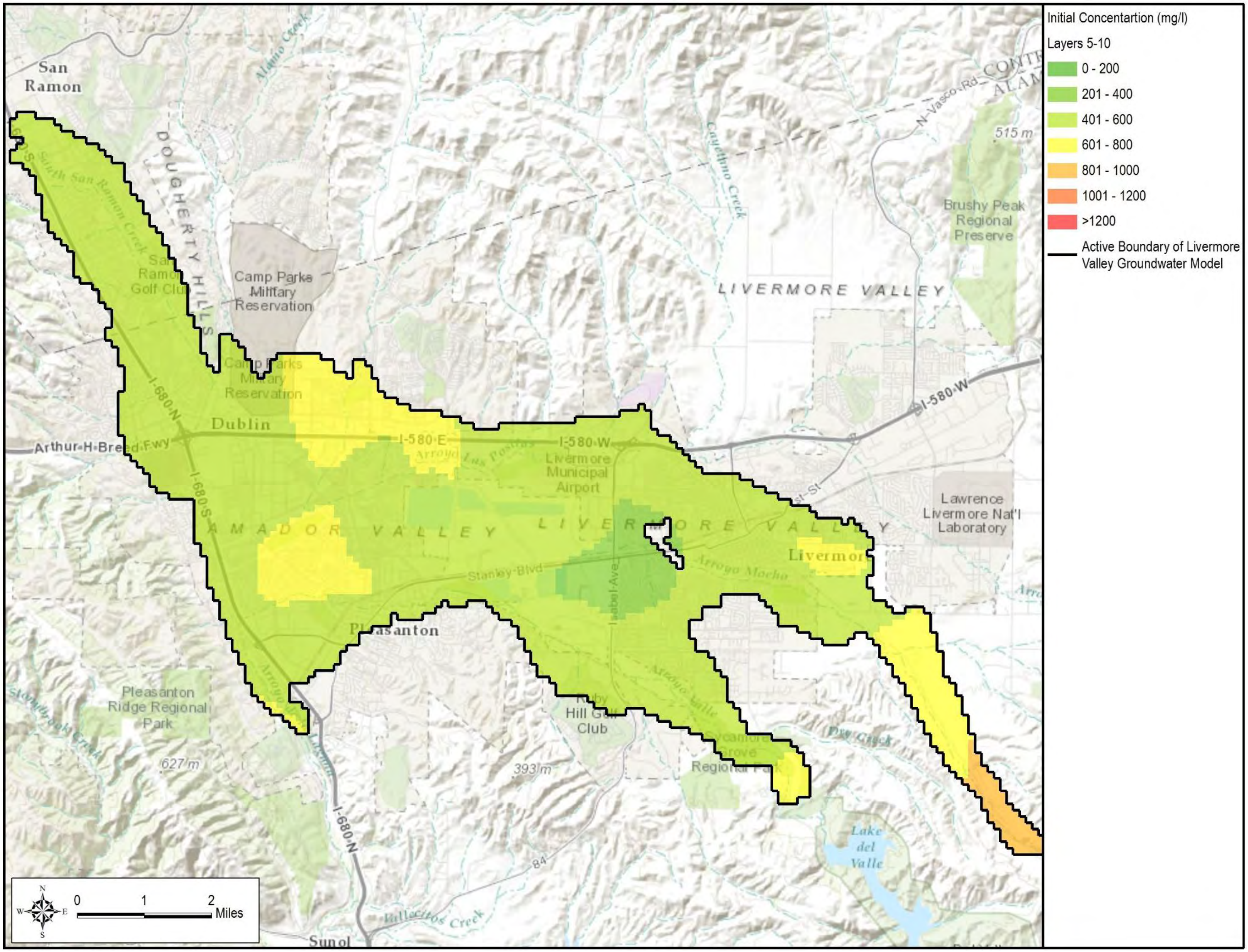

Figure 114: Initial Concentration in Layers 5 through 10 in the Livermore Valley Groundwater Basin

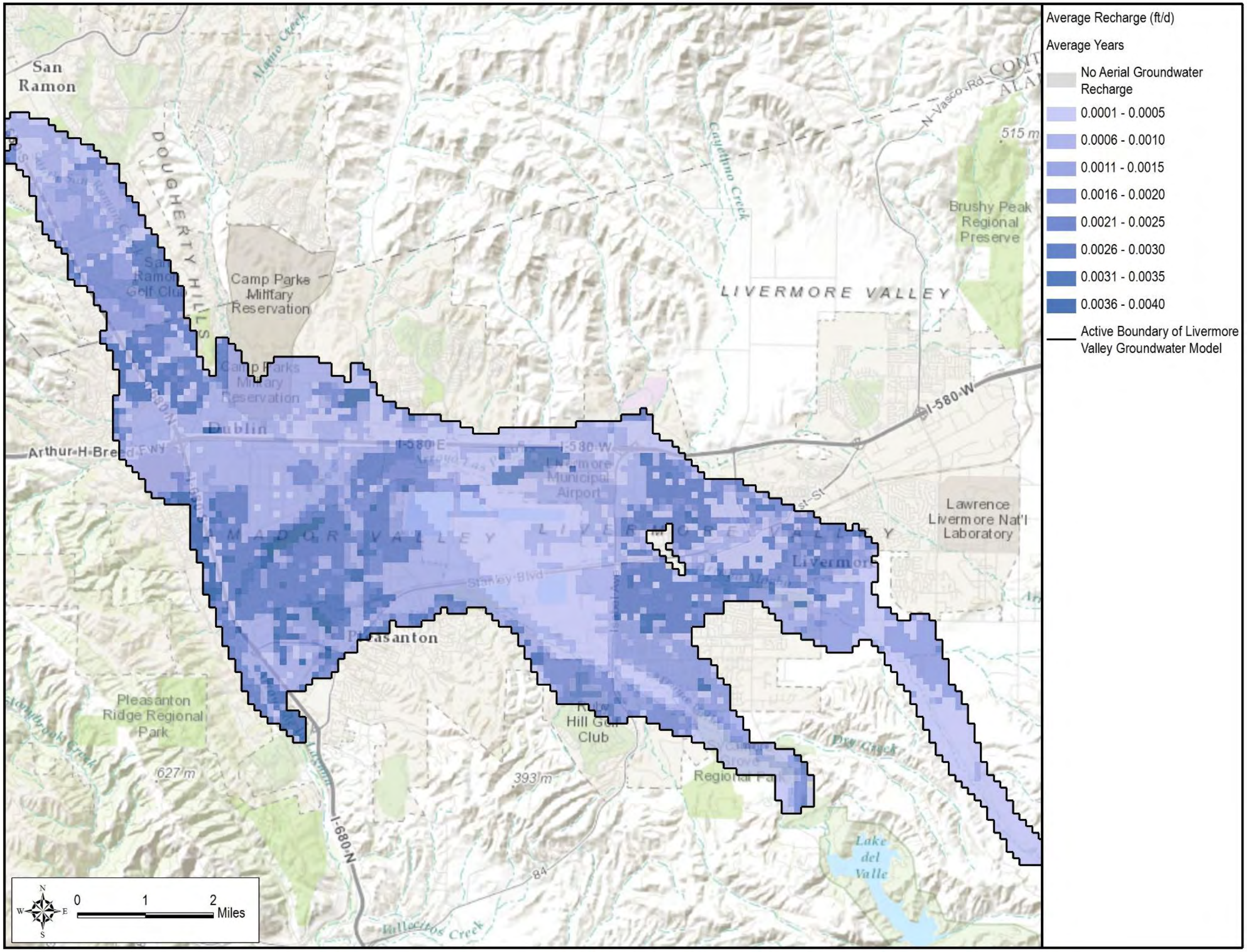

Figure 115: Average Areal Recharge in the Livermore Valley Groundwater Basin for the Average Simulation Years

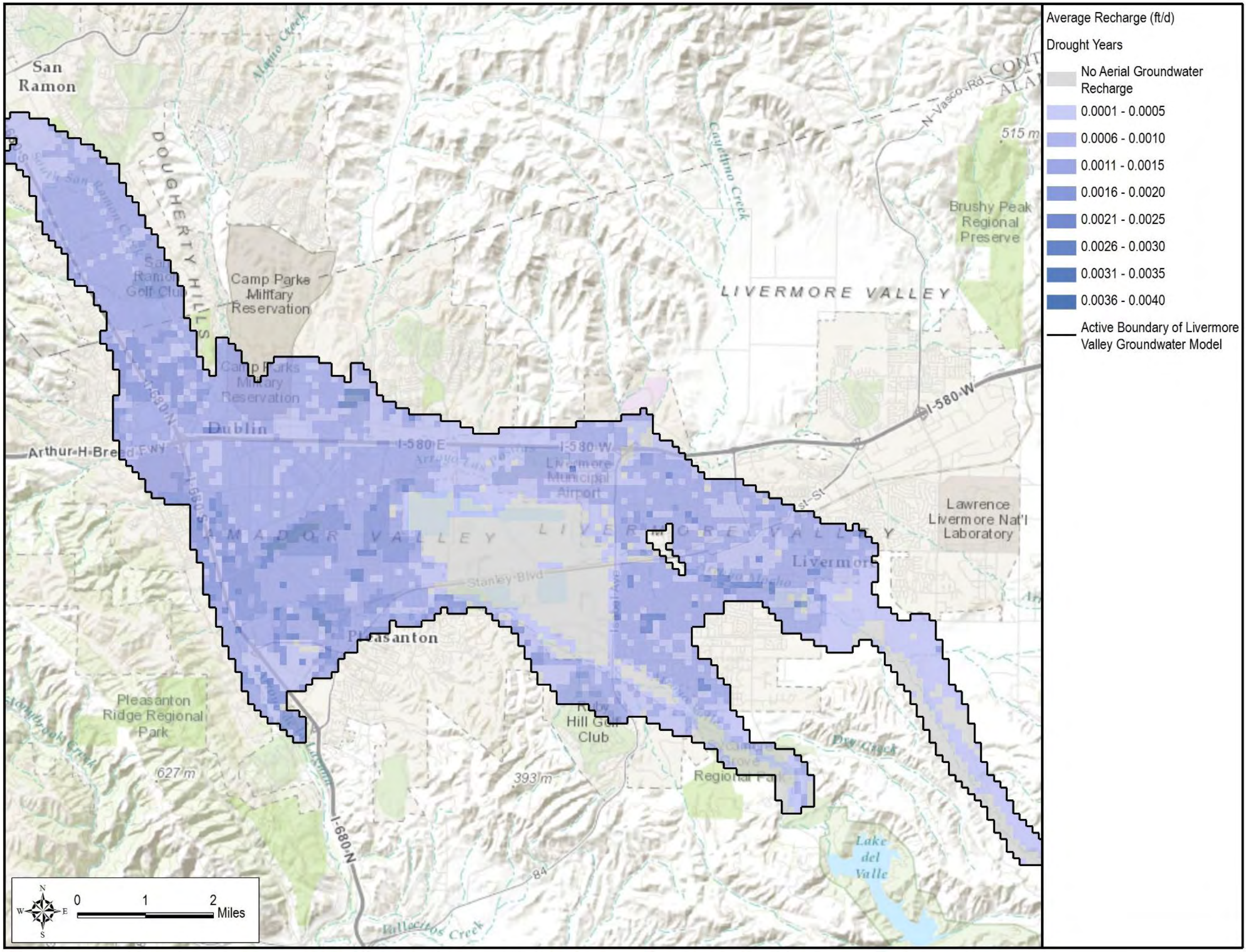

Figure 116: Average Areal Recharge in the Livermore Valley Groundwater Basin for the Drought Simulation Years

