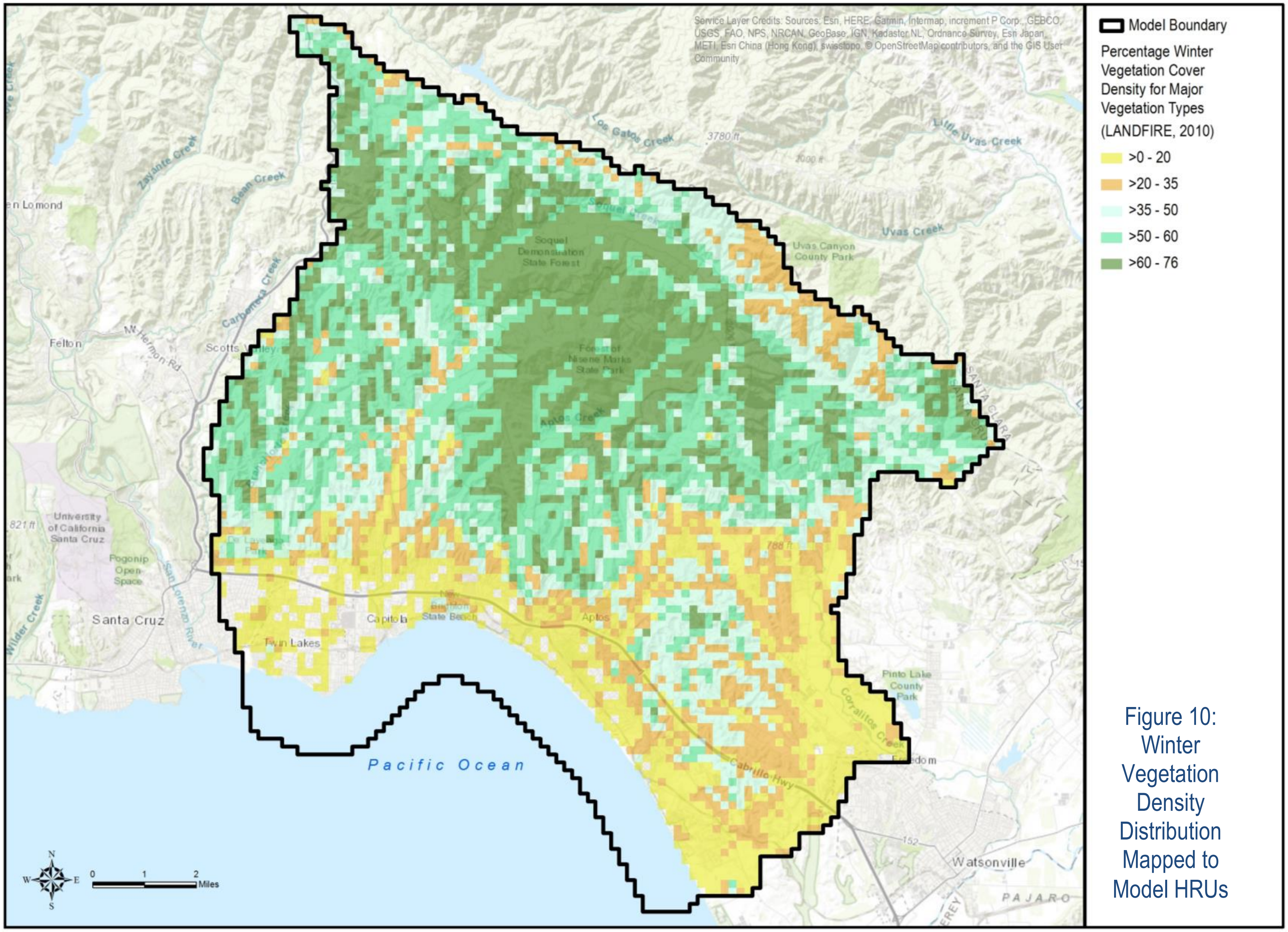


Figure 10: Winter Vegetation Density Distribution Mapped to Model HRUs

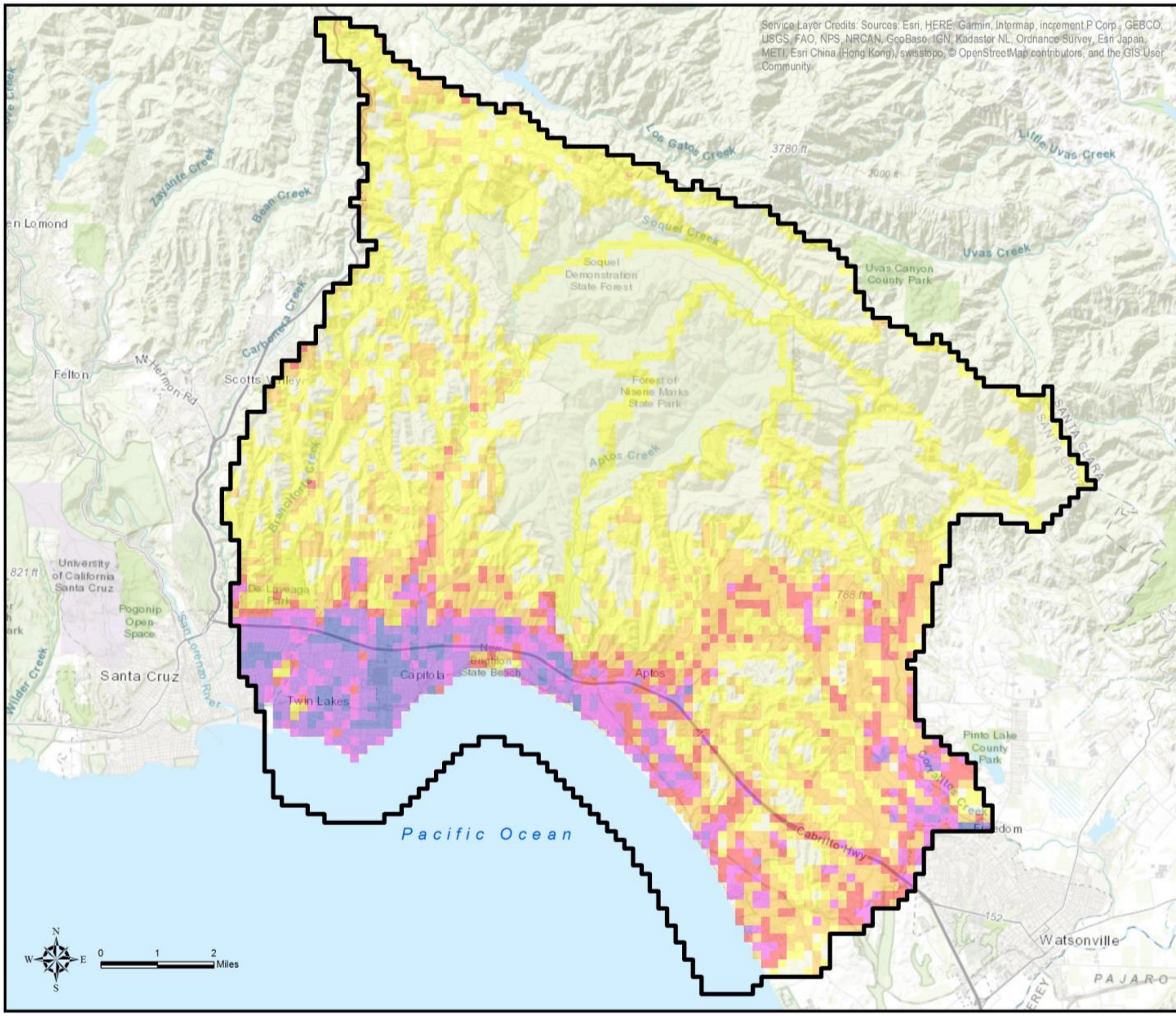


Figure 11. Percent Impervious Distribution Mapped to Model HRUs

4.3 Pumping Well Data

Groundwater pumping is implemented with the Multi-Node Well (MNW2) MODFLOW package. The MNW2 package calculates flow into the well from various model layers based on actual screen elevations. Where available for municipal wells, screened interval elevations are entered in the MNW2 package. An exception to this this is where Soquel Creek Water District (SqCWD) are screened within both the Aromas Red Sands and Purisima F unit. In this case we assigned all pumping to layer 3, representing the Purisima F unit, to simulate a confined aquifer response observed near the coast. As described in the *Santa Cruz Mid-County Basin Groundwater Flow Model: Water Use Estimates and Return Flow Implementation* memorandum (HydroMetrics WRI, 2017c), most non-municipal pumping is based on land use for a model cell, not actual, identified well locations. Table 4 lists the municipal wells explicitly simulated in the model. Non-municipal pumping is assigned to the layer representing the shallowest aquifer unit that is not outcropping at the estimated well location. Plate 3 shows simulated pumping well locations by model layer for each aquifer unit.

Table 4. Municipal Wells in Model Domain

Well Name	Agency	Pumping Data Range (Water Year)	Aquifer Unit in Model[1]
Beltz #12	City of Santa Cruz	1984-2016	AA, Tu
Beltz #1	City of Santa Cruz	1984-2015	A
Beltz #7	City of Santa Cruz	1984-2015	A, AA
Beltz #10	City of Santa Cruz	1984-2016	A, AA
Beltz #9	City of Santa Cruz	1984-2016	A
Beltz #4	City of Santa Cruz	1985-2015	A
Beltz #8	City of Santa Cruz	1984-2016	A, AA
CWD-2	CWD	1985-2002	DEF/F
CWD-3	CWD	1985-2014	DEF/F
CWD-5	CWD	1985-2014	DEF/F
CWD-4	CWD	1985-2016	Aromas, DEF/F
CWD-10	CWD	1985-2016	Aromas, DEF/F
CWD-12	CWD	1986-2016	Aromas, DEF/F
Cliff Well	SqCWD	1984-1986	DEF/F
O'Neill Ranch Well	SqCWD	2015-2016	AA, Tu
Opal Well #1	SqCWD	1984-2000	A
Polo Grounds Well	SqCWD	1985-2016	DEF/F
Tannery Well II	SqCWD	2002-2016	A, AA
Aptos Jr High Well	SqCWD	1985-2016	DEF/F

Well Name	Agency	Pumping Data Range (Water Year)	Aquifer Unit in Model[1]
Monterey Well	SqCWD	1984-2015	A
T-Hopkins Well	SqCWD	1990-2016	DEF/F
Ledyard Well	SqCWD	1986-2016	BC
Aptos Creek Well	SqCWD	1984-2016	DEF/F, BC
Estates Well	SqCWD	1986-2016	BC, A
Madeline Well #2	SqCWD	1984-2015	BC
Main Street Well	SqCWD	1988-2016	AA, Tu
Rosedale 2 Well	SqCWD	1984-2016	A, AA
Tannery Well	SqCWD	1984-2000	A, AA
Maplethorpe Well	SqCWD	1984-2015	A, AA
Garnet Well	SqCWD	1996-2016	A
Sells Well	SqCWD	1984-2015	Aromas
Altivo Well	SqCWD	1984-2015	Aromas
Bonita Well	SqCWD	1984-2016	DEF/F
Seascape Well	SqCWD	1984-2015	DEF/F
San Andreas Well	SqCWD	1992-2016	DEF/F
Country Club Well	SqCWD	1985-2016	DEF/F

[1]See *Soquel-Aptos Groundwater Flow Model: Subsurface Model Construction* (HydroMetrics WRI, 2015) for detailed model layer description.

Groundwater pumping volumes are based on a number of sources. Municipal pumping within the Basin is metered, and historical records have been supplied by the primary municipal pumping agencies. For non-metered areas, the amount of water use is estimated based on land use. The estimates for non-municipal domestic water use, including the methodology for estimating institutional, recreational, and agricultural irrigation water use, is described in detail in the *Santa Cruz Mid-County Basin Groundwater Flow Model: Water Use Estimates and Return Flow Implementation* memorandum (HydroMetrics WRI, 2017c).

Pumping data applied to the model are generally grouped into the following categories:

- Municipal pumping for the calibration period of October 1984 through October 2015 were obtained from SqCWD, the City of Santa Cruz, and CWD. Pumping from Watsonville or Pajaro Valley Water Management Agency (PVWMA) wells near the southeastern boundary of the model was not explicitly simulated in the model as the specified head boundary condition incorporates the effects of that pumping.

- Pumping for private water use was based on a count of residential buildings per model cell (HydroMetrics WRI, 2017c)

- Institutional water use was estimated or recorded at specific properties (HydroMetrics WRI, 2017c).
- Agricultural pumping was calculated based on crop demand and evapotranspiration demand (HydroMetrics WRI, 2017c). Evapotranspiration demand is calculated by PRMS for the 1984-2015 period as the difference between potential evapotranspiration and actual evapotranspiration from rainfall.

Figure 12 shows the simulated pumping flows by use type within the Santa Cruz Mid-County Basin (MCB) and in the model domain outside the Basin.

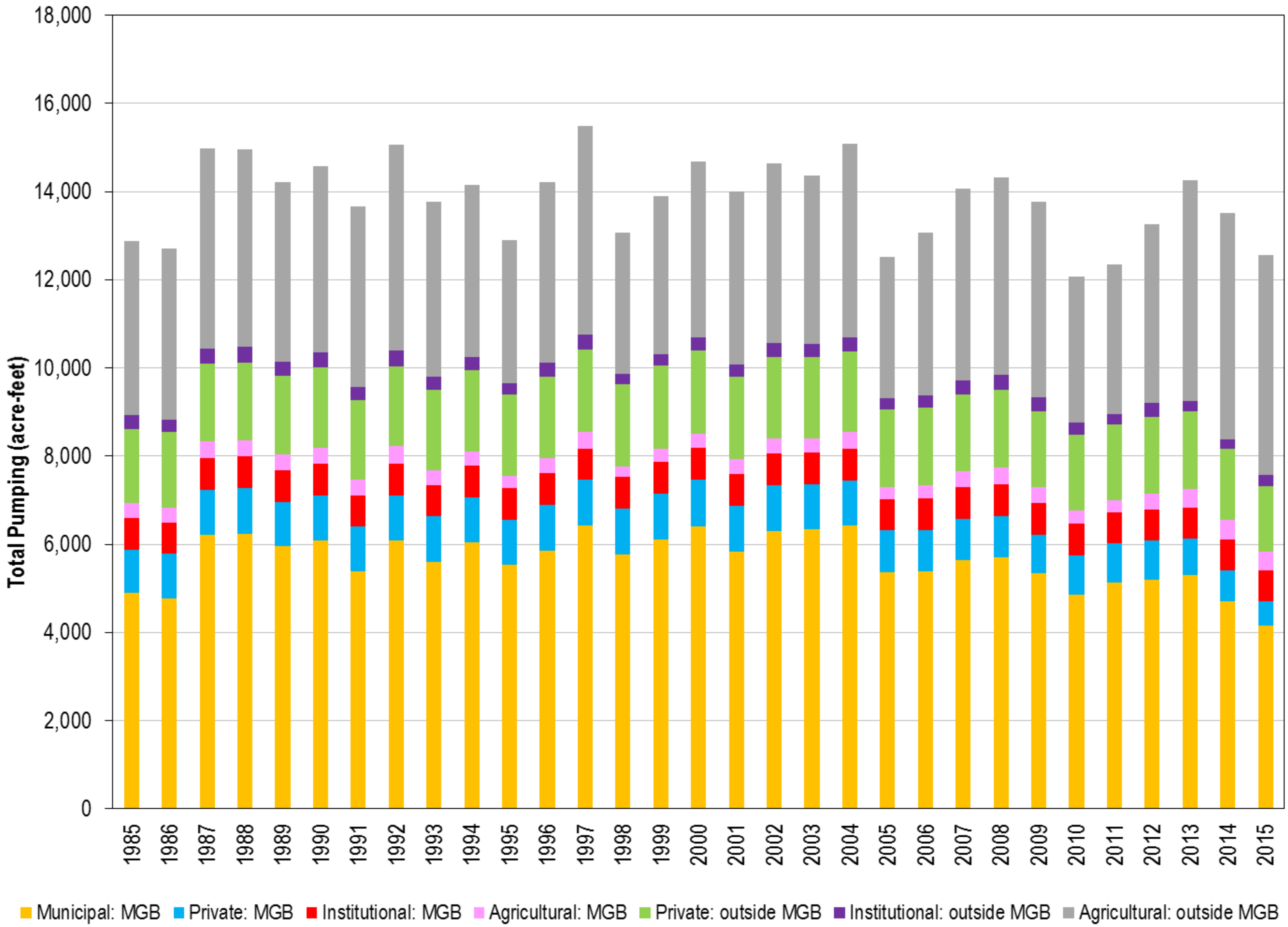


Figure 12. Simulated Groundwater Pumping by Use Type and Location

4.4 Return Flow Data

Return flow is implemented with the UZF package described in Section 3.5.4. There are a number of return flow components included in the groundwater model, as described below.

1. Return flow from system losses, which are losses from water, sewer and septic systems. Water system losses are estimated as a percentage of estimated deliveries to each service area and applied in UZF to model cells overlying those service areas. Details on the approach used to estimate municipal return flow estimates are provided in Appendix A. Municipal areas with system losses are City of Santa Cruz, CWD, SqCWD, and City of Watsonville. Sewer and septic system losses are estimated as a proportion of indoor water use overlying sewered and non-sewered areas, respectively, and applied in UZF to model cells underlying those areas. Indoor use is assumed to be 70% of total water use, and 90% of indoor water use is assumed to become wastewater (HydroMetrics WRI, 2017c). For wastewater return flows in sewered areas, return flows from sewer losses are assumed to be the same percentage used for system losses and losses area applied to model cells overlying sewered areas. For non-sewered areas, it was assumed 90% of wastewater becomes return flow through leakage from septic systems.

2. Return flow from the inefficient portion of municipal and non-municipal domestic and institutional irrigation. Return flow represented by the inefficient portion (10%) of large-scale irrigation of sports fields and parks in both municipal areas and for institutional use outside of municipal served areas is applied to model cells that overlie those irrigated areas. Large-scale irrigation demand is estimated as the difference between capillary zone PET and actual rainfall ET simulated by PRMS, the area being irrigated, and a crop factor. For return flow from non-municipal domestic irrigation, the inefficient portion (10%) of outdoor domestic use is applied in the model using the non-municipal domestic water use described in *Santa Cruz Mid-County Basin Groundwater Flow Model: Water Use Estimates and Return Flow Implementation* memorandum (HydroMetrics WRI, 2017c). It is assumed that approximately 30% of total domestic water use is outdoor use.

3. Return flow from the inefficient portion of agricultural irrigation. It was assumed that the return flow from agricultural irrigation is 10% of agricultural pumping or demand, described in Section 4.3. As described in the *Santa Cruz Mid-County Basin Groundwater Flow Model: Water Use Estimates and Return Flow Implementation* memorandum (HydroMetrics WRI, 2017c), agricultural return

flow is applied in UZF to model cells overlying areas with mapped irrigated agriculture.

Figure 13 shows return flows by use type within the Santa Cruz Mid-County Groundwater Basin (MGB) and in the model domain outside the Basin. The largest component of return flow in the model is from private groundwater use, which includes both the inefficient portion of landscape irrigation and leakage from septic systems. The second greatest component of return flow in the model is from municipal uses. This category includes system losses and the inefficient portion of domestic and large-scale landscape irrigation. Within the Mid-County Basin, return flow from municipal use is greater than from private use.

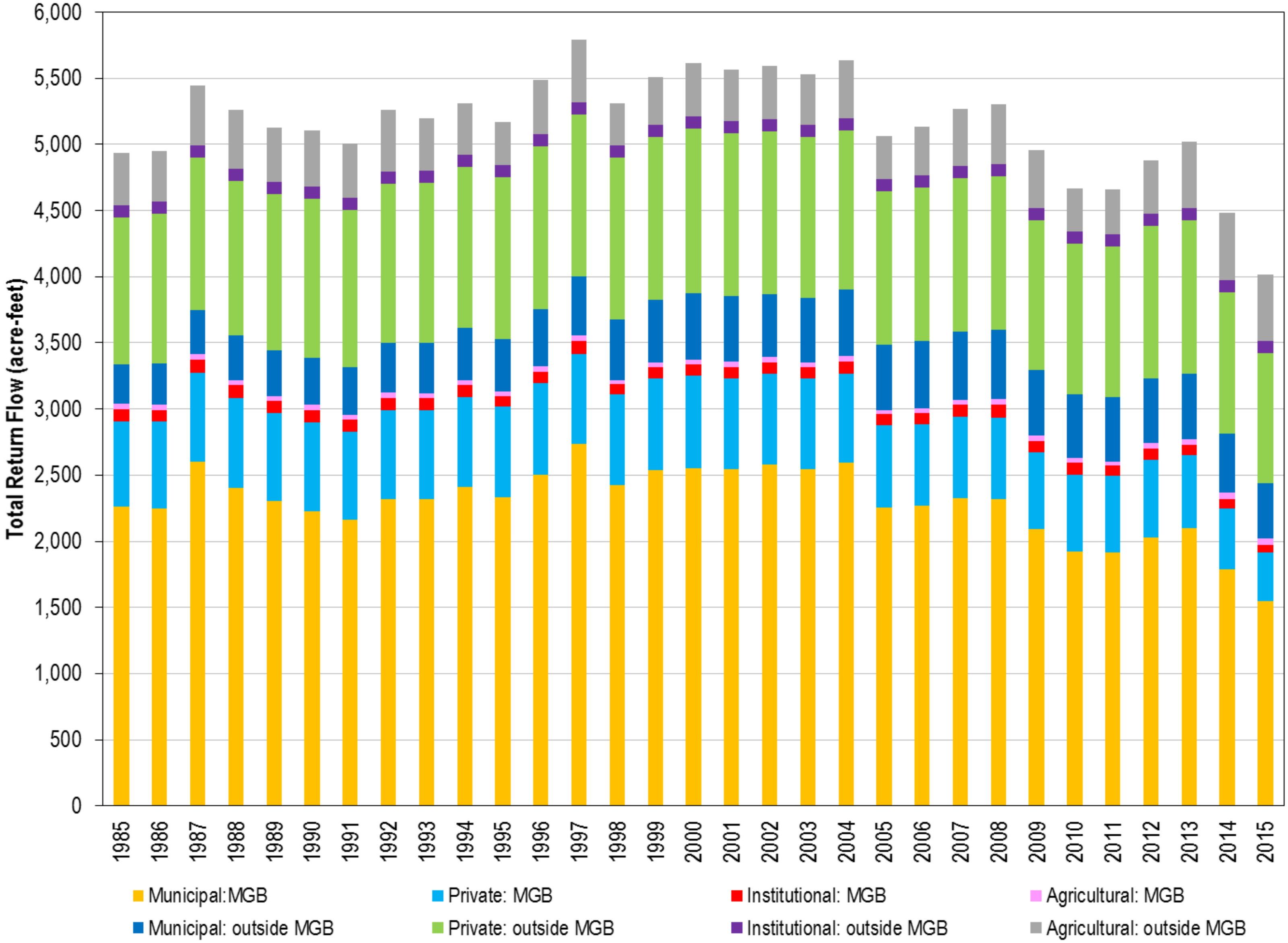


Figure 13: Simulated Return Flow by Use Type and Location

5 CALIBRATION TARGET DATA

This section describes the nature and source of observed data used to compare against simulated results during the calibration process.

5.1 Climate Calibration Targets

The first step in calibrating watershed processes is to calibrate how climate data are translated to available water in the watershed. The available water is the precipitation, less evapotranspiration. Target data that are calibrated in this step are solar radiation and potential evapotranspiration. Solar radiation data are measured at the De Laveaga CIMIS and Corralitos RAWS stations (Figure 7). Calibration target data for potential evapotranspiration at these stations are calculated based on solar radiation, temperature, humidity, and wind speed using the ASCE standard Penmen- Monteith equation for a grass reference surface (ASCE-EWRI, 2005).

5.2 Streamflow Calibration Targets

Streamflow data from eleven stream gauges within the model domain are available for use as calibration targets. Observed daily streamflow values are compared against simulated streamflow values at these gauges during the calibration process. Where data are not available at a gauge for the entire calibration period, synthetic data are produced based on linear regressions from double-mass curves.

Double-mass curves are generated between gauges with incomplete records and one of the two gauges with complete records for the concurrent data period. Linear regression equations are developed for each of the double-mass curves. Double-mass curves are extrapolated to the entire model calibration period based on the linear regression equation. Additional detail on this approach can be found in the *Estimation of Deep Groundwater Recharge Using a Precipitation-Runoff Watershed Model* report (HydroMetrics WRI, 2011)

Table 5 lists the gauges used for calibration of streamflow within the model. The location of these gauges is shown in Figure 5.

Table 5: Summary of Gauge Locations used as Calibration Targets

Gauge Name	Date Range of Available Data	Source of Data
West Branch	1984-2016	SqCWD
Upper Soquel Creek	10/1/1983 - 1/30/1986 11/21/1986 – present[1]	SqCWD
West Branch Soquel Creek near Soquel	10/1/1958 – 10/6/1972[2]	USGS[3]
Soquel Creek near Soquel	10/1/1968 – 9/30/1972[2]	USGS
Soquel Creek at Soquel	5/1/1951 – present	USGS
Aptos Creek near Aptos	10/1/1971 – 9/30/1985[2]	USGS
Aptos Creek at Aptos	10/1/1958 – 10/6/1972	USGS
Valencia Creek	10/1/2008 - 12/31/2009	Santa Cruz Co.
Branciforte Creek at Santa Cruz[4]	Estimated for model period[2]	USGS
Corralitos Creek near Corralitos	10/1/1957 – 10/11/1972[2]	USGS
Corralitos Creek at Freedom	10/1/1956 – present	USGS

[1] Data available intermittently
[2] Estimated for model period based on linear regressions from double-mass curves generated between gauges with incomplete records and one of the two gauges with complete records for overlapped data
[3] U.S. Geological Survey
[4] Part of watershed for gauge outside model domain

5.3 Groundwater Elevation Calibration Targets

5.3.1 Targets in Model Layers Representing Basin Aquifer Units

Groundwater elevations have been measured at a number of production and monitoring wells in the Purisima Formation and Aromas Red Sands within the model domain throughout the calibration period. A total of 121 individual monitoring locations were identified within the model domain, and groundwater level data from those wells were added to the model as calibration targets in model layers representing the Purisima Formation and Aromas Red Sands after excluding observations determined to be anomalous or unreliable. Observations from wells that are screened across multiple model layers are input into the model as composite water levels that are weighted by layer transmissivity according to the percentage of screened interval in each layer. Table 6 lists the wells used as groundwater level calibration targets in Basin aquifer units within the model. Plate 4 shows the location of these wells used as calibration targets within each aquifer layer of the model. Most calibration targets are south of the Aptos area horizontal flow barrier where it is modeled. There are no calibration targets north of the Zayante Fault.

Table 6. Wells used as Groundwater Elevation Calibration Targets in Basin Aquifer Units

Well Name	Associated Agency	Model Layer(s)[1]	Water Year Range of Calibration Data[2]
30th Ave-1	City of Santa Cruz	Tu	2013-2015
30th Ave-2	City of Santa Cruz	AA	2013-2015
Auto Plaza Deep	City of Santa Cruz	AA	2010-2015
Auto Plaza Medium	City of Santa Cruz	AA	2010-2015
Auto Plaza Shallow	City of Santa Cruz	A	2010-2015
Beltz #2	City of Santa Cruz	A	2004-2015
Beltz #6	City of Santa Cruz	A	2004-2015
Beltz #7 Deep	City of Santa Cruz	Tu	2013-2015
Beltz # 7 Test Well	City of Santa Cruz	Tu	2004-2015
Coffee Lane Park Deep	City of Santa Cruz	AA	2010-2015
Coffee Lane Park Shallow	City of Santa Cruz	AA	2010-2015
Corcoran Lagoon Deep	City of Santa Cruz	AA	2004-2015
Corcoran Lagoon Medium	City of Santa Cruz	A	2004-2015
Corcoran Lagoon Shallow	City of Santa Cruz	B Aquitard-A	2004-2015
Cory Street-4	City of Santa Cruz	Tu	2014-2015
Cory Street Deep	City of Santa Cruz	AA	2010-2015
Cory Street Medium	City of Santa Cruz	AA	2010-2015
Cory Street Shallow	City of Santa Cruz	A-AA	2010-2015
Moran Lake Deep	City of Santa Cruz	A	2004-2015
Moran Lake Medium	City of Santa Cruz	A	2004-2015
Moran Lake Shallow	City of Santa Cruz	A	2004-2015
Pleasure Point Deep	City of Santa Cruz	AA	2000-2015
Pleasure Point Medium	City of Santa Cruz	A	2000-2015
Pleasure Point Shallow	City of Santa Cruz	A	1989-2015
Schwan Lake	City of Santa Cruz	A	2004-2015
Soquel Point Deep	City of Santa Cruz	A-AA	2004-2015
Soquel Point Medium	City of Santa Cruz	A	2004-2015
Soquel Point Shallow	City of Santa Cruz	A	2004-2015
Thurber Ln Deep	City of Santa Cruz	Tu	2008-2015
Black	CWD	Aromas	1985-2014
Cox-3	CWD	DEF/F	1985-2015
CWD-B	CWD	Aromas	2006-2015
CWD-C	CWD	DEF/F	2006-2015
Altivo	SqCWD	Aromas	1984-2015
Bonita	SqCWD	Aromas-DEF/F	1984-2015

Well Name	Associated Agency	Model Layer(s)[1]	Water Year Range of Calibration Data[2]
Country Club	SqCWD	Aromas-DEF/F	1984-2015
Rob Roy-4	SqCWD	Aromas-DEF/F	1985-2015
San Andreas	SqCWD	Aromas-DEF/F	1992-2015
SC-10AAA	SqCWD	AA	1986-2015
SC-10AAR	SqCWD	AA	1986-2015
SC-11A-R	SqCWD	A	2006-2015
SC-11B	SqCWD	BC	2006-2013
SC-11C	SqCWD	D Aquitard-BC	2006-2013
SC-11D-R	SqCWD	DEF/F-D Aquitard	2006-2013
SC-11RB	SqCWD	BC	2014-2015
SC-13A	SqCWD	Tu	1995-2015
SC-14A	SqCWD	A-AA	1986-2015
SC-14B	SqCWD	BC-B Aquitard	1986-2015
SC-15A	SqCWD	AA	2006-2015
SC-15B	SqCWD	A	2006-2015
SC-16A	SqCWD	B Aquitard-A	1986-2015
SC-16B	SqCWD	D Aquitard-BC	2016-2015
SC-17A	SqCWD	B Aquitard-A	1986-2015
SC-17B	SqCWD	D Aquitard-BC	1986-2015
SC-17C	SqCWD	DEF/F-D Aquitard	2007-2015
SC-18AAR	SqCWD	Tu	1999-2017
SC-18A-R	SqCWD	AA	1999-2015
SC-19	SqCWD	DEF/F	2007-2015
SC-1A	SqCWD	A-AA	1986-2015
SC-20A	SqCWD	DEF/F	2010-2015
SC-21A	SqCWD	A-AA	2012-2015
SC-21AA	SqCWD	AA	2012-2015
SC-21AAA	SqCWD	Tu	2012-2015
SC-22A	SqCWD	A-AA	2013-2015
SC-22AAA	SqCWD	Tu	2012-2015
SC-23A	SqCWD	D Aquitard-BC	2014-2015
SC-23C	SqCWD	DEF/F	2014-2015
SC-3A-R	SqCWD	A-AA	1986-2009
SC-3B-R	SqCWD	BC-B Aquitard	1986-2005
SC-3C-R	SqCWD	BC	1990-2015
SC-5A-R	SqCWD	A-AA	1986-2015

Well Name	Associated Agency	Model Layer(s)[1]	Water Year Range of Calibration Data[2]
SC-5C-R	SqCWD	BC	1986-2015
SC-5D	SqCWD	D Aquitard-BC	1986-2000
SC-5RB	SqCWD	B Aquitard	2003-2015
SC-8A	SqCWD	A	1986-1992
SC-8B	SqCWD	BC-B Aquitard	1986-1992
SC-8RA	SqCWD	A	1996-2015
SC-8RB	SqCWD	BC	1996-2015
SC-8RD	SqCWD	D Aquitard	1996-2015
SC-9A-R	SqCWD	A	1986-2012
SC-9C-R	SqCWD	BC	1986-2012
SC-9E-R	SqCWD	DEF/F-D Aquitard	1988-2012
SC-A1B	SqCWD	DEF/F	1989-2015
SC-A1D	SqCWD	DEF/F	1989-2015
SC-A2A-R	SqCWD	DEF/F	1989-2015
SC-A2C-R	SqCWD	Aromas	1989-2015
SC-A3A	SqCWD	Aromas	1989-2015
SC-A4A	SqCWD	Aromas	2002-2015
SC-A4B	SqCWD	Aromas	2002-2015
SC-A5A	SqCWD	DEF/F	1994-2015
SC-A5C	SqCWD	Aromas	2002-2015
SC-A6A	SqCWD	DEF/F	2004-2015
SC-A7B	SqCWD	Aromas	2004-2015
SC-A7C	SqCWD	Aromas	2004-2015
SC-A8A	SqCWD	DEF/F	2008-2015
SC-A8C	SqCWD	Aromas	2008-2015
SC-A9A	SqCWD	DEF/F	2014-2015
SC-A9B	SqCWD	Aromas	2014
Seascape	SqCWD	Aromas	1986-2015
Sells	SqCWD	Aromas	1984-2015
01E04BP	Private	DEF/F	2009-2015
01E04DP	Private	Aromas	2009-2014
01E04EP	Private	DEF/F	2009-2015
01E04FP	Private	DEF/F	2009-2015
01E05AP	Private	DEF/F	2008-2015
01E06AS	Private	DEF/F	2009
01E08AS	Private	DEF/F	2008-2011

Well Name	Associated Agency	Model Layer(s)[1]	Water Year Range of Calibration Data[2]
01E08BS	Private	DEF/F	2008-2012
01E09AP	Private	DEF/F	2009-2013
01E09BP	Private	DEF/F	2009-2010
01E15AS	Private	Aromas	2008-2015
01E22AS	Private	Aromas	2009-2011
01E22BS	Private	Aromas	2009-2015
01W06AS	Private	Tu	2009-2015
01W06BS	Private	Tu	2009-2015
01W06DP	Private	Tu	2011-2015
01W14BP	Private	Tu	2008-2015
01W15AP	Private	Tu	2008-2015
01W22AS	Private	Tu	2008-2015
01W30AP	Private	Tu	2008-2015
01W32AS	Private	Tu	2009-2015

[1] See *Soquel-Aptos Groundwater Flow Model: Subsurface Model Construction* (HydroMetrics WRI, 2015) for detailed model layer descriptions
[2] Water year

5.3.2 Targets for Shallow Groundwater along Soquel Creek

As part of a scope for Santa Cruz County's Prop 1 grant for Counties with Stressed Basins, additional calibration was performed including shallow groundwater levels along Soquel Creek as targets. The purpose of this calibration is to improve simulation of stream-aquifer interaction along Soquel Creek to inform development of sustainability management criteria for streamflow depletion from pumping, including use of shallow groundwater levels as groundwater level proxies. Table 7 lists the shallow wells along Soquel Creek used as groundwater elevation targets. Figure 14 shows the locations of these shallow wells.

Table 7. Shallow Wells along Soquel Creek used as Groundwater Elevation Calibration Targets

Well Name	Associated Agency	Model Layer(s)[1]	Water Year Range of Calibration Data[2]
Simons	SqCWD	Alluvium overlying A	2002-2011
Balogh	SqCWD	Alluvium overlying A	2002-2015
Main St SW-1	SqCWD	Alluvium overlying A	2001-2015
Wharf Road SW	SqCWD	Alluvium overlying A	2013-2015
Nob Hil SW 2I	SqCWD	Alluvium overlying A	2001-2015

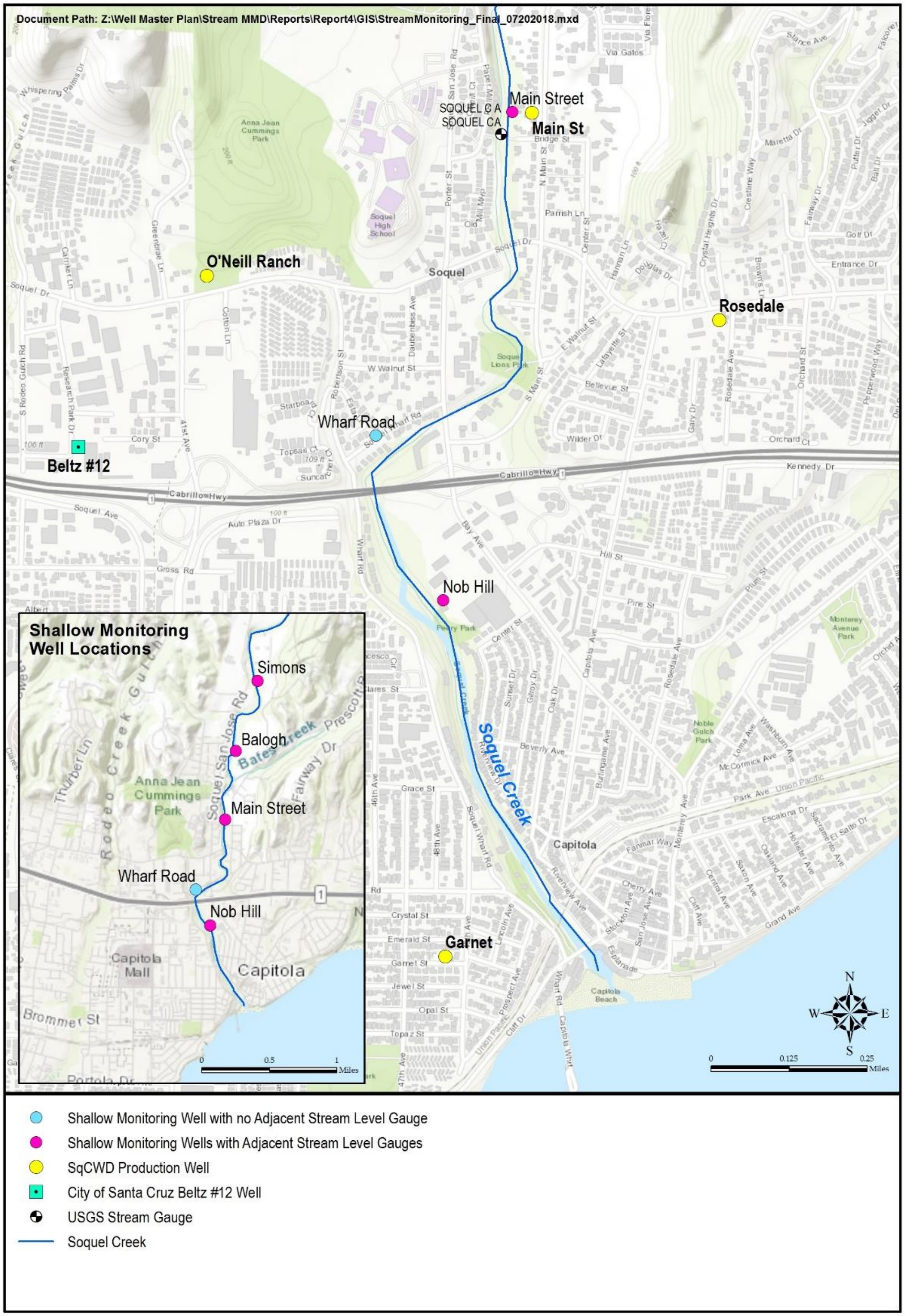


Figure 14. Locations of Shallow Groundwater Elevation Targets along Soquel Creek

These groundwater level targets are located in model layer 6 representing alluvium underlying Soquel Creek and overlying the Purisima A unit. Previous studies (LKA and LSCE, 2003) indicated that at least the Main St SW-1 is screened in the Purisima Formation, but the vertical gradient observed between the shallow groundwater levels and deeper Purisima Formation groundwater levels observed at monitoring well SC-18A justifies simulating the shallow wells in the model layer directly beneath Soquel Creek. Therefore, the model is calibrated to simulate the vertical connection of Soquel Creek to underlying Purisima Formation. The model does not simulate the horizontal connection of Soquel Creek to shallow wells along the Creek as the distance between the Creek and wells are less than the model cell width of 800 feet as shown in Figure 15.