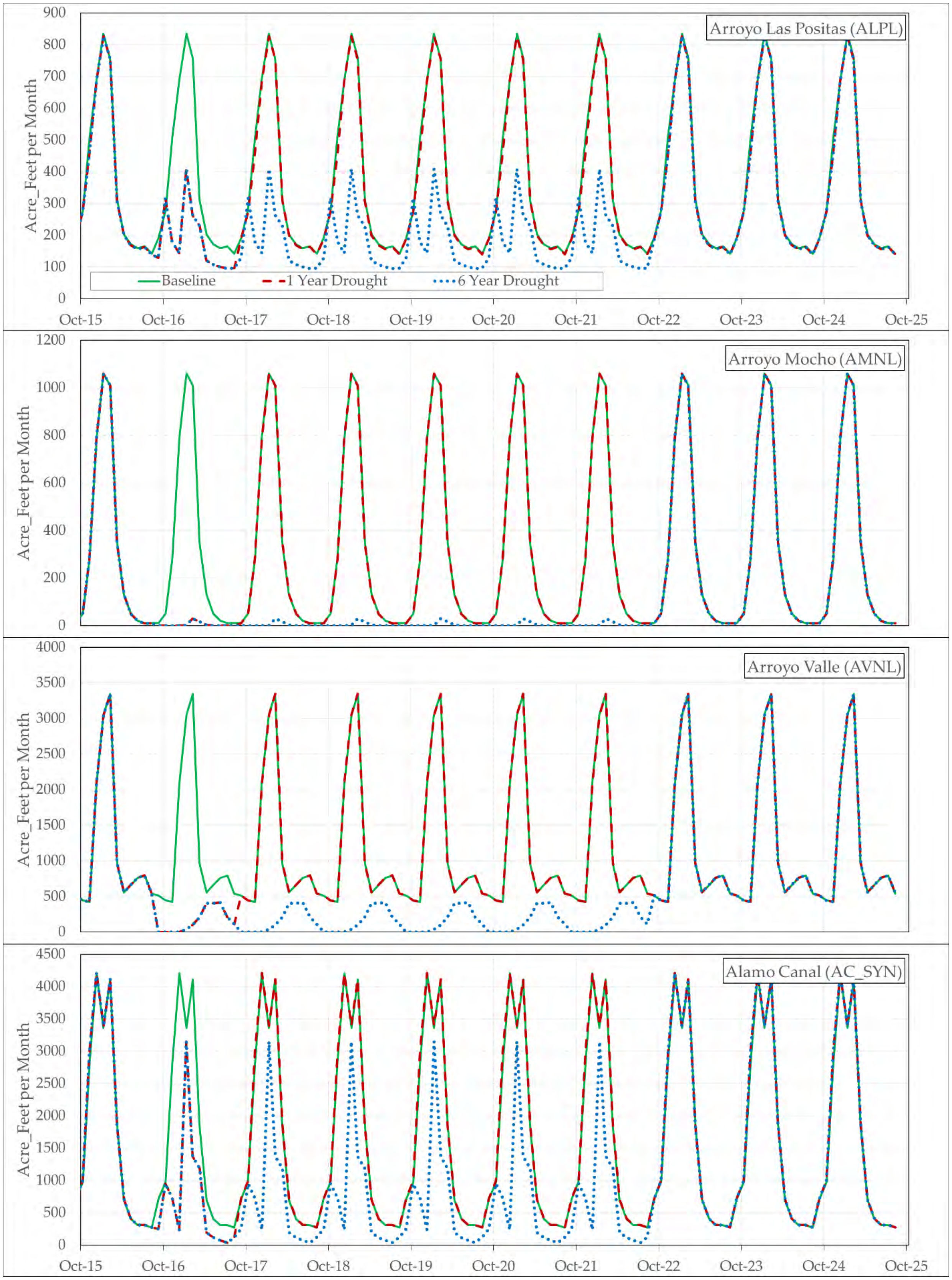

Figure 117: Monthly Inflow at Headwater Stations for Management Simulations

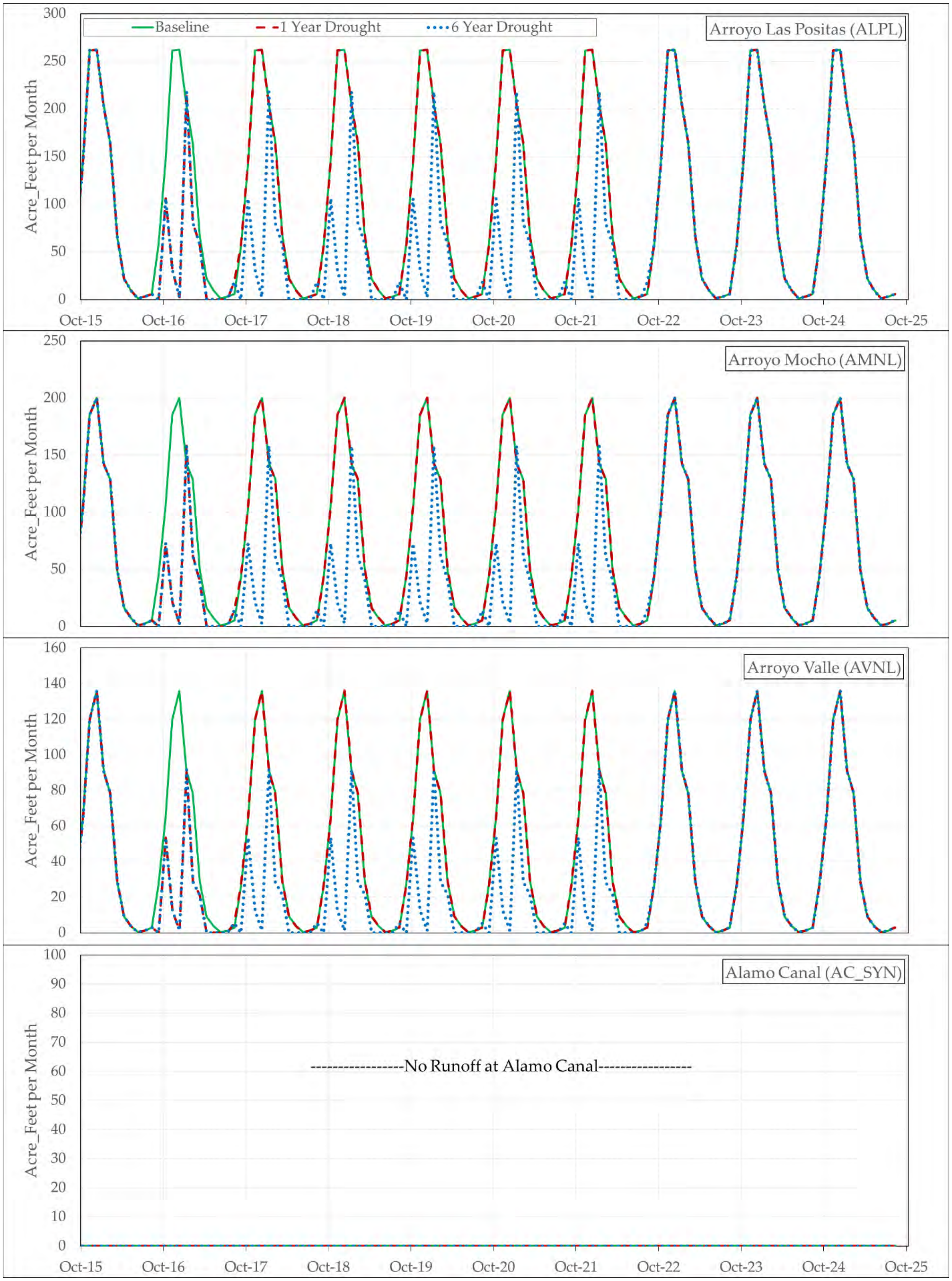

Figure 118: Monthly Runoff on the Arroyos for Management Simulations

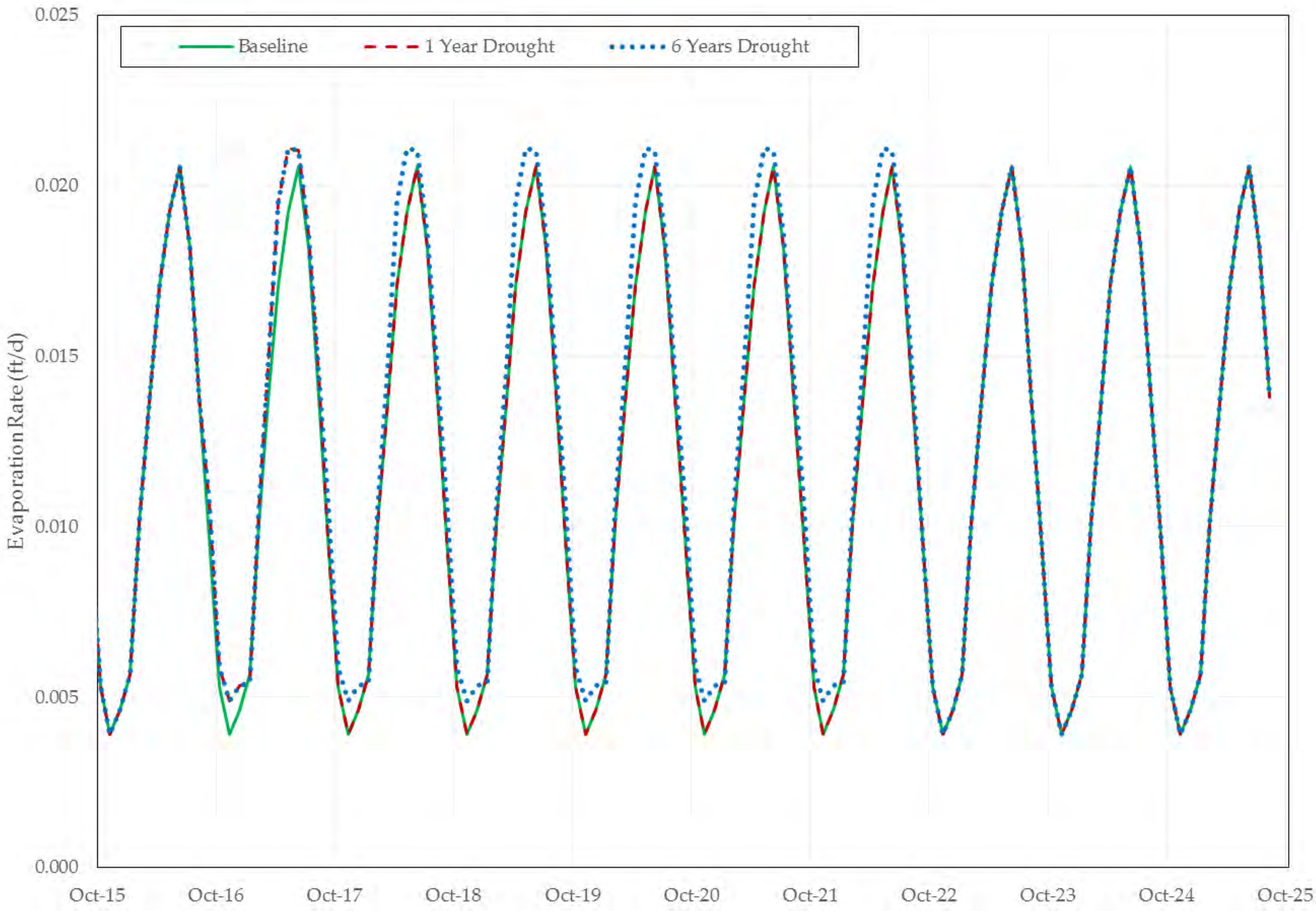

Figure 119: Evaporation Rate of Lakes for Management Simulations

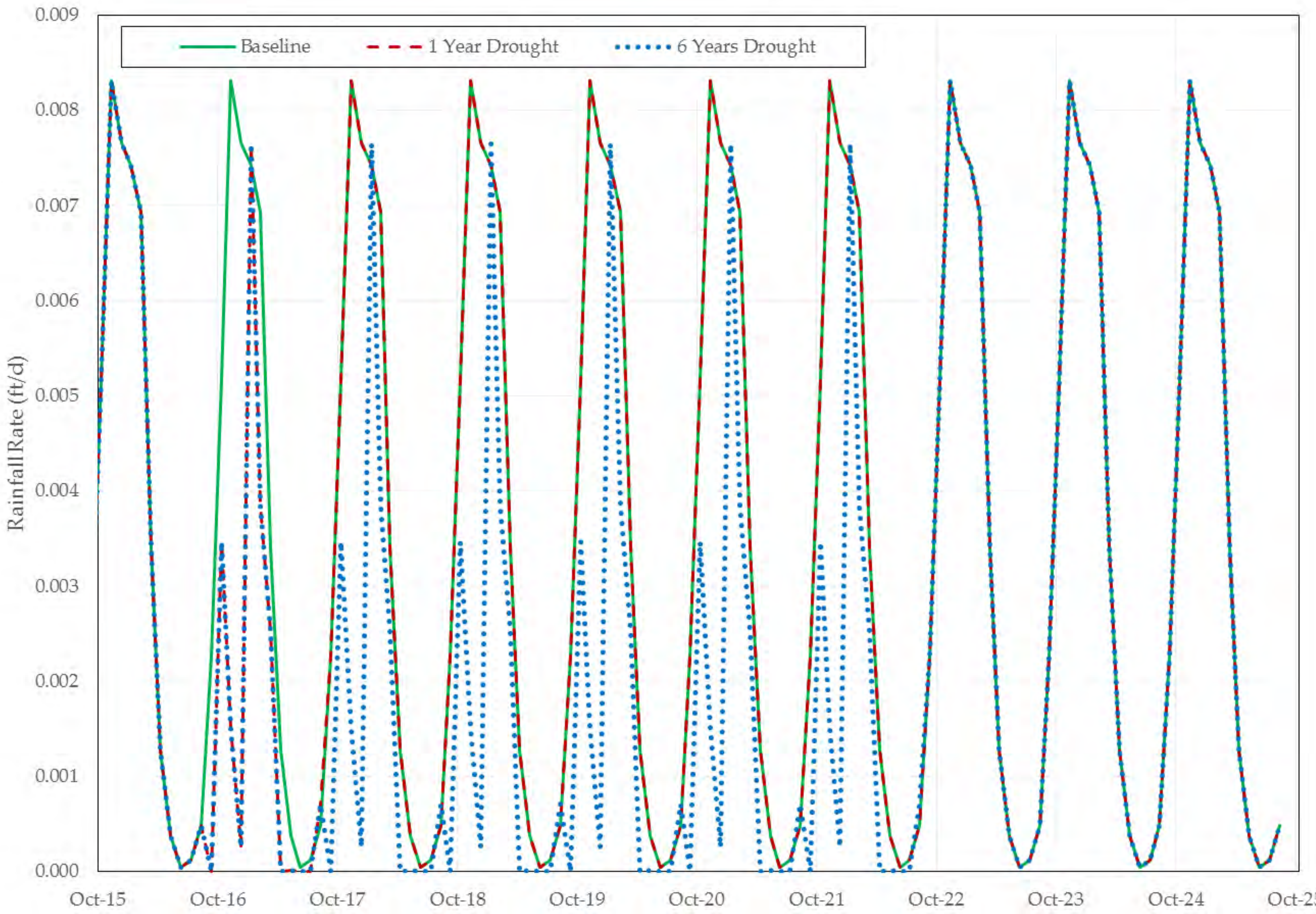

Figure 120: Rainfall Rate on Lakes for Management Simulations

5.1.5 Stream Inflow Concentrations

As described in Section 3.5.3, as streams (via "Headwater" segments) enter the boundary of Livermore Valley Groundwater Basin, they introduce additional loads of salt to the stream network and the groundwater basin. The TDS concentration of all "Headwater" segments for all simulation scenarios are assumed to be identical and constant for the entire simulation period except for the Arroyo Valle. Table 14 summarizes the TDS concentration used at each headwater station for the simulation scenarios. Figure 121 shows the TDS concentration for the Arroyo Valle Headwater Station (AVNL) for the different simulation scenarios. The higher concentrations during drought periods represent water quality changes of water supply provided by the State Water Project

Table 14: TDS Concentration at Headwater Segments

Stream	Station Name	TDS (mg/l)	Remarks
Alamo Canal	AC_Syn	786	Constant and identical for all Scenarios
Arroyo Las Positas	ALPL	1000	Constant and identical for all Scenarios
Arroyo Mocho	AMNL	470	Constant and identical for all Scenarios
Arroyo Valle	AVNL		Varies between different Scenarios and with time

5.1.6 Pumping

The pumping that was assigned to wells in the MNW2 package during years with average hydrology as discussed in Section 5.1.4 was estimated based on average annual pumping for the Water Years 2002 to 2014 and typical monthly municipal demands throughout the Water Year. The pumping in the drought year of the 1 Year Optimization Simulation was iteratively tested to maximize Zone 7 pumping while maintaining groundwater levels in the Amador and Bernal Sub-basins above historic lows. The pumping in the drought years of the 6 Years Drought Simulation was based on Zone 7 planned drought pumping. The pumping for the four simulations is summarized below:

- The Baseline Simulation assumes average annual pumping for the entire 10 year (Water Years 2016-2015) simulation period.
- The 1 Year Drought Optimization Simulation assumes average annual pumping for year 1 (Water Year 2016) and years 3-10 (Water Years 2018-2025). Three distributions of pumping in the drought year of the 1 Year Optimization Simulation (Water Year 2017) were tested to maximize Zone 7 pumping while

maintaining groundwater levels in the Amador and Bernal Sub-basins above historic lows. Figure 122 shows the difference in annual pumping for the drought year from average annual pumping used for the nine non-drought years in this simulation and all years in the Baseline Simulation.