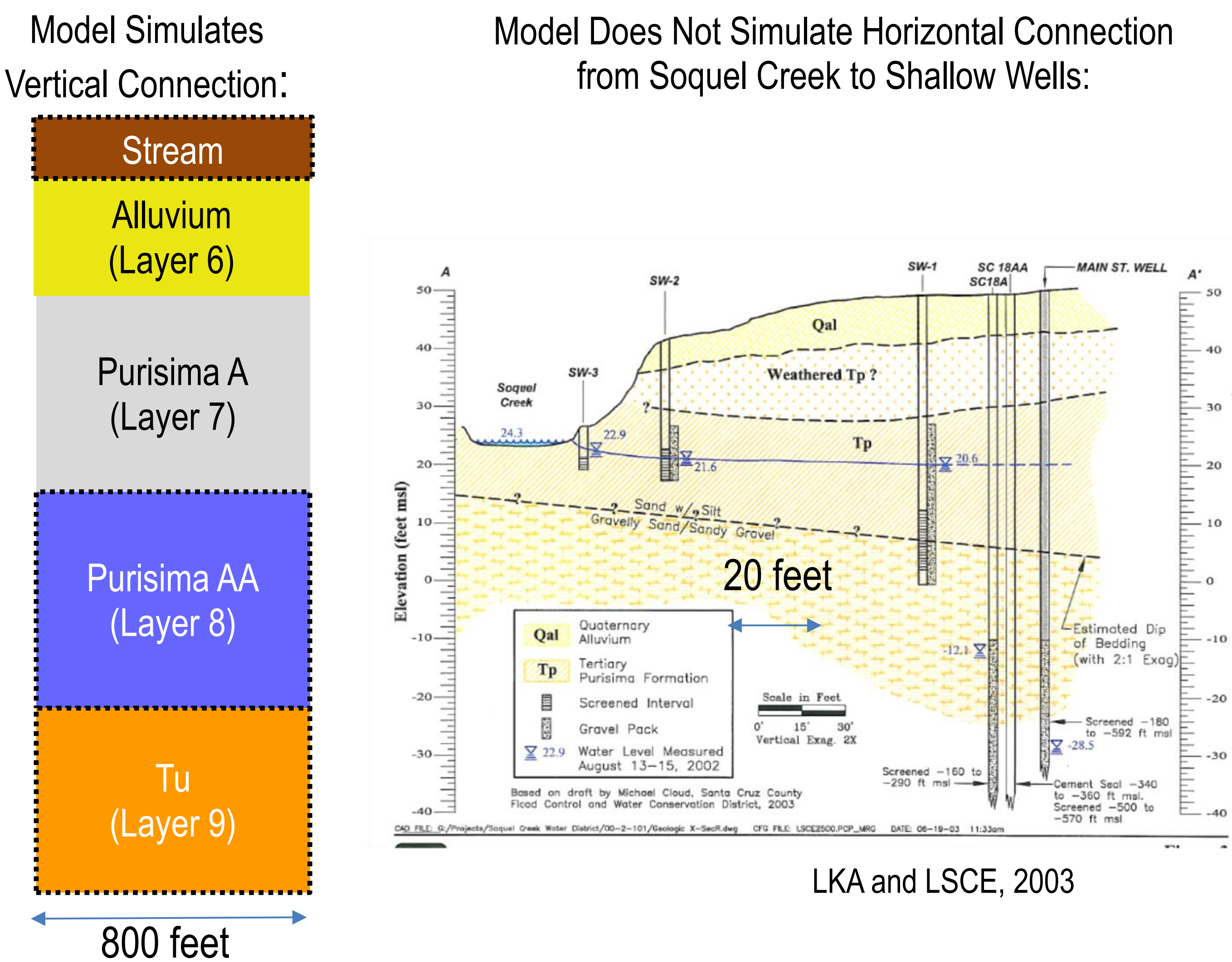


Figure 15. Model Simulation of Vertical Connection between Stream-Aquifers

6 CALIBRATION PROCESS

Calibrating the Basin model involves successive attempts to match simulated output to calibration targets during the calibration period. Simulated climate, streamflow and groundwater elevation data are compared to observed values, and surface and groundwater parameters are adjusted between model runs to improve the fit of simulated to observed values.

Preliminary work calibrating the model involved using separate models. One model calibrated climate and surface water flow using only the PRMS watershed model. A second model calibrated groundwater-only flow using the MODFLOW model. A major factor contributing to this decision was the relative model run times of the separate model packages compared to the integrated GSFLOW model. Separate models used to calibrate different datasets were as follows:

1. PRMS only runs for Water Years 1985-2015 to calibrate to climate output of solar radiation and potential evapotranspiration. Solar radiation and potential evapotranspiration calculations remain consistent when run as part of GSFLOW.

2. GSFLOW runs for Water Years 1992-1995 to calibrate to streamflow. Streamflow calibrated to PRMS only runs did not remain consistent when run as part of GSFLOW due to simulation of groundwater discharge to the soil zone in GSFLOW. The US Geological Survey recommended calibrating to a shorter time period to reduce run times. Water Years 1992-1995 includes variation in climate that makes it appropriate for calibrating streamflow under different climate conditions.

3. MODFLOW only runs for Water Years 1985-2015. When an acceptably-calibrated model fit to streamflow observations was achieved, a GSFLOW run for Water Years 1985-2015 was run to estimate recharge and a corresponding MODFLOW-only model using the recharge estimates was created to change groundwater parameters to achieve calibration to groundwater observations to understand model sensitivities and develop strategies for calibrating to groundwater levels.

4. GSFLOW runs for Water Years 1992-1995 to recalibrate to streamflow again. Changes to groundwater parameters did not change streamflow calibration substantially, but streamflow calibration was adjusted for consistency.

5. GSFLOW runs for Water Years 1985-2015. There are some differences in groundwater results provided by MODFLOW only and GSFLOW runs so final calibration to groundwater levels was based on GSFLOW runs. Further adjustment of climate or watershed parameters was not necessary as part of this calibration.

6. Under the scope for Santa Cruz County's Prop 1 grant. GSFLOW runs for Water Years 1985-2015 to calibrate to shallow groundwater levels along Soquel Creek while maintaining streamflow calibration and calibration in underlying Purisima Formation aquifer units.

7 MODEL CALIBRATION

This section presents the model calibration that includes calibrating to climate, streamflow, and groundwater level targets.

7.1 Climate Calibration

PRMS solar radiation and potential evapotranspiration parameters were first calibrated to measured solar radiation (SR) and calculated potential evapotranspiration (PET) at the Delaveaga CIMIS and Corralitos RAWS stations (HydroMetrics WRI, 2016a). PRMS calculates solar radiation using the ddsolrad module where the parameters are slope and intercept of the maximum temperature per degree day linear relationship. Monthly parameters (dday_intcp and dday_slope) are calibrated (Table 8) to monthly averages of solar radiation (Figure 16 and Figure 17). Based on calibrated solar radiation, monthly coefficients (pt_alpha) for the Priestly-Taylor equation (Table 8) are adjusted to calibrate simulated potential evapotranspiration to average potential evapotranspiration at the stations (Figure 18 and Figure 19). The Priestly-Taylor equation requires relative humidity so average monthly relative humidity from the Santa Cruz Co-op station is used (Table 8).

Table 8. Monthly Parameters for Solar Radiation and Potential Evapotranspiration

Parameter Name	dday_intcp	dday_slope	hum_pct	pt_alpha
Parameter Description	Intercept in temperature degree-day relation	Slope in temperature degree-day relation	Monthly relative humidity percent	Monthly adjustment factor used in Priestly-Taylor PET calculations
January	-13.6453	0.2715	75	0.9116
February	-20.0454	0.3977	72	0.7988
March	-26.6630	0.5290	70	0.7668
April	-34.9496	0.6562	70	0.78520
May	-44.0930	0.7574	72	0.7383
June	-54.5417	0.8769	75	0.7574
July	-54.1731	0.8449	80	0.7514
August	-49.4067	0.7701	82	0.7531
September	-39.2594	0.6358	75	0.7731
October	-28.2960	0.4917	70	0.8563
November	-15.3850	0.3092	70	0.9507
December	-11.2614	0.2698	76	0.9002

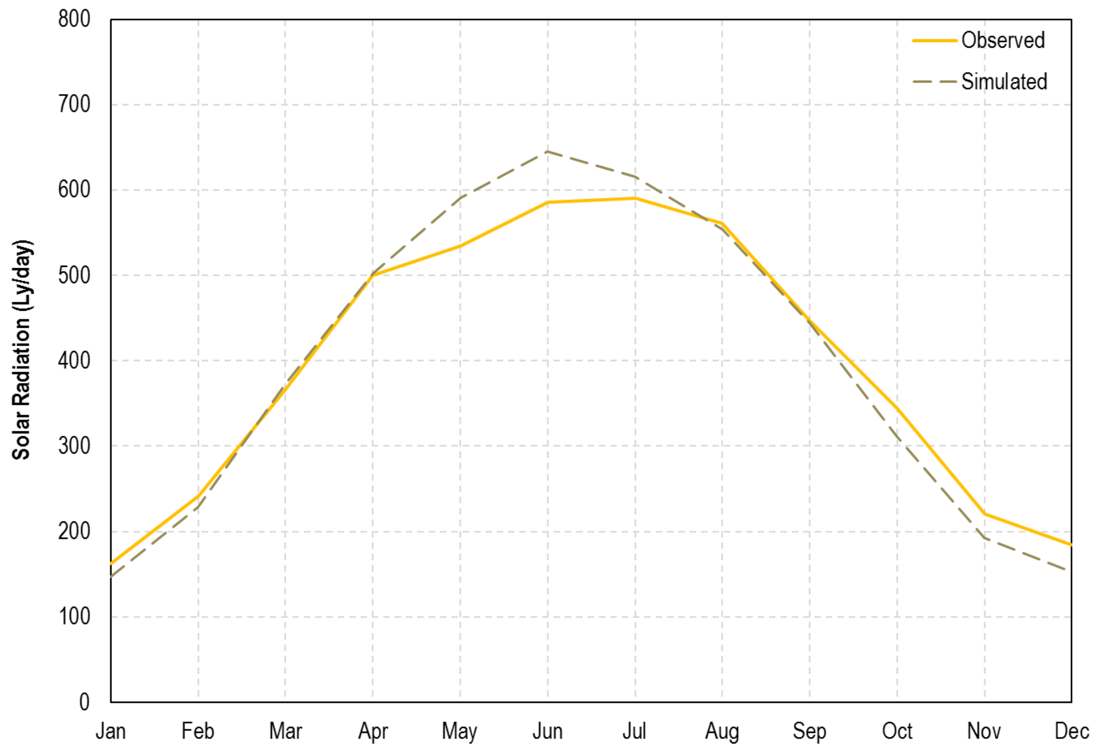


Figure 16. Calibration of Solar Radiation at de Lavega CIMIS Station

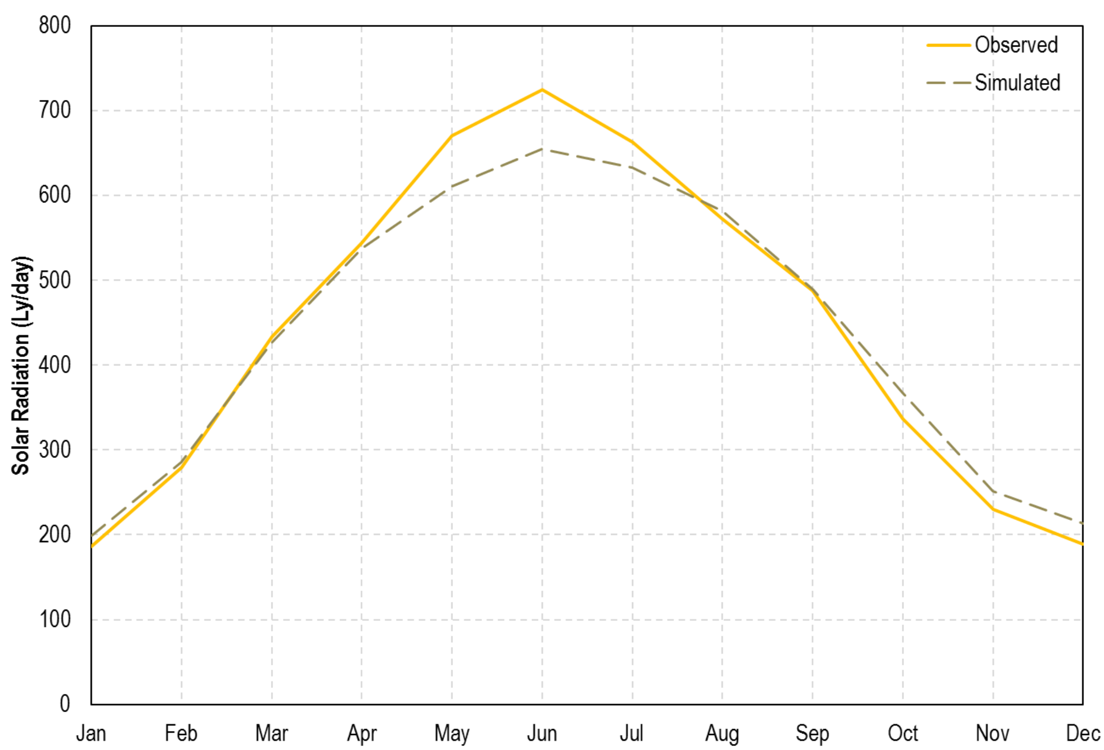


Figure 17. Calibration of Solar Radiation at Corralitos RAWS Station

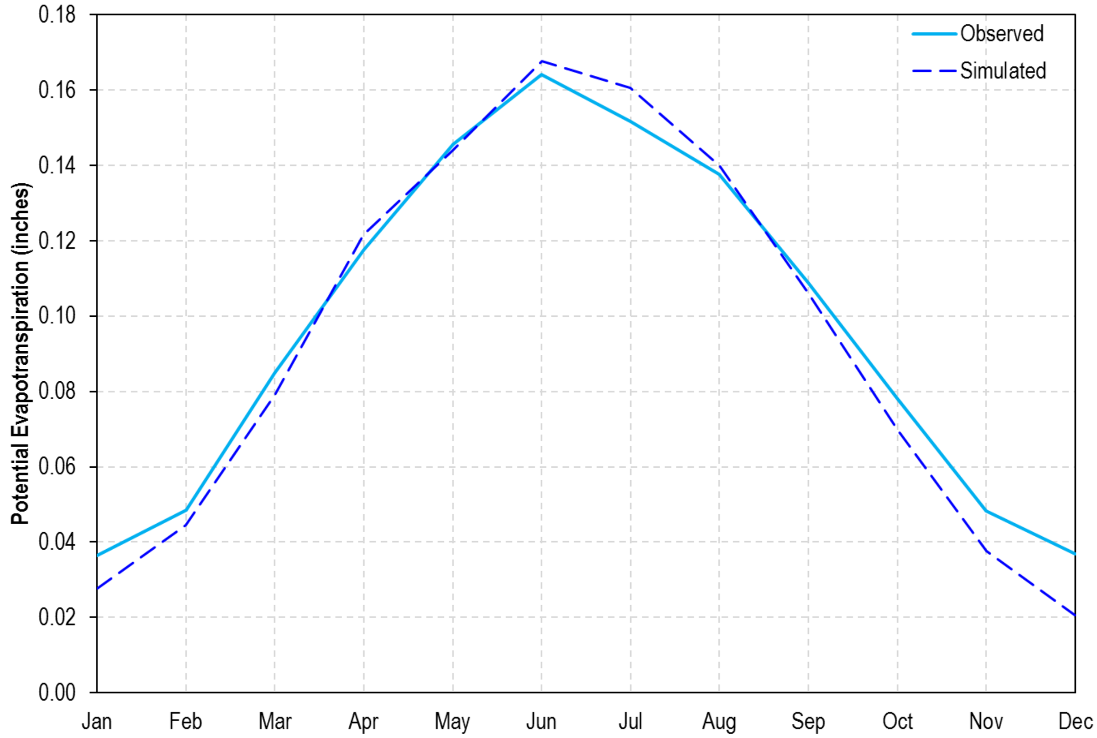


Figure 18. Calibration of Potential Evapotranspiration at de Lavega CIMIS Station

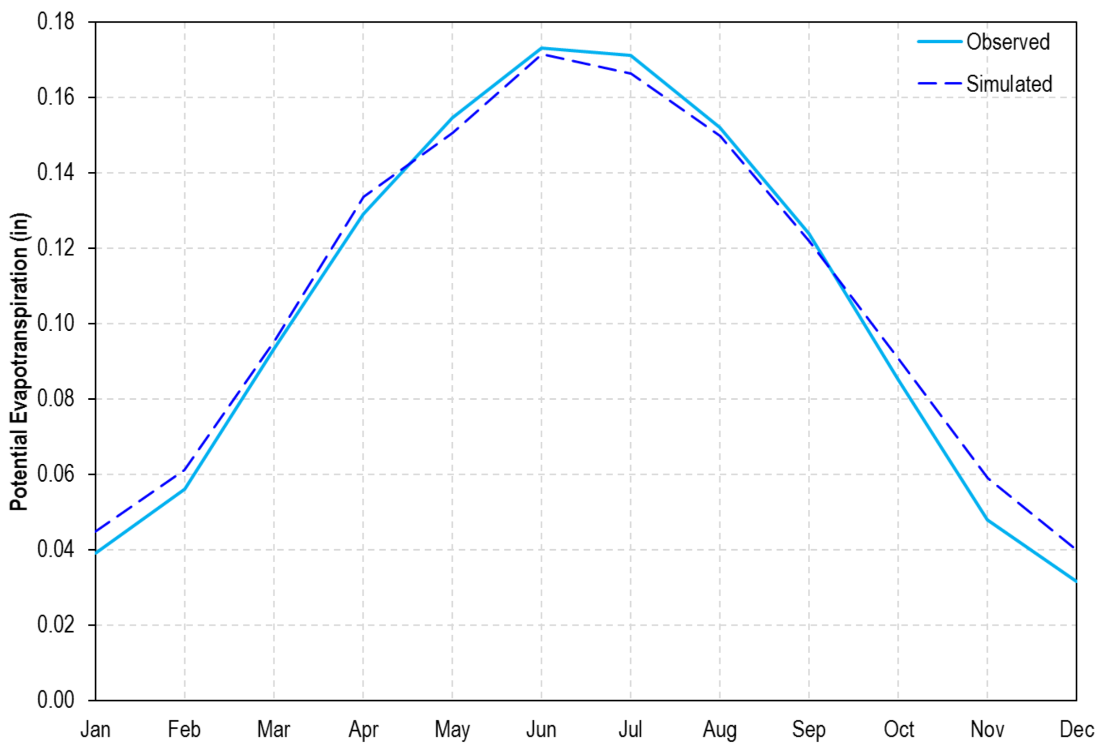


Figure 19. Calibration of Potential Evapotranspiration at Corralitos RAWS Station

7.2 Surface Water Calibration

Calibration of the surface water component of the model with the GSFLOW run simulating Water Years 1992-1995 compares GSFLOW model MODFLOW GAGE package output at stream gauges with daily observations at the stream gauge. Watershed parameters were adjusted to improve the match between simulated output and observations.

7.2.1 Watershed Parameters by Zone

Watershed parameters were adjusted by zones for Soquel Creek, Aptos Creek, and Corralitos Creek upstream and downstream of Zayante Fault, which is the northern boundary of the Basin (Figure 5). Gauges on these creeks can be sorted into upstream and downstream gauges with the simulated streamflow at the upstream gauges primarily affected by parameters in its watershed upstream of Zayante Fault and simulated streamflow at the downstream gauges affected by parameters at both zones in the watershed. The watershed parameters affect the streamflows shown in Figure 22.

Some parameters represent the soil zone reservoir volumes and other parameters represent coefficients for empirical equations describing flows to and from soil zone reservoirs. Table 9 describes the watershed parameters and provides their calibrated values.

The capillary zone capacities soil_moist_max and soil_rechr_max have spatial variation within each PRMS parameter zone based on calculations using the SSUGRO soils dataset for the previous PRMS recharge dataset (HydroMetrics WRI, 2011). Zone based factors multiplying spatial variation within the zones are used for calibration. Figure 20 shows the calibrated results of this multiplication.

In general, parameters representing flows from the soil zone are on the low end of the expected range while parameters representing soil moisture capacities (sat_threshold, soil_moist_max, and soil_rechr_max) are relatively high. This facilitates soil zone only slowly releasing water to streams and groundwater to calibrate slow recession curves observed at stream gauges in the watersheds.

Table 9. Watershed Parameters by Zone

Parameter Name	Parameter Description	Associated Flow	Upper Soquel	Lower Soquel	Upper Aptos	Lower Aptos	Upper Corralitos	Lower Corralitos
fastcoef_lin	Coefficient to route preferential-flow storage down slope	fast interflow	0.023	0.443	0.012	0.010	0.389	0.910
fastcoef_sq	Coefficient to route preferential-flow storage down slope	fast interflow	0.003	0.028	0.000	0.315	0.790	0.818
gwflow_coef	Groundwater routing coefficient	Groundwater Flow	1E-06	1E-06	1E-06	1E-06	1E-06	1E-06
gwsink_coef	Groundwater sink coefficient	Groundwater sink	1	1	1	1	1	1
imperv_stor_max	Maximum impervious area retention storage for each HRU	Hortonian Surface Flow	0	0.490	0.126	1	1	1
pref_flow_den	Preferential-flow pore density	Preferential flow	0.1064	0.0912	0.0841	0.2107	1E-05	1E-05
sat_threshold	Soil saturation threshold, above field-capacity threshold	gravity and preferential flow	11.31	250.72	38.20	184.35	7.27	6.96
slowcoef_lin	Coefficient to route gravity-flow storage down slope	slow interflow	0.0023	1.341E-05	0.0143	0.0009	5.146E-05	0.0012
slowcoef_sq	Coefficient to route gravity-flow storage down slope	slow interflow	0.0204	0.000	0.000	0.0041	0.0034	0.1746
smidx_coef	Coefficient in non-linear contributing area lgorithm	Hortonian Surface Flow	0.0011	0.0010	0.0010	0.0023	0.0010	0.0010
smidx_exp	Exponent in non-linear contributing area algorithm	Hortonian Surface Flow	0.1934	0.1	0.2005	0.1271	0.1	0.1

Parameter Name	Parameter Description	Associated Flow	Upper Soquel	Lower Soquel	Upper Aptos	Lower Aptos	Upper Corralitos	Lower Corralitos
soil_moist_max	Maximum available water holding capacity of soil profile. Soil profile is surface to bottom of rooting zone	NA	21.5	8.5	13.3	20.0	24	24
soil_rechr_max	Maximum value for soil recharge zone (upper portion of soil moisture zone where losses occur as both evaporation and transpiration)	NA	13	7.25	9.71	0.67	9.27	13
soil2gw_max	Maximum amount of the capillary reservoir excess that is routed directly to the GWR for each HRU	Direct Recharge	1.98E-05	0.0025	0.0015	0.0414	0.2337	0.0005
ssr2gw_rate	Coefficient in equation used to route water from the subsurface reservoirs to the groundwater reservoirs	Gravity Drainage	2.5909	0.0045	3.9344	0.1350	0.0203	0.2560
ssr2gw_exp	Coefficient in equation used to route water from the subsurface reservoirs to the groundwater reservoirs	Gravity Drainage	0.0079	0.0162	0.0005	0.0010	0.0102	0.2993

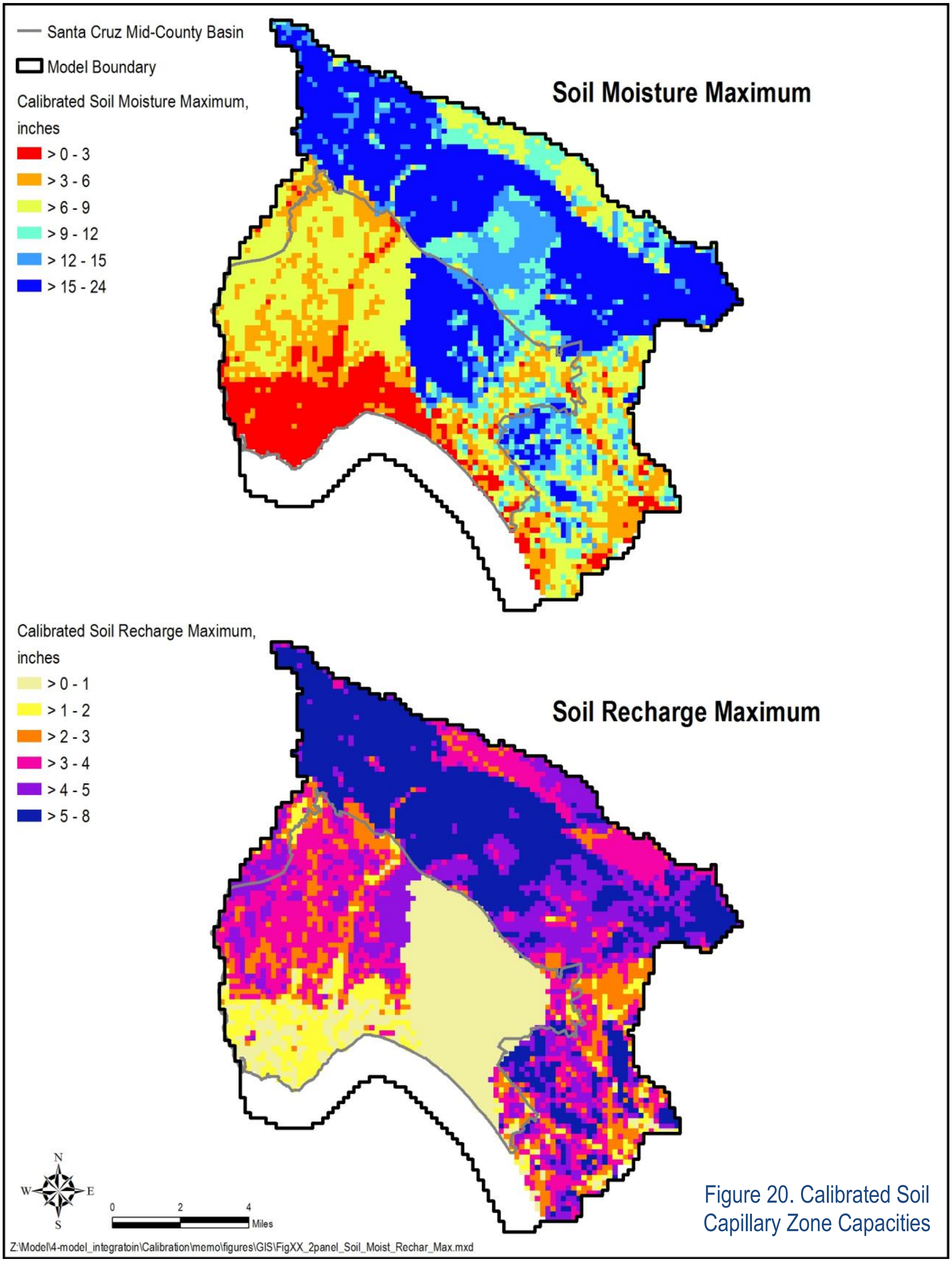


Figure 20. Calibrated Soil Capillary Zone Capacities

7.2.2 MODFLOW SFR Streambed Hydraulic Conductivity

As part of the streamflow calibration with GSFLOW, hydraulic conductivities for streambeds in the MODFLOW SFR package controlling flows between streams and groundwater were calibrated. Figure 21 shows the calibrated streambed hydraulic conductivities by SFR segment. For uniform streambed thickness of 3.28 feet, hydraulic conductivities of 3 x 10^{-}-^{3} feet per day are used for all streams except along lower Soquel Creek where shallow groundwater levels are available for calibration. Values of streambed hydraulic conductivity are relatively low throughout the watershed to facilitate simulation of slow recession curves controlled by soil retention of precipitation.

As calibrated for the Santa Cruz County Prop 1 grant scope, streambed hydraulic conductivities along Soquel Creek are higher (7 x 10^{-2} to 0.3 feet per day) where shallow groundwater level data are available. The data show connection between the shallow groundwater and Soquel Creek because the difference between shallow groundwater and stream stages is relatively small. Therefore, based on these available data, the model simulates more groundwater interaction with the stream for this area than what is simulated for the rest of the model. Simulating a relationship between shallow groundwater levels and flows between groundwater and streams is consistent with use of shallow groundwater levels as groundwater level proxies for streamflow depletion. However, data quantifying flows between the stream and shallow groundwater are not available for calibration so there is high uncertainty of the magnitude of simulated flows between stream and aquifer calculated by the model.

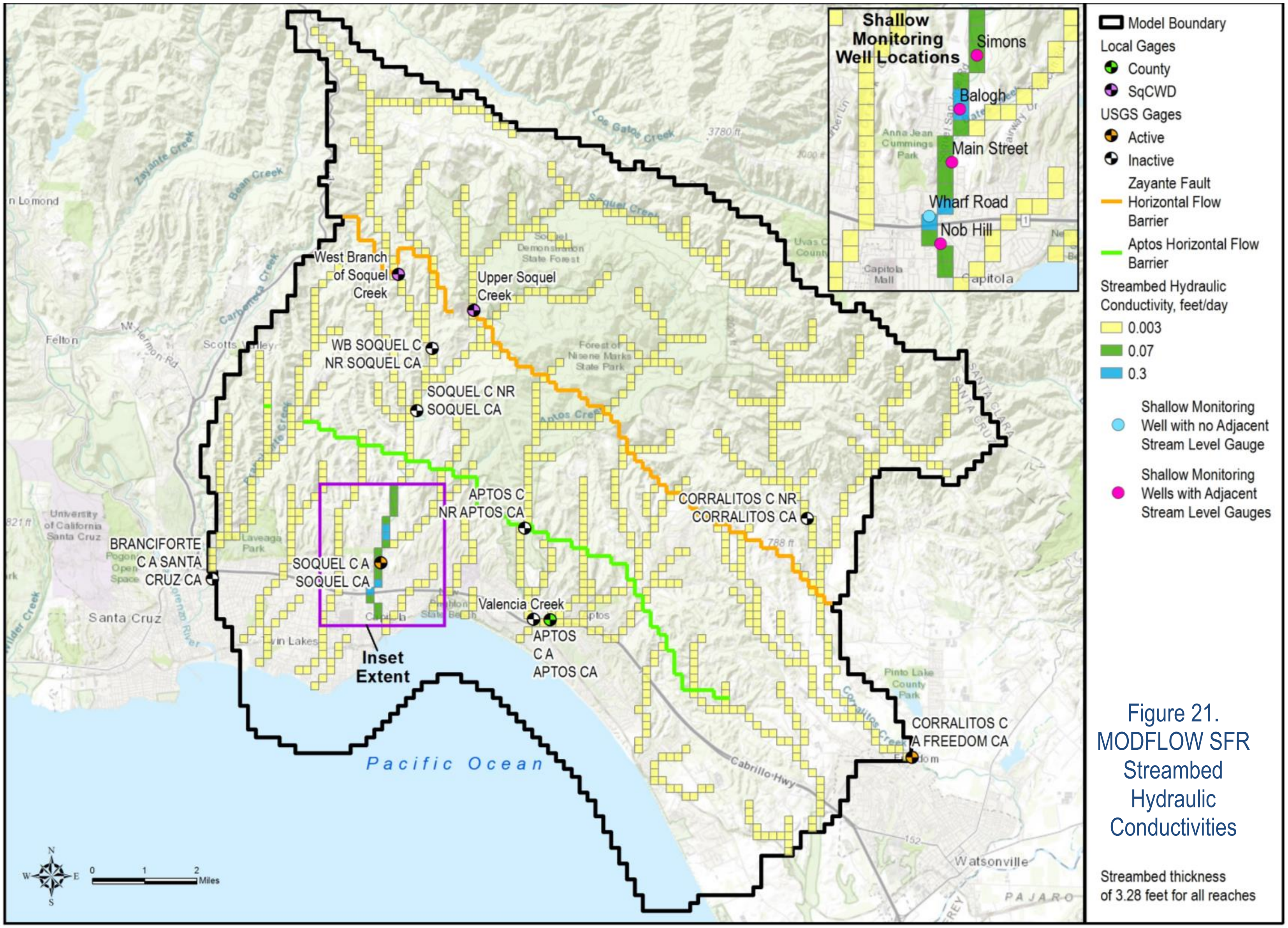


Figure 21. MODFLOW SFR Streambed Hydraulic Conductivities

7.2.2.1 Streamflow Calibration Results

Streamflow calibration results did not change substantially between the second step of streamflow calibration using GSFLOW for Water Years 1992-1995 and final calibration of GSFLOW for Water Years 1985-2015 that calibrated to shallow groundwater levels along Soquel Creek.

Measured streamflows were reasonably simulated at the two stream gauges with the most complete record of data: Soquel Creek at Soquel Gauge and Corralitos Creek at Freedom Gauge (see HydroMetrics WRI, 2016a for preliminary calibration results for PET and streamflow). Figure 22 shows simulated and observed streamflow for the two gauges over time.

Figure 23 and Figure 24 present observed *versus* simulated daily streamflow for calibration targets at the stream gauges with the most complete record of data. Results from an unbiased model (*i.e*., a perfectly-calibrated model) will align with the 45-degree line plotted on the figures. These plots demonstrate good and relatively unbiased calibration over the majority of streamflow ranges observed in the data, with some divergence in the simulated daily flows at very low (<1 cubic feet per second [cfs]) flow rates.

Goodness of fit between the simulated and observed streamflow was initially only assessed at annual time steps for preliminary model simulations, and was further evaluated at monthly and daily time steps using the Nash-Sutcliffe statistic (Nash and Sutcliffe, 1970). As a more quantitative measure of how well the model predicted streamflow, the Nash-Sutcliffe goodness of fit (NS) statistic was calculated for each of the gauges. This statistic has been used previously in other PRMS models to evaluate the performance of the PRMS calibration (Hay et al., 2006; Dudley, 2008; Viger *et al*., 2010). The NS statistic provides a measure of whether the PRMS model is a better predictor of annual streamflows than the average streamflow.