- The 6 Years Drought Simulation assumes average annual pumping for year 1 (Water Year 2016) and years 8-10 (Water Years 2023-2025). The pumping distribution for all six drought years (Water Years 2017-2022) of the 6 Years Drought Simulation was based on Zone 7 planned drought pumping. Figure 123 shows the difference in annual pumping for the six drought years from average annual pumping used for the four non-drought years in this simulation and all years in the Baseline Simulation.
- The No Groundwater Demineralization Simulation assumes the same pumping as the Baseline Simulation.

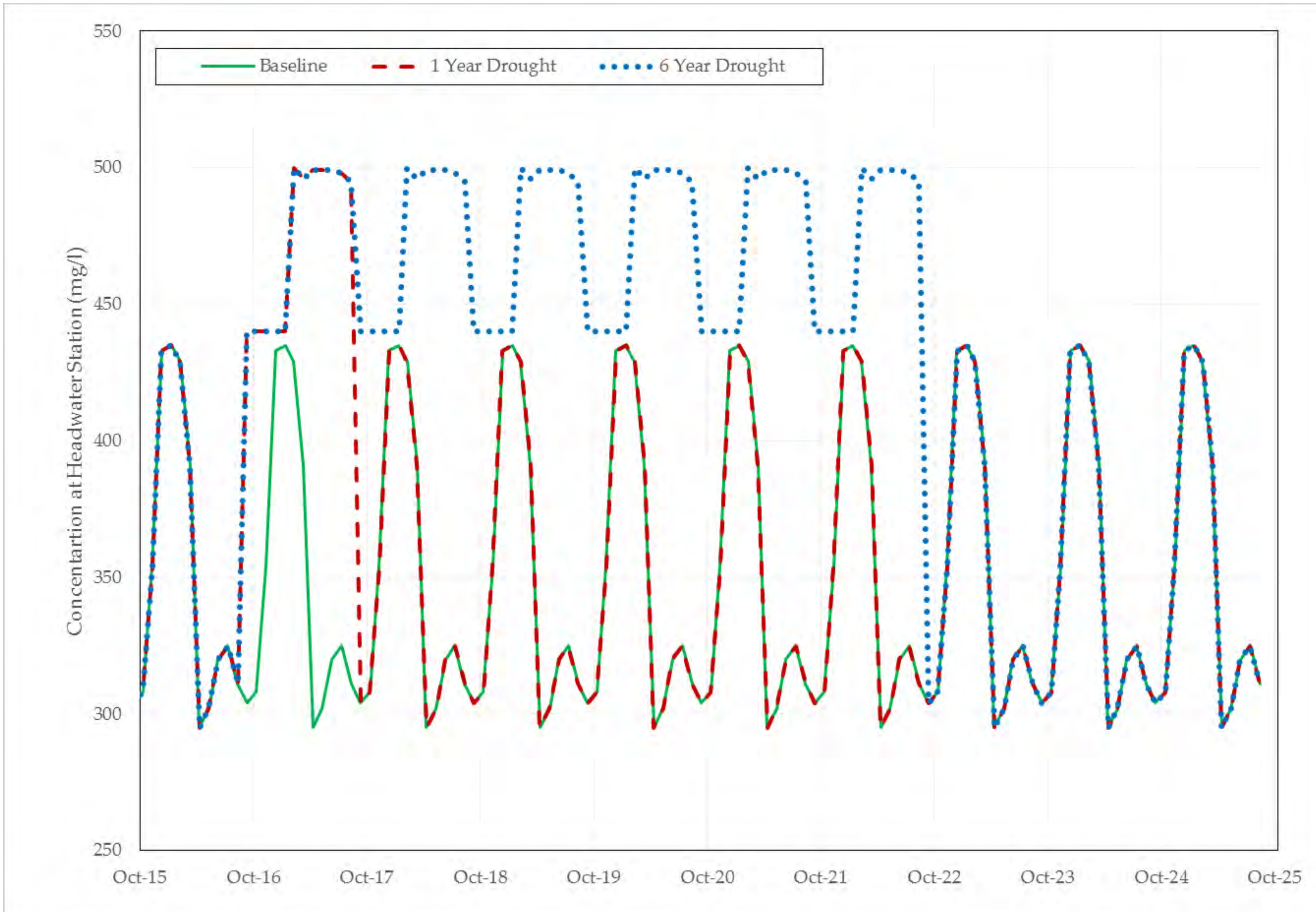

Figure 121: TDS Concentration for Arroyo Valle Headwater Segment (AVNL) used for Simulations

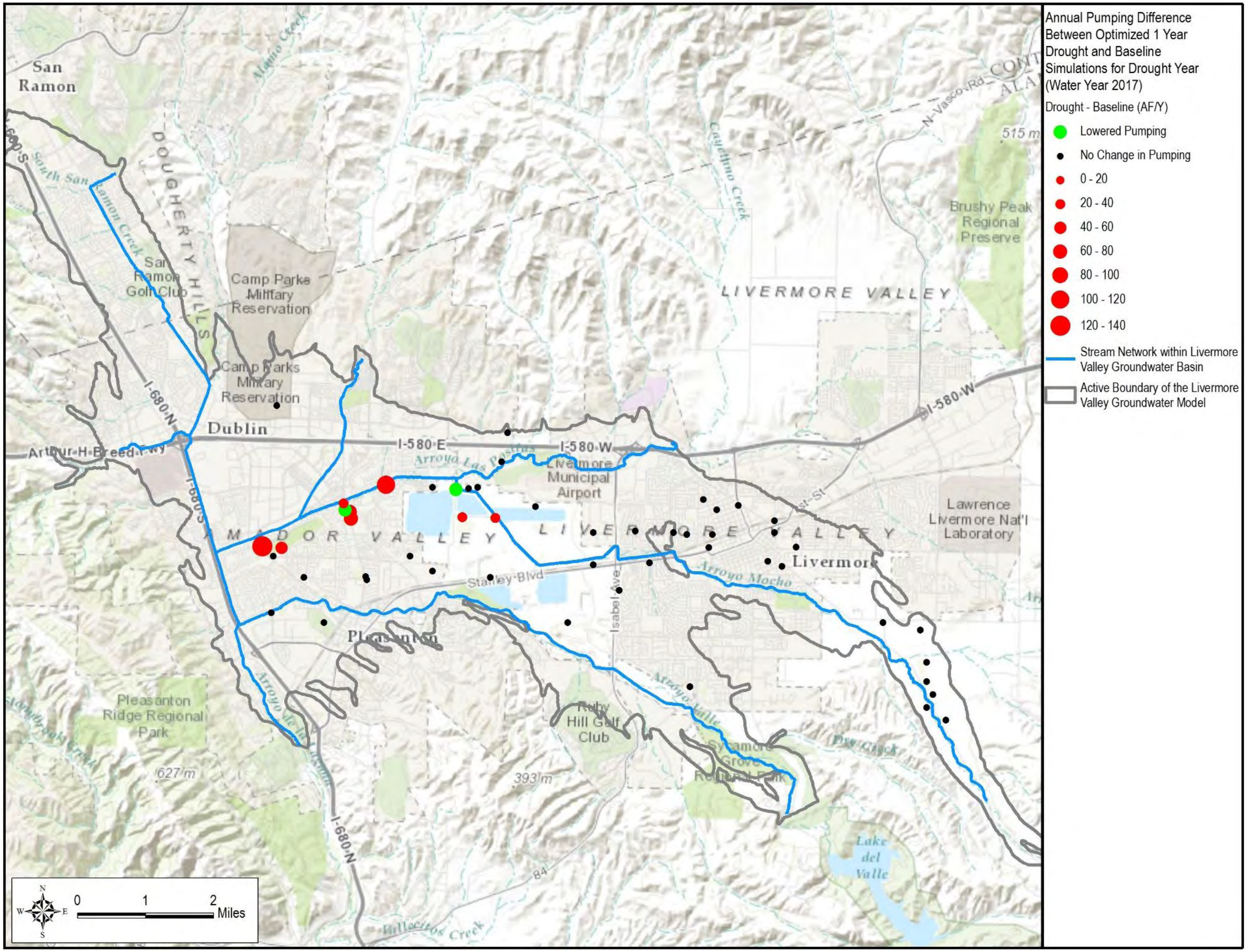

Figure 122: Difference in Annual Pumping for Water Year 2017 Between 1 Year Drought Optimization and Baseline Simulations

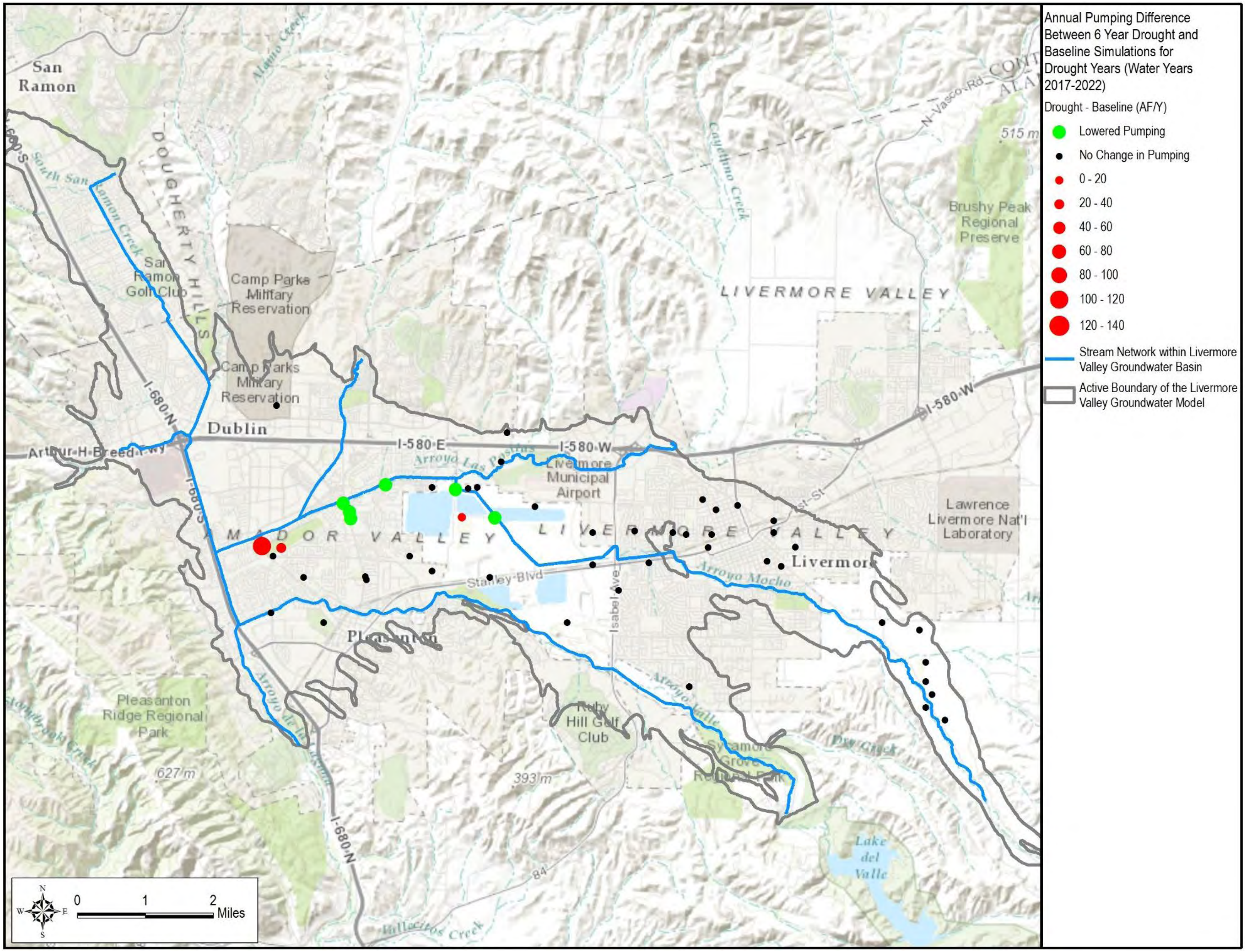

Figure 123: Difference in Annual Pumping for Water Years 2017-2022 Between 6 Year Drought and Baseline Simulations