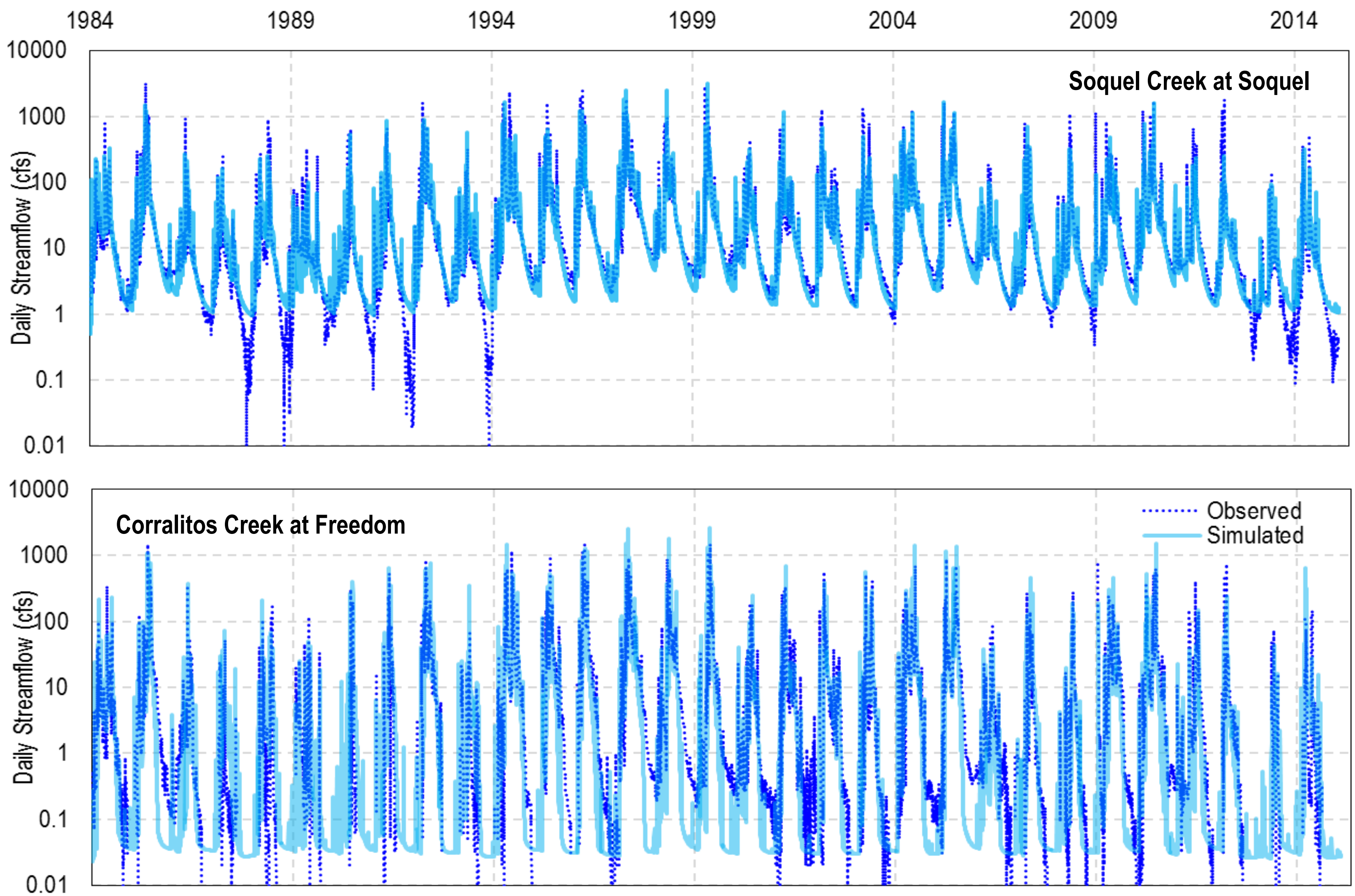


Figure 22. Simulated and Observed Streamflow: Soquel Creek at Soquel and Corralitos Creek at Freedom Gauges

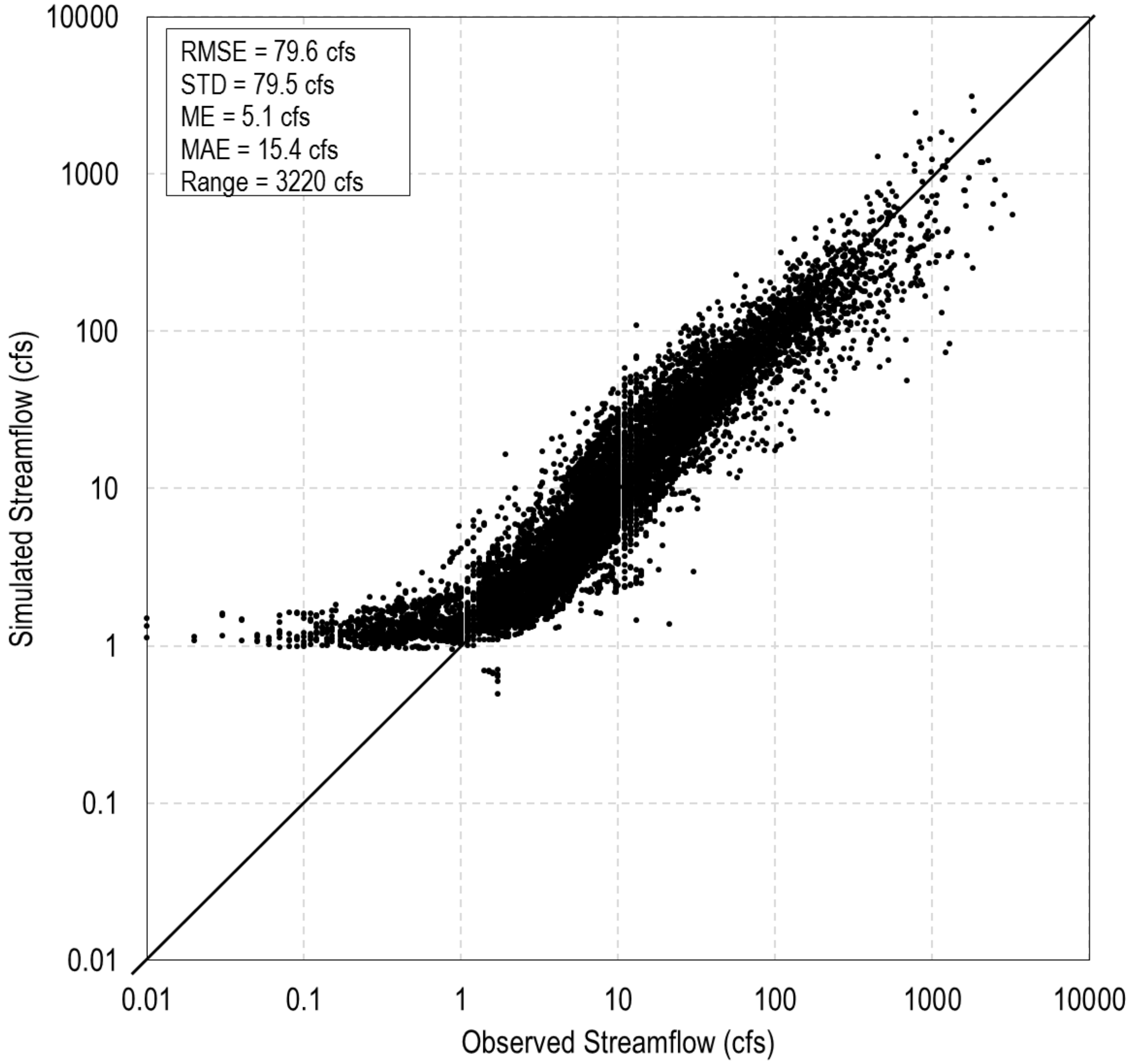


Figure 23. Soquel at Soquel Gauge Observed vs. Simulated Daily Streamflow

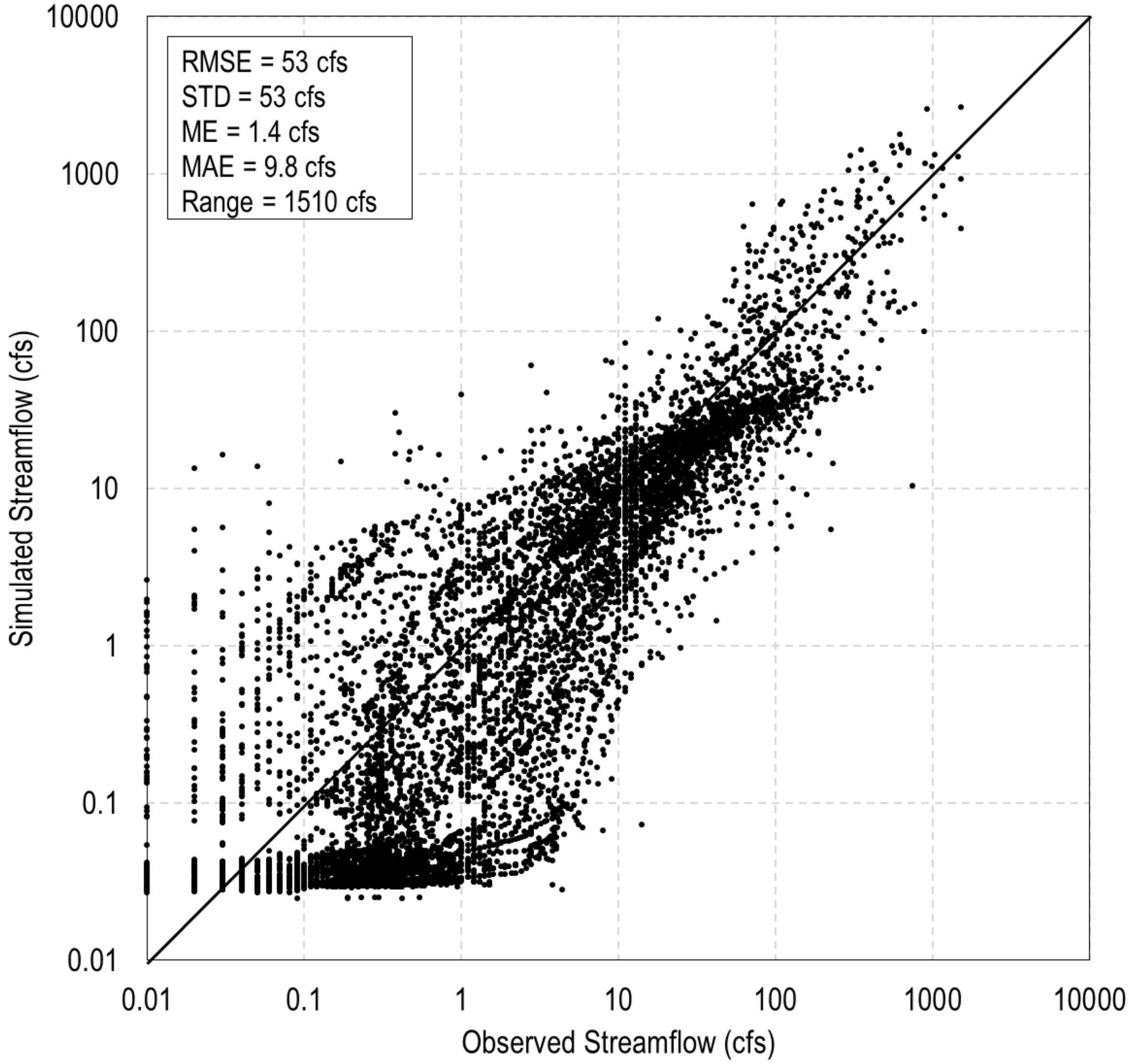


Figure 24. Corralitos at Freedom Gauge Observed vs. Simulated Daily Streamflow

The NS value is calculated for each water year as follows (Moriasi et al., 2007; Nash and Sutcliffe, 1970):

$$NS = 1.0 - \sum_{n=1}^{ndays} (MSD_n - SIM_n)^2 / \sum_{n=1}^{ndays} (MSD_n - MN_n)^2$$

where MSD = measured daily runoff values,

SIM = simulated daily runoff values,

MN = average of the measured values, and

n = the number of values out of a total of n days (ndays).

An NS value of one indicates a perfect fit between observed and simulated. A value of zero indicates that predicting annual streamflows with the PRMS model is as good as using the average value of all the observed data. Any value above zero is considered acceptable, and indicates that predicting annual streamflows with the PRMS model is better than using the average value of all the observed data. Figure 25 and Figure 26 present Nash-Sutcliffe results for stream gauges with the most complete record of data. Based on the NS charts presented for the Soquel at Soquel Gauge and the Corralitos at Freedom Gauge in Figure 25 and Figure 26, it can be inferred that predicting annual streamflows with the current PRMS model is better than using the average value of all the observed data.

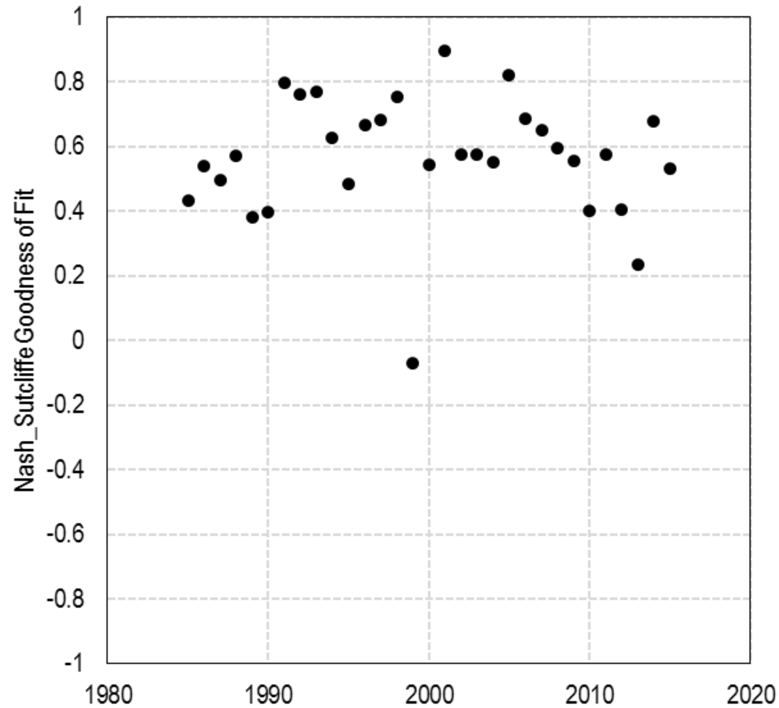


Figure 25. Nash-Sutcliffe Goodness of Fit, Soquel at Soquel Gauge

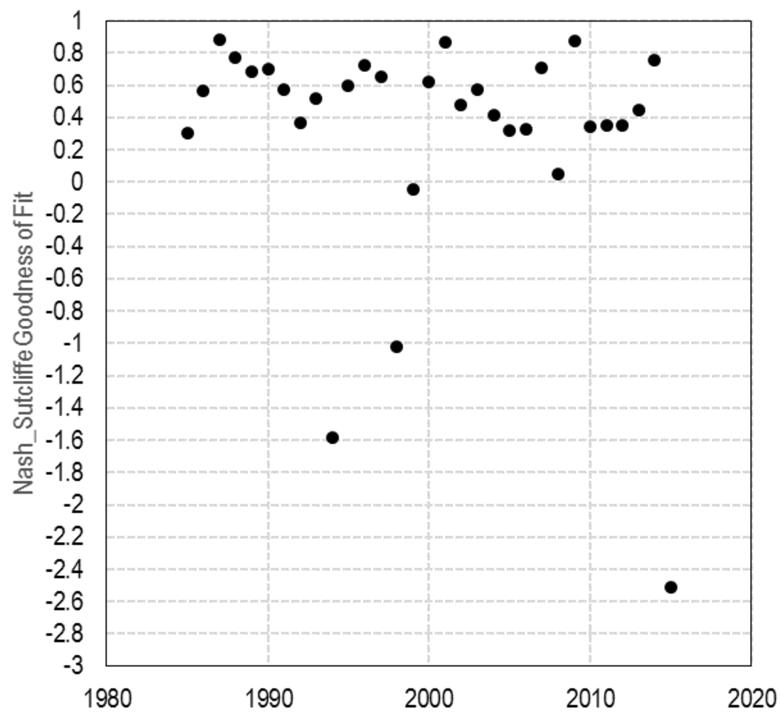


Figure 26. Nash-Sutcliffe Goodness of Fit, Corralitos at Freedom Gauge

7.3 Groundwater Calibration

The primary groundwater model parameters adjusted during calibration were as follows:

- The horizontal and vertical components of hydraulic conductivity (Kh and Kz, respectively.
- Storage parameters specific storage (Ss) and specific yield (Sy).
- GHB conductances of the offshore, seafloor, Santa Margarita Basin, and southeastern GHBs.
- Fault conductances for both the Zayante Fault and Aptos-area faulting, as represented by conductance values within the horizontal flow barrier (HFB) package in MODFLOW.

7.3.1 Groundwater Parameters Distributed by Pilot Point Method

A pilot point approach was taken to distribute the Kh, Kz, Ss, and Sy aquifer properties within the Basin model during calibration. This approach is documented by John Doherty (2003), and is similar to the approach used for the CWD groundwater model (HydroMetrics, 2014b).

The pilot point methodology estimates aquifer properties at specific points within the model domain, and interpolates the values between those points over the entire domain. Pilot points are generally placed where more calibration target data are available; in this Basin model, points clustered near the coastal well areas. Points were also distributed between pumping wells and outflow boundaries, and in areas to eliminate large spatial gaps between points. Pilot points for Kh, Kz, Ss, Sy were co-located, and their distribution in each model layer is presented on Plate 5 and Figure 27.

Plate 6 through Plate 9 show the distribution for calibrated horizontal and vertical hydraulic conductivity, specific storage and specific yield for each model layer. Plate 8 shows the approximate maximum area that is confined where the specific storage aquifer property applies. Plate 9 shows the approximate maximum area that is unconfined where the specific yield aquifer property applies.

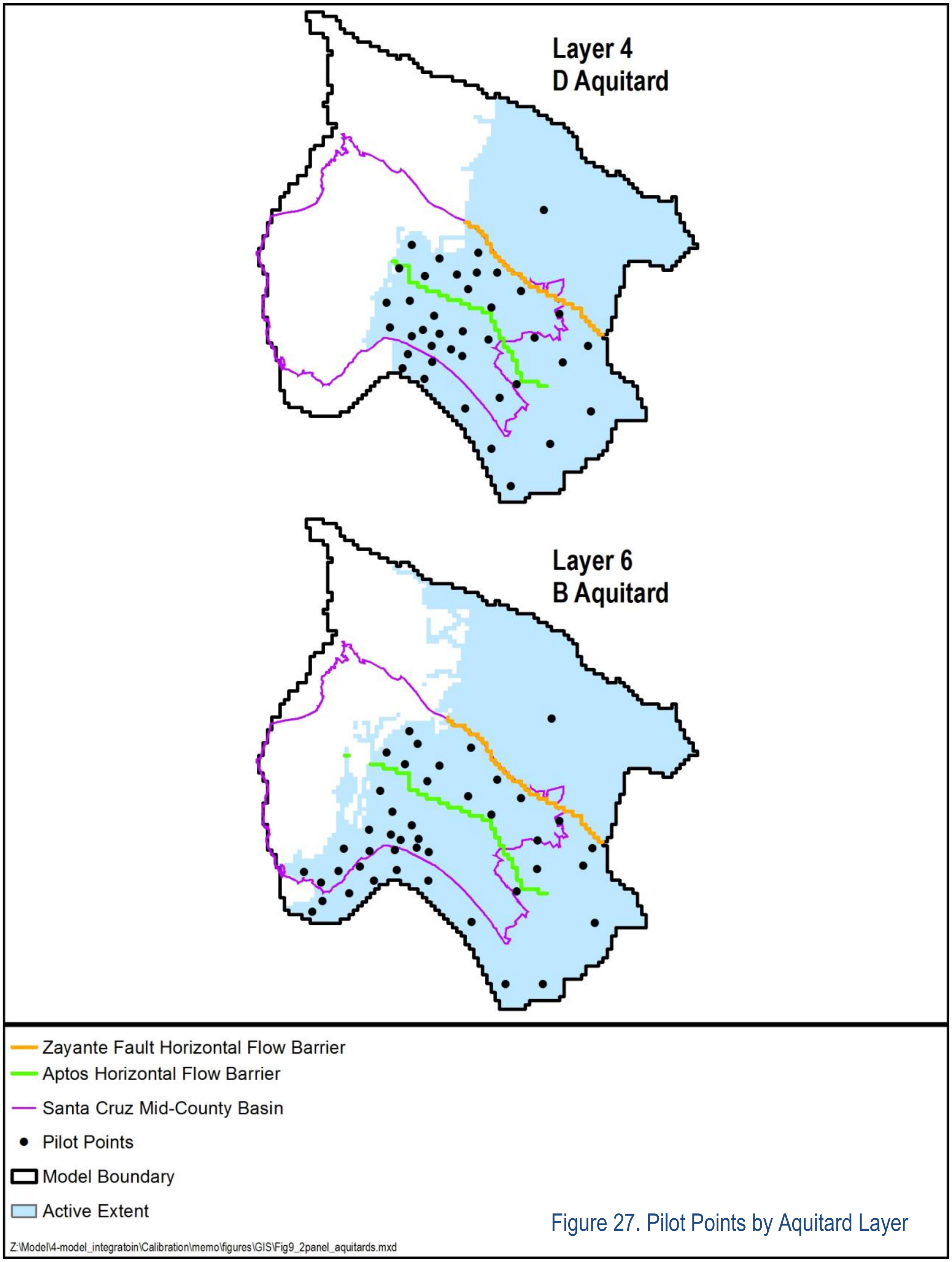


Figure 27. Pilot Points by Aquitard Layer

7.3.2 Hydraulic Properties by Basin Aquifer and Aquitard Layers

The following describes calibrated hydraulic properties by layer, focusing on the area where calibration targets exist. This area includes parts of Santa Cruz Mid-County Basin and Pajaro Valley Subbasin for the Aromas Red Sands Formation (model layer 2), south of the modeled Aptos area fault for the Purisima Formation (model layers 3-8), and the area providing municipal supply in the Tu unit (model layer 9).

- The Aromas Red Sands Formation (model layer 2) generally has higher horizontal hydraulic conductivity than other layers, though hydraulic conductivity in the Santa Cruz Mid-County Basin is generally lower than the Pajaro Valley Subbasin. Specific yield is modeled as relatively homogenous in this layer.

- The harmonic average of calibrated vertical hydraulic conductivity for Aromas Red Sands Formation and Purisima F aquifer units (model layers 2 and 3) that controls vertical flow between the layers is relatively high compared to vertical conductivity in other layers consistent with lack of a well-defined aquitard between the Aromas Red Sands and Purisima Formations.

- The Purisima F Unit (the eastern portion of model layer 3) has higher horizontal hydraulic conductivity than the Purisima DEF Unit (the western portion of model layer 3). The Purisima F Unit area has relatively high specific storage consistent with fast recovery observed at the SqCWD and CWD Rob Roy wells in the area. The Purisima DEF unit area has low specific yield in an area simulated as unconfined; however the DEF unit is more likely confined in this area and the combination of F and DEF units in the model make it difficult to simulate the confined response in the DEF Unit.

- Vertical hydraulic conductivity of the Purisima D Unit (model layer 4) is low consistent with this well-defined hydrostratigraphic unit being an aquitard.

- The Purisima BC Unit (model layer 5) has relatively low horizontal hydraulic conductivity and low specific storage consistent with the low yield and larger drawdowns of the aquifer.

- Vertical hydraulic conductivity of the Purisima B Unit (model layer 6) is low consistent with this well-defined hydrostratigraphic unit being an aquitard.

- The Purisima A Unit (model layer 7) has larger onshore areas of relatively high hydraulic conductivity (> 5 feet/day) compared to layers representing the Purisima Formation DEF, BC, and AA units, consistent with this unit having the largest number of productive wells in the Purisima. There is high hydraulic conductivity offshore to increase the connection with the offshore boundary condition. Specific storage along the coast is low to better match the groundwater level response at coastal monitoring wells to pumping.

- The Purisima AA Unit (model layer 8) has lower horizontal hydraulic conductivity than the Purisima A unit onshore in the Western Purisima area where the two units are pumped, but also has high hydraulic conductivity offshore in the west to increase the connection with where Purisima A unit outcrops. Horizontal hydraulic conductivity is high where Purisima AA unit outcrops inland. Specific storage is relatively high, especially for areas south of the horizontal flow barrier representing Aptos area faulting.

- Vertical hydraulic conductivities of the Purisima A and AA Units (model layers 7 and 8) controlling flow between the aquifer units are higher than for the Purisima D and B units (model layers 4 and 6) representing well defined aquitards. The vertical hydraulic conductivities offshore are high to connect the AA Unit with offshore outcrop that only occurs in the A Unit. In order to calibrate observed response in shallow groundwater levels to deeper Purisima Formation pumping, Purisima A unit vertical hydraulic conductivity is relatively high underlying Soquel Creek.

- The Tu Unit (model layer 9) has high horizontal hydraulic conductivity where SqCWD and City wells pump in the unit with moderate conductivities west to the approximate outcrop of the Santa Margarita Formation. The limited area of moderate and high conductivities is consistent with the apparent limits to recharge supplying the SqCWD and City wells in the unit. The vertical conductivity of the Tu Unit is very low to provide minimal connection between the Tu and the Purisima Formation. Specific storage is low to better match drawdown responses to pumping.

- Properties in areas without calibration data, such as north of the Zayante Fault and in most layers between the Zayante Fault and the HFB representing Aptos area faulting, are simulated as homogenous. Values in these areas are assigned to simulate water budget that facilitates calibration where data are available.

Hydraulic properties for the model were not calibrated to estimates for hydraulic properties obtained from pumping tests at wells in the Basin. The purpose of the Basin model is to simulate regional aquifer response to groundwater use and management in the Basin and therefore calibrating to static groundwater levels at monitoring wells is more appropriate for that purpose. Pumping tests typically provide near-well data for the response at the pumping well to pumping at the same well and therefore are more representative of conditions at the well and the immediately vicinity of the well. For reference, Appendix B provides a comparison of modeled hydraulic properties near wells with pumping test data with estimates of properties from the pumping test data.

7.3.3 Hydraulic Properties for Stream Alluvium and Terrace Deposit

Model cells underlying stream alluvium and representing overlying Terrace Deposits are mostly homogenous with high hydraulic conductivities (Kx=50 feet per day and Kz=0.1 feet per day) and relatively high specific yield of 0.15. These properties were mostly not adjusted during calibration except for two exceptions. Specific yield in the stream alluvium where shallow monitoring wells along Soquel Creek are located were lowered to 0.015 to simulate observed response to seasonal pumping cycles. Hydraulic conductivity was lowered (Kx=1 feet per day and $Kz=1x10^{-4}$ feet per day) for Terrace Deposit in model layers 6 and 7 to reduce vertical recharge into the Purisima Formation from these western areas.

7.3.4 Boundary Condition Calibration

Plate 10 presents calibrated estimates of GHB conductance by aquifer layer. Conductance is the hydraulic conductivity multiplied by cross-sectional area of flow divided by distance to boundary, which represent's the GHB's ability to transmit flow. Most of the GHB conductances represent the conceptual model for the GHB and did not require much adjustment during calibration. These GHBs include the offshore GHBs at the model boundaries, the Pajaro Valley Subbasin GHBs on each side of the Zayante Fault, and the Santa Margarita Basin GHBs.

- GHBs at the model boundary one mile offshore have very high conductances because it is assumed that groundwater is full strength seawater at the location.
- GHBs along the side boundaries that connect the shore out to the boundary one mile offshore have very low conductance to emphasize the effect of GHBs one mile offshore and for outcrops under the Bay.
- GHBs in the Pajaro Valley Subbasin south of Zayante Fault have low conductance to reflect the distance to the offshore location defining the GHB head.
- GHBs in the Pajaro Valley Subbasin north of Zayante Fault have low conductance to reflect stream conductance within Ryder Gulch that defines the GHB head.
- GHBs in the Santa Margarita Basin have high conductance to better represent nearby observations of groundwater levels.

The GHBs with conductances adjusted most in calibration were the GHBs representing offshore outcrops of aquifer units underneath Monterey Bay.

- GHBs in the Aromas Red Sands Formation (model layer 2) have low conductances for a limited connection between onshore groundwater levels with the offshore boundary. Since brackish groundwater occurs in part of the Aromas Red Sands Formation, implementation of the SWI2 seawater intrusion package may improve simulation of onshore groundwater levels in model layer 2 given presence of the freshwater-seawater interface onshore.

- GHBs in the Purisima DEF/F and BC Units (model layers 3 and 5) have low conductances for a limited connection between onshore groundwater levels with the offshore boundary. Since brackish groundwater occurs in part of the the Purisima F unit, implementation of the SWI2 seawater intrusion package may improve simulation of onshore groundwater levels in this area of model layer 3 given presence of the freshwater-seawater interface onshore.

- GHBs in the Purisima A Unit (model layer 7) have high conductances for a greater connection between onshore groundwater levels with the offshore boundary.

Plate 10 also presents calibrated estimates of horizontal flow barrier (HFB) leakance by aquifer layer to represent faulting. Leakance, or the HFB hydraulic characteristic, is equivalent to the hydraulic conductivity of the HFB divided by HFB width that represents the HFB's ability to transmit flow. In general, leakances for the HFB representing faulting in the Aptos area are lower than leakances for the Zayante Fault. Groundwater level data show a large gradient across the Aptos area, while some amount of flow across the Zayante Fault is necessary for the water budget.

7.3.5 Calibration of Groundwater Elevations in Basin Aquifer Units

Groundwater model calibration is commonly evaluated by comparing simulated groundwater levels to observed groundwater levels that make up the groundwater calibration targets as described in the sections above. Hydrographs of simulated groundwater elevations should generally match the trends and fluctuations observed in measured hydrographs. Selected hydrographs showing both observed and simulated groundwater elevations are provided in Appendix C. The hydrographs included in Appendix C were selected to represent different areas and aquifers within the model. Also, monitoring wells separated from production wells are prioritized to represent regional aquifer response to pumping. The hydrographs demonstrate that the model is accurately simulating historical hydrologic trends and response to pumping within the major aquifers of interest in the Basin, particularly at coastal monitoring wells where groundwater levels are evaluated against protective elevations to assess risk of seawater intrusion. Figure 28 through Figure 31 show hydrographs for the coastal monitoring wells that are representative monitoring points in the GSP with groundwater elevations used as proxies for seawater intrusion. The calibration supports use of model results at these wells from simulations of future conditions for comparison to the proxies to evaluate whether sustainability is achieved for the seawater intrusion indicator.

Areas where model fit is less accurate typically fall in to two categories:

- Areas where calibration target wells exhibit a confined response to pumping but fall within areas where the layer in which they are screened are unconfined within the model. This is a limitation in the vertical discretization of the model, as in Layer 3, which is a combination of the DEF and F units of the Purisima.

- Inland areas of the model where calibration target density and associated parameter pilot point density is low. These wells are often private wells with little information in areas relatively far from areas where protective groundwater elevations have been determined.

In general, the accuracy of the model to groundwater conditions within the protected aquifers, especially in regions near the coast, will make this model a robust platform for future predictive scenario of management alternatives and other groundwater infrastructure projects within the Basin.

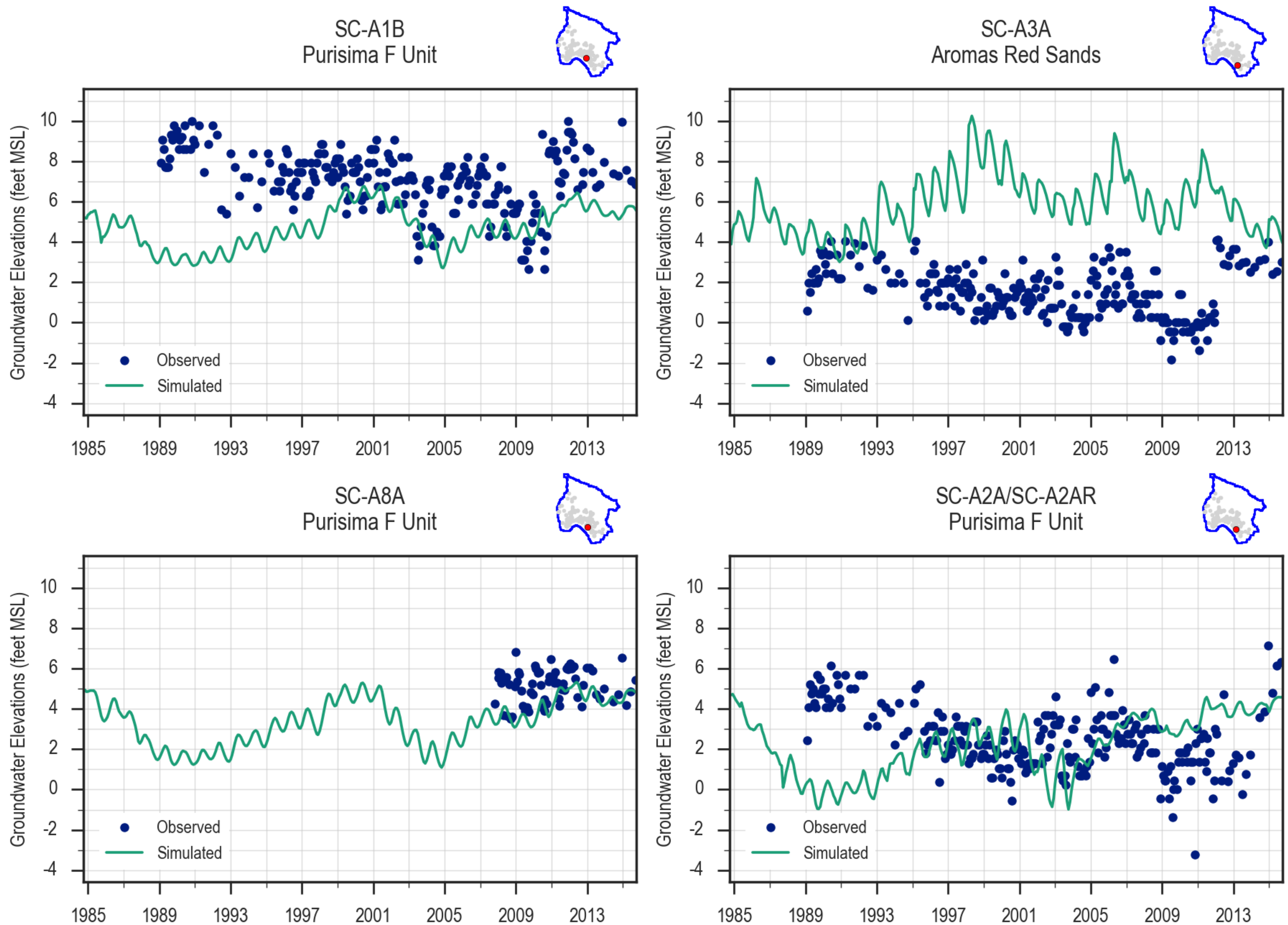


Figure 28. Calibration Hydrographs at Coastal Monitoring Wells in Aromas and Purisima F Units

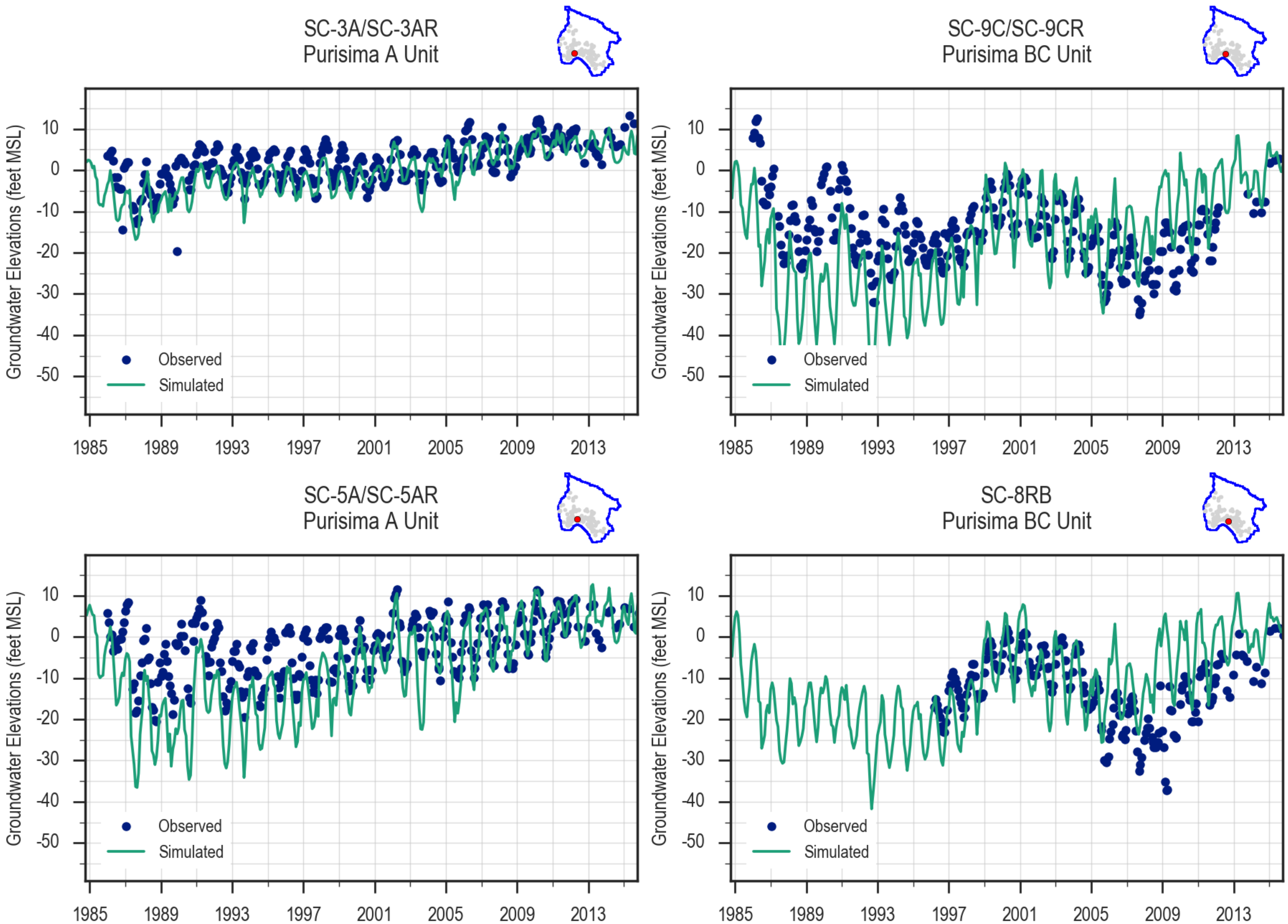


Figure 29. Calibration Hydrographs at Coastal Monitoring Wells in Purisima BC and A Units

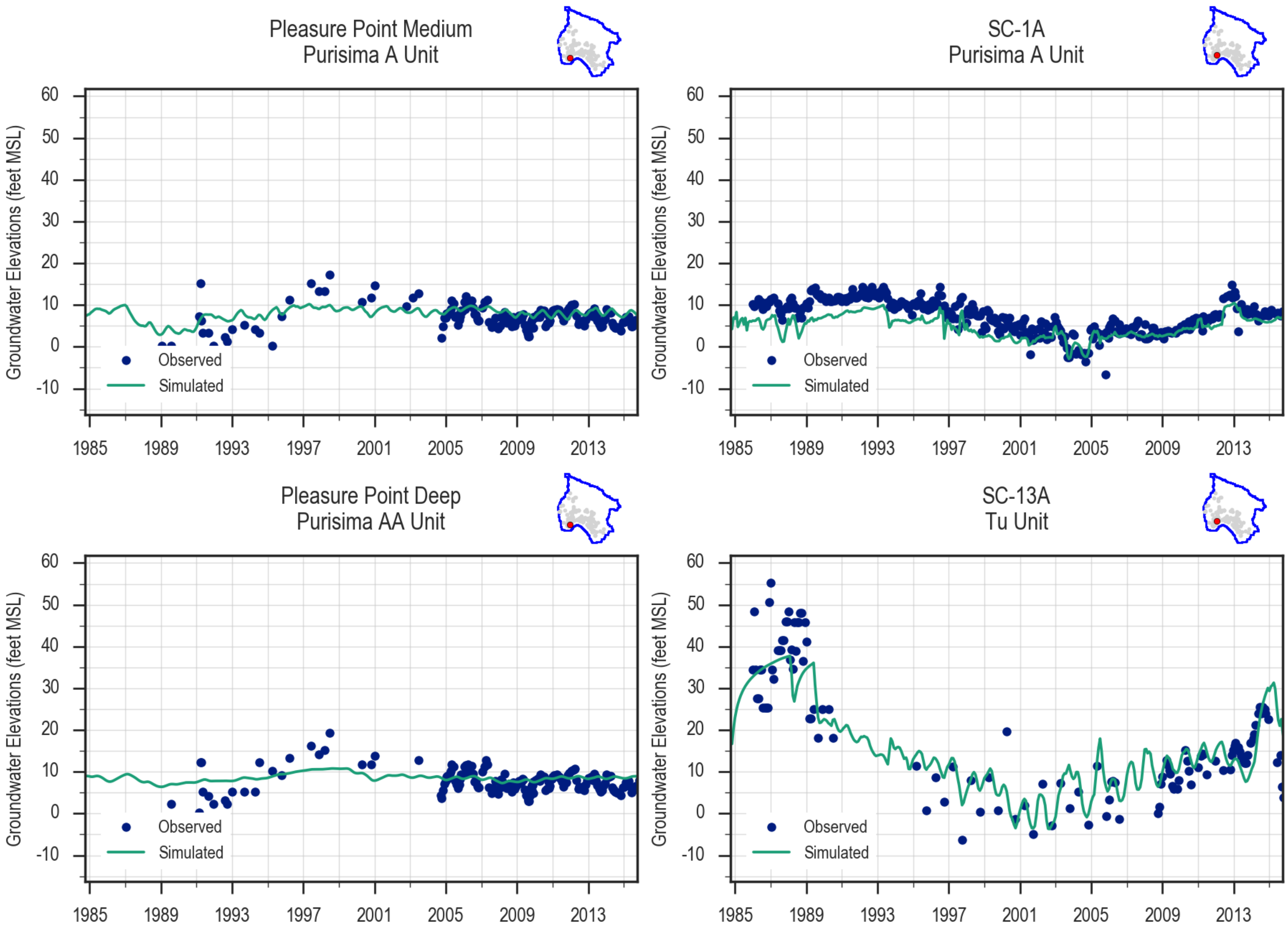


Figure 30. Calibration Hydrographs at Coastal Monitoring Wells in Purisima A and AA Units and Tu Unit

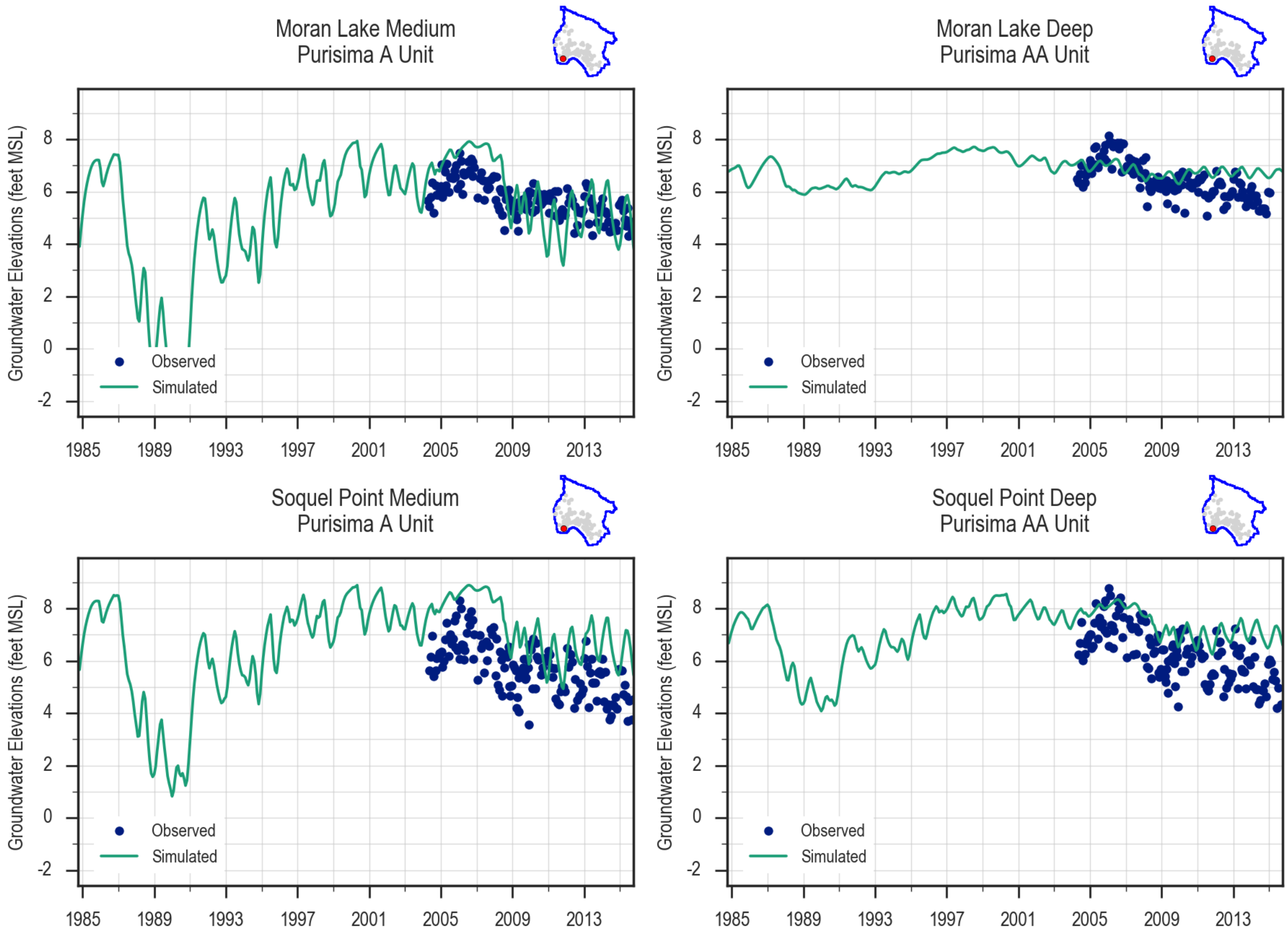


Figure 31. Calibration Hydrographs at Coastal Monitoring Wells in Purisima A and AA Units

Various graphical and statistical methods can be used to demonstrate the magnitude and potential bias of the calibration errors. Figure 32 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, shown as a solid black 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 distribution of data points on Figure 32 show that they cluster along the 45º line, indicating that the model results are not biased towards overestimating or underestimating average groundwater level differences.