5.1.7 AREAL RECHARGE CONCENTRATIONS

Areal recharge concentrations vary with monthly hydrology assumed as described in Section 5.1.4. Dry months have higher concentrations. Except for the No Demineralization Simulation, normal operation of the Demineralization Plant is assumed. The assumptions for areal recharge concentrations are described below for each simulation:

- The Baseline Simulation assumes monthly areal recharge concentrations based on average monthly hydrology for the entire 10 year (Water Years 2016-2025) simulation period. Figure 124 shows the average areal recharge concentrations for all years of this simulation.
- The 1 Year Drought Optimization Simulation assumes monthly areal recharge concentrations based on average monthly hydrology for year 1 (Water Year 2016) and years 3-10 (Water Years 2018-2025). Figure 124 shows the average areal recharge concentrations for these years. Monthly areal recharge concentrations for Year 2 (Water Year 2017) of this simulation are based on Water Year 2014 drought hydrology. Figure 125 shows the average recharge concentrations for the drought year.
- The 6 Year Drought Simulation assumes monthly areal recharge concentrations based on average monthly hydrology for Year 1 (Water Year 2016) and Years 8-10 (Water Years 2023-2025). Figure 124 shows the average areal recharge concentrations for these years. Monthly areal recharge concentrations for Year Years 2-7 (Water Years 2017-2022) of this simulation are based on Water Year 2014 drought hydrology. Figure 125 shows the average recharge concentrations for the drought years.
- The No Demineralization Simulation assumes average monthly hydrology like the Baseline Simulation except applied water concentrations are uniformly increased to represent no operation of the Demineralization Plant. Figure 126 shows the average areal recharge concentrations for all years of this simulation.

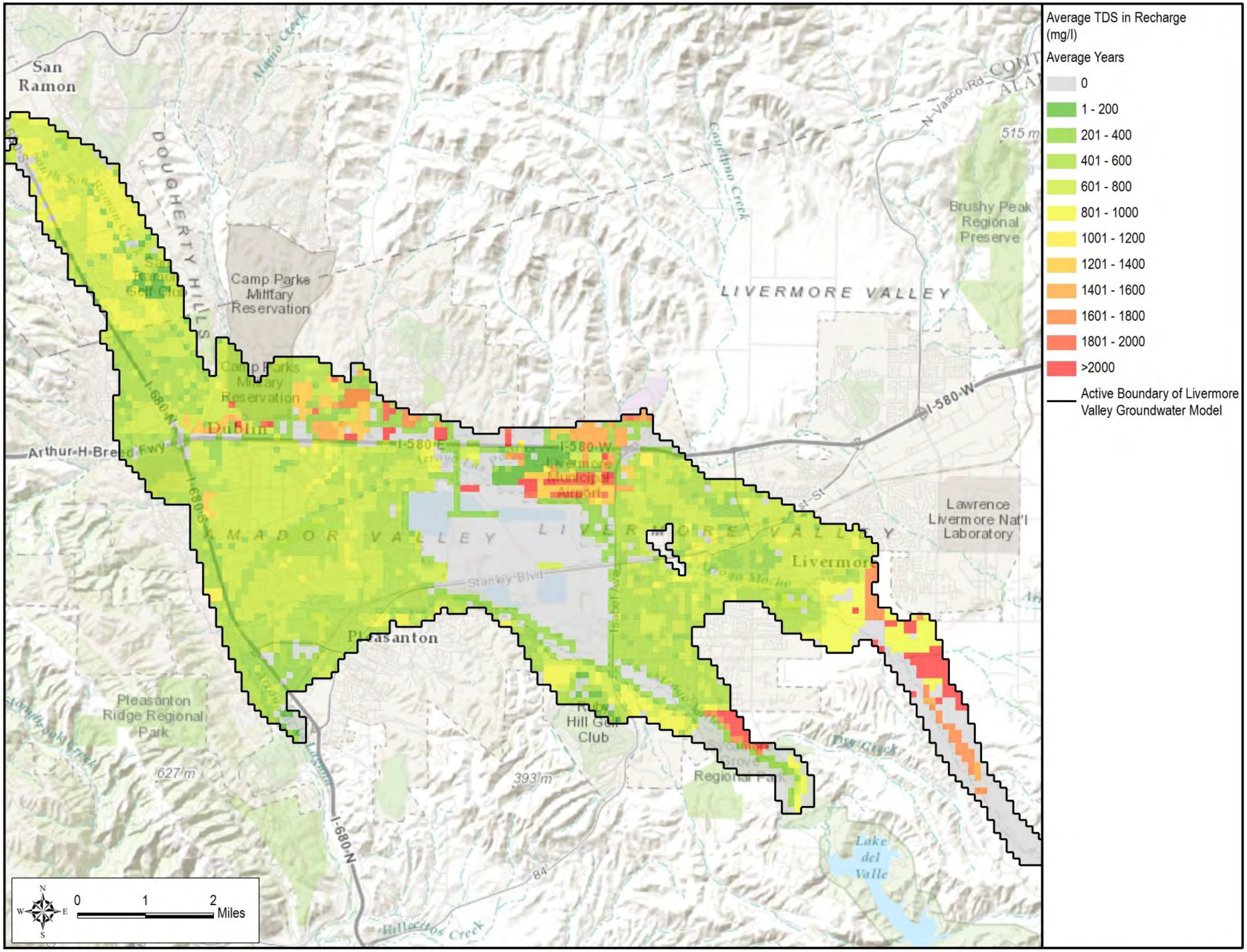

Figure 124: Average TDS Concentrations in Areal Recharge for Management Simulation Average Hydrology Years

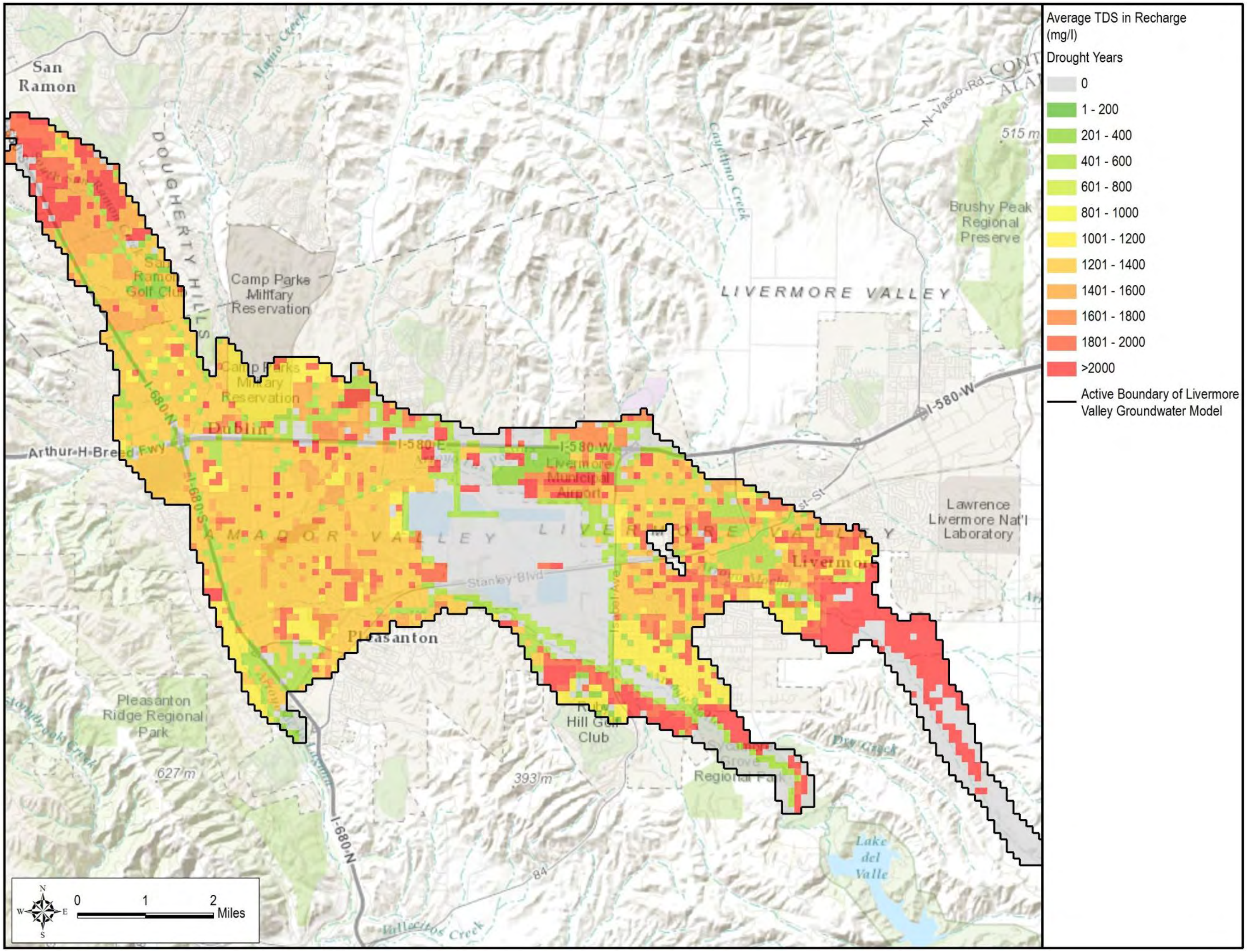

Figure 125: Average TDS Concentrations in Areal Recharge for Management Simulation Drought Hydrology Years

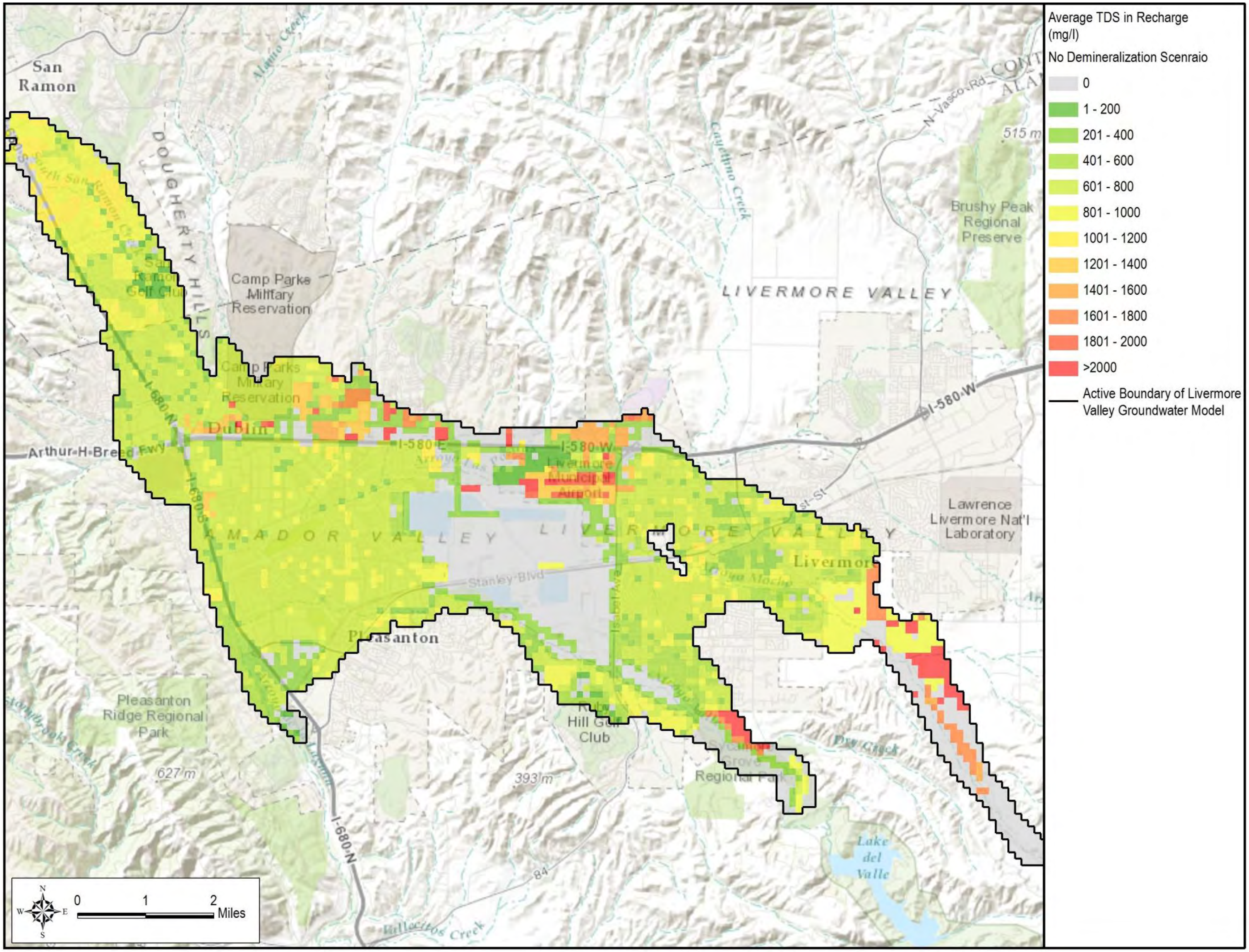

Figure 126: Average TDS Concentrations in Areal Recharge for No Demineralization Simulation

5.2 Flow Simulation Results

5.2.1 Simulated Water Budget for Management Simulations

Figure 127 through Figure 131 show simulated annual water budget components for the management simulations. Recharge (Figure 127) and pumping (Figure 128) reflect model inputs. The model simulates approximately 18,350 acre-feet of pumping in non-drought years. During the single-year drought of the 1 Year Drought Optimization Simulation (Water Year 2017), this pumping increases to nearly 34,000 acre-feet of pumping. During the six drought years in the 6-Years Drought Simulation, the model simulates approximately 20,000 acre-feet of pumping per year.