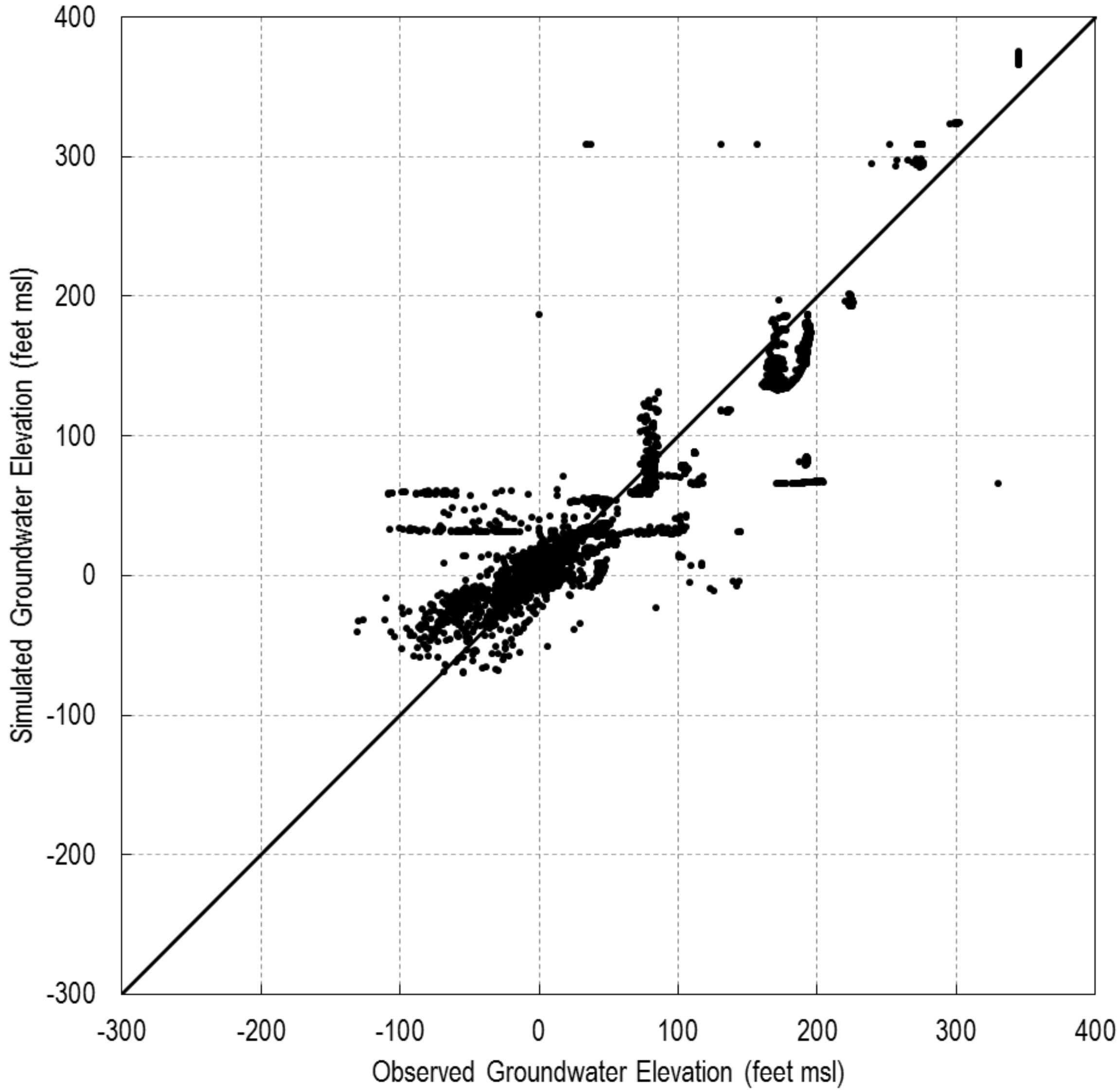


Figure 32. Observed vs. Simulated Groundwater Elevations from Groundwater Calibration Targets in Model

Table 10 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 32.

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

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.

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

The standard deviation of the errors is one measure of the spread of the errors around the 45º line in Figure 32. The population standard deviation is used for these calculations.

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

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 32, 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 22.13 feet is approximately 2.3% of the total head range of 983.60 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 10.17 feet is approximately 1.0% of the total head range. Therefore, on average, the model errors are within an acceptable range.

Table 10. Statistical Measures of Model Calibration

Statistical Measure	Abbreviation	Measure Value	Ratio of Measure to the Range of Observed Values
Root Mean Square Error	RMSE	22.13	2.3%
Standard Deviation	STD	22.09	2.2%
Mean Error	ME	1.29	0.1%
Mean Absolute Error	MAE	10.17	1.0%
Range of Observed Values	Range	983.60	

7.3.6 Groundwater Elevation Calibration in Shallow Wells along Soquel Creek

Under Santa Cruz County's Prop 1 grant, the model was calibrated to shallow groundwater elevations along Soquel Creek in order to support use of the model to evaluate streamflow depletion from pumping. The purpose of this focused calibration is for the model to simulate the long-term trends where shallow aquifer response to deeper pumping is observed. This is primarily achieved by adjusting hydraulic parameters that control the vertical connection between the stream, the layer representing shallow alluvium, and the deeper Purisima Formation units (Figure 15). The main hydraulic parameters controlling this connection is streambed hydraulic conductivity (Section 7.2.2) and Purisima Formation vertical conductivity (Section 7.3.2).

In order to show the vertical connection, hydrographs of simulated results and observations at shallow wells are shown with hydrographs of simulated results in underlying Purisima Formation layers. As described in Section 7.3.5 , the model is calibrated to simulate response to pumping in the Purisima Formation. Figure 33 shows the hydrographs of the upstream Simons and Balogh shallow wells where observed shallow groundwater levels do not show the long term trend of a response to Basin pumping simulated in the underlying Purisima A unit. The model is calibrated also to not simulate a shallow aquifer response to pumping.

The Main Street shallow well is adjacent to the Main Street production well that is screened in the deeper Purisima AA unit and Tu unit. Figure 34 shows a muted response at the Main Street shallow wells to pumping compared to the response simulated in the Purisima AA unit, but observed groundwater levels at the Main Street shallow well do follow the long-term trend of groundwater level recovery from 2001 to 2011, then a brief increase in drawdown in 2012-2013, with increased pumping from the Main Street well and a rebound thereafter.

Figure 35 shows similar simulation of long-term trends at the Nob Hill shallow well.

These shallow monitoring wells are representative monitoring points in the GSP with groundwater elevations used as proxies for the streamflow depletion sustainable management criteria. The basis for the use of these proxies is that the higher shallow groundwater levels indicate greater groundwater flow to streams, and lower shallow groundwater levels indicate less groundwater flow to streams based on the apparent connection between stream stages and shallow groundwater levels. The model is calibrated to simulate the observed shallow groundwater elevations in response to groundwater levels and pumping in deeper Purisima units. The calibration supports use of model results for simulations of future conditions at these wells. The results can be compared to groundwater level proxies for evaluating whether sustainability is achieved for the depletion of interconnected surface water indicator. Therefore, the model can be used to evaluate effects of projects and management actions in the deeper Purisima units on shallow groundwater levels for comparison to the groundwater level proxies.

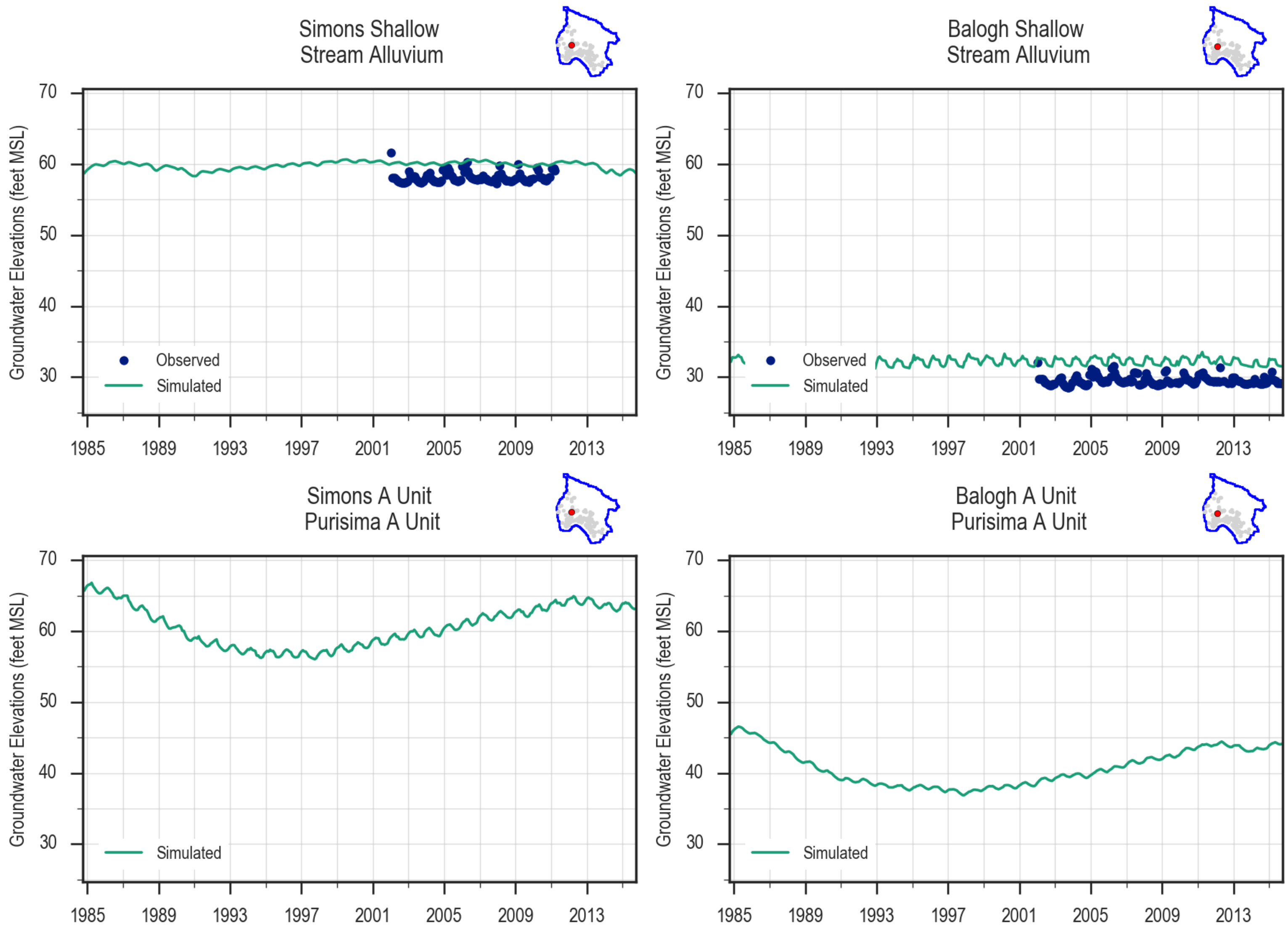


Figure 33. Calibration Hydrographs at Simons and Balogh Shallow Wells and Underlying Purisima A Unit

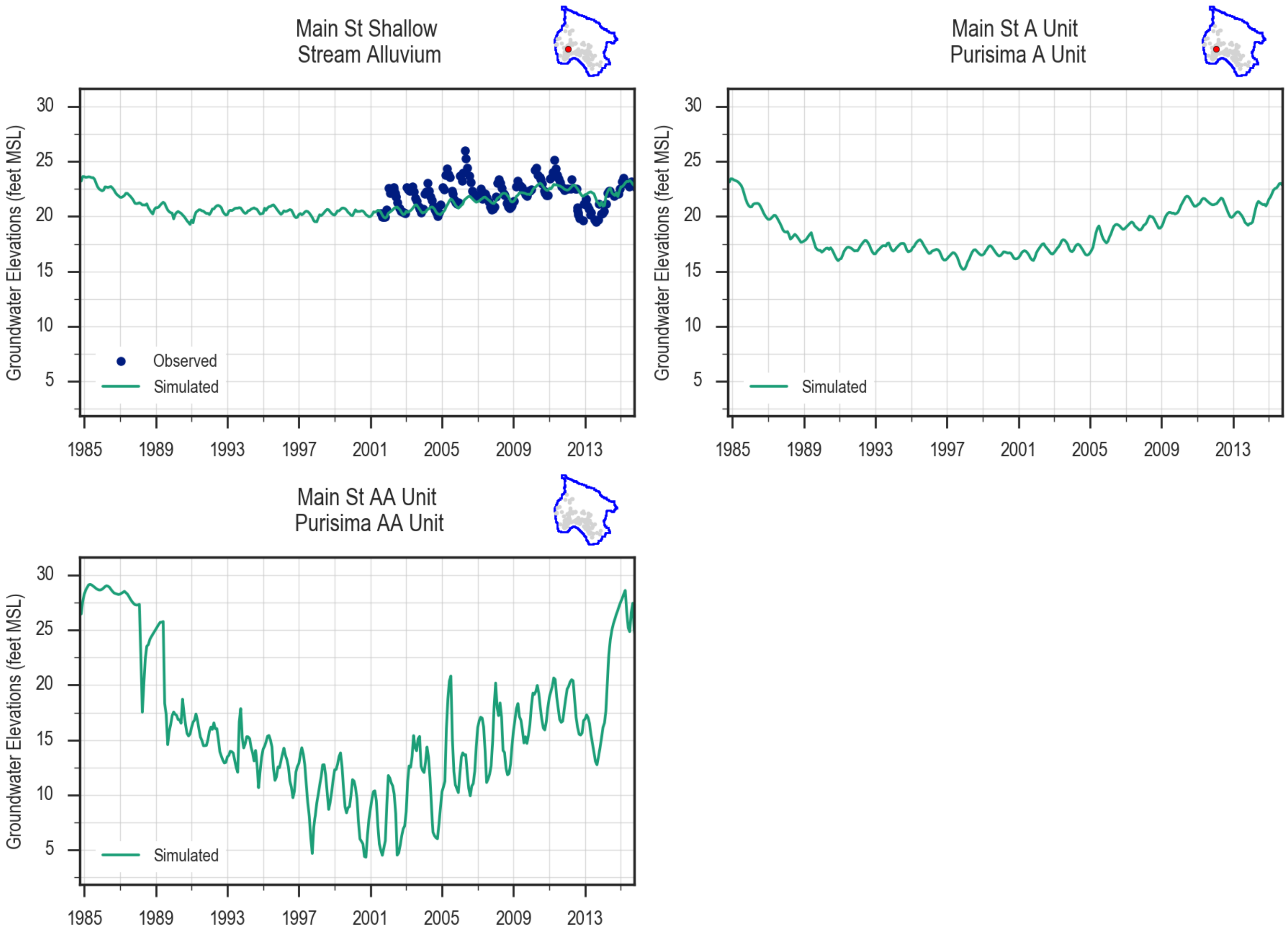


Figure 34. Calibration Hydrographs at Main St. SW 1 and Underlying Purisima A and AA Units

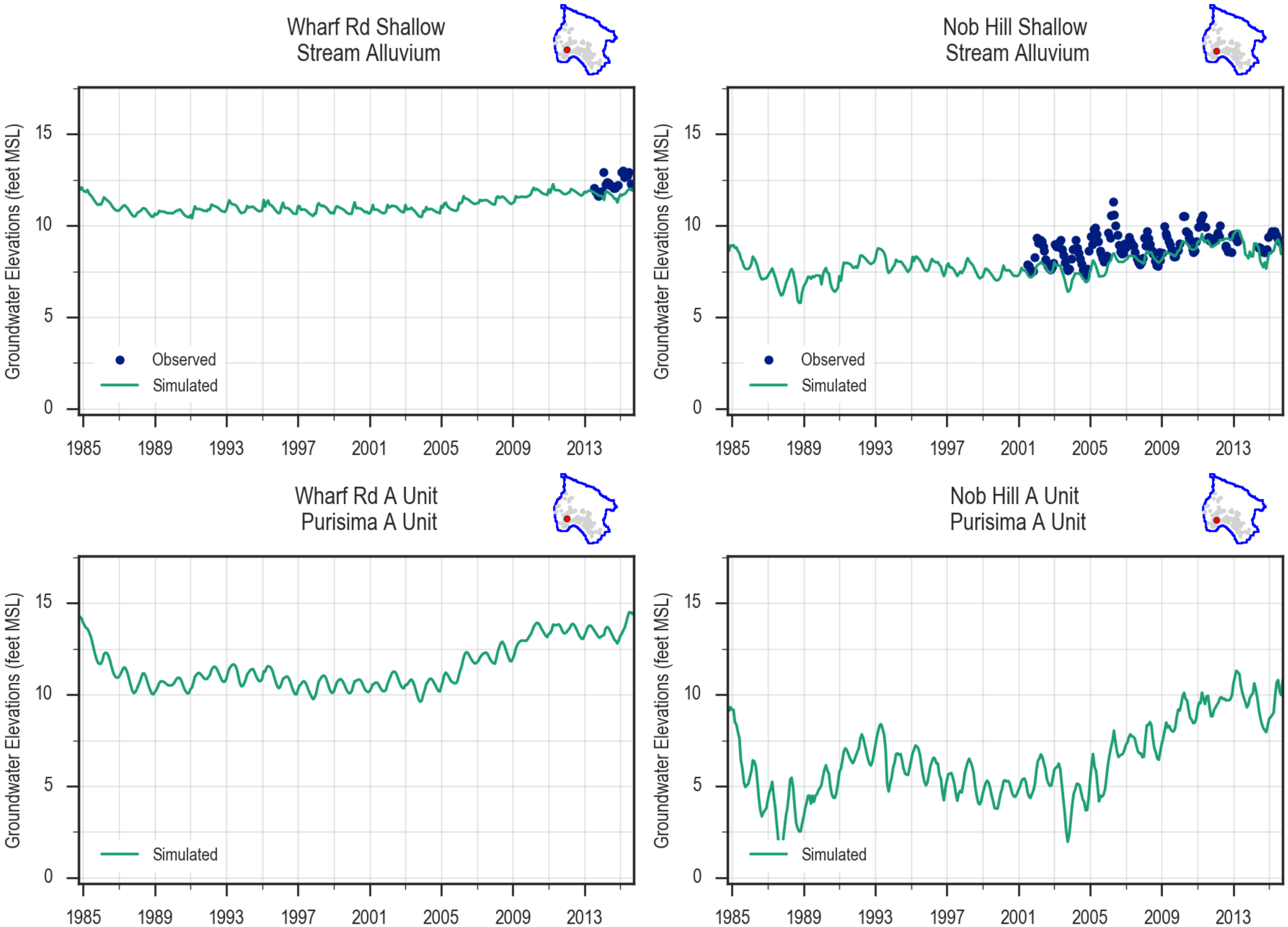


Figure 35. Hydrographs at Wharf Rd. and Nob Hill Shallow Wells and Underlying Purisima A Unit

8 RESULTS FOR CALIBRATED MODEL

8.1 Groundwater Elevation Contours

Plate 11 through Plate 14 show simulated groundwater elevations within each aquifer layer of the model at September 1994 and March 2015. September 1994 is a representative time for when groundwater elevations are low throughout the Basin. March 2015 is the representative time for when groundwater elevations are high throughout the Basin. Plate 11 and Plate 13 show groundwater elevations for these time periods. These maps show the simulated regional groundwater directions and gradients within the Basin by aquifer.

- The Aromas Red Sands Formation (model layer 2) generally shows flow toward the coast within the Basin but the 10 foot above mean sea level (amsl) contour moves toward the coast over time as pumping decreases.
- The Purisima F unit portion (eastern part of layer in Basin) of model layer 3 shows flat gradient of 0-10 feet amsl near the coast, but pumping depressions near the coast are eliminated over time. Inland contours move farther inland over time as pumping at the inland Rob Roy wells, Aptos Jr. High well, and Polo Grounds wells come online.
- The Purisima DEF unit portion (western part of layer) of model layer 3 shows increased pumping depressions over time as pumping shifted from the Aptos Creek well also screened in the BC unit to T. Hopkins well screened only in the DEF time.
- The Purisima BC unit (model layer 5) shows a large pumping depression below sea level that lessens over time such that groundwater elevations rise to and above sea level at the coast.
- The Purisima A unit (model layer 7) shows pumping depressions below sea level that lessen over time such that groundwater elevations rise to and above sea level at the coast.
- The Purisima AA unit (model layer 8) shows a small pumping depression that lessens over time.
- The Tu unit (model layer 9) shows larger pumping depressions in the fall and less in the spring. Spring 2015 is prior to Tu pumping being increased with new wells at Beltz #12 and O’Neill Ranch in summer and fall 2015.

Plate 12 and Plate 14 show the areas that are dry, unconfined, and confined for each aquifer layer of the model. The confined area is where specific storage (Plate 10) applies and the unconfined area is where specific yield (Plate 9) applies. The Aromas Red Sands Formation (model layer 2) is mostly unconfined within the Basin so confined response to pumping that is sometimes observed in the Basin is not well simulated, which is why some wells that may be screened across both the Aromas Red Sands Formation and Purisima F unit (model layer 3) are simulated as pumping from model layer 3 only. Much of the Purisima DEF unit area, western portion of model layer 3, is unconfined, and the model does not simulate the confined response to pumping in this area. Adding more layer discretization to these areas would be necessary to better simulate the confined response that is observed.

8.2 Surface Water Budget

In this sub-section, the surface water budget of the Basin is described. The surface water budget is described for the watershed and for the stream system within the Basin. The watershed budget is based on model results for how precipitation is apportioned. The stream system budget describes inflows and outflows to streams in the Basin.

For the watershed budget, the model simulates annual precipitation over the calibration period in the Basin as ranging from less than 16 inches to over 65 inches (1990 and 1998 respectively). On average, the model simulates 66% of precipitation that lands on the Basin as evaporated or transpired without reaching a surface water body. The model simulates another 27% as overland flow that eventually enters streams and creeks within the Basin. Five percent of precipitation is simulated to percolate beyond the root zone and enters the underlying aquifer as unsaturated zone flow (UZF) recharge, Terrace Deposits recharge, or stream alluvium recharge. The remaining portion (2%) reflects the net change in soil moisture stored in the soil layer over the Basin area. In most years this value is negative, reflecting gaining soil moisture conditions. However, in some years this value is positive, reflecting decreasing moisture in the soil layer. Typically this occurs during relatively dry years following a wet period, as evapotranspiration (ET) receives larger contributions from the soil layer during the drier year. The precipitation budget over time is presented in Figure 36.

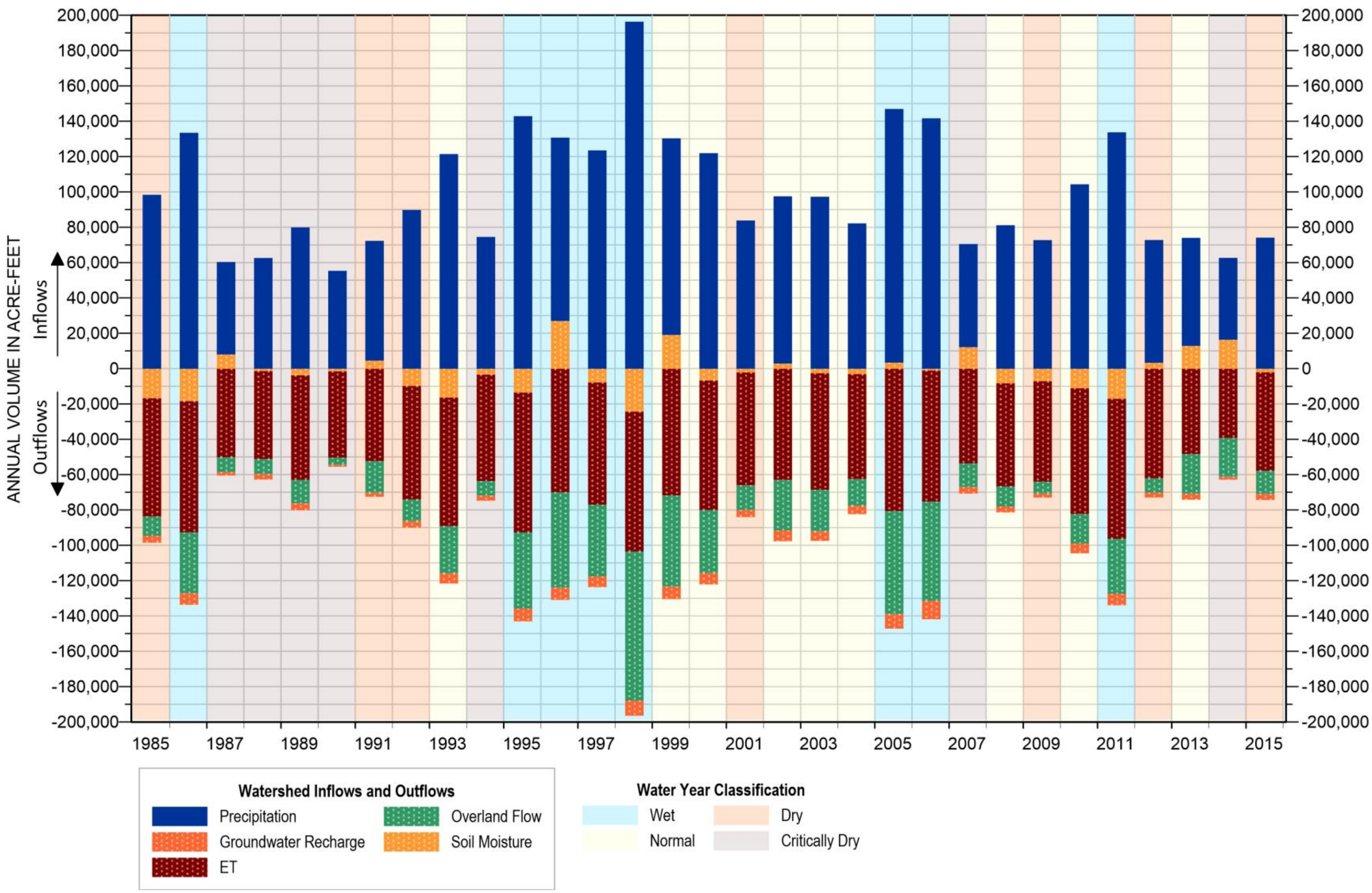


Figure 36. Annual Watershed Budget for Santa Cruz Mid-County Basin

For the stream system budget, the model simulates around 56% of inflow to the Basin's surface water system occurs due to overland flow entering streams and rivers within the Basin. The model simulates an additional 26% as entering the Basin from the area overlying Purisima Highlands Subbasin to the north. Primary water bodies supplying this inflow include Soquel Creek, Hester Creek, Hinckley Creek, and Aptos Creek. The model simulates 16% as entering from the adjacent Santa Margarita Basin, primarily from Branciforte and Granite Creeks. The remaining 3% of inflow to the surface water system is from net inflow from groundwater to streams (2%) and a few small creeks entering from the Pajaro Valley Subbasin (1%).

Surface water outflows in the model are dominated by outflow to ocean (89%). Nine percent leaves the Basin via Carbonara Creek, which enters the area overlying the Santa Cruz Terrace Subbasin just north of the City of Santa Cruz. The remaining 2% comprises minor amounts of surface water flowing into the Pajaro Valley Subbasin and Santa Margarita Basin, and small soil moisture fluctuations in the soil layer. The historical stream system water budget is presented in Figure 37.

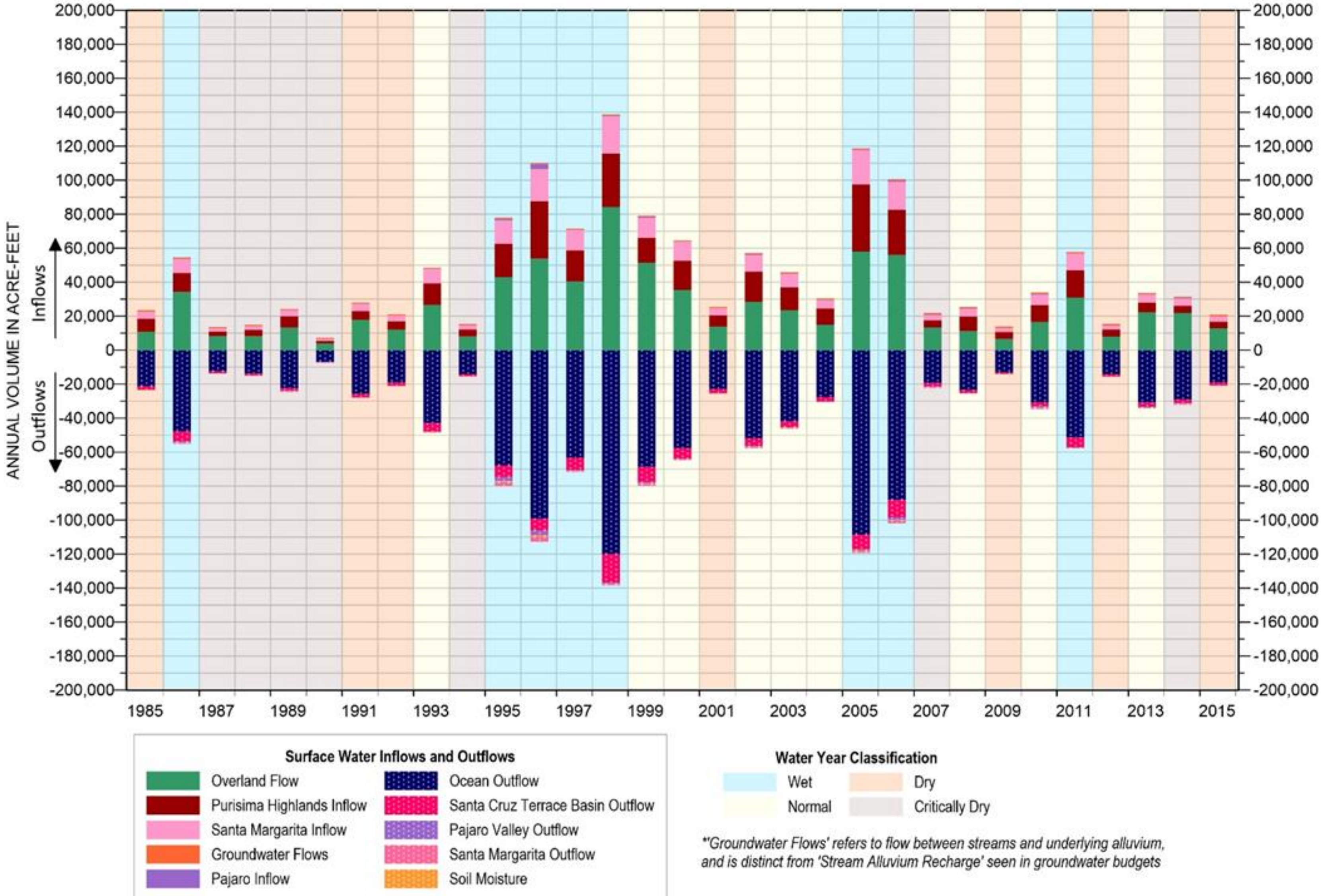


Figure 37. Annual Stream System Budget for Santa Cruz Mid-County Basin

8.3 Groundwater Budget

In this section, the groundwater budget of the Basin is described. Components of the groundwater budget are discussed in the subsections below. The groundwater budget discussion and associated charts separate the areas north and south of the horizontal flow barrier (HFB) representing Aptos area faulting because the groundwater budget south of this HFB Fault is more instructive for evaluating seawater intrusion, which is the sustainability indicator that has driven designation of the Basin as being in critical overdraft. In addition, the majority of pumping in the Basin, including all of the municipal pumping, occurs south of the Aptos area faulting (Figure 12) and most of the calibration data are from south of the Aptos area faulting (Plate 4).

Figure 38 and Figure 39 show the annual groundwater budget either side of the HFB representing Aptos area faulting, within the Basin. As discussed earlier, there are limited pumping activities north of the Aptos area faulting, with the majority of Basin pumping occurring south of Aptosarea faulting. The water budget north of the Aptos area faulting mainly comprises natural areal recharge (included as “UZF Recharge” on figures), stream recharge (shown as “Stream Alluvium” on figures), inflows from Purisima Highlands Subbasin, and outflows to Pajaro Valley Subbasin. Groundwater flows across basin boundaries south of the Aptos area faulting are not as substantial part of the water budget as they are north of the Aptos area faulting. Instead the water budget south of the Aptos area faulting in the Basin is influenced mostly by groundwater pumping, areal recharge, stream recharge, and flows offshore.

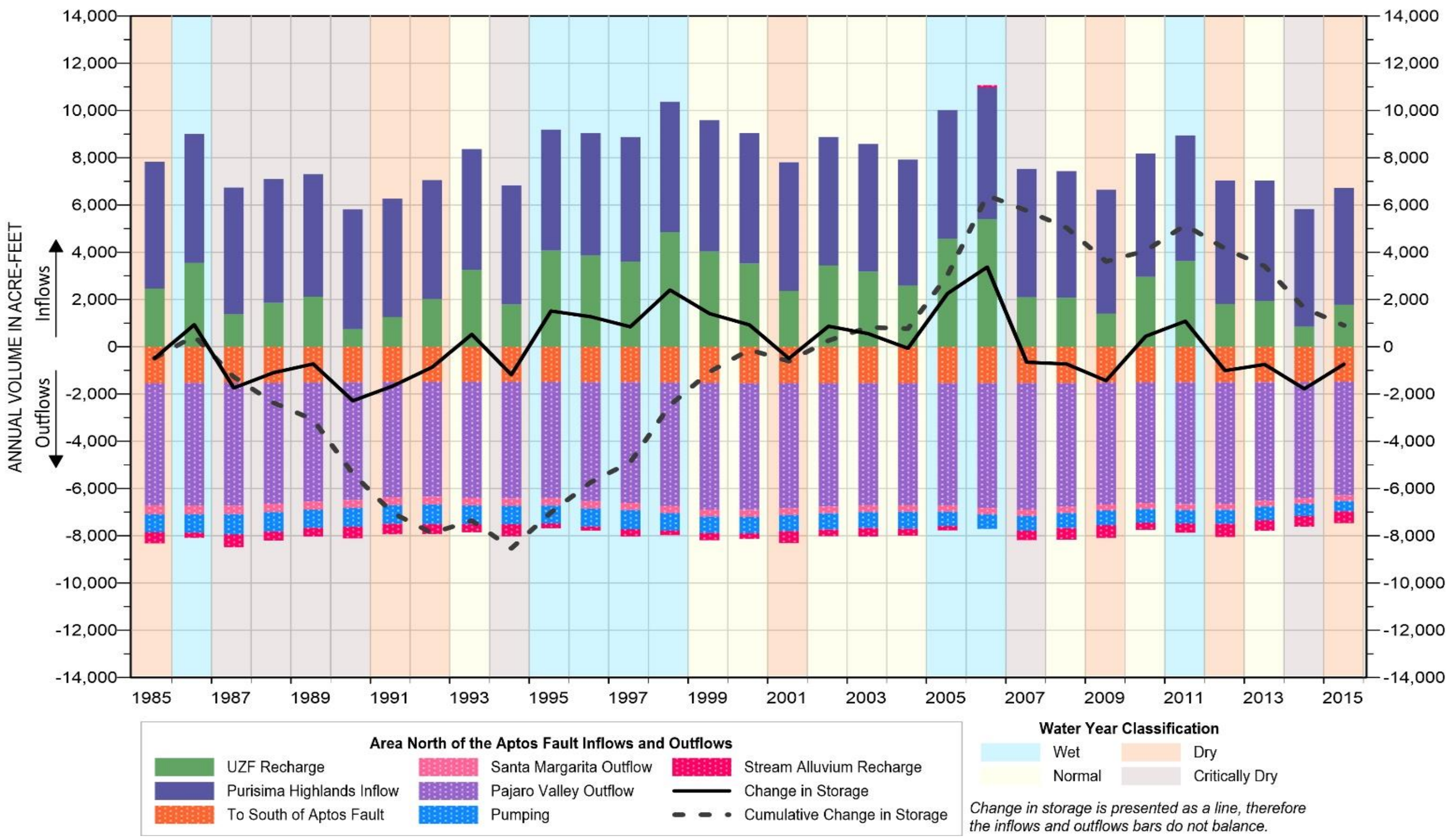


Figure 38. Annual Groundwater Budget in Santa Cruz Mid-County Basin, North of HFB for Aptos Faulting

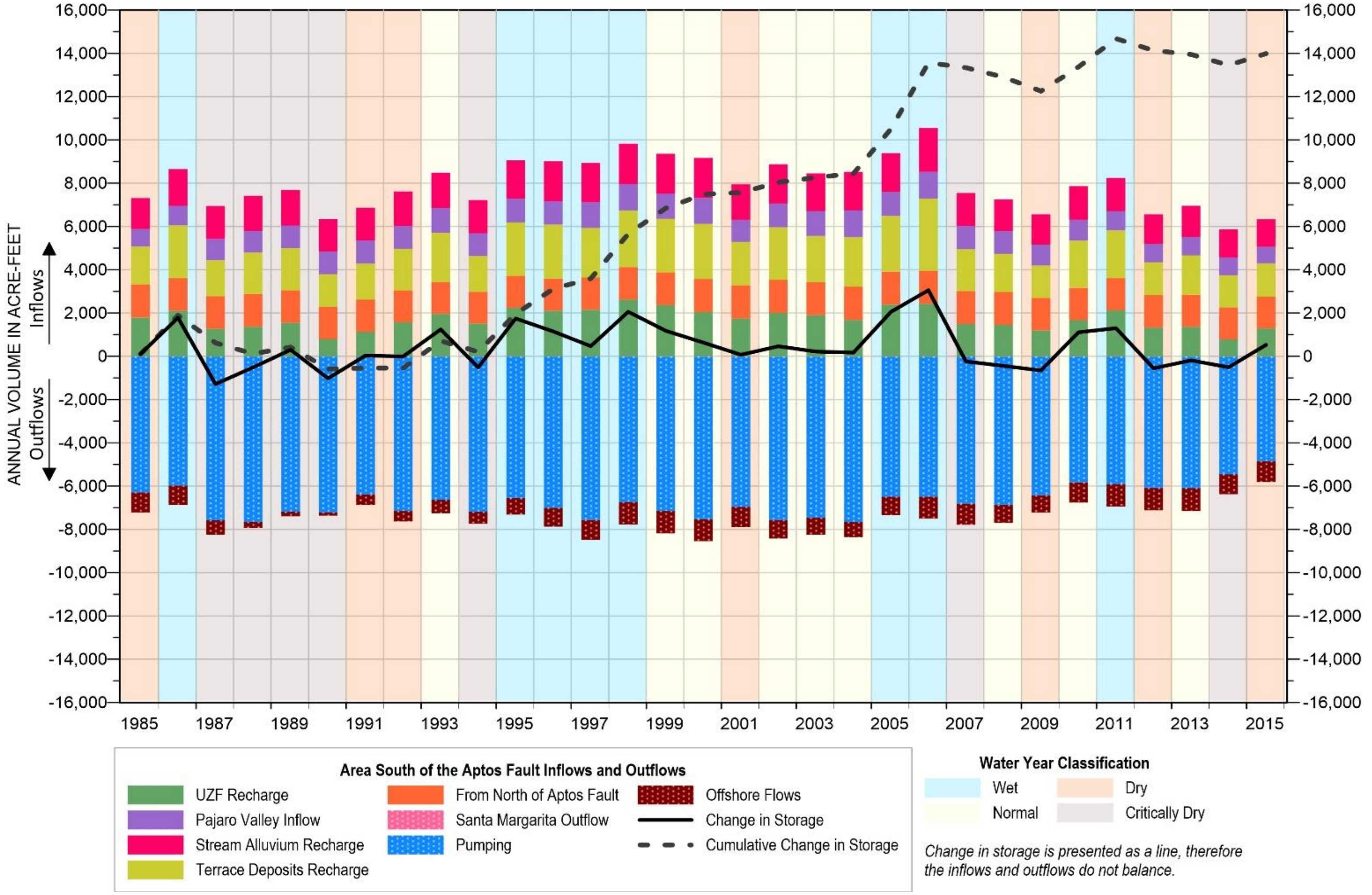


Figure 39. Annual Groundwater Budget in Santa Cruz Mid-County Basin, South of HFB for Aptos Faulting

8.3.1 Flows within Basin Boundaries

8.3.1.1 UZF recharge

This component of the groundwater budget includes components of areal recharge calculated by PRMS from climate inputs (direct recharge and gravity drainage in Figure 3) and return flows that are described in Section 4.4. These flows are always inflows to the Basin.