Figure 129 shows the water budget contribution of stream recharge for the drought simulations. The calibration results in Section 4.5 shows that during times of average stream recharge, the groundwater model accurately simulates groundwater levels. However, calibration does not show simulation of the full range of groundwater fluctuations, possibly due to the current stream simulation setup that does not limit groundwater recharge at low streamflows and results in overprediction of stream recharge during drought years when compared to hydrologic inventory estimates. Therefore, the model is not able to simulate streamflow recharge based on the worst-case conditions as designed and groundwater elevations under those worst-case conditions would be lower than simulated.

Even though the model is limited in its ability to simulate drought conditions, the streamflow recharge simulated for drought years are similar to estimates of streamflow recharge in historically dry years and therefore are representative of historically dry conditions. For the simulated drought year of the 1 Year Drought Optimization Simulation. the model predicts approximately 5,700 acre-feet of stream recharge, which would be the second lowest amount of total stream recharge since 1974 (Figure 108). Therefore, the 1 Year Drought Optimization Simulation is representative of conditions under a historically one year severe drought. The model predicts streamflow recharge of 5,700-6,400 acre-feet per year for the six years of the 6 Years Drought Simulation with each year having less stream recharge than estimated for all but three years since 1974. Therefore, the simulation of six straight years of that level of low stream recharge is representative of historically unprecedented conditions.

Figure 129 along with Figure 130 for lake seepage also shows the effect of groundwater head dependence of the streams and lakeswith the implementation of the SFR and LAK packages in this model update. This is shown in the decreasing stream recharge as groundwater levels rise throughout the Baseline Simulation and after droughts in the two drought simulations as well as the changing lake seepage over time in the simulations. Figure 131 shows gains in groundwater storage over time. This figure does not show total groundwater storage, but rather annual gains and losses in groundwater storage. After the droughts, the rate of groundwater storage increases significantly. The rate of groundwater storage then declines as rising groundwater levels decrease the volume of aquifer available for additional storage.