UZF recharge varies with climatic conditions. UZF recharge is greater north of the HFB representing Aptos area faulting than south of the HFB, but this is partly because recharge to Terrace Deposits is calculated separately from UZF recharge (see subsection below).

8.3.1.2 Flows between Alluvium to Aquifers and Aquitards of the Basin

The groundwater budget is calculated for layers representing the stacked aquifer and aquitard units of the Basin. Aromas Red Sands, Purisima Formation units, and Tu unit. Therefore, the water budget includes flows from overlying cells representing stream alluvium and Terrace Deposits (Figure 40).

Flow from stream alluvium is an important component of the Basin's groundwater budget and includes both streambed recharge and areal recharge through these areas. The volumes shown on the water budget charts represent net flows from stream alluvium to underlying aquifer and aquitard layers. There are areas and months where groundwater from the aquifers and aquitards flow into the stream alluvium, but overall the annual net flow is from stream alluvium to underlying stacked units of the Basin. Meanwhile, the surface water budget (Figure 37) shows net groundwater discharge from stream alluvium to streams. Thus, the stream alluvium is a net source of water for both streams and the underlying stacked aquifer and aquitard units of the Basin.

South of the Aptos area faulting, flow from alluvium includes flow from Terrace Deposits overlying the layers. This is a type of areal recharge to the coastal areas of the Basin and are always inflows.

Appendix D includes the annual water budget for each model layer in the Basin.

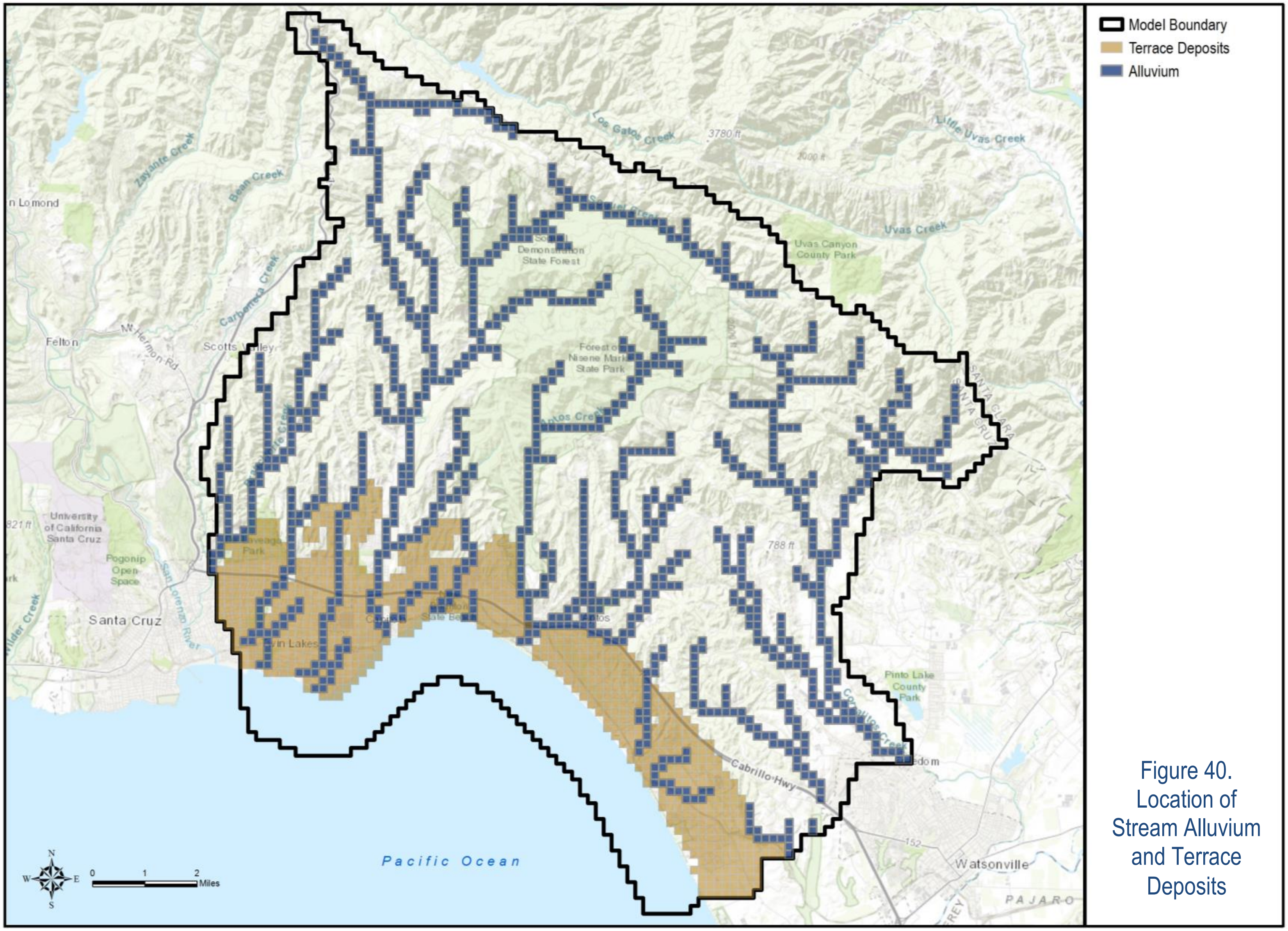


Figure 40. Location of Stream Alluvium and Terrace Deposits

8.3.1.3 Groundwater Pumping

Groundwater pumping is described in Section 4.3. Simulated groundwater pumping is less than the estimates for non-municipal pumping input into the model because pumping at wells in a model cell are turned off if the model cell goes dry.

8.3.2 Flows Across Basin Boundaries

8.3.2.1 Flows between other Basins

Groundwater flow occurs between the Basin and adjacent basins: Purisima Highlands, Pajaro Valley, and Santa Margarita Basins. Substantial inflows occur from Purisima Highlands across the Zayante Fault representing the northern boundary of the Basin. The inflow is relatively constant compared to other inflow components such as UZF recharge and flows from alluvium.

Relatively small flows occur north of HFB representing Aptos area faulting between the Basin and Santa Margarita Basin. These flows only occur in model layer 9 (Tu unit). The basin boundary with Santa Margarita Basin occurs in an area of model layer 9 that is separated from the high conductivity area of model layer 9 representing the Tu unit pumped by the City of Santa Cruz and SqCWD.

Substantial outflows occur from the Basin to the Pajaro Valley Subbasin, but mostly north of the HFB representing Aptos area faulting. This is consistent with observations of high groundwater levels to the northwest and lower groundwater levels in Pajaro Valley near the coast. The model layer with the largest amount of this type of outflow is model layer 3, which represents both the Purisima F and DEF units which are not significantly pumped by pumpers in Pajaro Valley. The model layer with the second largest amount of outflow is model layer 2, representing the Aromas Red Sands, which is the primary aquifer for pumpers in Pajaro Valley.

South of the HFB representing Aptos area faulting, there is net inflow from the Pajaro Valley Subbasin. This is primarily due to the geometry of the basin boundary, which is based on the administrative boundary of Pajaro Valley Water Management Agency (PVWMA). PVWMA covers the area inland of SqCWD Service Areas III and IV so inland groundwater flow to SqCWD production wells in those areas towards the coast is inflow into the Mid-County Basin.

8.3.2.2 Offshore Flows

An important component of the groundwater budget for evaluating groundwater sustainability are flows between the Basin and the ocean (offshore) because seawater intrusion is the sustainability indicator that is the basis for the Basin's overdraft condition. This flow only occurs south of Aptos area faulting. The water budget south the HFB reprenting of Aptosarea faulting (Figure 39) is more instructive for evaluating these flows than the water budget for the entire Basin. Net outflows (negative in the water budget charts) of some magnitude is required to prevent seawater intrusion. Net inflows (positive in the water budget charts) are indicative of flow conditions that will eventually result in seawater intrusion.

Figure 39 shows Basin net offshore outflows and Figure 41 shows the net offshore outflows by layer with the y-axis reversed. Figure 41 shows there has been net inflow in model layers 3 (Purisima F/DEF) and 7 (Purisima A) indicating the high risk of seawater intrusion into these aquifer units historically. Although inflows from the ocean have decreased more recently, inflows still indicate seawater intrusion risk. Net outflows simulated in the Purisima BC and Purisima A aquifer units where seawater intrusion risk has been identified have increased over time. However, water budget results should not be the primary model results for evaluating seawater intrusion because freshwater outflow offshore may not be enough to prevent denser seawater from intruding. In addition, net flows representing flows across the entire coastal boundary may not represent the localized risk near pumping centers. The primary model results for evaluating seawater intrusion should be simulated groundwater levels at coastal monitoring wells compared to established protective elevations.

8.3.3 Change of Groundwater in Storage

Figure 42 shows the cumulative groundwater in storage change for each model layer as well as the entire Basin. Figure 42 depicts that the loss of groundwater in storage in the Basin early in the period was mainly governed by the groundwater in storage loss in model layers 3 (Purisima F/DEF) and 7 (Purisima A); where the majority of Basin pumping occurs. Figure 43 and Figure 44 show the cumulative groundwater in storage change for each model layer in the Basin north and south of the HFB representing Aptos area faulting respectively. The same conclusion can be drawn on these figures as from Figure 42 which is that the loss of groundwater in storage was governed by the loss of storage in model layers 3 and 7, south of the Aptos area faulting where the most pumping occurs in the basin (Figure 39).

An important note is that a reduction of groundwater in storage is not the reason behind the critical overdraft conditions in the Basin. The cause has been the risk of seawater intrusion, which has been due to low groundwater levels near the coast in specific aquifer units. Figure 38 and Figure 39 show that offshore flows are a small part of the water budget compared to changes in groundwater in storage, but offshore flows are what indicate seawater intrusion risk.

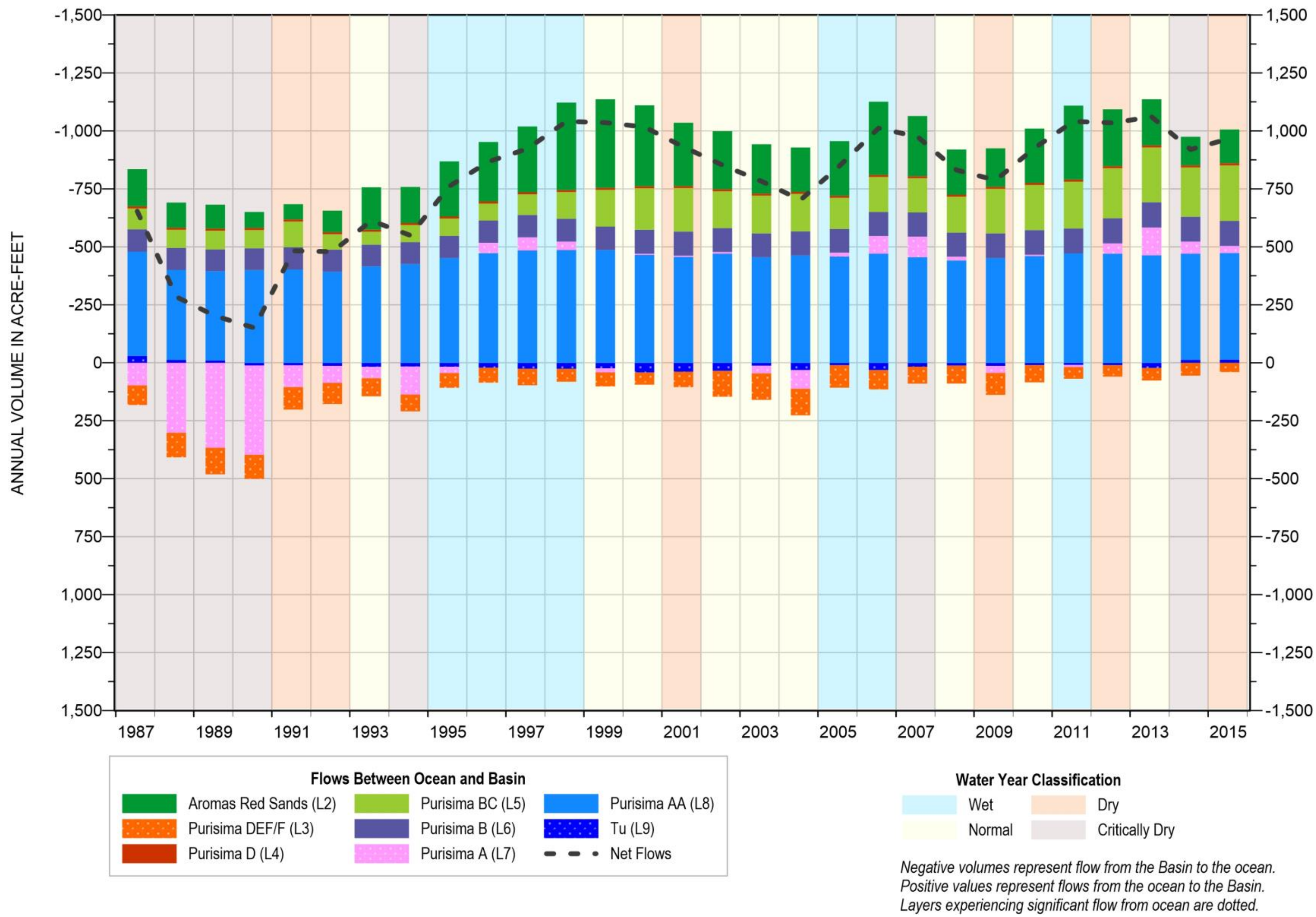


Figure 41. Offshore Groundwater Flow to Mid-County Basin for each Model Layer

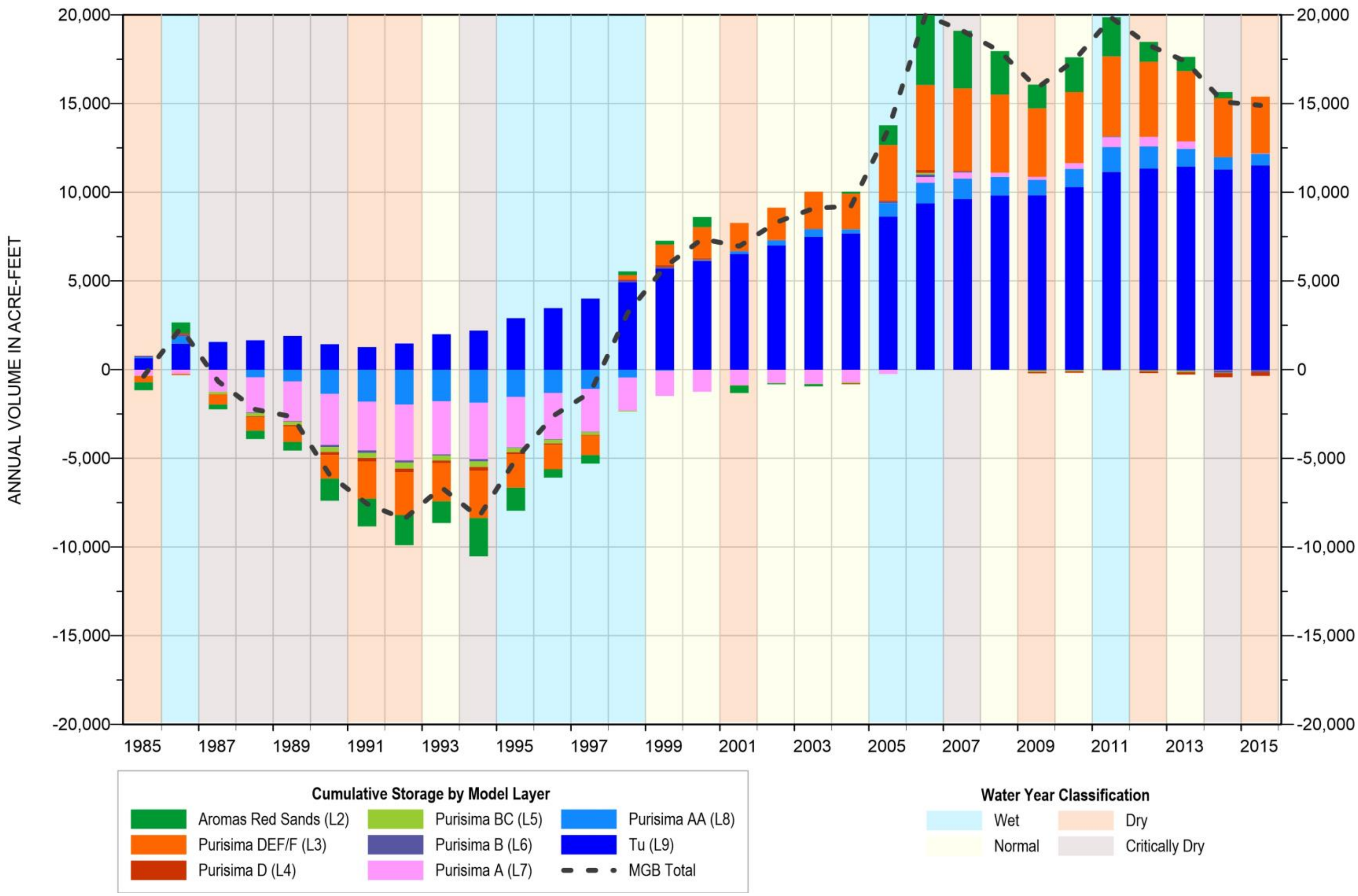


Figure 42. Cumulative Change in Storage Change in Mid-County Basin

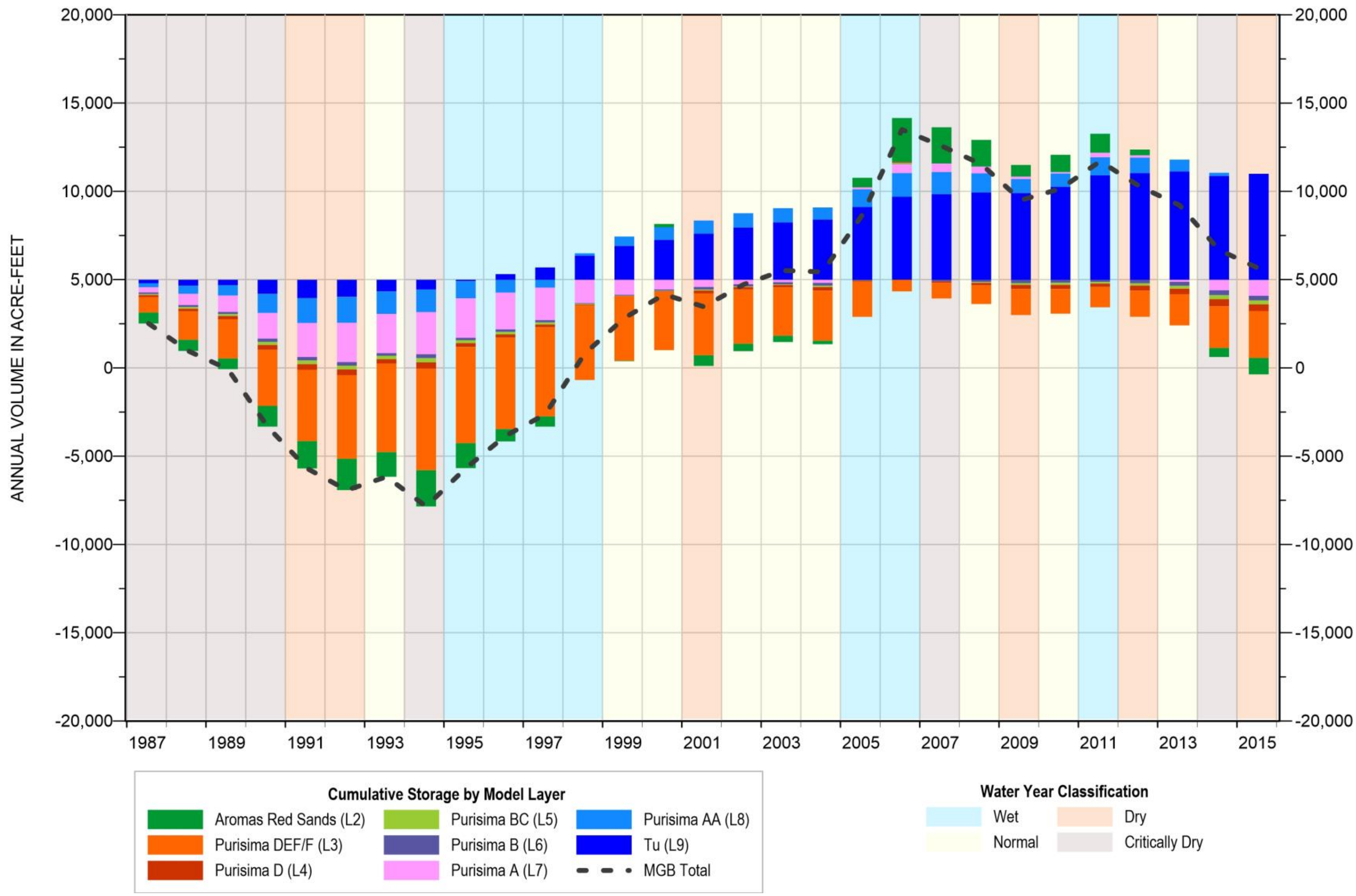


Figure 43. Cumulative Change in Storage in Mid-County Basin; North of HFB for Aptos Faulting

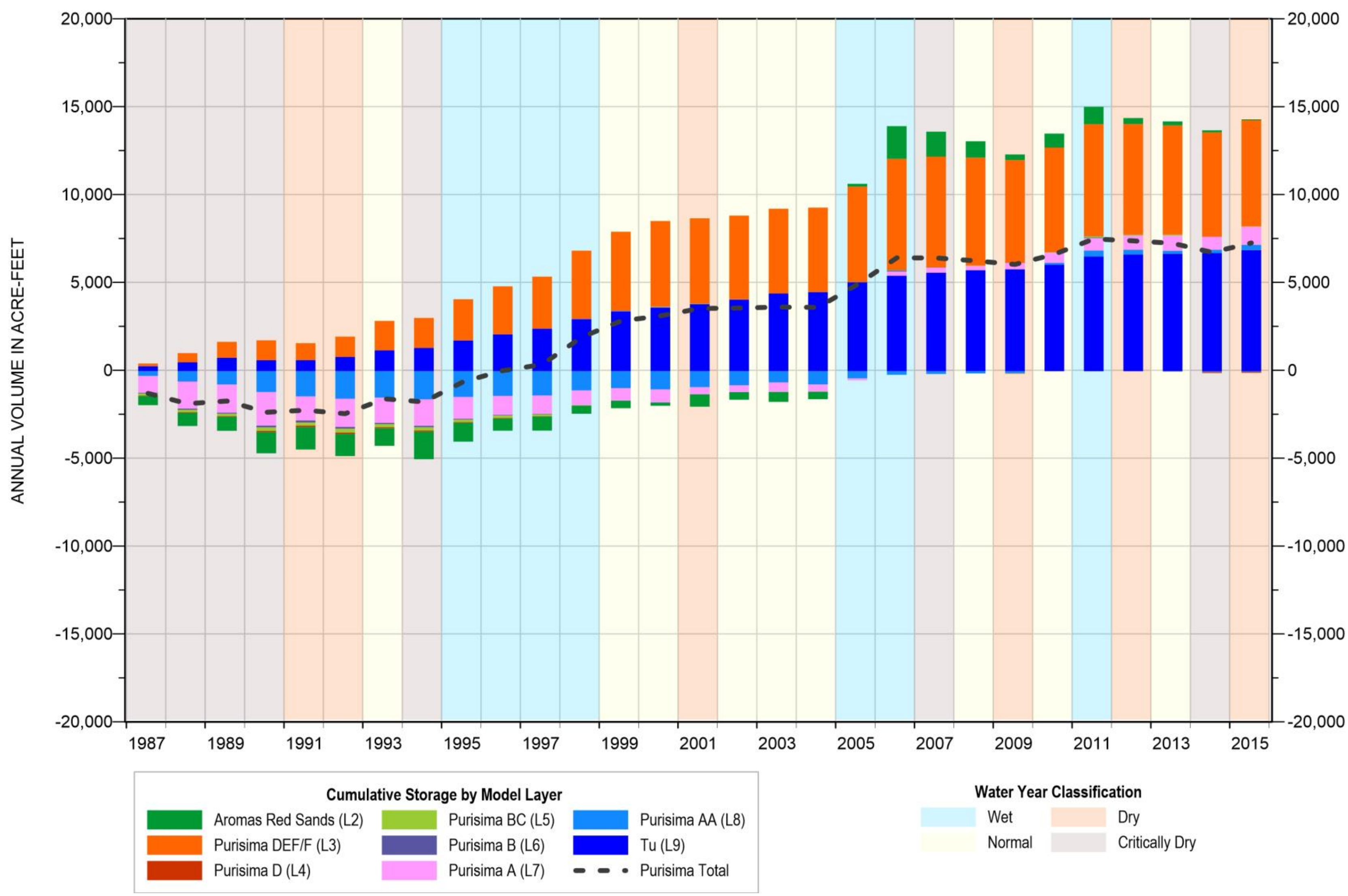


Figure 44. Cumulative Change in Storage in Mid-County Basin, South of HFB for Aptos Area Faulting

8.4 Stream-Aquifer Interactions

The model is used to evaluate stream-aquifer interactions in several ways including identifying where streams are interconnected with groundwater, where shallow pumping may affect streamflows, and estimating groundwater contributions to streamflow. The development of these evaluations were undertaken for Santa Cruz County's Prop 1 grant for stressed basins.

8.4.1 Interconnected Streams with Groundwater

The sustainability indicator in the Groundwater Sustainability Plan (GSP) related to surface water is depletion of interconnected surface water caused by groundwater use. Interconnected surface water is defined in DWR's regulations for GSPs as "surface water that is hydraulically connected at any point by a continuous saturated zone to the underlying aquifer." The model is used to identify how often streams in the Basin are connected with groundwater in the underlying aquifer representing stream alluvium based on output from the model's stream (SFR) package. Figure 45 shows that Soquel Creek is simulated as connected to groundwater more than other streams in the Basin and streams overlying the Purisima F unit and Aromas Red Sands such as Valencia Creek are mostly simulated as not connected to groundwater, which is consistent with the conceptual understanding for the Basin

8.4.2 Depth to Groundwater

In order to identify where shallow pumping wells are more likely to exist and contribute to streamflow depletion in the Basin, Figure 46 shows modeled depth to the water table in March 2015. March 2015 is the representative time for when groundwater levels are high throughout the Basin.

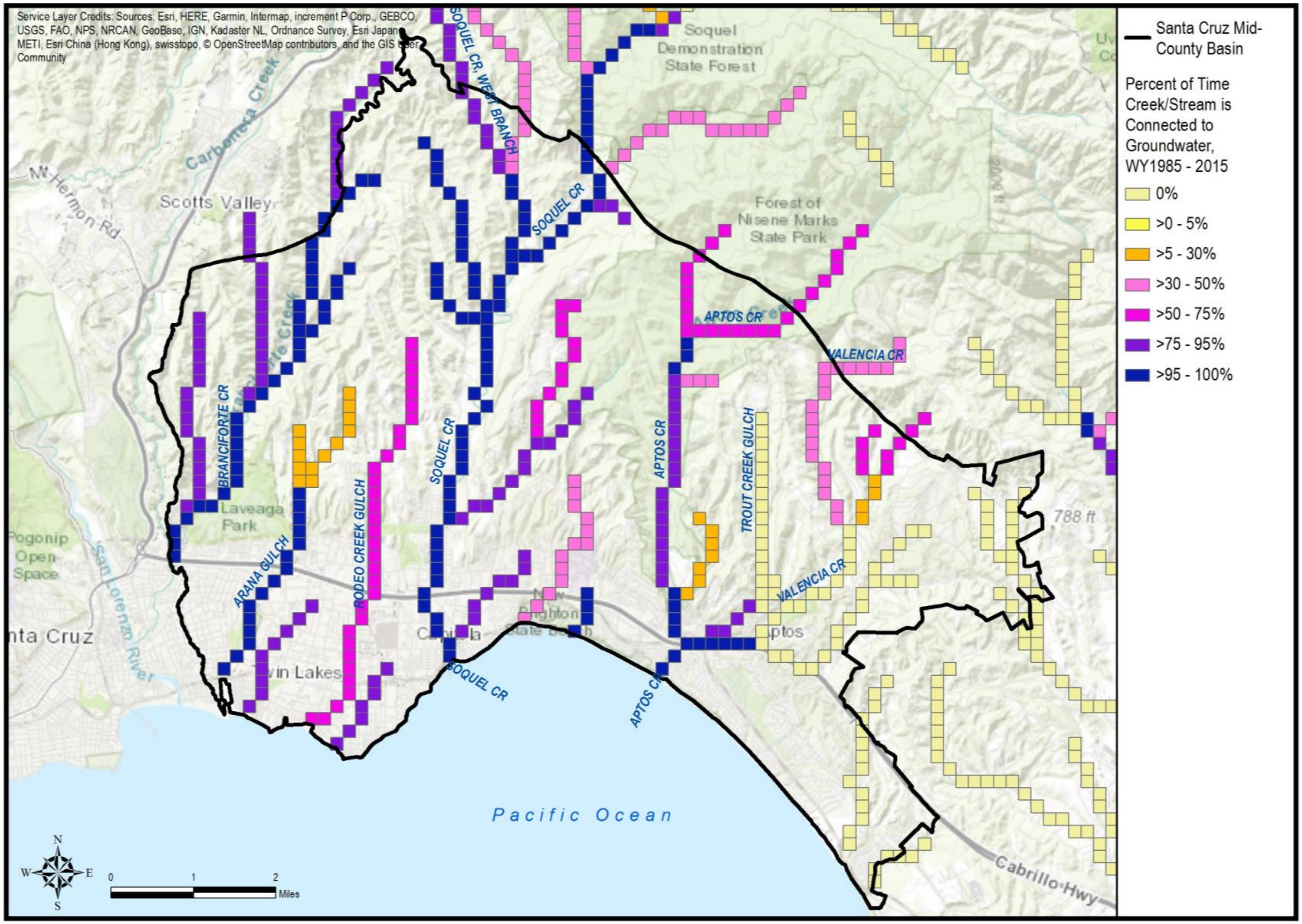
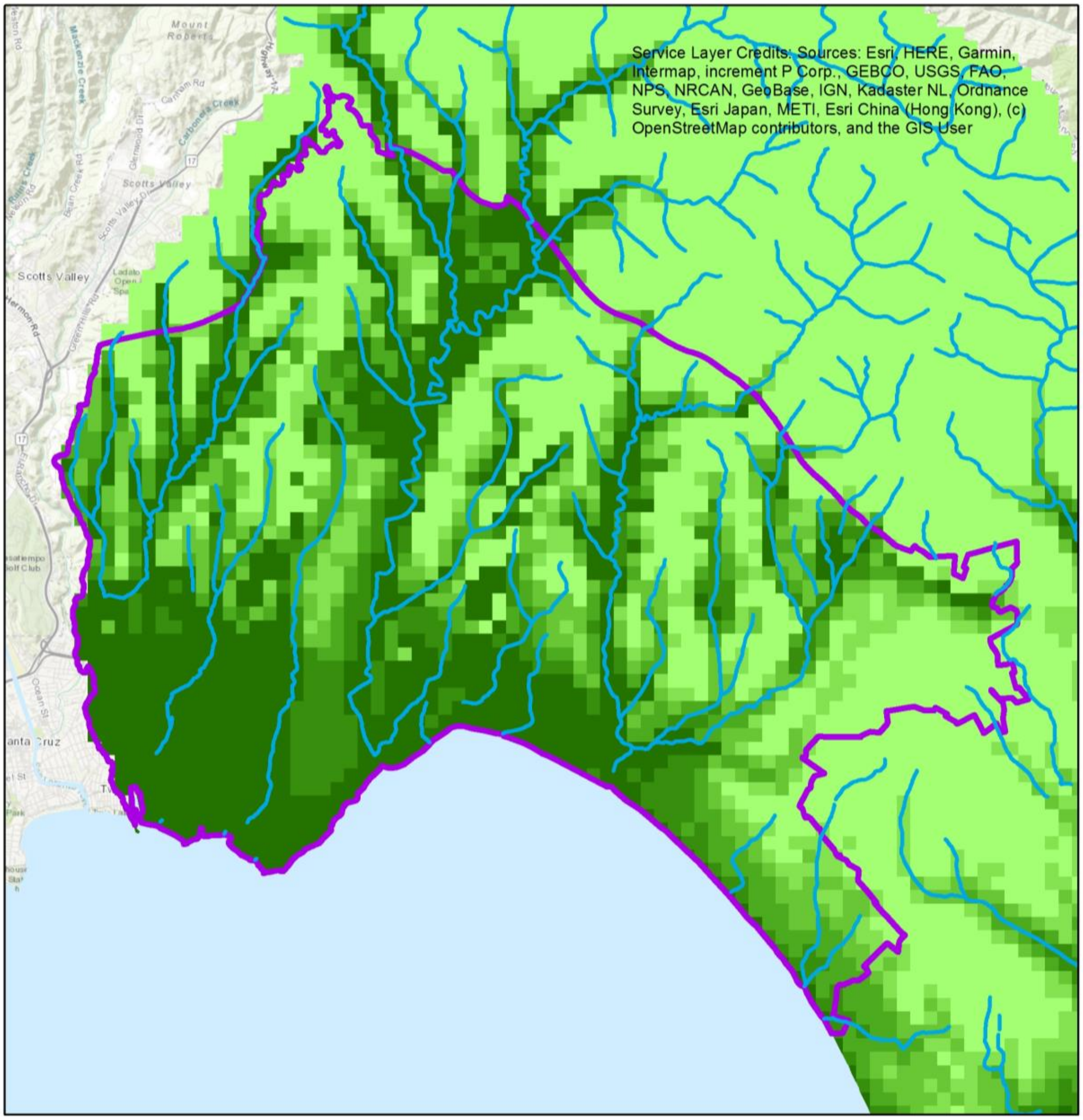


Figure 45. Percent of Time Surface Water and Groundwater are Connected



EXPLANATION

Depth to Water, feet below ground surface

- <50
- 51 - 100
- 101 - 150
- 151 - 200
- 201 - 250
- >250
- Santa Cruz Mid-County Basin
- Streams

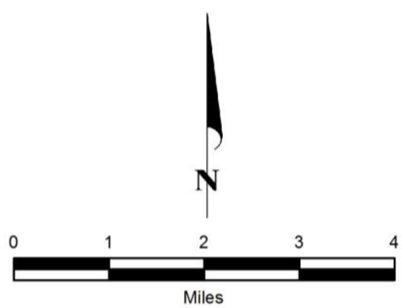


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Figure 46. Depth to Shallowest Groundwater in March 2015

8.4.3 Groundwater Contribution to Soquel Creek Flow

Based on the calibration of shallow groundwater levels along Soquel Creek (Section 7.3.6), the model is used to estimate groundwater contribution to Soquel Creek where calibration data are available and vertical connection between stream and underlying aquifers is higher than the rest of the model. Figure 47 and Figure 48 show the groundwater contribution to Soquel Creek for the minimum flow month in each year to provide an estimate of the groundwater contribution when streamflow depletions are most likely to result in significant and unreasonable conditions. Figure 47 shows the stretch from Moores Gulch to Bates Creek where the Simons and Balogh shallow wells are located (Figure 21). Figure 48 shows the stretch downstream of Bates Creek where the Main Street, Wharf Road, and Nob Hill shallow wells are located. Most of the streamflow is simulated to come from upstream. Groundwater contribution to streamflow along these stretches is less than 0.5 cfs consistent with estimates from previous studies that streamflow depletion has not been observed because depletion of up to 0.5 cfs cannot be observed from the data (Johnson et al., 2004). As described previously, more precise data for groundwater contribution to streamflow are not available for calibration. Therefore, the model could estimate groundwater contribution of any value from 0 to 0.5 cfs and be consistent with the conclusion from Johnson et al., 2004, which indicates the uncertainty of these groundwater contribution flow estimates.

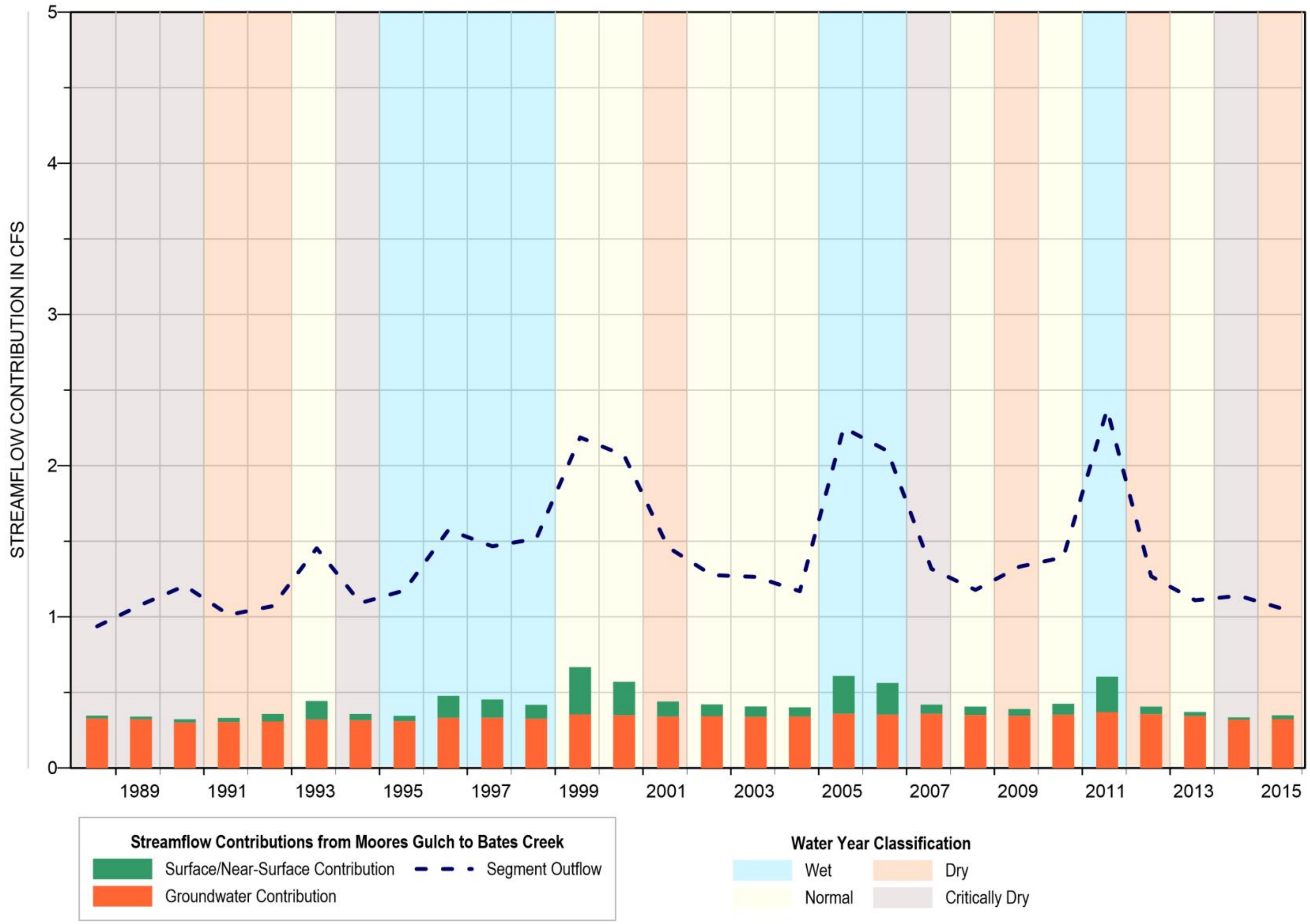

Figure 47. Simulated Minimum Monthly Flows from Moores Gulch to Bates Creek

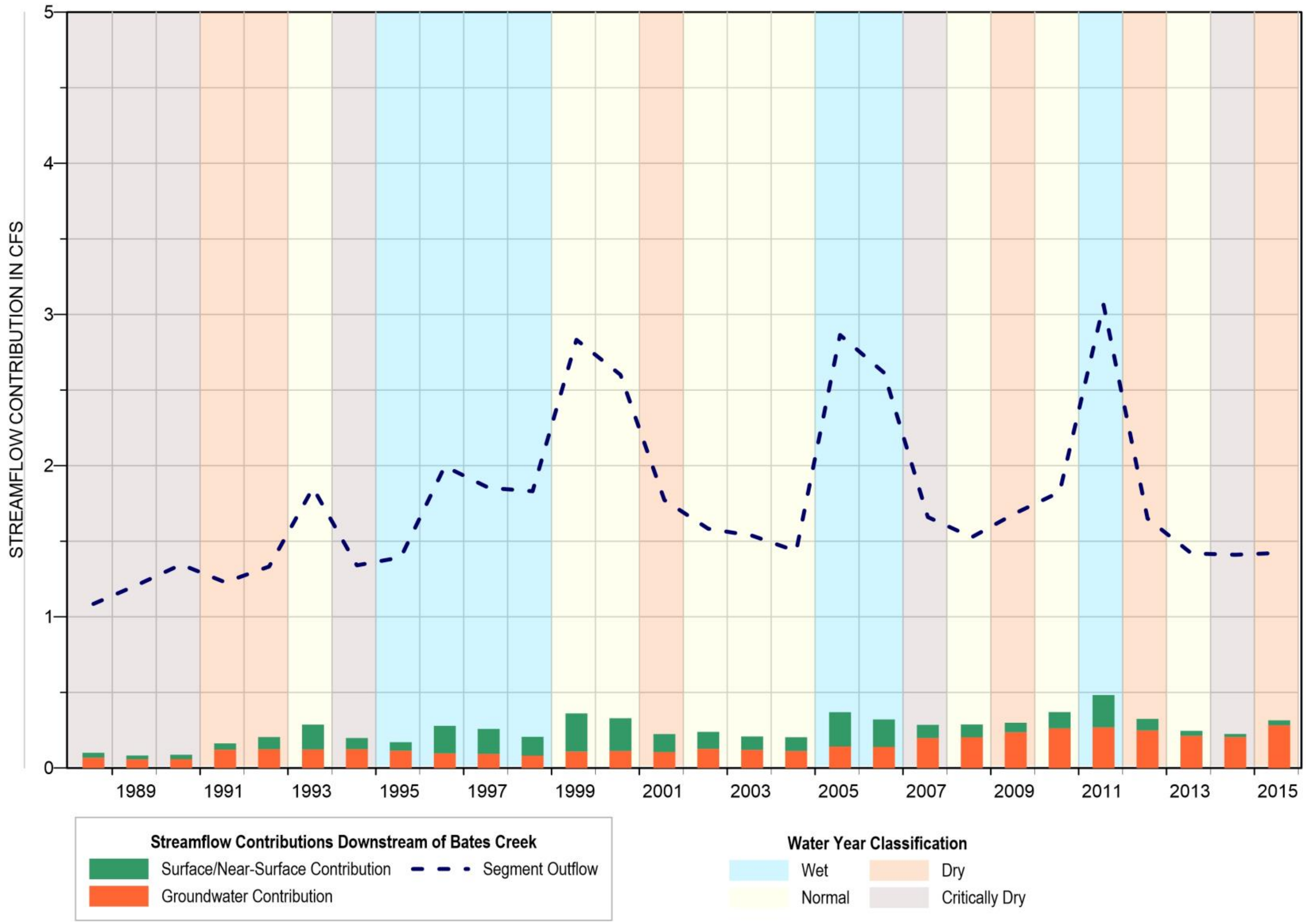

Figure 48. Simulated Minimum Monthly Flows Downstream of Bates Creek

9 SENSITIVITY RUNS

Several sensitivity runs were conducted to evaluate effects of different water use types and assumptions on sustainability for the Basin. The results of these runs are compared to the results of the calibration run described above to evaluate these effects. Sensitivity runs included a run to support development of the streamflow depletion sustainable management criteria:

- Remove all Basin pumping and associated return flow to estimate streamflow depletion in Soquel Creek from Basin groundwater use.

The following sensitivity runs were also performed as part of the scope for Santa Cruz County's Prop 1 grant.

- Remove inland pumping and associated return flow to evaluate effects of inland groundwater use.
- Re-assign non-municipal pumping underneath stream alluvium and Terrace deposit cells to overlying alluvium and Terrace deposit cells to evaluate potential effects of shallow pumping on streamflow.
- Remove non-municipal pumping in lower Soquel Creek and Bates Creek Valleys to evaluate effects of non-municipal pumpers on Soquel Creek streamflow.
- Reduce septic return flow assuming 50% return flow in septic areas instead of 90% currently assumed.

The sensitivity of sustainability to these changes is evaluated by comparing model results to the calibration run. Model results that are compared include:

- Groundwater levels at coastal monitoring wells that are representative monitoring points with groundwater elevation proxies for seawater intrusion in the GSP;
- Groundwater levels at shallow wells along Soquel Creek that are representative monitoring points with groundwater elevation proxies for seawater intrusion in the GSP; and
- Differences in groundwater contribution to streamflow in Soquel Creek watershed during the month with minimum streamflow for each year.

- These sensitivity runs change model output beyond what is calibrated and therefore the results include substantial uncertainty.

9.1 Estimate of Streamflow Depletion from Basin Groundwater Use

In order to establish sustainable management criteria for streamflow depletion, the model is used to estimate historical streamflow depletion in Soquel Creek from Basin groundwater use. This estimate is based on a sensitivity run that removes all Basin pumping and associated return flow over the calibration period. Pumping and return flow simulated for the Basin and removed for this sensitivity run are shown in Figure 12 and Figure 13, respectively. The estimate of streamflow depletion from historical Basin groundwater use is based on the difference in groundwater contributions to streamflow in the Soquel Creek watershed between the sensitivity run and the calibration run. As described previously, the model is not calibrated to precise estimates of flows between groundwater and streams, so estimates of streamflow depletion from the model have high uncertainty. Additionally, sensitivity runs provide estimates of streamflow depletion resulting from groundwater use and incorporating other assumptions. It is important to note that these estimates represent conditions that have not occurred historically and are therefore uncalibrated to any data, which introduces additional uncertainty.

Figure 49 shows the groundwater and surface/near-surface contributions for Soquel Creek watershed in the minimum flow month for each water year of the calibration run. As in Section 8.4.3, the minimum flow month for each year is evaluated because these are the months when streamflow depletions are most likely to result in significant and unreasonable conditions. With all of Basin pumping removed, the increase in total streamflow for the watershed in these minimum flow months are almost all due to higher contributions from groundwater. Removing all Basin pumping in the model results in an increased groundwater contribution to Soquel Creek of up to 1.4 cfs. Therefore, the estimate of historical streamflow depletion based on the model is 1.4 cfs.

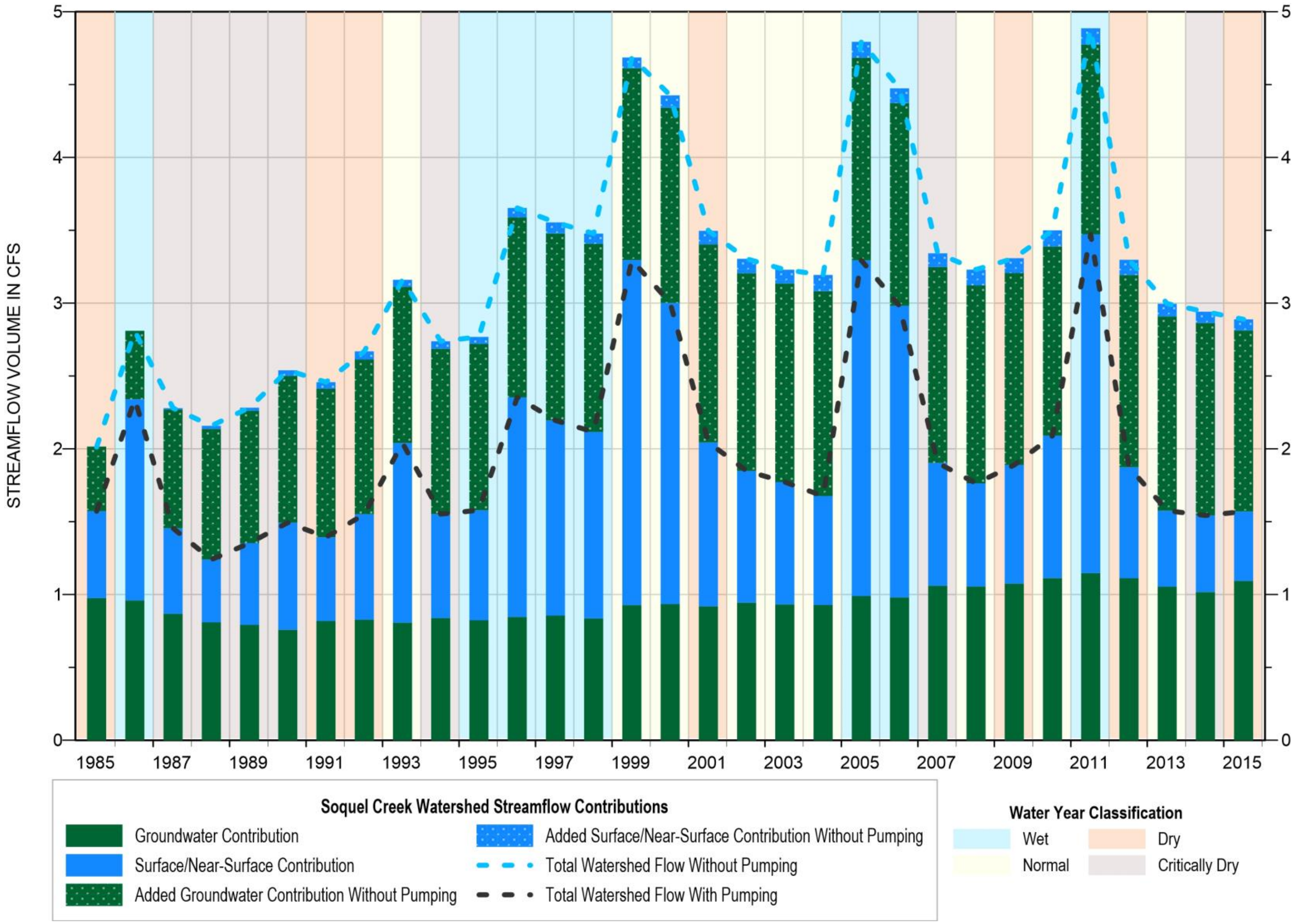

Figure 49. Simulated Contributions to Soquel Creek Watershed Streamflow in Minimum Flow Month with and without Historical Pumping

9.2 Effects of Inland Groundwater Use

For this sensitivity run, inland pumping and associated return flow was removed from the area shown in Figure 50 where groundwater elevations are estimated by the model to be above 50 feet msl. The average decrease in pumping is approximately 1,000 acre-feet per year and the average decrease in return flow is approximately 400 acre-feet per year.

This sensitivity run indicates that inland groundwater use has minimal effect on Basin sustainability. At coastal monitoring wells that are representative monitoring points for seawater intrusion, Figure 51 and Figure 52 show that the increase in groundwater levels resulting from removal of the inland groundwater use is very slight.

Sensitivity of streamflow depletion to inland groundwater use is larger than sensitivity related to seawater intrusion, but still small. At shallow wells along Soquel Creek that are representative monitoring points for streamflow depletion, there are small increases in groundwater levels with removal of the inland groundwater use (Figure 53). Based on the increase in groundwater contribution to streamflow resulting from this groundwater use removal during months with minimum streamflow, the model estimates streamflow depletion effects of this inland pumping as up to 0.1 cfs (Figure 54).

9.3 Effects of Pumping from Shallow Groundwater

In the calibrated model, non-municipal pumping is assumed to occur in the shallowest Basin aquifer unit in the Aromas Red Sands and Purisima Formation, not the stream alluvium and Terrace deposits. For this sensitivity run, non-municipal pumping assumed to occur from Basin aquifer units underlying stream alluvium and Terrace Deposits shown in Figure 40 is moved up to extract from the stream alluvium and Terrace Deposits instead. Approximately 30 acre-feet per year of pumping is moved up to the Terrace Deposits and approximately 250 acre-feet per year is moved up to the stream alluvium.

The run tests the sensitivity of streamflow depletion along Soquel Creek to shallow pumping. Moving pumping to the stream alluvium results in decreases in shallow groundwater levels along Soquel Creek as shown in Figure 53. Based on the decrease in groundwater contribution to streamflow resulting from moving pumping to shallow alluvium and Terrace Deposits during months with minimum streamflow months, the model estimates streamflow depletion effects of potential shallow pumping as approximately 0.1 cfs (Figure 54).

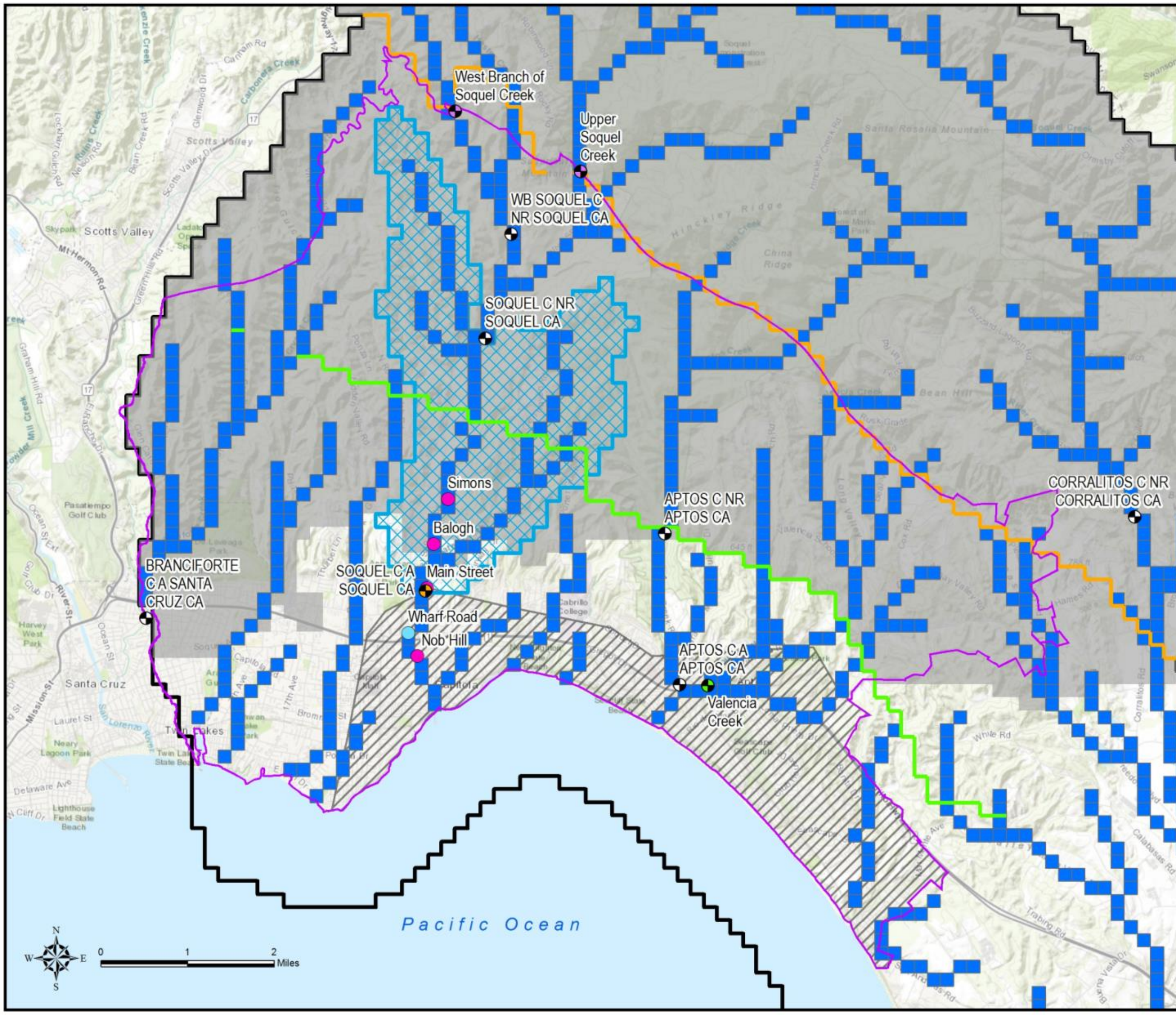

Figure 50. Areas of Removed Groundwater Use for Sensitivity Runs

Streambed thickness of 3.28 feet for all reaches

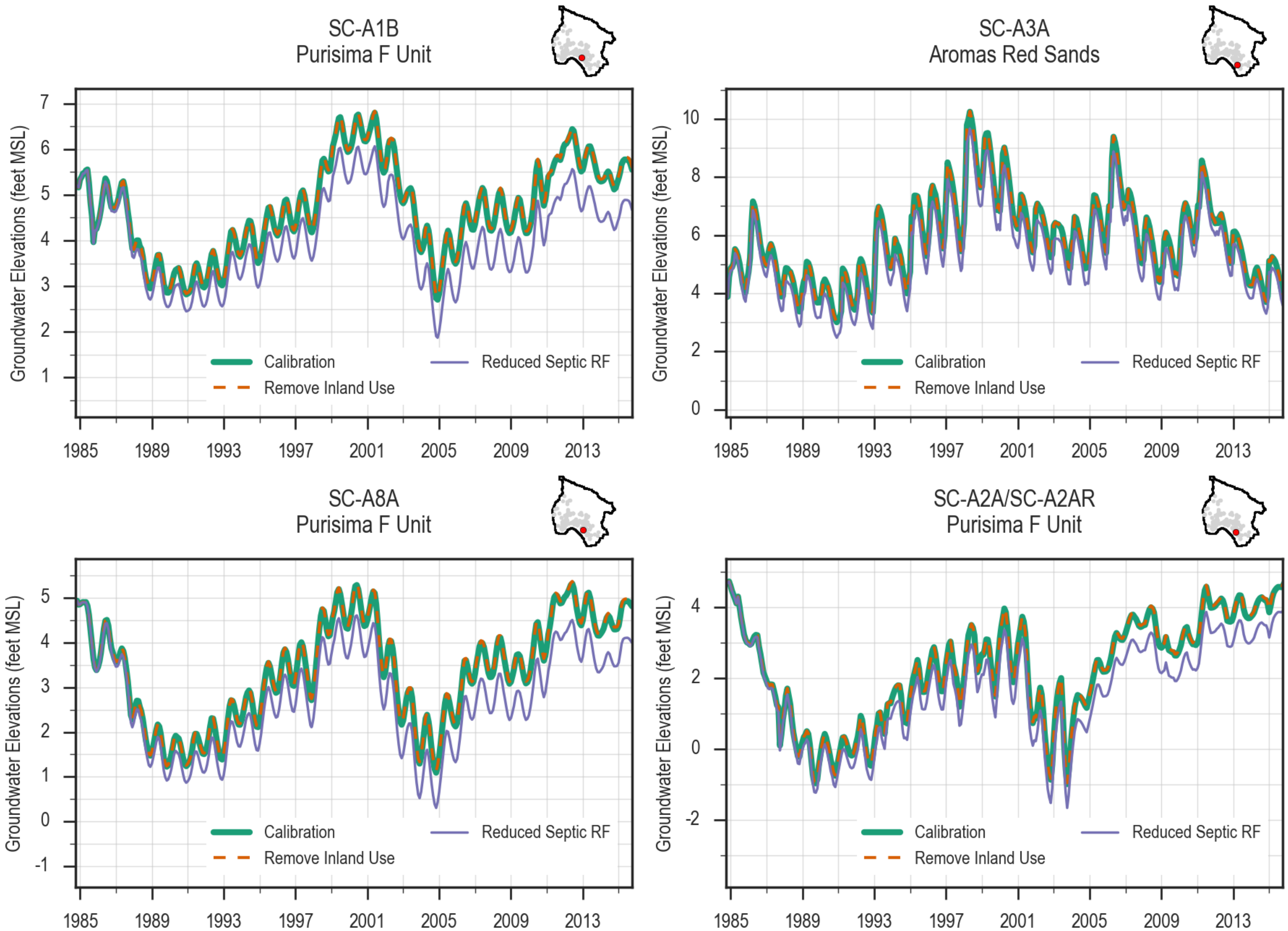

Figure 51. Sensitivity Hydrographs at Coastal Monitoring Wells in Aromas and Purisima F Units

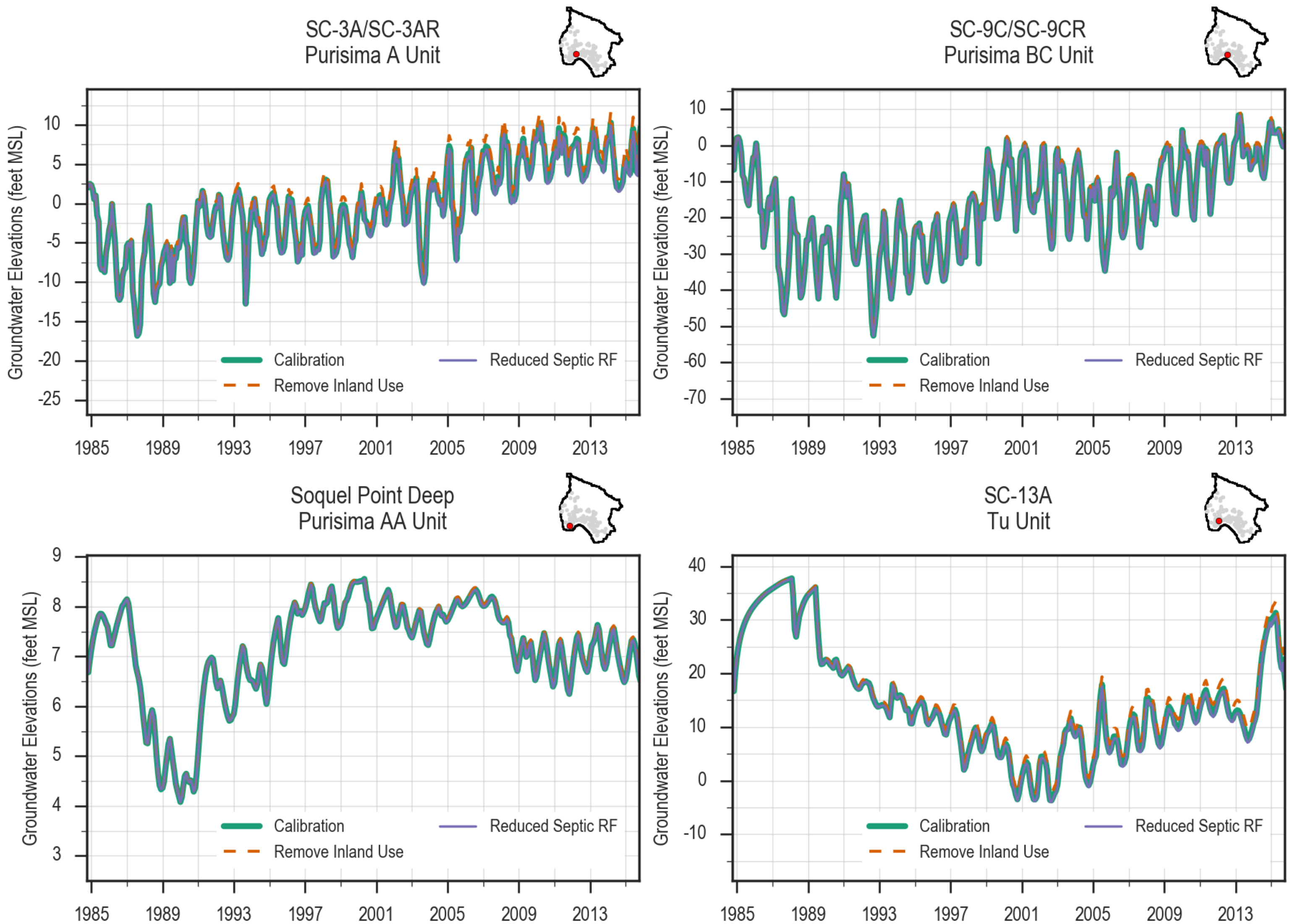

Figure 52. Sensitivity Hydrographs at Coastal Monitoring Wells in Purisima and Tu Units

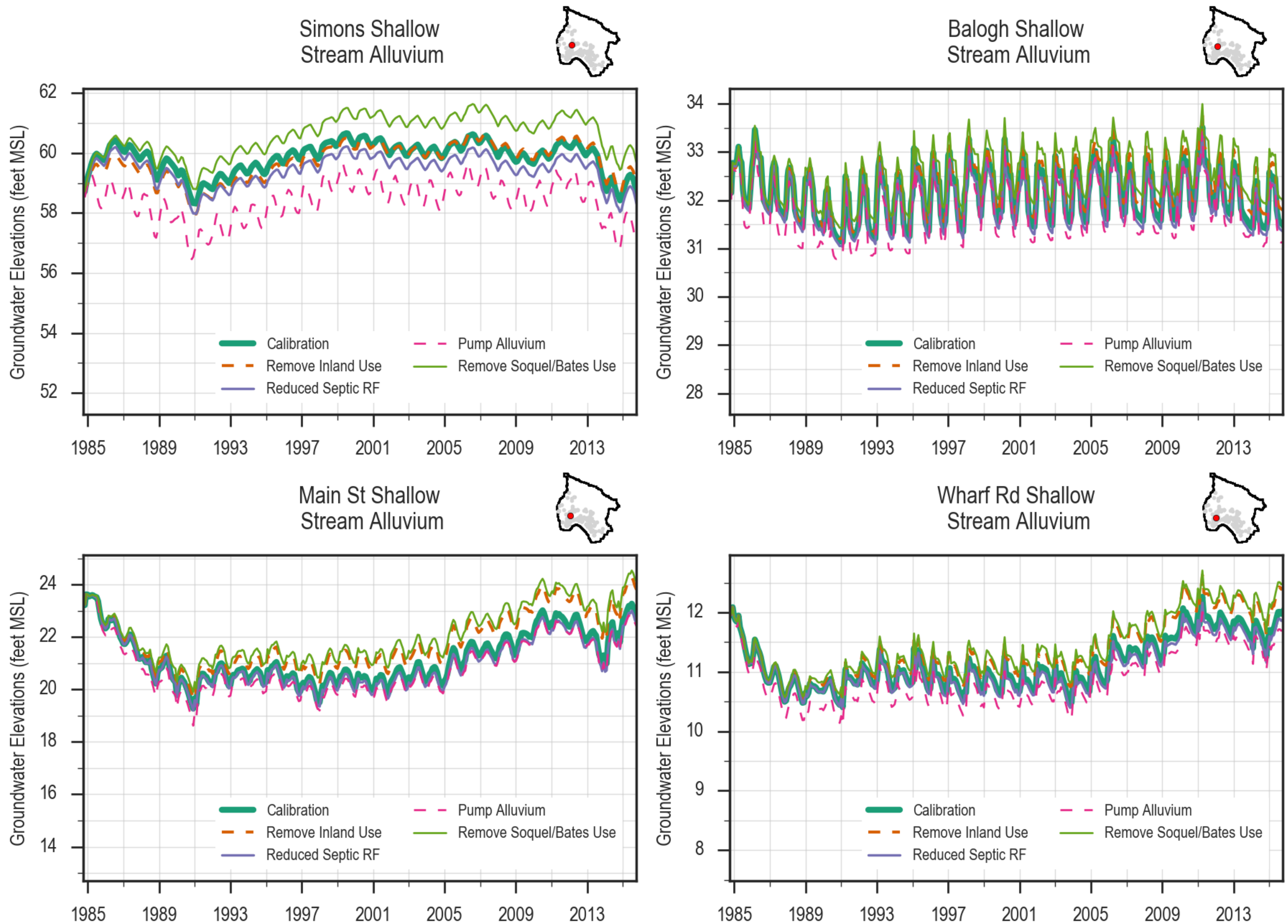

Figure 53. Sensitivity Hydrographs at Shallow Wells along Soquel Creek

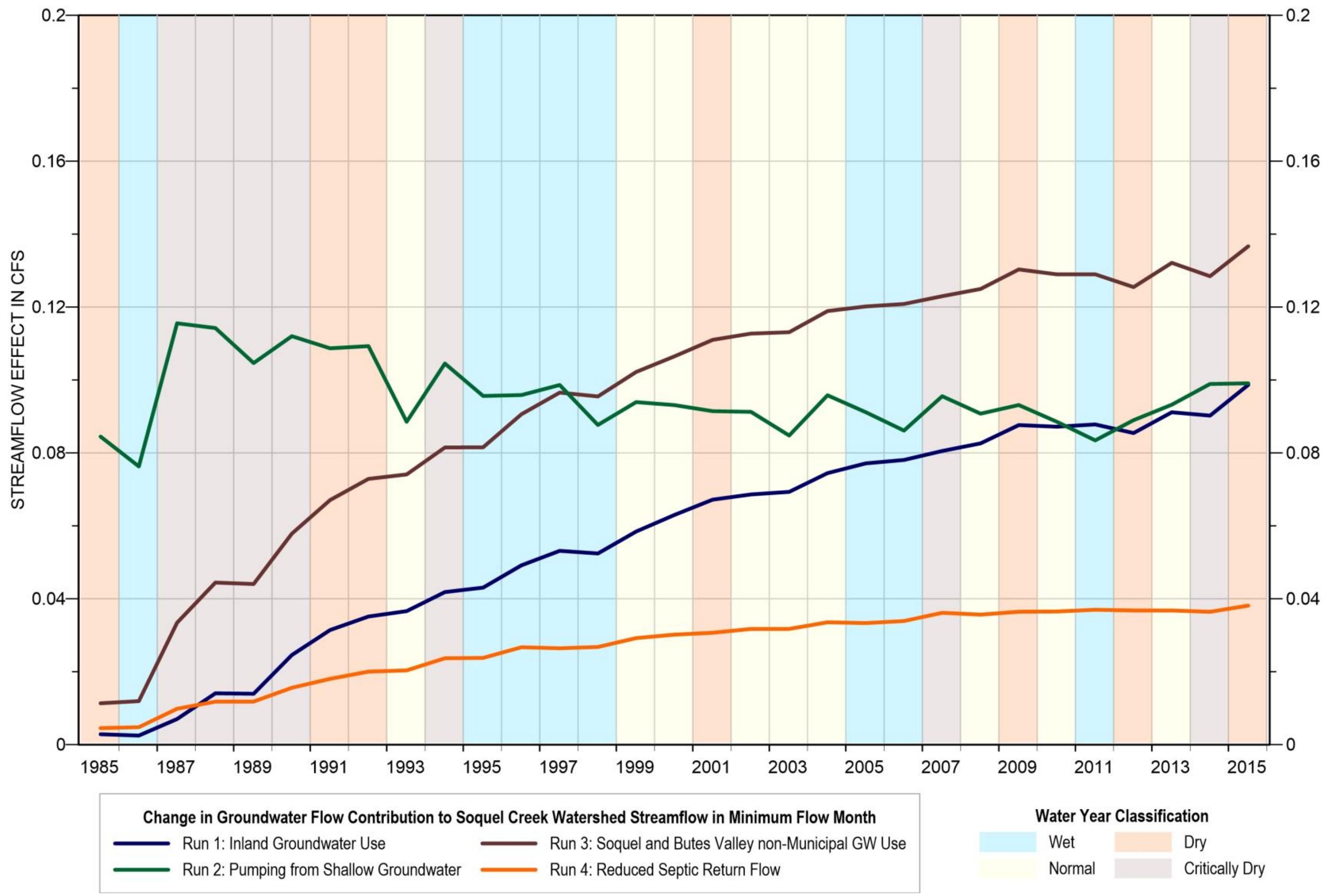

Figure 54. Sensitivity of Stream Depletion Effects

9.4 Effects of Pumping from Soquel Creek and Bates Creek Valleys

For this sensitivity run, non-municipal pumping was removed from Soquel Creek and Bates Creek Valleys, for the area shown on Figure 50. The run tests the sensitivity of streamflow depletion along Soquel Creek to shallow pumping. The average decrease in pumping was approximately 370 acre-feet per year.

As expected, groundwater use in the Soquel Creek and Bates Creek Valleys shows a larger effect on streamflow than other sensitivity runs except the run that removed all Basin groundwater use. At the shallow wells along Soquel Creek, there are small increases in groundwater levels with removal of inland groundwater use (Figure 53). Based on the decrease in groundwater contribution to streamflow resulting from removing pumping in this area during the months with minimum, the model estimates streamflow depletion effects of potential shallow pumping as up to 0.15 cfs (Figure 54).

9.5 Effects of Reduced Septic Return Flow

In the calibrated model, 90% of indoor use in septic areas are assumed to become return flow. The model adds the return flow volumes as recharge below the soil zone to the UZF package. For this sensitivity run, it is assumed that only 50% of indoor use in septic areas are assumed to become return flow to test the effect of the septic return flow assumption. The approximately 45% reduction in septic return flow results in an average decrease in return flow of 300 acre-feet per year.

This sensitivity run indicates that the septic return flow assumption has a small effect on model evaluation of Basin sustainability. At coastal monitoring wells that are representative monitoring points for seawater intrusion, Figure 51 shows the decrease in groundwater levels resulting from reduction of septic return flow is up to 1 foot in the Purisima F unit and Aromas Red Sands where there are septic areas near the coast. There is almost no effect of the assumption in the deeper Purisima and Tu unit.

Sensitivity of streamflow depletion to the assumption for septic return flow is very small. At shallow wells along Soquel Creek that are representative monitoring points for streamflow depletion, there are very small decreases in groundwater levels with reduction of septic return flows. Based on the decrease in groundwater contribution to streamflow during the minimum streamflow months resulting from this removal, the model estimates streamflow depletion effects of this assumption as less than 0.05 cfs.

10 SIMULATING SEAWATER INTERFACE

We previously recommended to implement the MODFLOW SWI2 package (Bakker et al., 2013) in the model to be able to simulate movement of the seawater interface and evaluate potential effects of projects and management actions on the seawater interface. The SWI2 package has not been implemented in the model as it is not necessary for the GSP to simulate the seawater interface because groundwater elevation proxies are being used for the seawater intrusion sustainable management criteria. Model results of groundwater elevations can be used to compare to those groundwater elevation proxies to evaluate the benefits of projects and management actions for preventing undesirable results in seawater intrusion.

We are now recommending that the SWI2 package not be implemented in the model for two reasons.

1. The effort to overcome challenges in implementing the SWI2 package would not be cost-effective given that it is not necessary for evaluating Basin sustainability;
2. Implementing the SWI2 package would not answer the questions from the GSP Advisory Committee about movement of the seawater interface related to the use of five year groundwater elevation averages for seawater intrusion sustainability management criteria.

10.1 Challenges for Implementation of SWI2 package in Santa Cruz Mid-County Basin Model

SWI2 stability and convergence of the solution is highly dependent on having the 3-dimensional representation of the initial salt water interface surface properly and adequately defined over the entire model domain. Defining the current seawater interface configuration poses challenges given current data gaps in the understanding of the interface over the entire model domain. For example, the SKYTEM survey identifying salty water in aquifer units offshore could not be extended onshore over most of the model area and an understanding of how salinity concentrations change with depth in the deeper aquifers is limited both by the lack of deep well data covering the near coastal areas and the limitation on the depth of investigation of the SKYTEM survey. Because the shape of the interface in the lower aquifers is not well understood or constrained, this creates a challenge in representing and modeling the 3-dimensional interface.