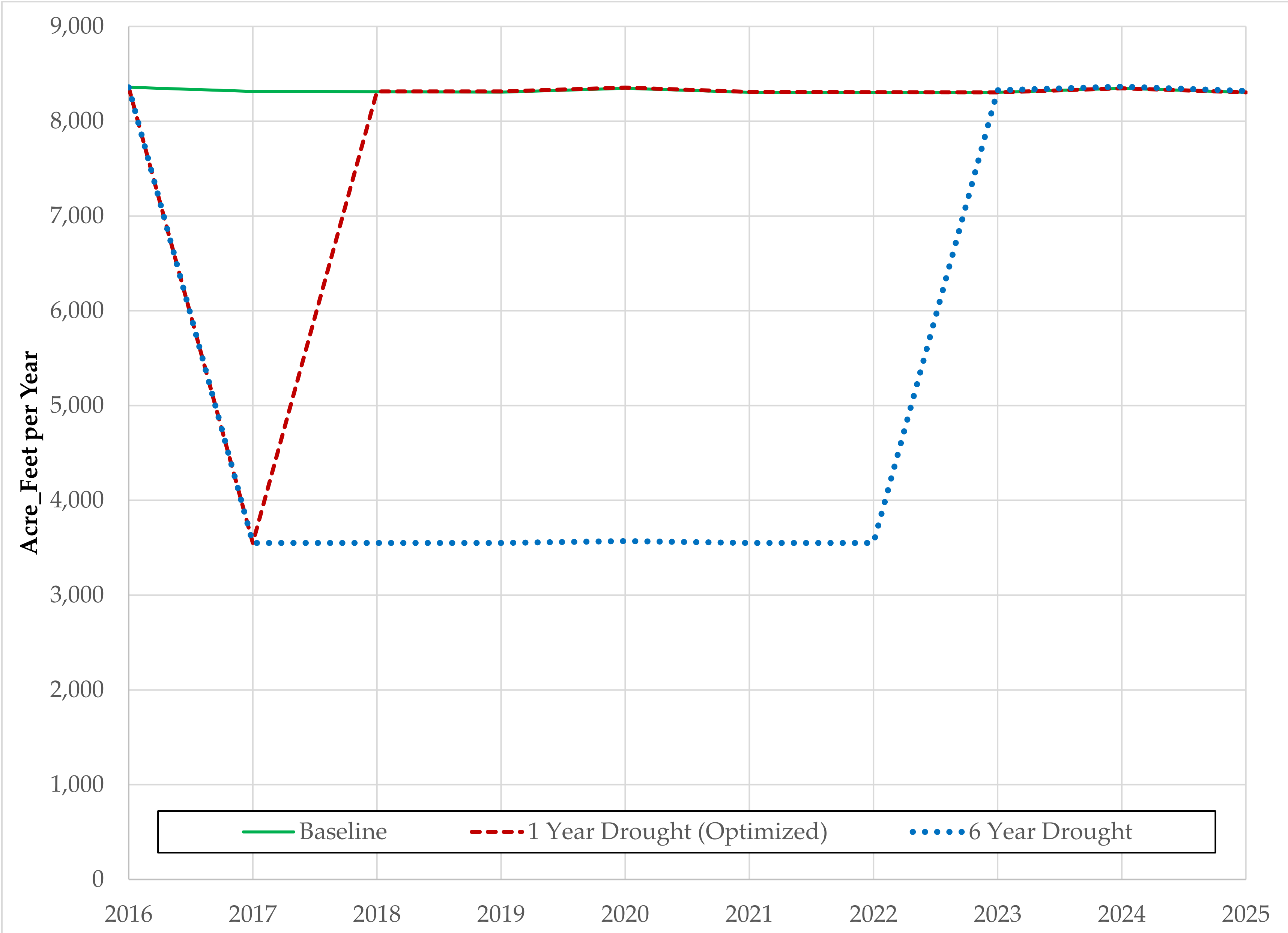

Figure 127: Simulated Annual Water Budget for Areal Recharge

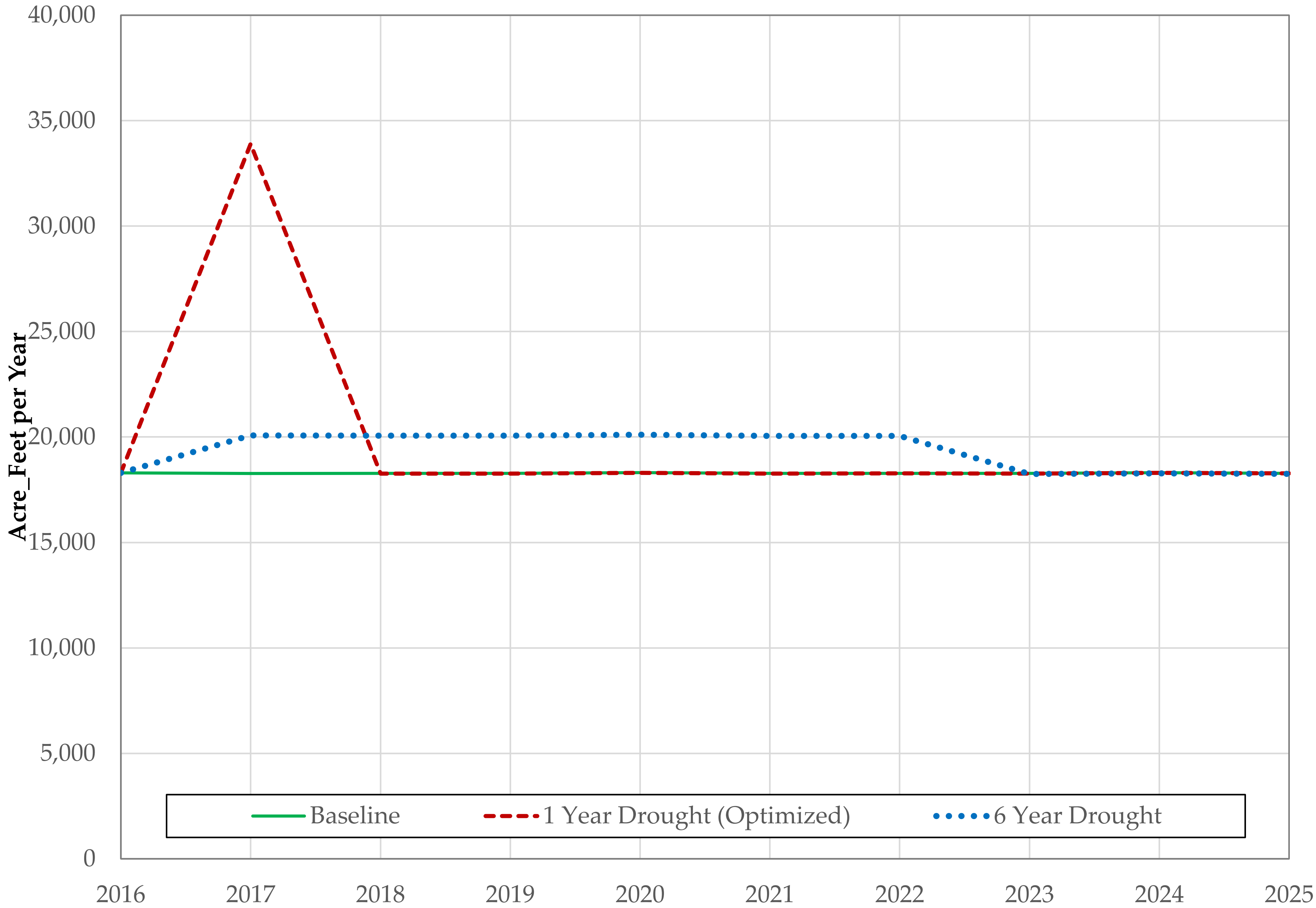

Figure 128: Simulated Annual Water Budget for Pumping

Figure 129: Simulated Annual Water Budget for Annual Stream Recharge

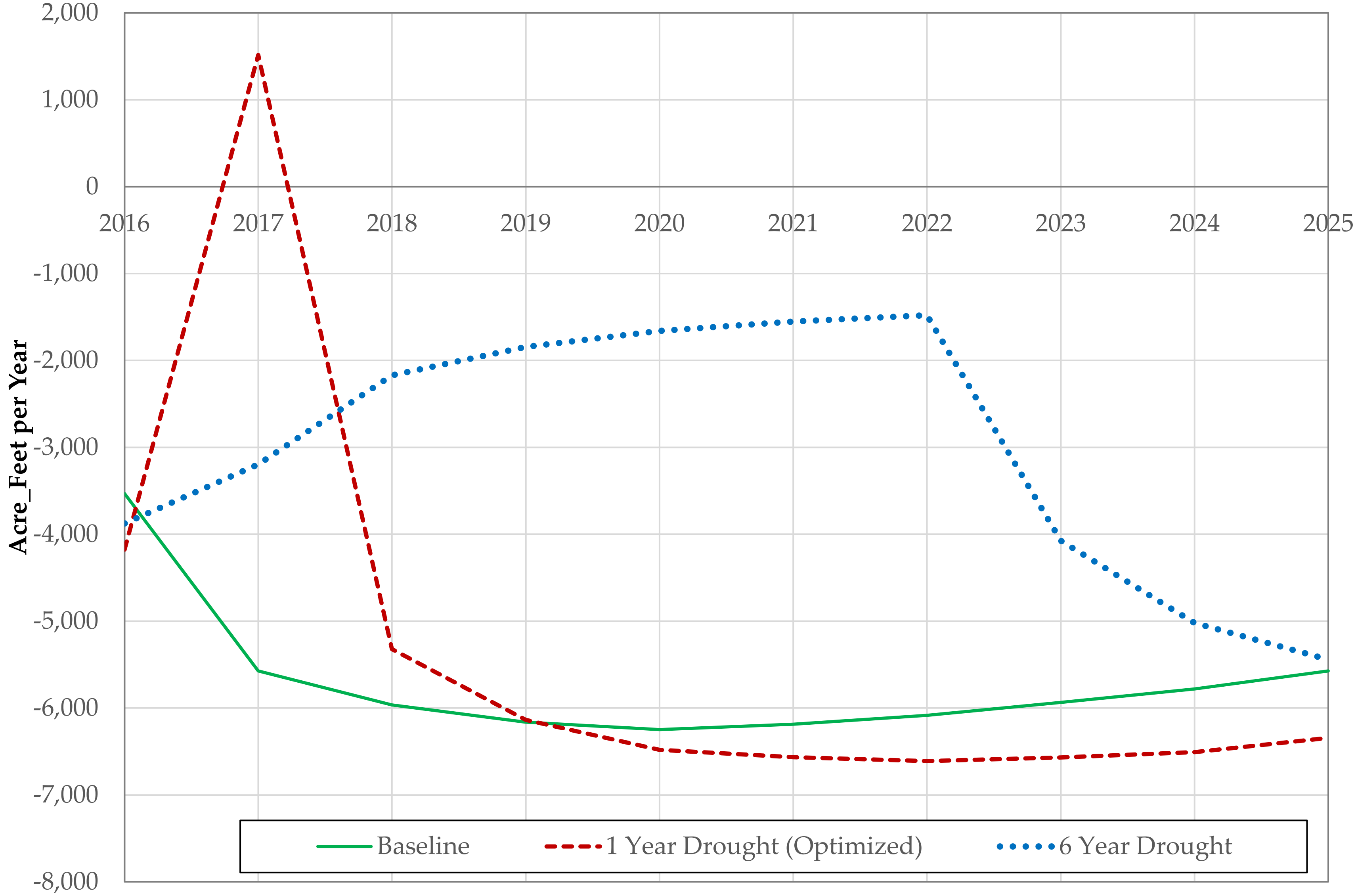

Figure 130: Simulated Annual Water Budget for Lake Seepage

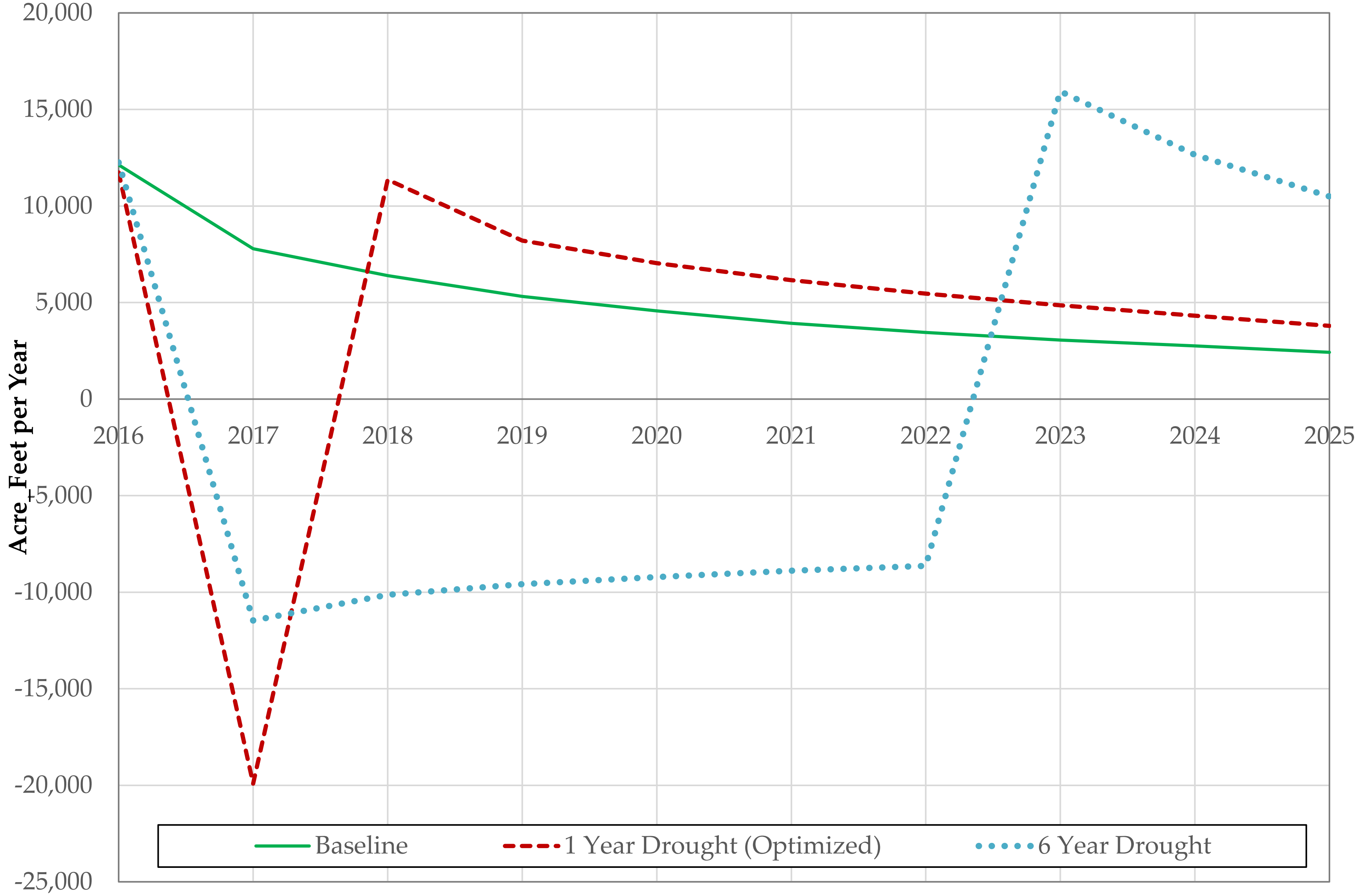

Figure 131: Simulated Water Budget for Annual Storage

5.2.2 GROUNDWATER ELEVATIONS

Groundwater elevations from the simulations are compared to historic low groundwater elevations at wells where Zone 7 has identified historic lows. Figure 132 shows example hydrographs for three wells in the Amador Sub-basin and one well in the Bernal Sub-basin. APPENDIX H: includes hydrographs for all wells with identified historic lows. The hydrographs show the Baseline Simulation results in rising groundwater elevations throughout the basin. The hydrographs show the One Year Drought Optimization Simulation groundwater levels dropping during the simulated drought year of Water Year 2017 and then recovering to end up generally higher at the end of the ten year simulation than initial heads. The hydrographs show a steady decline over the six year drought period (Water Years 2017-2022) of the 6 Year Drought Simulation than recovery in the final three years of the simulation, but groundwater levels are generally below initial heads at the end of the ten year simulation.

The One Year Drought Optimization Simulation results are based on a third iteration of a pumping distribution (Figure 122) designed to maximize Zone 7 pumping in the Amador and Bernal Sub-basins while keeping groundwater levels above historic lows in those sub-basins. As shown in Figure 132, the MOCHO4 well is the limiting well that has groundwater levels fall to historic lows in the northwest part of the Amador Sub-Basin. Figure 133 shows the difference between groundwater levels for this simulation at the end of the drought Water Year 2017 and a raster surface of historic lows interpolated from wells identified to have historic lows. APPENDIX I: shows the results for all three iterations of the One Year Drought Optmization Simulation at wells with historic lows. At some California Water Service (CWS) wells in the Mocho II Sub-basin, historic low groundwater elevations are high as the wells are near the edge of the sub-basin and simulated groundwater elevations do fall below historic lows. Pumping at CWS wells are constant between all simulations assuming CWS pumps its Groundwater Pumping Quota (GPQ).

Figure 134 shows the difference between groundwater levels for the 6 Year Simulation at the end of the six year drought (Water Year 2022) and the raster surface of historic lows. It shows a similar difference to the groundwater levels simulated by the One Year Drought Optimization Simulation after the one year drought (Water Year 2017) with maximized pumping.

Maps of simulated piezometric surfaces are displayed in APPENDIX J:. The maps can be used to compare 1) the groundwater elevation of the Baseline scenario and the 1 year Drought Optimization Simulation at the end of the drought (end of the Water Year

2017), 2) the groundwater elevation of the Baseline Simulation and the 6 Year Drought Simulation at the end of the extended drought (end of the Water Year 2022), 3) the groundwater elevation of the Baseline Simulation and both drought simulations at the end of the 10 years simulation (end of the Water Year 2025). The maps show results from model layers 2 and 6, representing the top aquifer units in the upper and lower aquifers. The maps reveal that the Amador and Bernal basins will experience the most adverse effects from the drought as they can completely dry in the shallow aquifer under the extended drought condition.

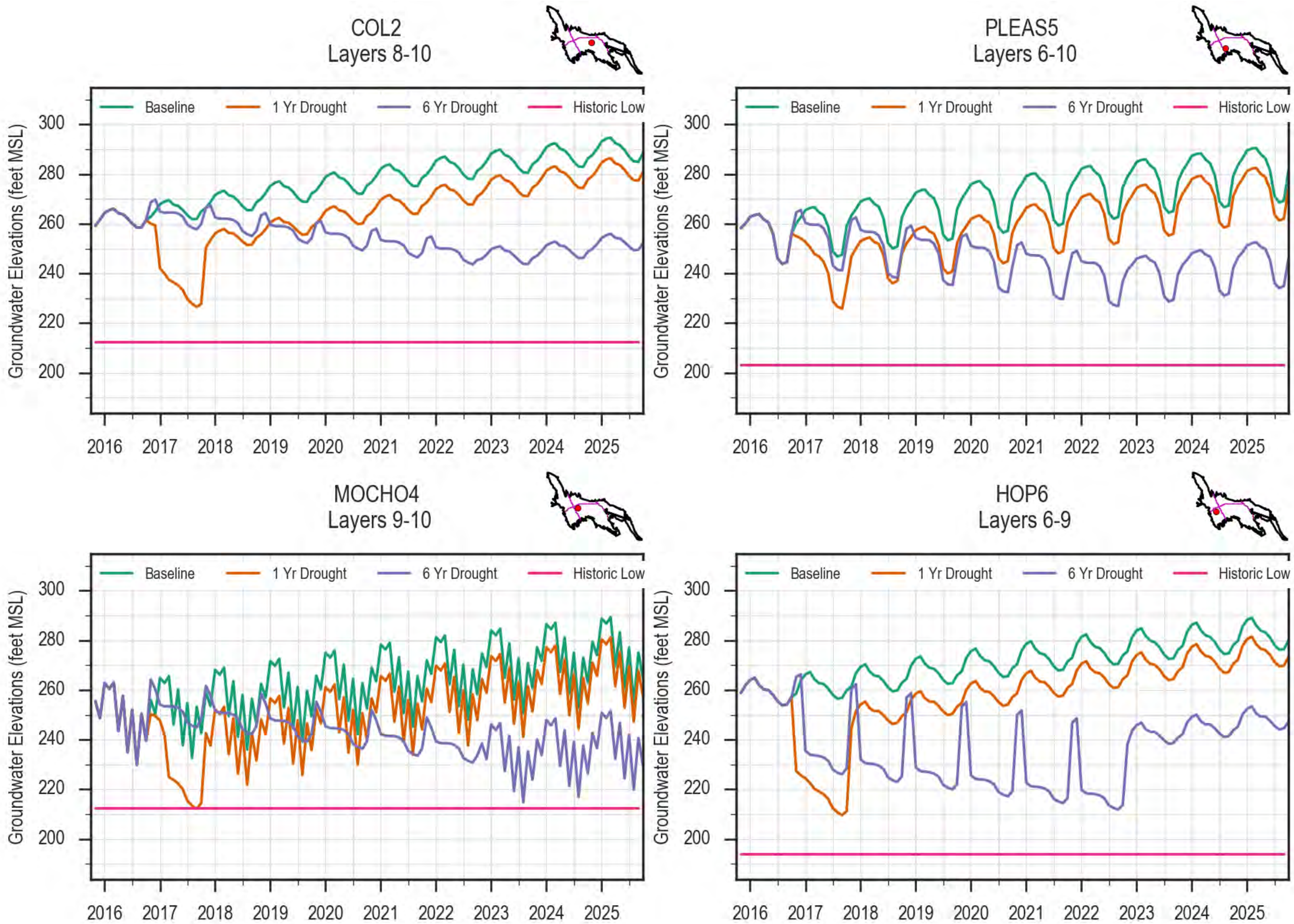

Figure 132: Example Groundwater Elevation Hydrographs

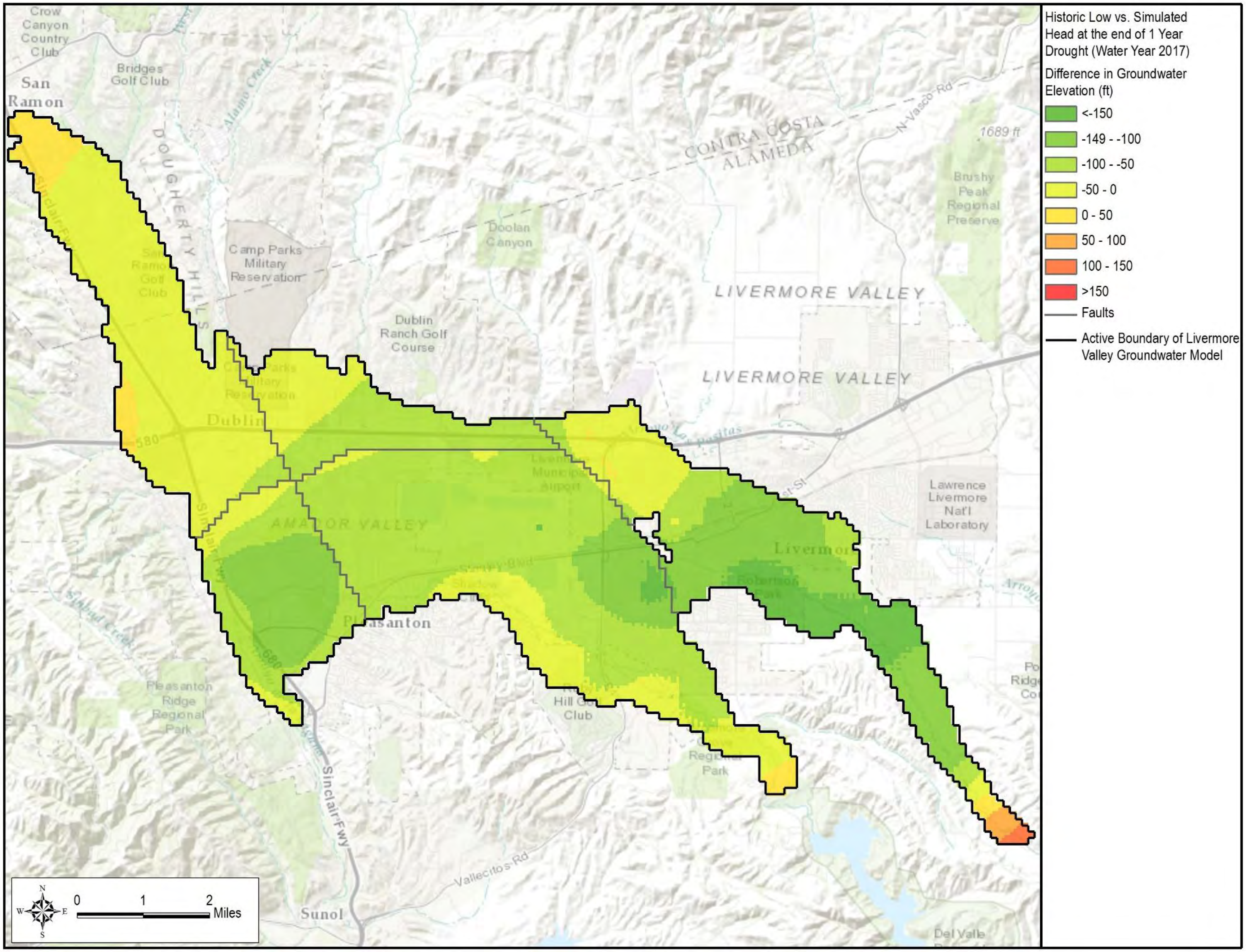

Figure 133: Groundwater Elevation above Historic Low for 1 Year Drought Optimization Simulation End of Water Year 2017