10.2 Model Evaluation of Five Year Groundwater Elevation Averages for Seawater Intrusion Sustainability Management Criteria

A GSP Advisory Committee helped develop sustainability management criteria for the GSP. The main questions that arose from the Committee on the movement of the seawater interface were related to the appropriateness of using a five year average as groundwater elevation proxies for seawater intrusion sustainability management criteria. Using a five year average allows for time periods when groundwater elevations are lower than the criteria even if they are offset by times when groundwater elevations are higher than the criteria. The GSP provides sufficient rationale for why the five year average is appropriate, but the MGA may want to evaluate further during GSP implementation.

The SWI2 package cannot be used for this evaluation as it only simulates the movement of a sharp interface. Part of the concern of using the five year average is that time periods of lower groundwater elevations will allow seawater to intrude and even as higher groundwater elevations push out the average location of the interface, salty water will remain inland. Simulating only the sharp interface will not simulate this potential spreading of salty water as groundwater elevations vary.

One potential alternative to implementing the SWI2 package is to use two-dimensional cross-sectional models with the SEAWAT package (Langevin et al., 2008) similar to the models previously used to estimate the protective elevations (HydroMetrics LLC, 2009) used as groundwater level proxies for seawater intrusion sustainable management criteria. SEAWAT represents advection and dispersion of salinity fronts needed to address this issue. In addition, developing a two-dimensional representation of the interface will be simpler than developing a three-dimensional representation. Output from the Mid-County Basin GSFLOW model simulations of projects and management actions can be used as boundary condition inputs to the cross-sectional models to represent expected changes in coastal groundwater elevations over time under the GSP.

11 CONCLUSIONS

This report describes the development and calibration of the integrated surface water-groundwater model of the Santa Cruz Mid-County Basin, which has been used to develop sustainability management criteria and to project future Basin conditions for evaluating water management scenarios during GSP implementation. The GSFLOW model was constructed to evaluate seawater intrusion, simulate groundwater and surface water processes, and is calibrated to groundwater level and streamflow data for the period from Water Year 1984 through 2015.

The PRMS portion of the model is calibrated to measured streamflow and allows for estimation of recharge to Basin aquifers and aquitard units. Groundwater aquifer properties have been calibrated to observed groundwater levels for most coastal groundwater wells. The calibrated model can be used to evaluate groundwater management projects with the primary goal of preventing seawater intrusion. Groundwater level calibration also supports evaluating groundwater level responses to projects in areas where observation data show past responses to municipal pumping (i.e. south of the simulated horizontal flow barrier (HFB) representing Aptos area faulting).

Calibration to shallow groundwater levels along Soquel Creek supports using the model to simulate shallow groundwater level responses to groundwater management projects for evaluating sustainability of streamflow depletion. The model is not calibrated to precise estimates of flows between groundwater and streams, so estimates of streamflow depletion from the model have high uncertainty. Additionally, sensitivity runs provide estimates of streamflow depletion resulting from groundwater use and incorporating other assumptions. It is important to note that these estimates represent conditions that have not occurred historically and are therefore uncalibrated to any data, which introduces additional uncertainty.

The remainder of the model area does not have the benefit of measured shallow groundwater data from which to calibrate the model and therefore the simulation of shallow groundwater and stream-aquifer interactions is much more uncertain than in areas with shallow monitoring wells.

The current model is not recommended for evaluating responses in the Purisima DEF unit due to limitations associated with the current vertical discretization of model layers in this area, which prevents simulation of the observed confined aquifer response. The current model is also not recommended for evaluating responses to pumping or managed recharge north of Aptos area faulting as there lacks measured groundwater level data showing past responses to regional pumping.

The use of the model in evaluating proposed projects should be with respect to protective groundwater elevation for preventing seawater intrusion and whether or not a project recovers and maintains groundwater levels at protective elevations. The model can also be used to evaluate effects of projects on meeting sustainability criteria for streamflow depletion by predicting shallow groundwater levels along Soquel Creek. The model can also be used to evaluate groundwater level effects of projects throughout the area south of the Aptos area faulting, such as at existing or planned well locations.

The model should not be used to define a single number that any project or combination of projects needs to supply to achieve sustainability, as the ability to prevent seawater intrusion and avoid other undesirable results depends on the specifics of each project. The model can be used to define a single number for planning purposes, but it will be based on specific assumptions for projects and management actions to achieve sustainability.

The water budgets calculated by the model can be used for groundwater sustainability planning, but it must be understood that there are significant differences for the portions of the basin north and south of the Aptos area faulting. It is also important to understand that even components of the water budget that make up a small percentage of the total budget, such as offshore outflows which regulate seawater intrusion, can actually have greater importance on basin sustainability than other water budget components with larger volumes.

The following is a list of recommendations for future improvements of the model:

- Consider splitting layer 3 to separately simulate the Purisima DEF and F units which have different observed confined and unconfined aquifer responses in some areas of the model
- Calibrate inland groundwater levels after five years of data become available from representative monitoring points.
- Calibrate shallow groundwater levels along additional creeks after five years of data become available from representative monitoring points.

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13 ACRONYMS & ABBREVIATIONS

AFY................acre-feet per year
ASR................aquifer storage and recovery
amsl................above mean sea level
bgs..................below ground surface
cfs...................cubic feet per second
cfs...................cublic feet per second
COOP.............Cooperative Observer Network
CRT................Cascade Routing Tool
CWD..............Central Water District
DEM...............digital elevation model
GHB...............general head boundary
GIS.................geographic information systems
HFB................horizontal flow barrier
HRU...............hydrologic response unit
Kh...................horizontal hydraulic conductivity
Kv...................vertical hydraulic conductivity
MAE...............mean absolute error
ME..................mean error
MGA ....Mid-County Groundwater Agency
MGB ....Mid-County Groundwater Basin
MNW2...........Multi-Node Well
NHD...............National Hydrography Dataset
NS ....Nash-Sutcliffe goodness of fit
NWS...............National Weather Service
PET ....potential evapotranspiration
PRMS.............Precipitation-Runoff Modeling System
PVWMA.........Pajaro Valley Water Management Agency
PWS ....Pure Water Soquel
RMSE.............root mean squared error
SFR ....Streamflow-Routing
SWI ....Seawater Interface
SqCWD..........Soquel Creek Water District
SR...................solar radiation
Ss....................specific storage
STD................standard deviation

Sy ....specific yield
USGS .............U.S. Geological Survey
UZF ....Unsaturated-Zone Flow

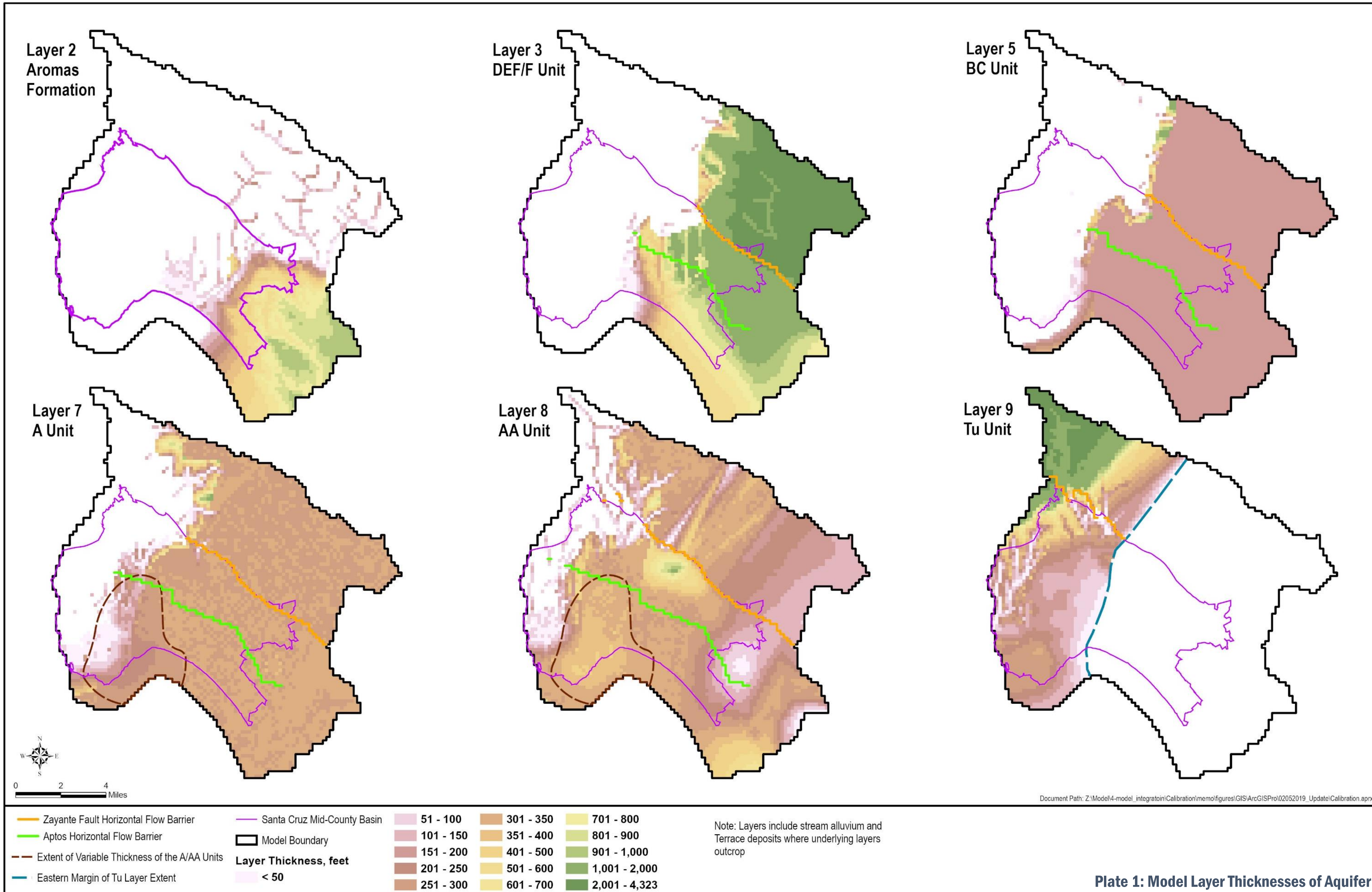


Plate 1: Model Layer Thicknesses of Aquifer

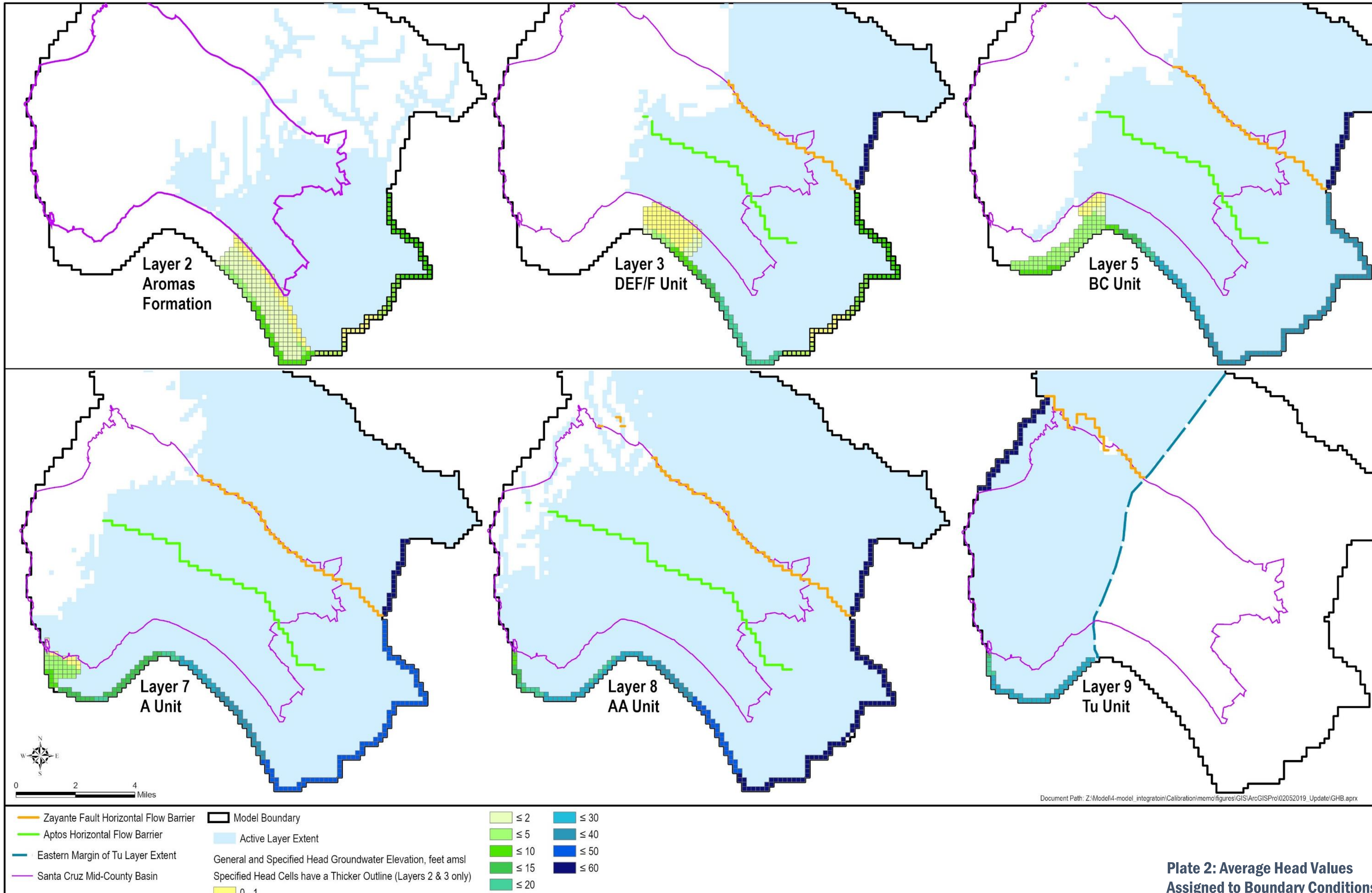


Plate 2: Average Head Values Assigned to Boundary Conditions

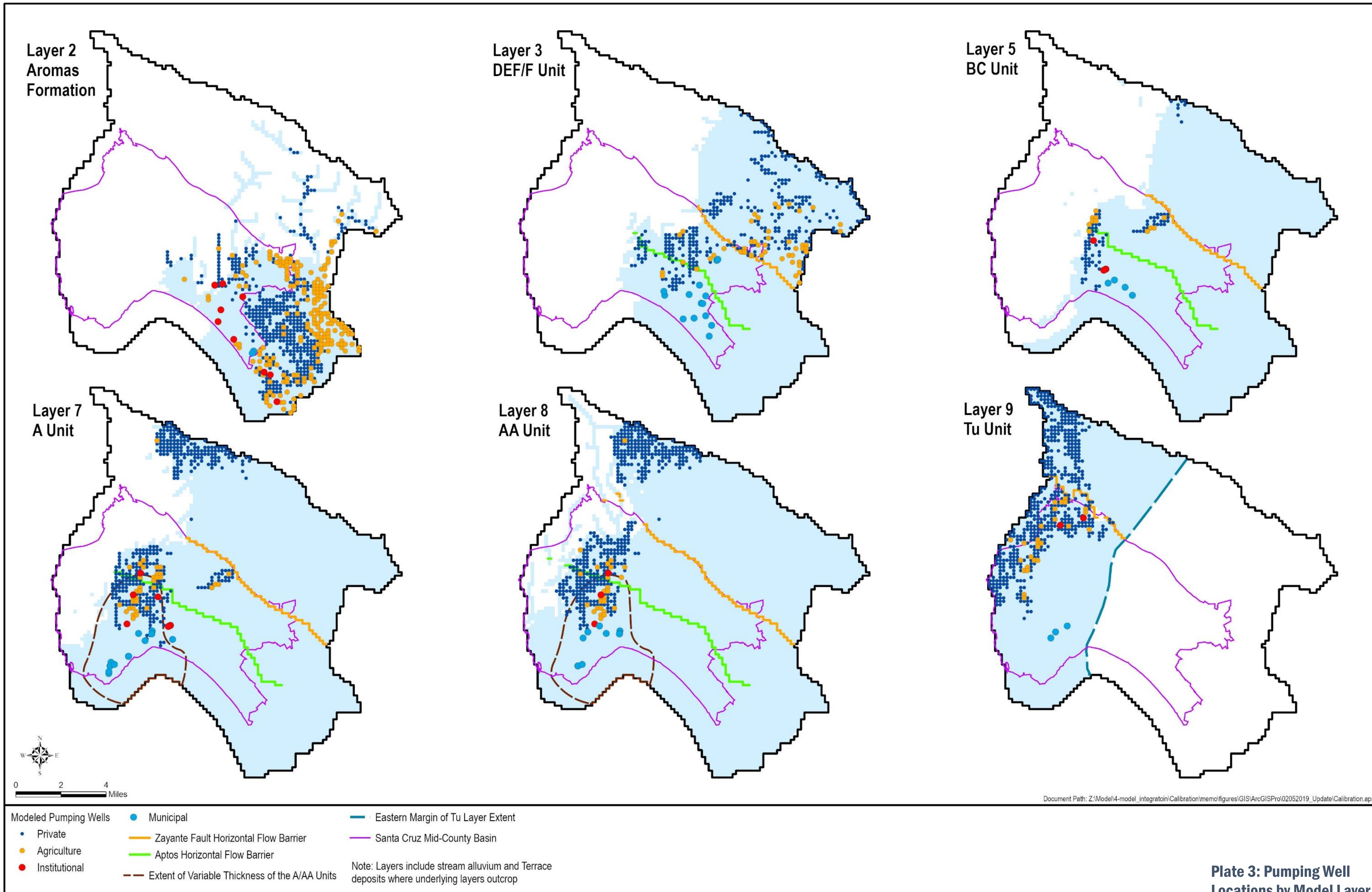
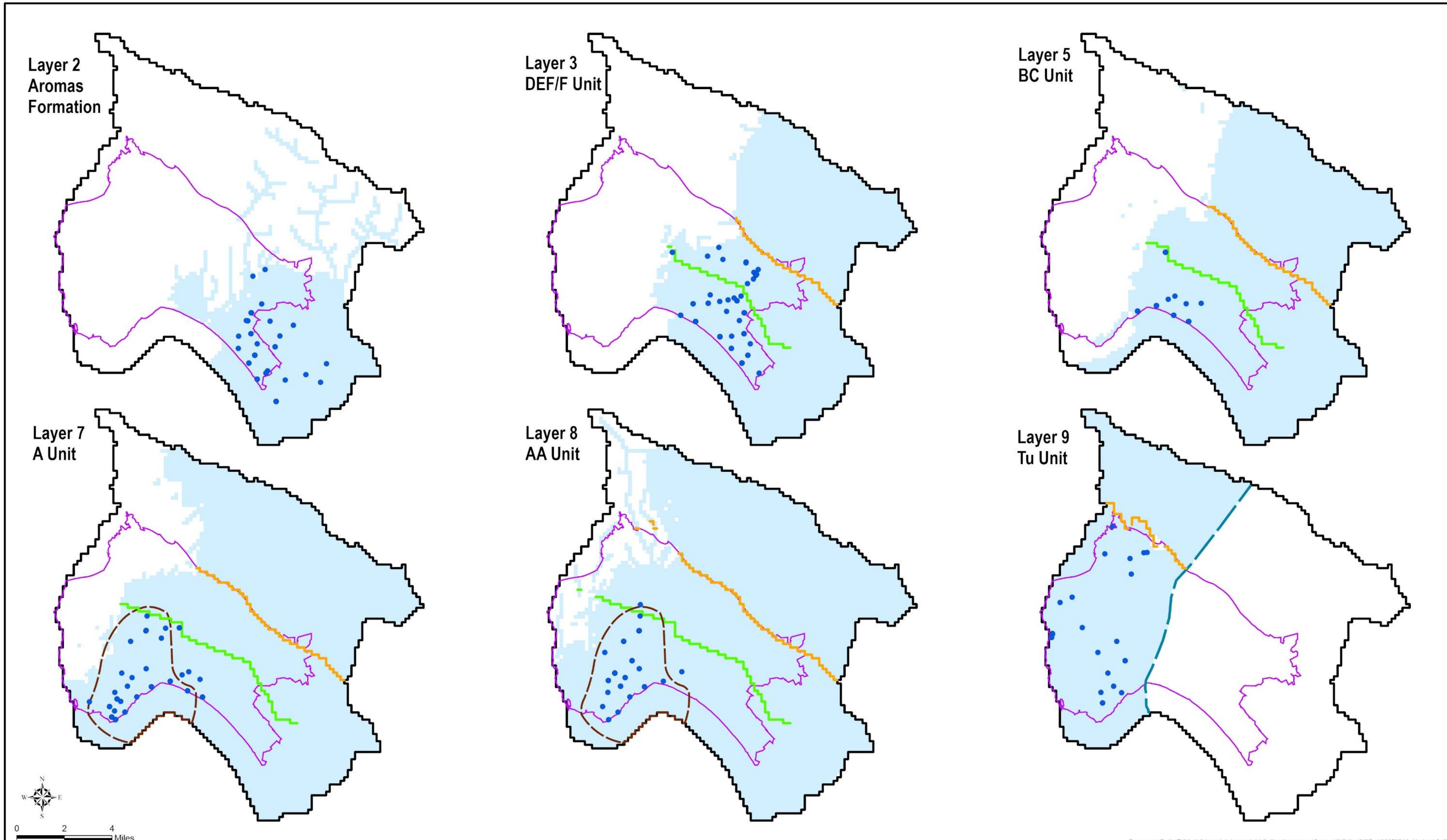


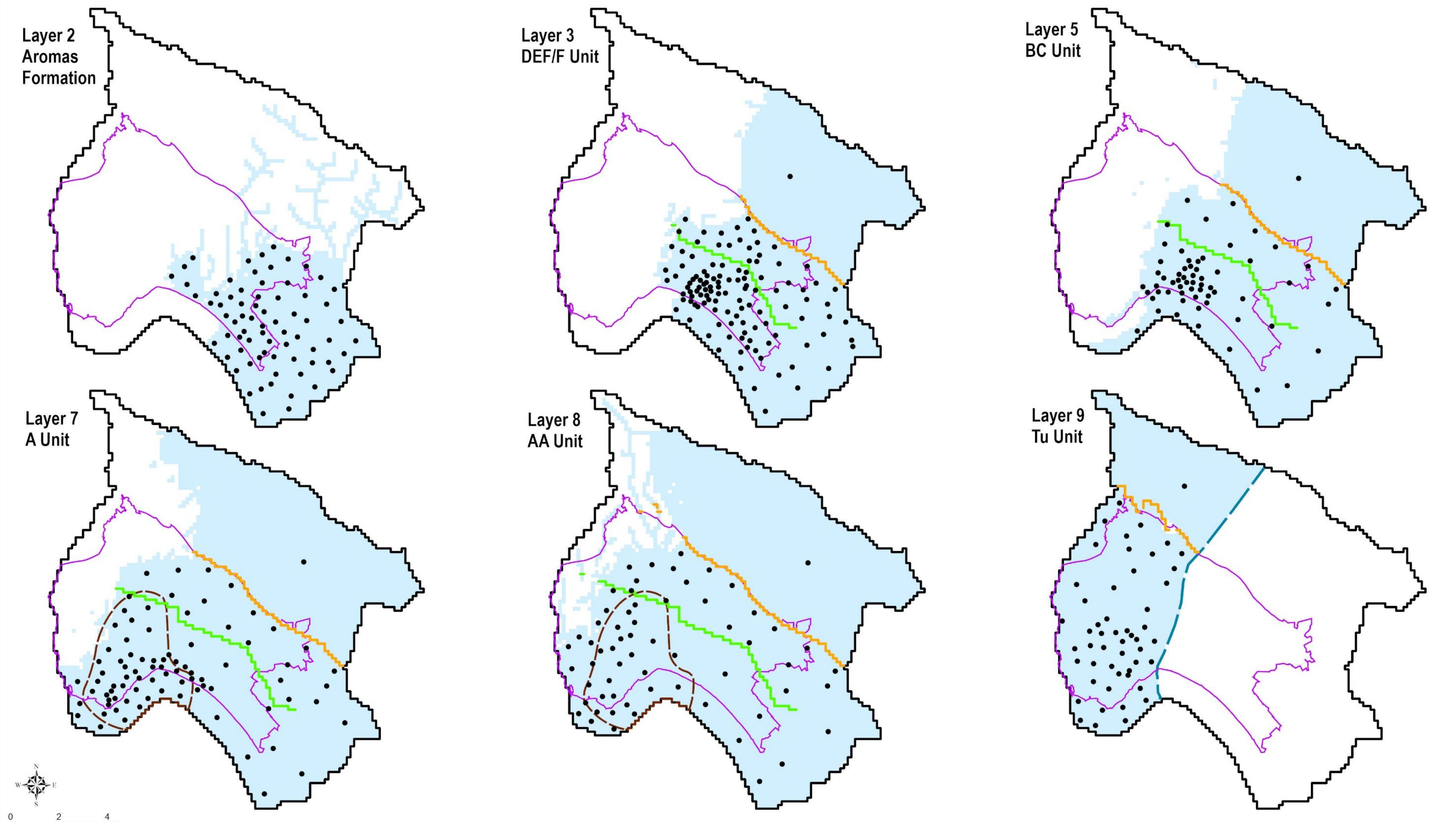
Plate 3: Pumping Well Locations by Model Layer



Calibration Targets
Zayante Fault Horizontal Flow Barrier
Aptos Horizontal Flow Barrier
Santa Cruz Mid-County Basin
Extent of Variable Thickness of the A/AA Units
Eastern Margin of Tu Layer Extent
Model Boundary
Active Extent

Note: Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Plate 4: Distribution of Groundwater Elevation Calibration Targets in Model Aquifer Layers



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- Pilot Points for Hydraulic Conductivity Calibration
- Zayante Fault Horizontal Flow Barrier
- Aptos Horizontal Flow Barrier
- Extent of Variable Thickness of the A/AA Units
- Eastern Margin of Tu Layer Extent
- Santa Cruz Mid-County Basin
- Model Boundary
- Active Extent

Note: Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Plate 5: Pilot Points by Aquifer Layer

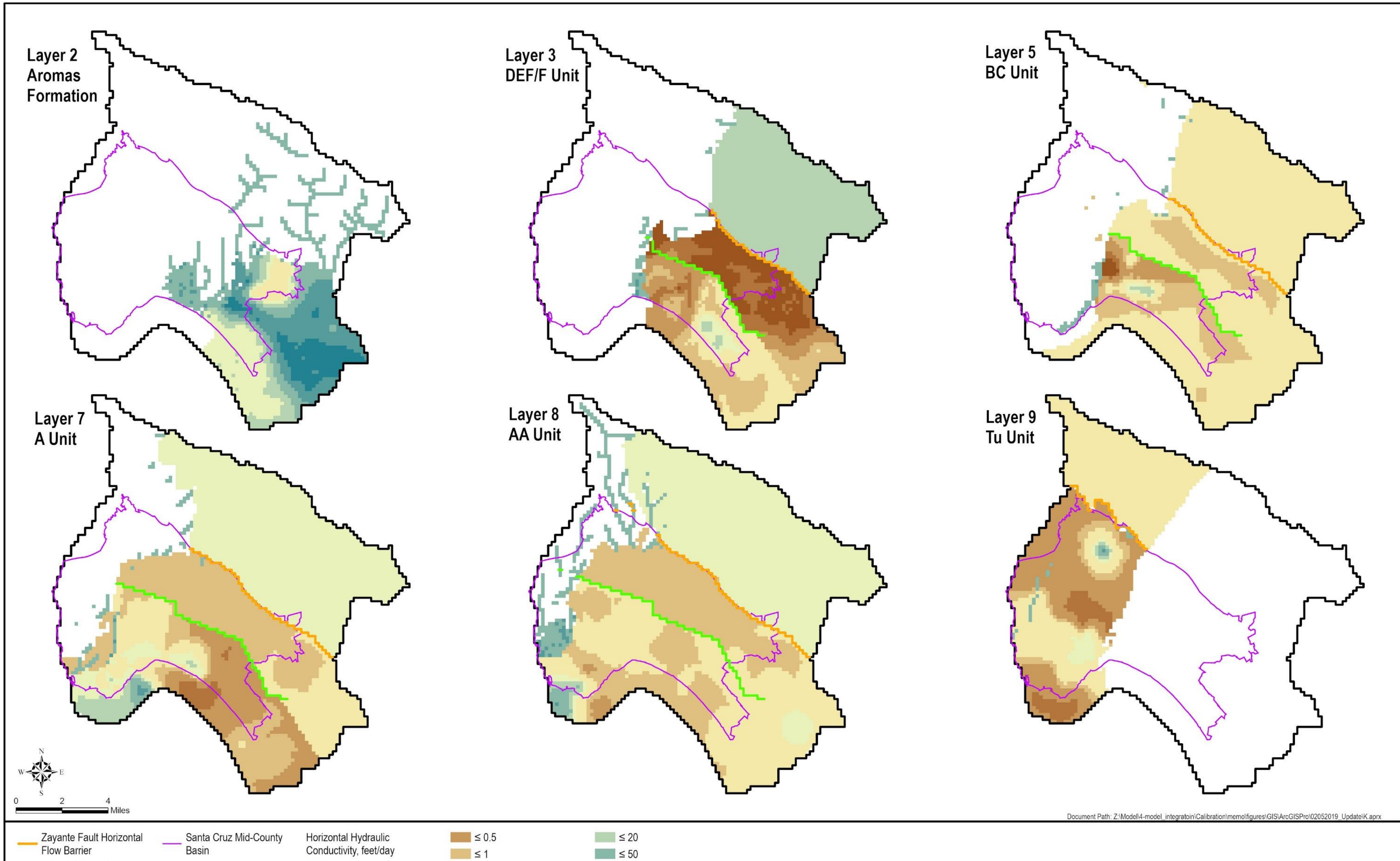
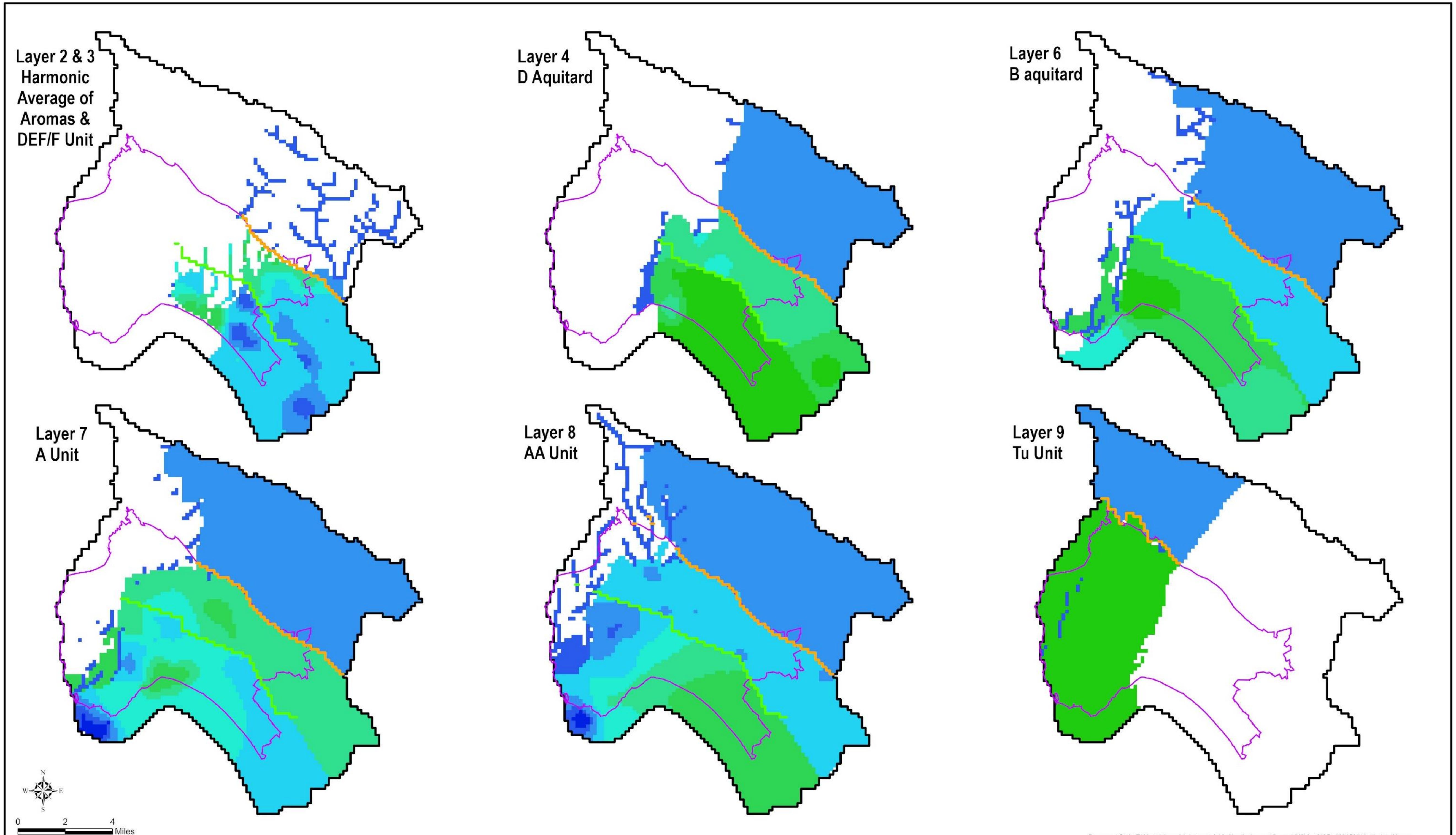


Plate 6: Distribution of Calibrated Horizontal Hydraulic Conductivity in Model Aquifer Layers



Zayante Fault Horizontal Flow Barrier

Aptos Horizontal Flow Barrier

Santa Cruz Mid-County Basin

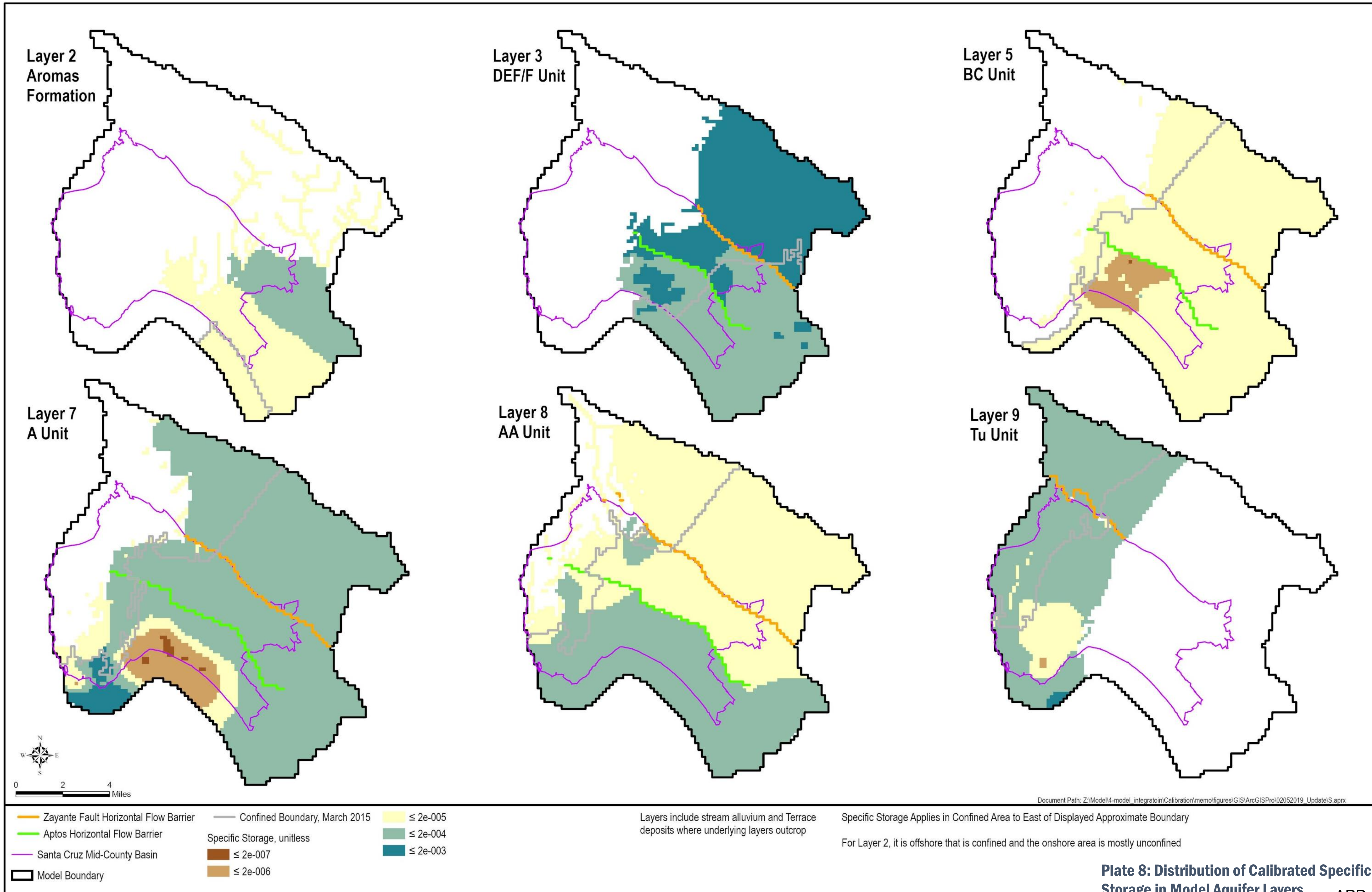
Model Boundary

Vertical Hydraulic Conductivity, feet/day

- ≤ 1.0e-05
- ≤ 1.0e-04
- ≤ 1.0e-03
- ≤ 0.01
- ≤ 0.1
- ≤ 0.5
- ≤ 1
- ≤ 1.4

Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Plate 7: Distribution of Calibrated Vertical Hydraulic Conductivity in Model Aquifer Layers



Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Specific Storage Applies in Confined Area to East of Displayed Approximate Boundary

For Layer 2, it is offshore that is confined and the onshore area is mostly unconfined