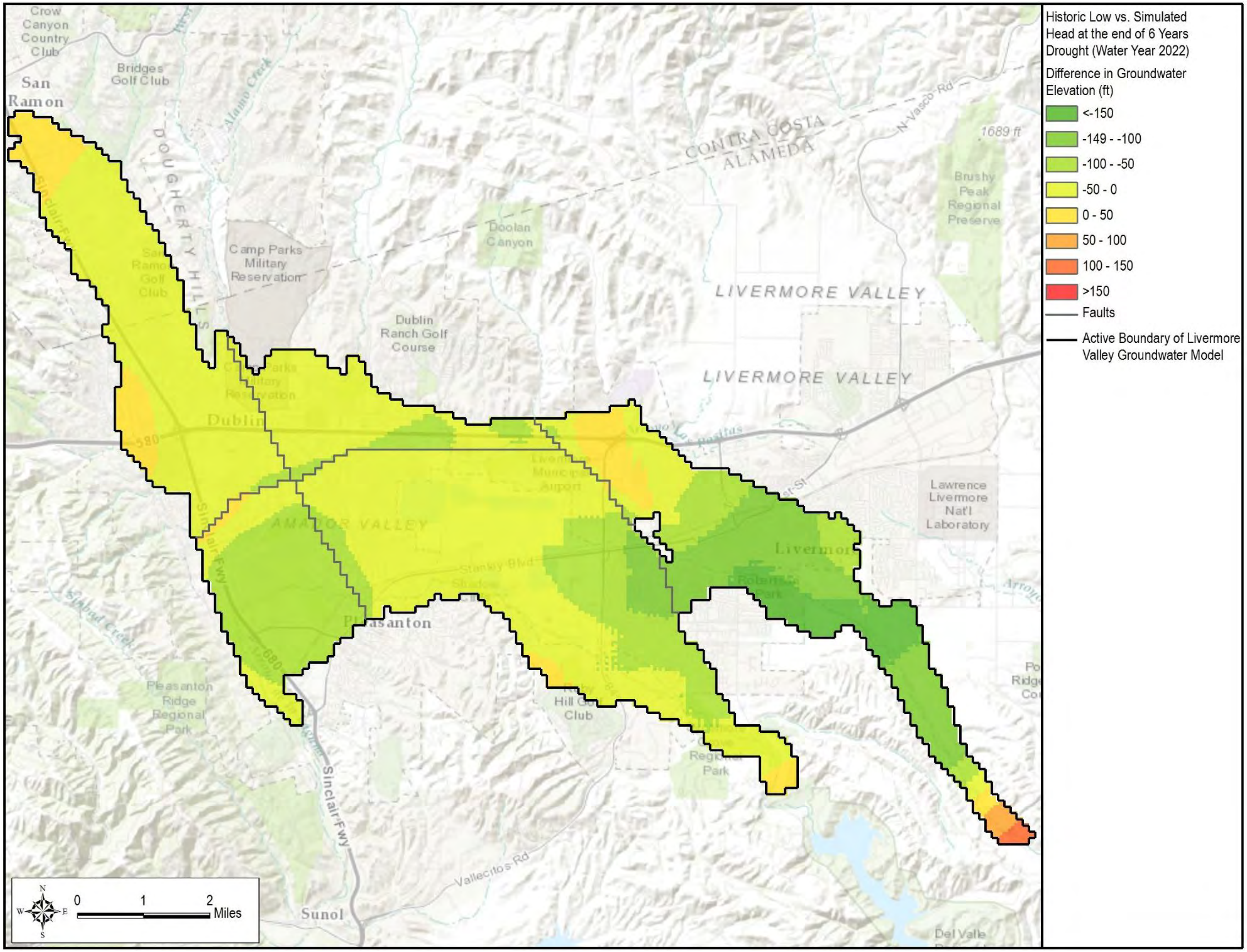

Figure 134: Groundwater Elevation above Historic Low for 6 Year Drought Simulation End of Water Year 2022

5.3 Transport Simulation Results

5.3.1 Groundwater TDS Concentrations

Figure 135 through Figure 138 show chemographs for key wells in the main basin. These chemographs show TDS concentrations in aquifer layers for the four simulations. In the Baseline Simulation, concentrations in Upper Aquifer layers decrease over time while concentrations in Lower Aquifer layers are relatively stable. The No Deminerilzation Simulation shows Upper Aquifer layer concentrations that are higher than in the Baseline Simulation but the effect of applied water with higher concentrations is not evident in the Lower Aquifer layers within the ten year simulation.

The drought simulations show increased concentrations in the Upper Aquifer layers during the drought years when compared to the Baseline Simulation but little difference in the deepest layers. Increased concentrations occur in the Upper Aquifer layer 2 during the drought year (Water Year 2017) of the 1 Year Drought Optimization Simulation, but the trend over the ten year simulation period is similar to the Baseline Simulation. Larger increases in concentrations in Upper Aquifer layers 2 and 4 are evident over the six year drought period (Water Years 2017-2022) of the 6 Year Drought Simulation. Increases in concentrations over the ten year simulation also can be identified in layer 6, the top layer of the Lower Aquifer. The increases in Upper Aquifer concentrations appear to be related to declining groundwater levels and not increases in salt mass. This is shown by the increasing layer 2 concentrations leading up to the layer going dry in the 6 Year Drought Simulation as represented by gaps in the chemograph line. As the Upper Aquifer layers desaturate, salt is transported down to deeper layers.

Maps of simulated TDS concentrations are displayed on APPENDIX K:. The maps can be used to compare 1) the TDS concentrations in Upper Aquifer layer 2 of the Baseline Simulation and the 1 Year Drought Simulation at the end of the drought Water Year 2017, 2) the TDS concentrations in Upper Aquifer layers 2 and 4 of the Baseline Simulation and the 6 Year Drought Simulation at the end of the six year drought (Water Year 2022), 3) the TDS concentrations in all aquifer layers of the Baseline Simulation, two drought simulations, and No Demineralization Simulation at the end of the 10 year simulation (Water Year 2025). The maps reveal that the Amador and Bernal Sub-basins will experience the most adverse effects from the drought. The Demineralization of groundwater has minimal effect on the Bernal Sub-basin, however, Amador Sub-basin is the most impacted basin by the Demineralization activities especially at the western areas of the sub-basin.

5.3.2 SIMULATED SALT BALANCE FOR MANAGEMENT SIMULATIONS

Figure 139 shows total salt mass over time for the management simulations. The trend under average hydrologic and pumping conditions over ten years is increasing salt mass. However, salt mass does appear to level off toward the end of the ten year simulation under the Baseline Simulation. The No Demineralization Simulation shows the greatest increase in salt mass. There is a decrease in salt mass during drought periods as lower stream inflows at the arroyos result in lower salt loading.

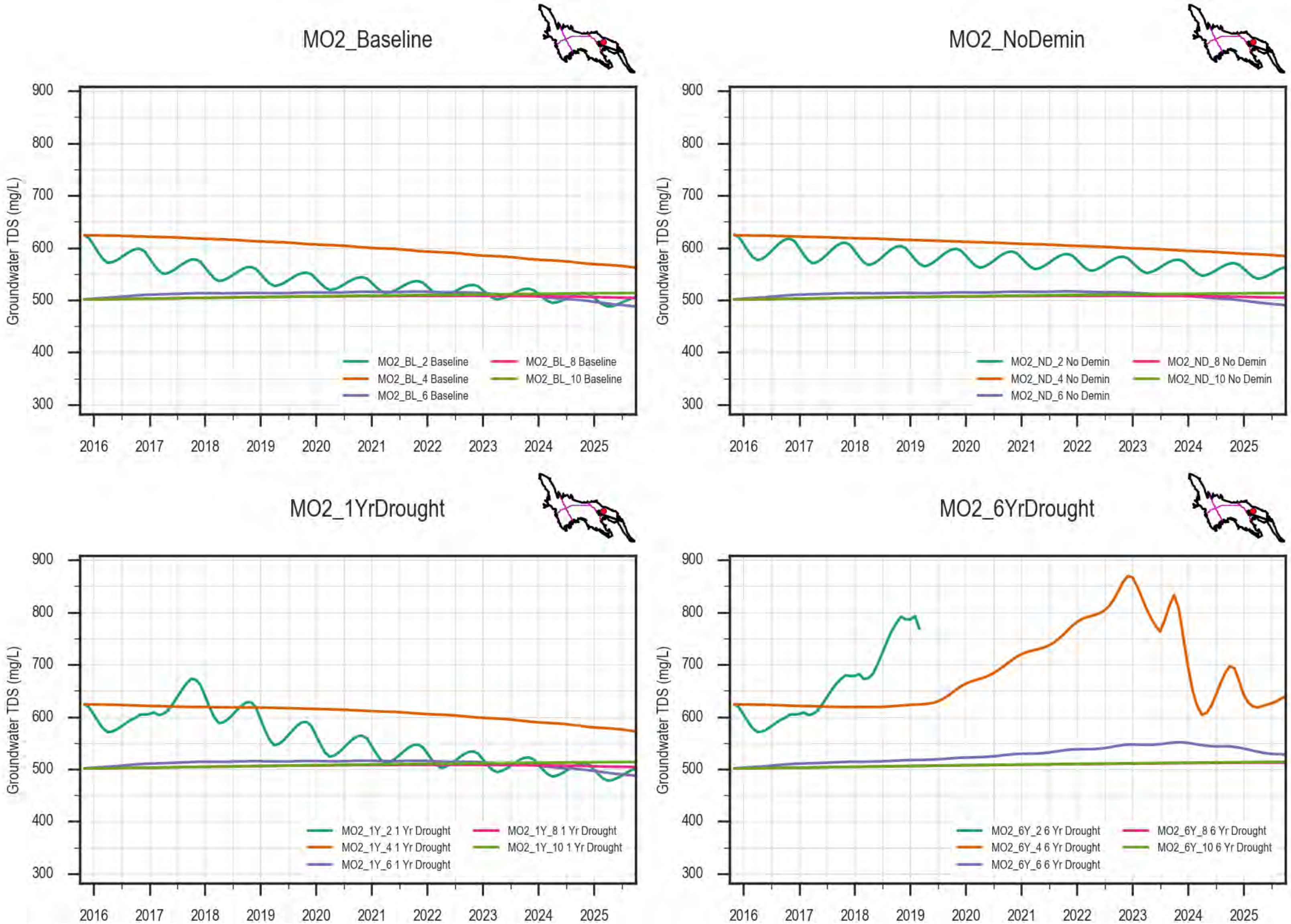

Figure 135: Groundwater TDS Chemographs for Management Simulations at Mocho 2 Key Well by Aquifer Layer

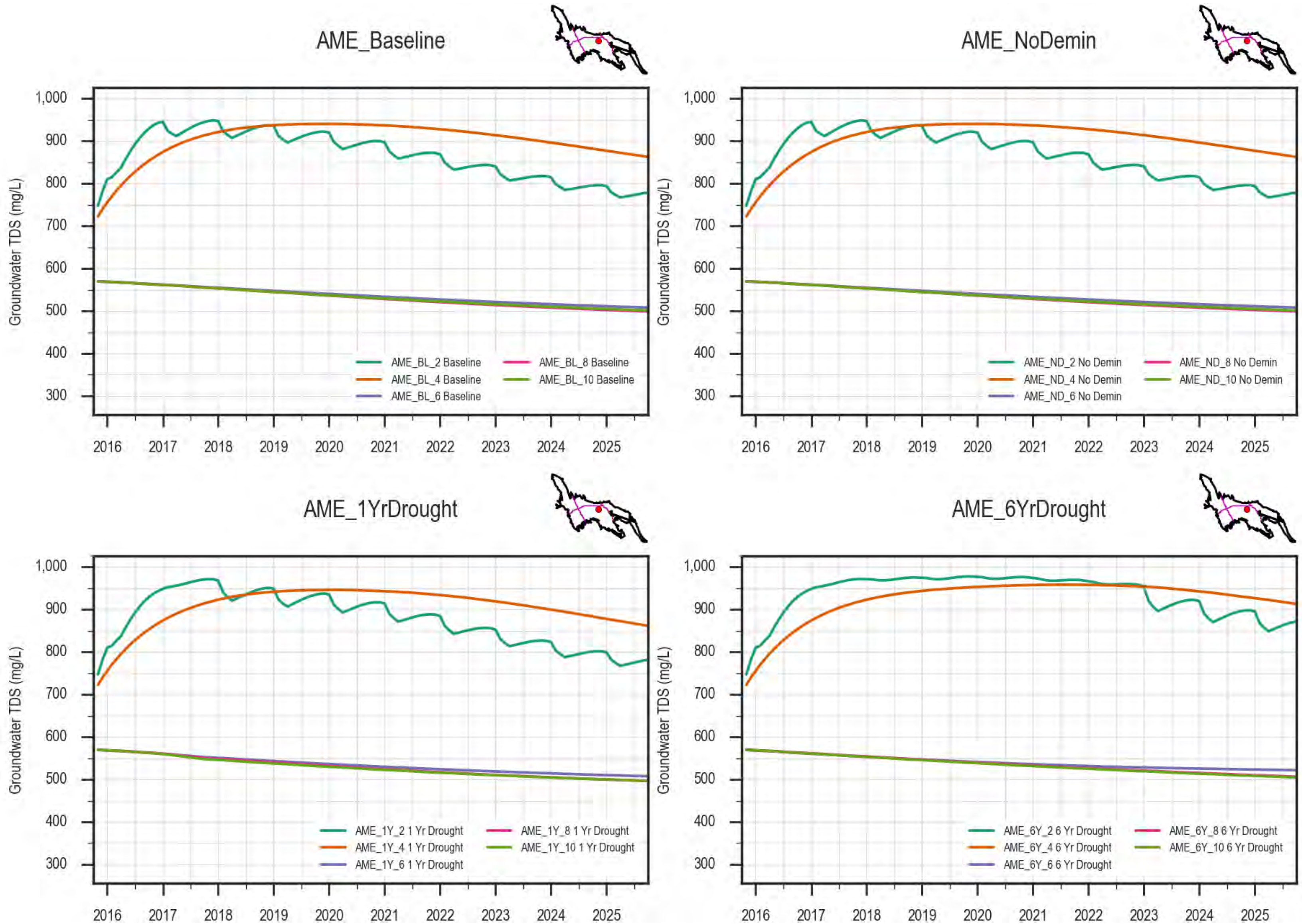

Figure 136: Groundwater TDS Chemographs for Management Simulations at Amador East Key Well by Aquifer Layer

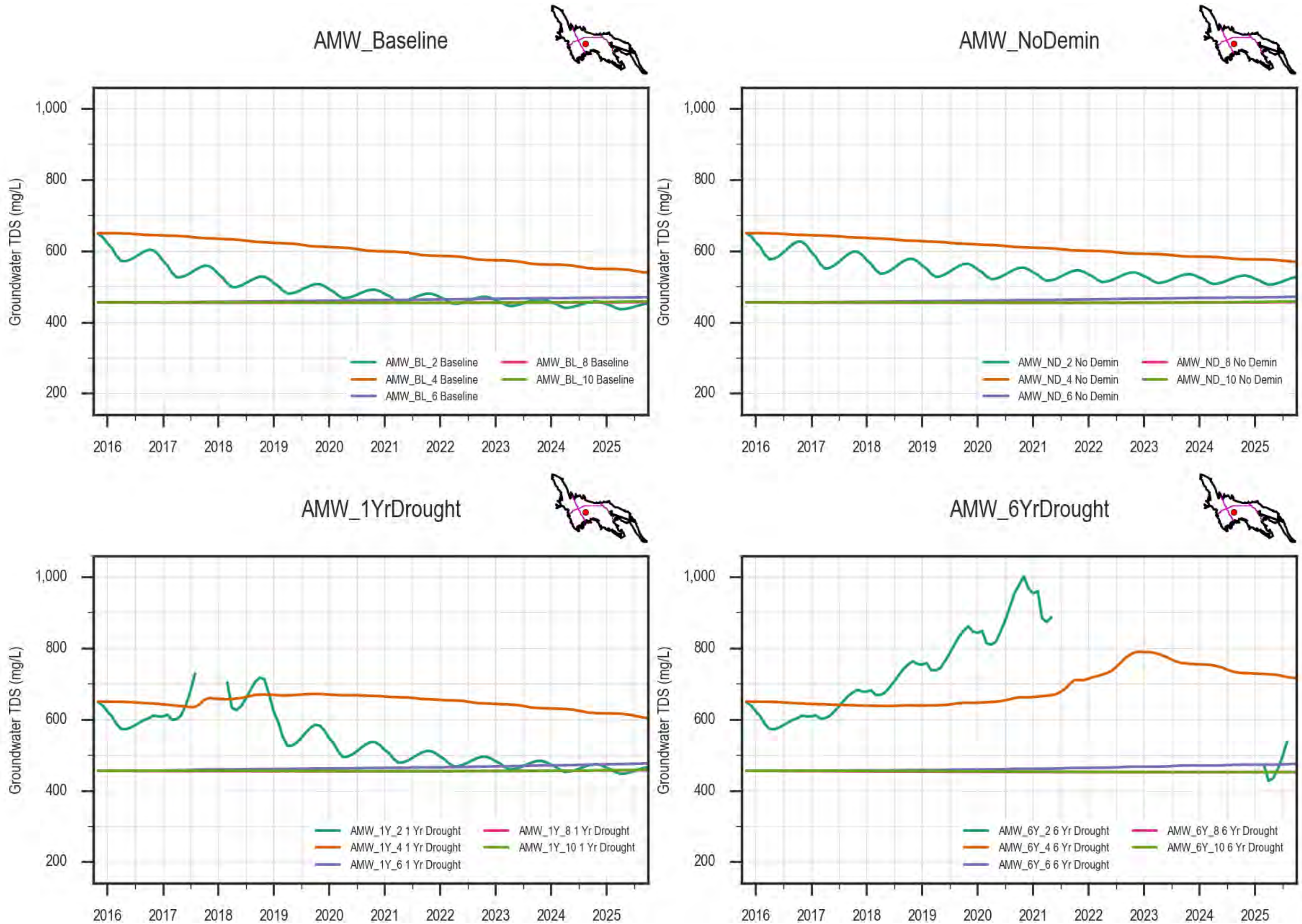

Figure 137: Groundwater TDS Chemographs for Management Simulations at Amador West Key Well by Aquifer Layer

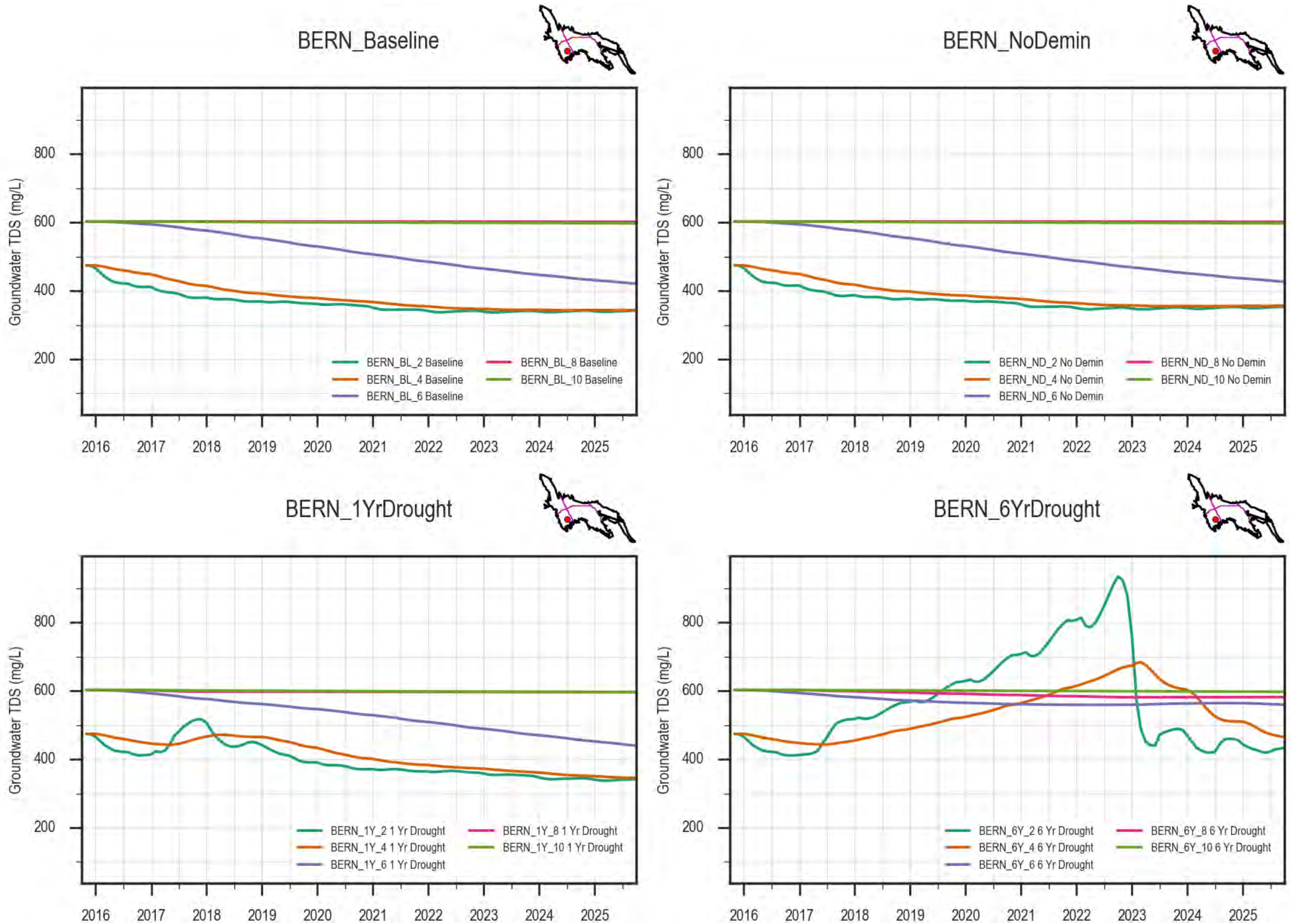

Figure 138: Groundwater TDS Chemographs for Management Simulations at Bernal Key Well by Aquifer Layer

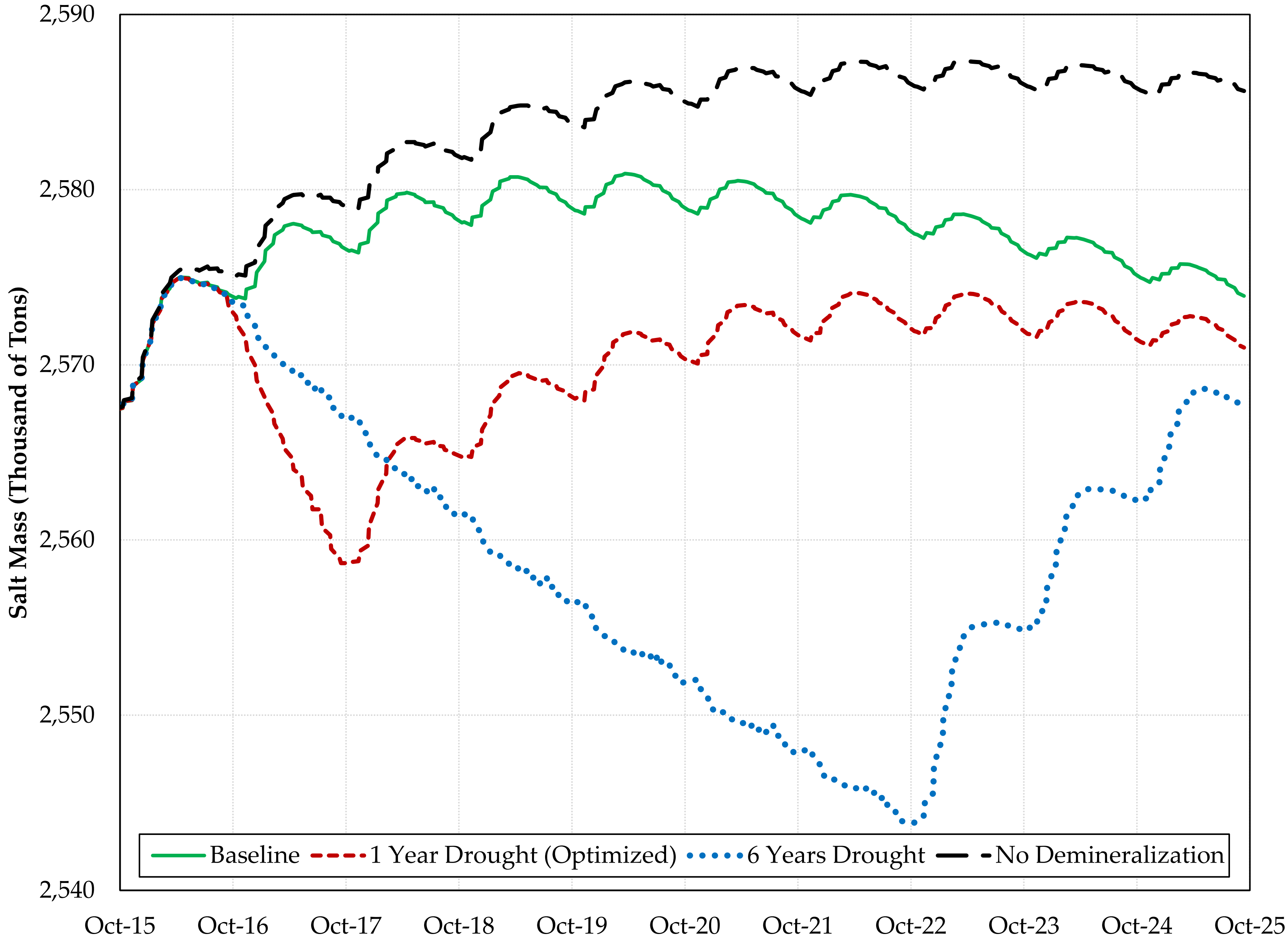

Figure 139: Simulated Salt Mass for Management Simulations

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SECTION 6
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