Plate 8: Distribution of Calibrated Specific Storage in Model Aquifer Layers

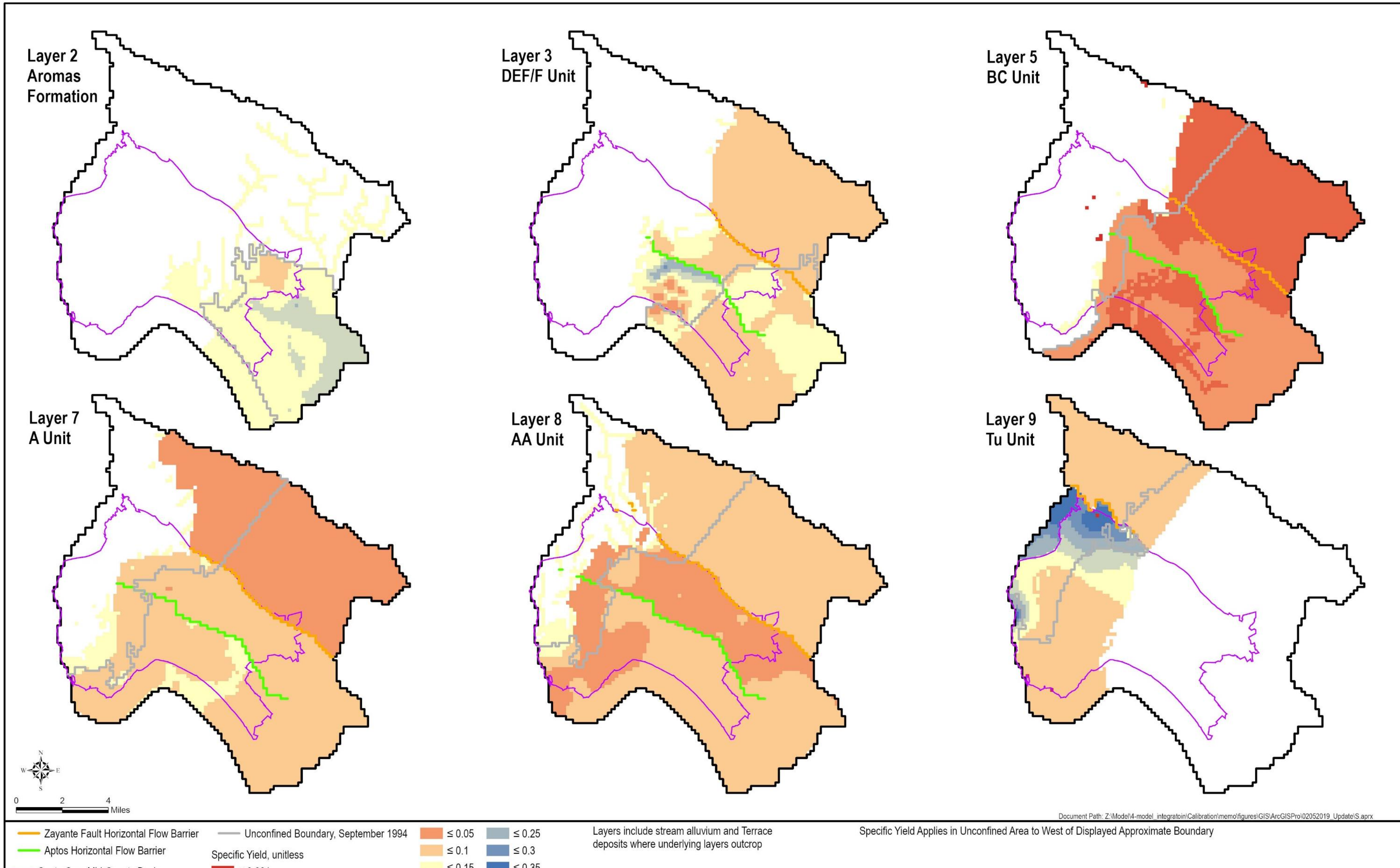


Plate 9: Distribution of Calibrated Specific Yield in Model Aquifer Layers

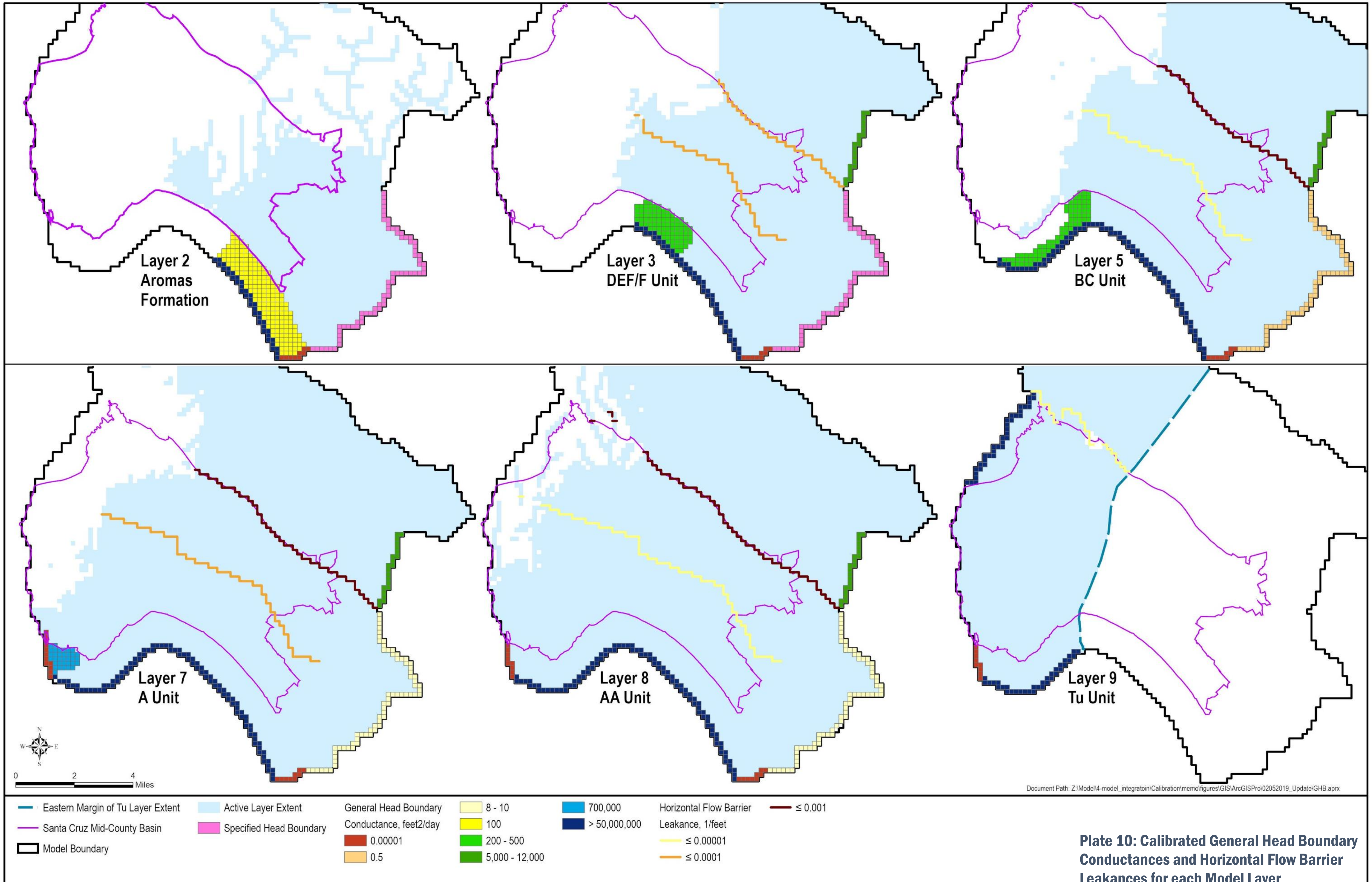
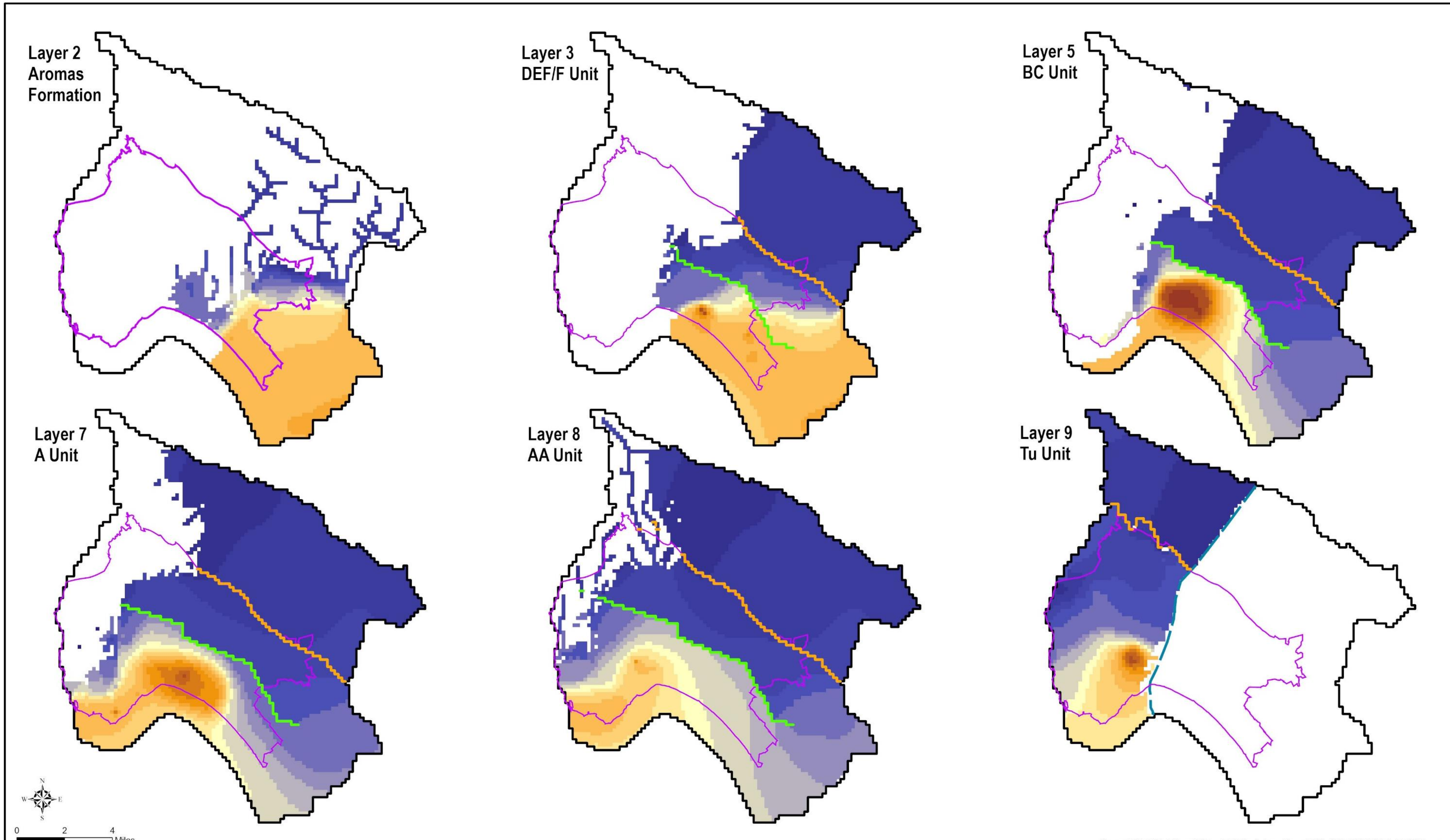


Plate 10: Calibrated General Head Boundary Conductances and Horizontal Flow Barrier Leakances for each Model Layer



Zayante Fault Horizontal Flow Barrier
Aptos Horizontal Flow Barrier
Eastern Margin of Tu Layer Extent
Santa Cruz Mid-County Basin

Model Boundary

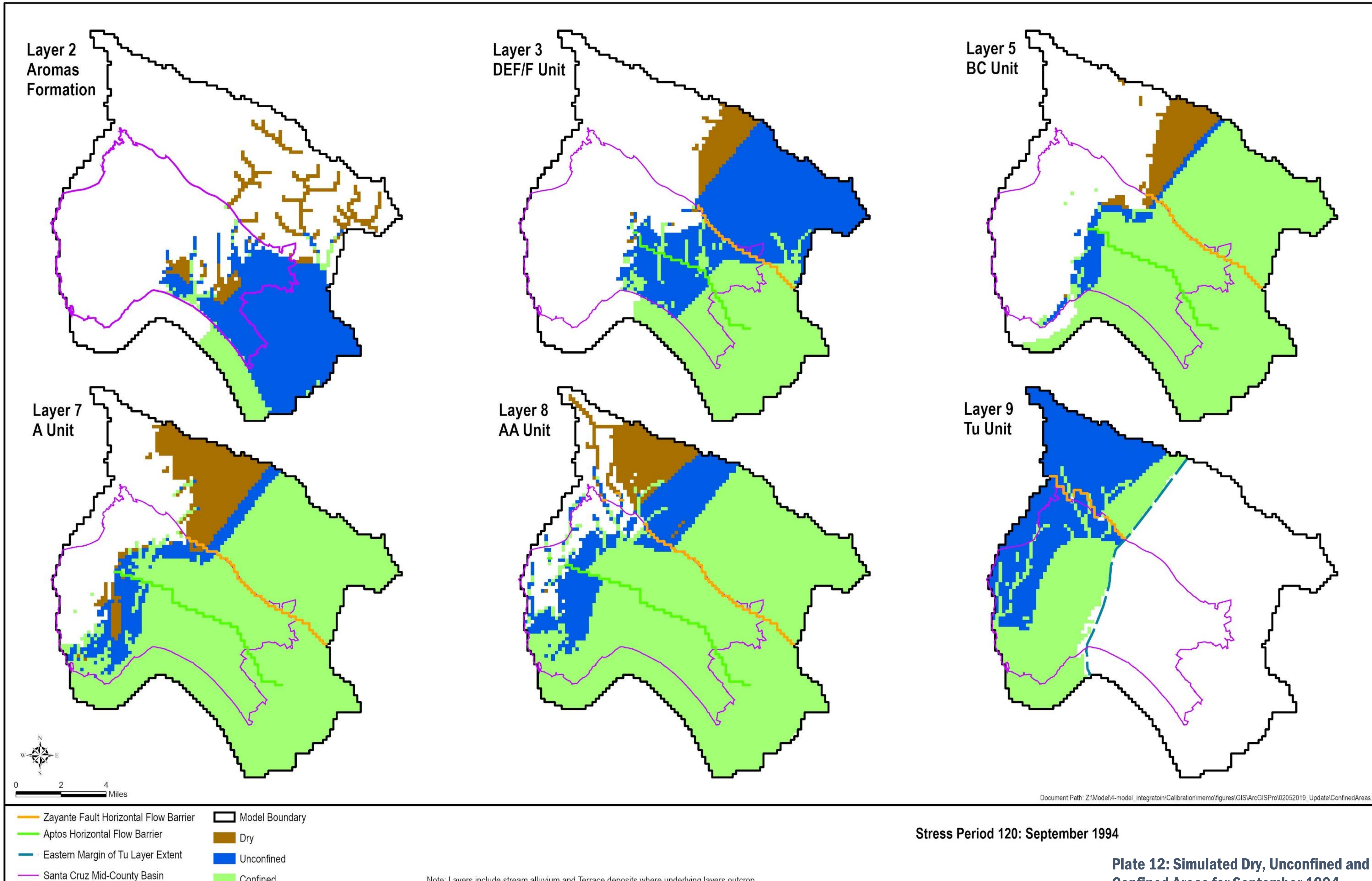
Groundwater Elevation, feet amsl

-83 - -80
-79.9 - -60
-59.9 - -40
-39.9 - -30
-29.9 - -20
-19.9 - -10
-9.9 - 0
0.1 - 10
10.1 - 20
20.1 - 30
30.1 - 40
40.1 - 60
60.1 - 80
80.1 - 100
100.1 - 200
200.1 - 300
300.1 - 400
400.1 - 500
500.1 - 1,000
1,000.1 - 1,500
1,500.1 - 2,000

Stress Period 120: September 1994

Note: Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Plate 11: Simulated Groundwater Levels for September 1994



Note: Layers include stream alluvium and Terrace deposits where underlying layers outcrop

Stress Period 120: September 1994

Plate 12: Simulated Dry, Unconfined and Confined Areas for September 1994

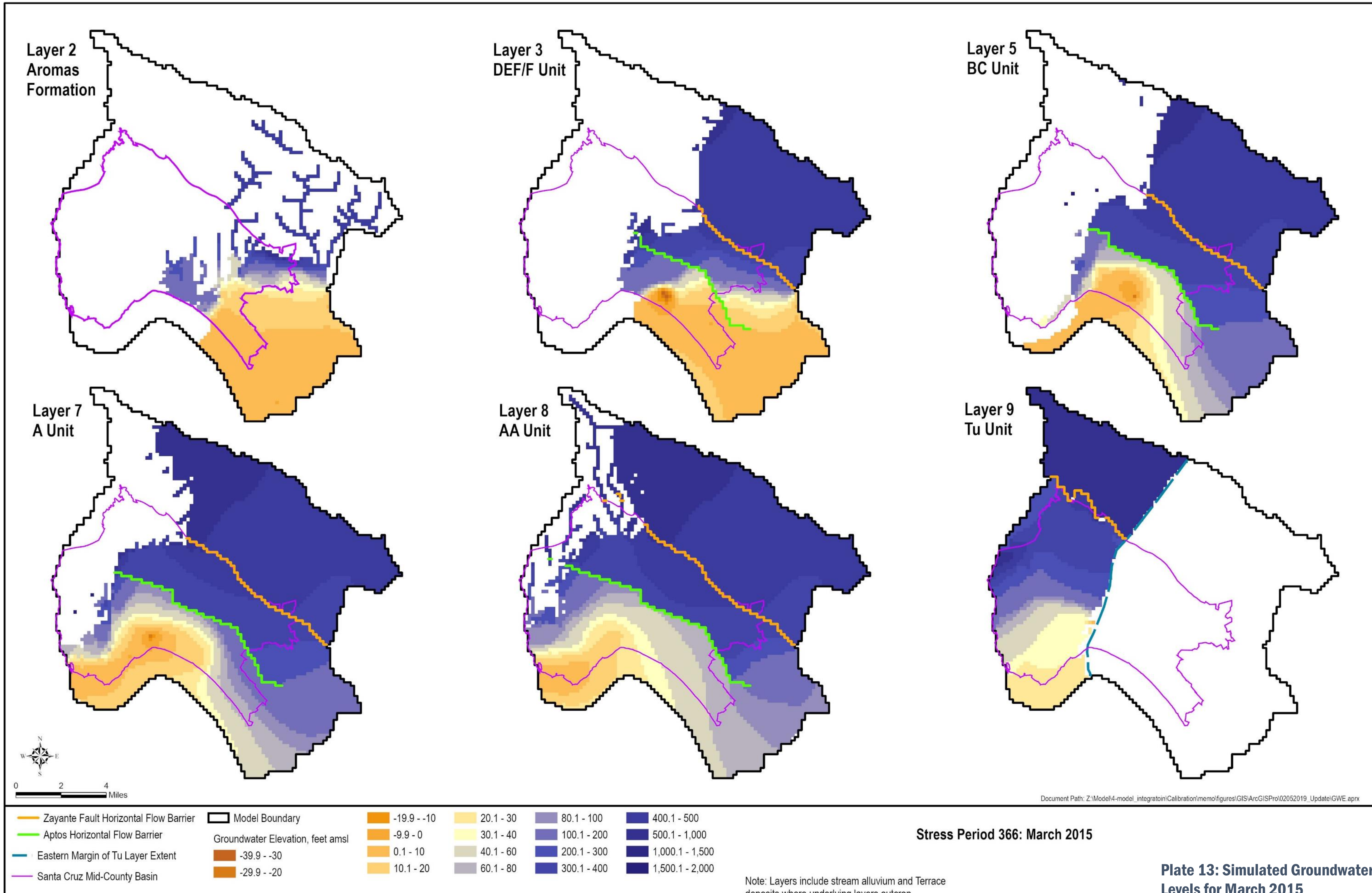


Plate 13: Simulated Groundwater Levels for March 2015

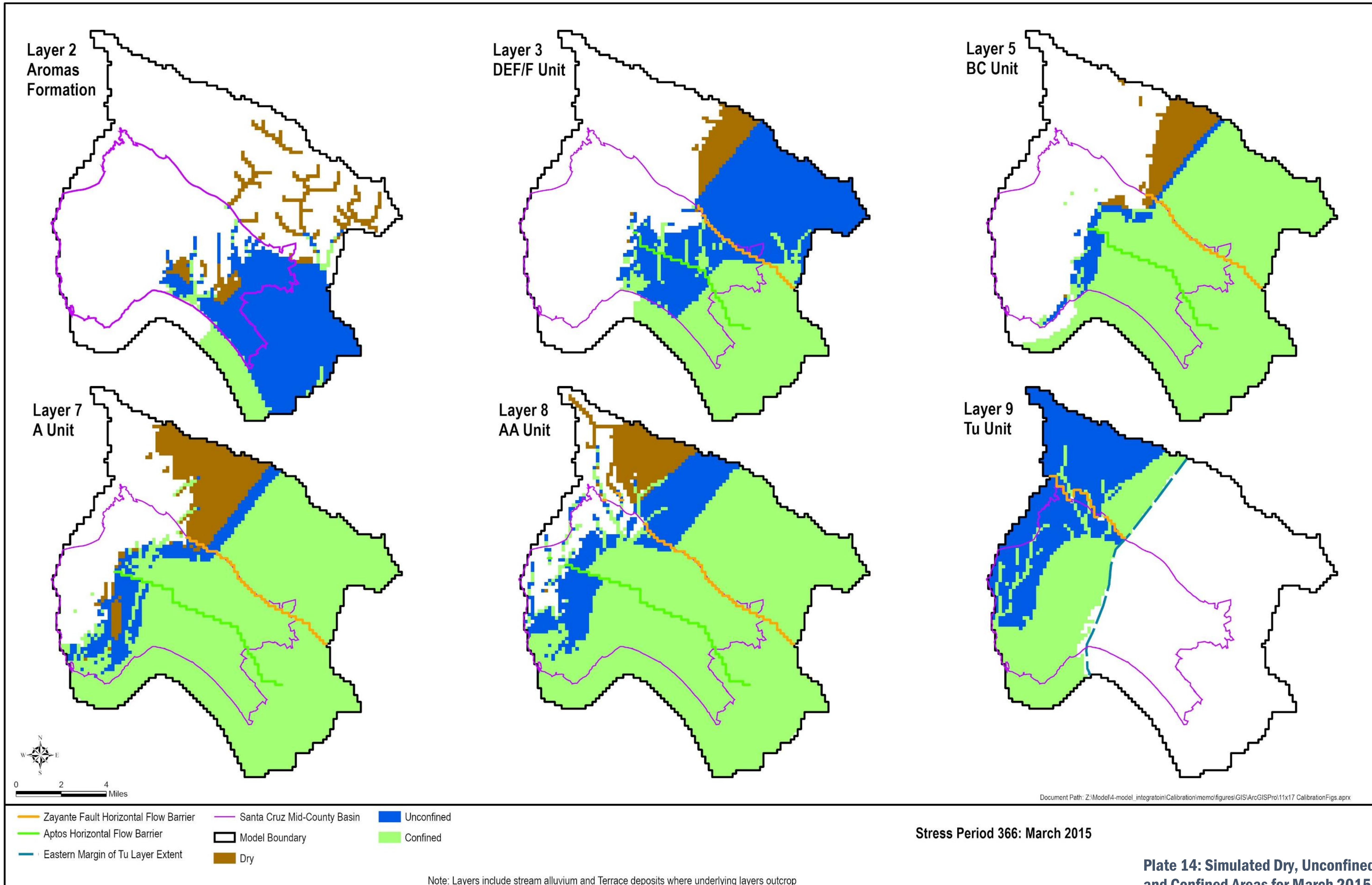


Plate 14: Simulated Dry, Unconfined and Confined Areas for March 2015

Appendix A

Municipal Return Flow Estimate Approach

TECHNICAL MEMORANDUM

DATE: August 28, 2019

TO: Santa Cruz Mid-County Groundwater Agency

FROM: Georgina King and Cameron Tana

PROJECT: Santa Cruz Mid-County Basin Groundwater Model

SUBJECT: Municipal Return Flow

SERVICE AREA WATER SUPPLY

Water supplied or delivered to the various municipal service areas in the model is the source of water from which different components of return flow are estimated.

Individual municipal return flow components estimated are:

1. Water system losses,
2. Large-scale landscape/field irrigation,
3. Small-scale landscape irrigation (residential and commercial), and
4. Sewer system losses, and septic tank leakage.

The amount of water supplied to each service area is obtained from readily available data provided by the four municipal water agencies in the model area: City of Santa Cruz, Soquel Creek Water District (SqCWD), Central Water District (CWD), and City of Watsonville. If monthly data are not available, annual data are used.

Annual data are used for the Cities of Watsonville and Santa Cruz. Both these municipalities deliver water to customers from both groundwater and surface water sources. Both CWD and SqCWD are able to provide monthly water supply data from well production records as groundwater is their sole source of water.

City of Watsonville

The City of Watsonville was not able to provide readily available water delivery data for the portion of their service area within the model. Their annual water supply (AWS) is estimated as the sum of residential water use and large-scale landscape irrigation, plus 6% to account for water system losses of that water (City of Watsonville, 2016). As an estimate of residential water use, building counts, similar to the approach taken for private water use, are used to estimate annual residential water use to supply areas. The amount of large-scale landscape irrigation is estimated based on irrigated area, water demand, turf crop factor and irrigation inefficiency. The top two rows of Figure 1 show the calculations for estimating AWS for those portions of the City of Watsonville service area within the model.

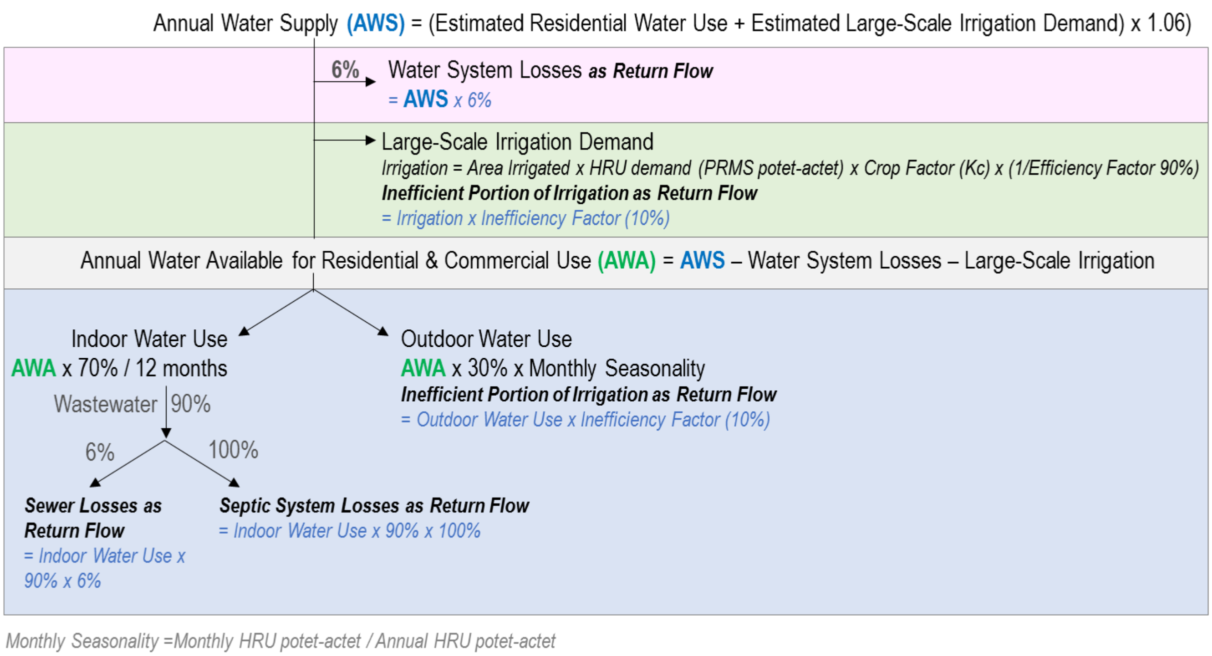


Figure 1: City of Watsonville Return Flow Calculations

City of Santa Cruz

As no delivery data are readily available that are specific to the model area, the City of Santa Cruz provided its entire service area annual consumption data from 1983 – 2015 for its different use types. The amount of water delivered to users in the model area was determined from the percentage of each use type within the model area compared to the entire service area (Table 1). The General Plan land use was used to determine relative land use percentages in the model area. As the City of Santa Cruz's consumption data are generated at meters, 7.5% assumed for water losses (WSC, 2016) was added to the consumption data to estimate AWS within their service area in the model. The top line of Figure 2 shows the calculations to estimate AWS.

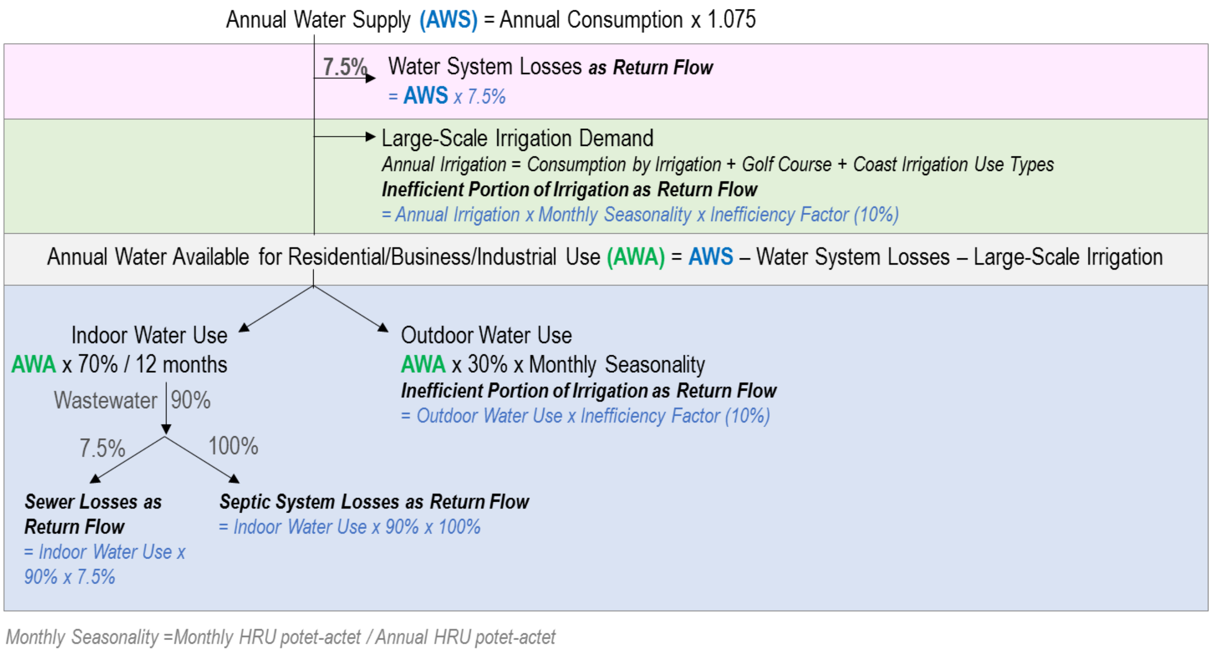


Figure 2: City of Santa Cruz Return Flow Calculations

Table 1: Percentage of All City of Santa Cruz Water Use Types within Model Area

Use Type	Percentage of Total City Land Use within Model Area
Single Family Residential	49%
Multiple Residential	50%
Business	55%
Industrial	34%
Municipal	33%
Irrigation (Large-Scale)	38%
Golf Course Irrigation	100%
Coast Irrigation	55%
Other (Construction & Hydrants)	38% (but negligible return flow assumed)

Central Water District

Groundwater pumped from CWD wells is delivered to both residential/commercial and agricultural customers. The amount of water available for residential/commercial purposes is estimated as the difference between the amount pumped and the amount supplied for agriculture, as shown on Figure 3. Water losses from 1985-1999 are 12%, from 2000-2007 are 7%, and from 2008-2016 are 4%. CWD system loss varies over time based on unaccounted water losses recorded by CWD each fiscal year.

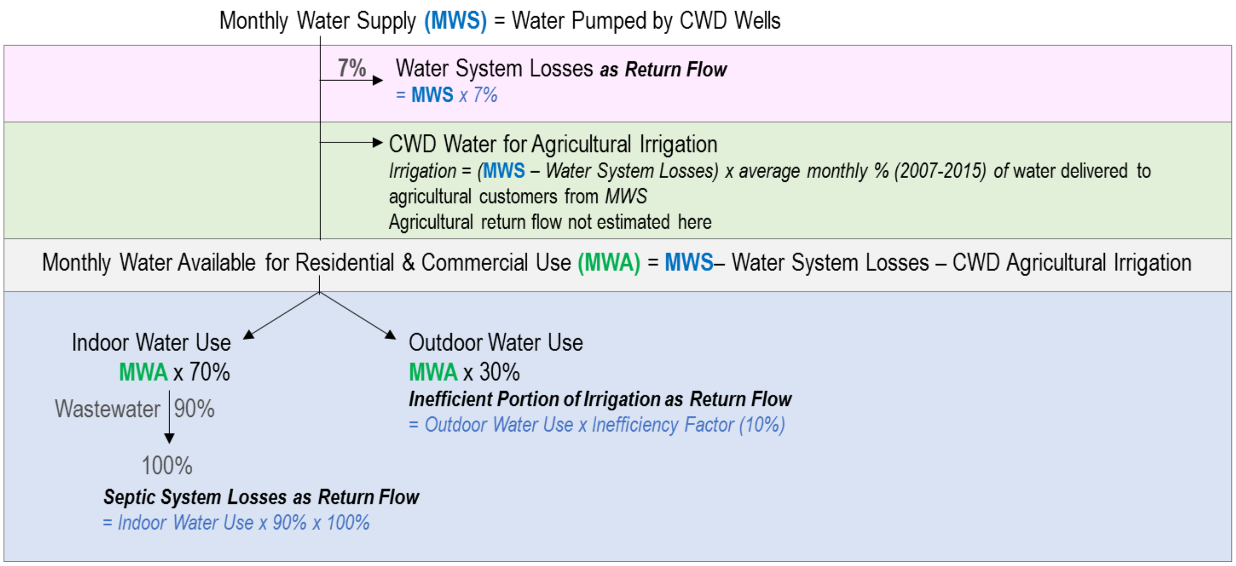


Figure 3: Central Water District Return Flow Calculations

Soquel Creek Water District

Water delivered to each of their four service areas (SA) is determined from the amount of groundwater pumped within each SA plus factoring in transfers that occur between service areas. Delivery data for each SA compared to groundwater pumped within each SA from 2014-2016 was used to estimate the average transfer from SA1 to SA2, SA3 to SA2, and SA3 to SA4. Table 2 summarizes the transfers used to estimate water delivered to each SA that is then used to estimate various components of return flow. The top line on Figure 4 shows the calculation to estimate monthly water supply to each SA. A water loss percentage of 7% is assumed from groundwater pumped (WSC, 2016).

Table 2: Summary of SqCWD Service Area Transfers between 2014 and 2016

Transfer From/To	Percent of Groundwater Produced in Originating Service Area
SA1 to SA2	8.5%
SA 3 to SA2	1.7%
SA3 to SA4	14.3%

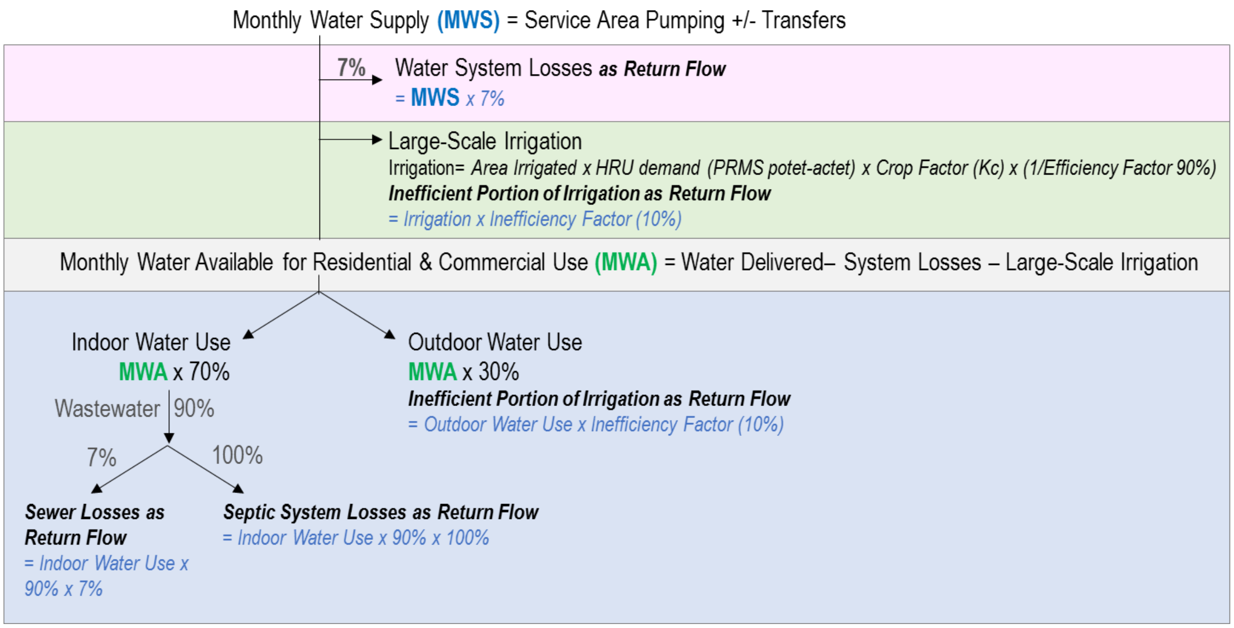


Figure 4: Soquel Creek Water District Return Flow Calculations

RETURN FLOW ESTIMATES

Different municipal water uses have their own proportion of water that percolates into the ground as return flow. Water system losses from both the water distribution and sewer systems are considered return flow. Water system losses are subtracted from water supply and thereafter, any water required to meet large-scale irrigation demand is subtracted from the supply. This leaves an amount of water that can be used for residential/commercial indoor and outdoor use. Assumed indoor and outdoor use is 70% and 30%, respectively. We assume 90% of indoor use becomes wastewater. For areas not connected to sewers, it is further assumed that 100% of wastewater percolates from septic systems into the unsaturated zone as return flow.

Inefficiencies in both residential irrigation (outdoor use) and large-scale irrigation result in an assumed return flow of 10% of the applied water. For the Cities of Santa Cruz and Watsonville, CWD, and SqCWD, Figure 1 through Figure 4, respectively, illustrate the methods for estimating each municipality's return flow estimates. Summaries by water year of each component of return flow are provided in Table 3 through Table 6. The last column of these tables provides the percentage of the total water supply that comprises return flow.

The return flow estimates are applied to the model cells based on the ratio of the area of the model cell that receives municipal water for residential /commercial use compared to the entire service area. Figure 5 shows the location of the residential/commercial and large-landscape irrigation areas within each service area. Figure 6 shows the location of sewered and unsewered (septic tank) areas. Both figures also show model cell boundaries for the municipal water uses.

HOW WATER DELIVERED IS APPLIED TO MODEL CELLS FOR EACH MONTHLY MODEL STRESS PERIOD

For CWD and SqCWD, where monthly data are available, the deliveries to each service area are obtained from the service area pumping +/- any transfers, as described above. For the Cities of Watsonville and Santa Cruz, where annual data are only available, the amount of water applied to each model cell is distributed differently for indoor residential and irrigation use. Monthly indoor use is estimated as 70% of annual water delivered divided by 12 months. Monthly outdoor residential/commercial and large-scale irrigation use are based on irrigation demand (difference between monthly PRMS modeled potential ET (potet) and actual ET (actet)).

- For the City of Santa Cruz, where the water use type was 100% irrigation, the annual volume is distributed to months based on the ratio of monthly to annual irrigation demand for each model cell. For the outdoor portion of residential and commercial water use, the same ratio of monthly to annual irrigation demand for each model cell is used to distribute the annual volumes to monthly volumes.
- For the City of Watsonville, the amount of water to apply to each model cell for either large-scale or residential irrigation is distributed to months based on the ratio of monthly to annual irrigation demand for each model cell.

REFERENCES

City of Santa Cruz Water Department, 2016, City of Santa Cruz Water Department 2015 Urban Water Management Plan. August 2016.

City of Watsonville, 2016 City of Watsonville 2015 Urban Water Management Plan.

Water Systems Consulting, Inc., 2016, Soquel Creek Water District 2015 Urban Water Management Plan. Prepared for Soquel Creek Water District, June 2016.

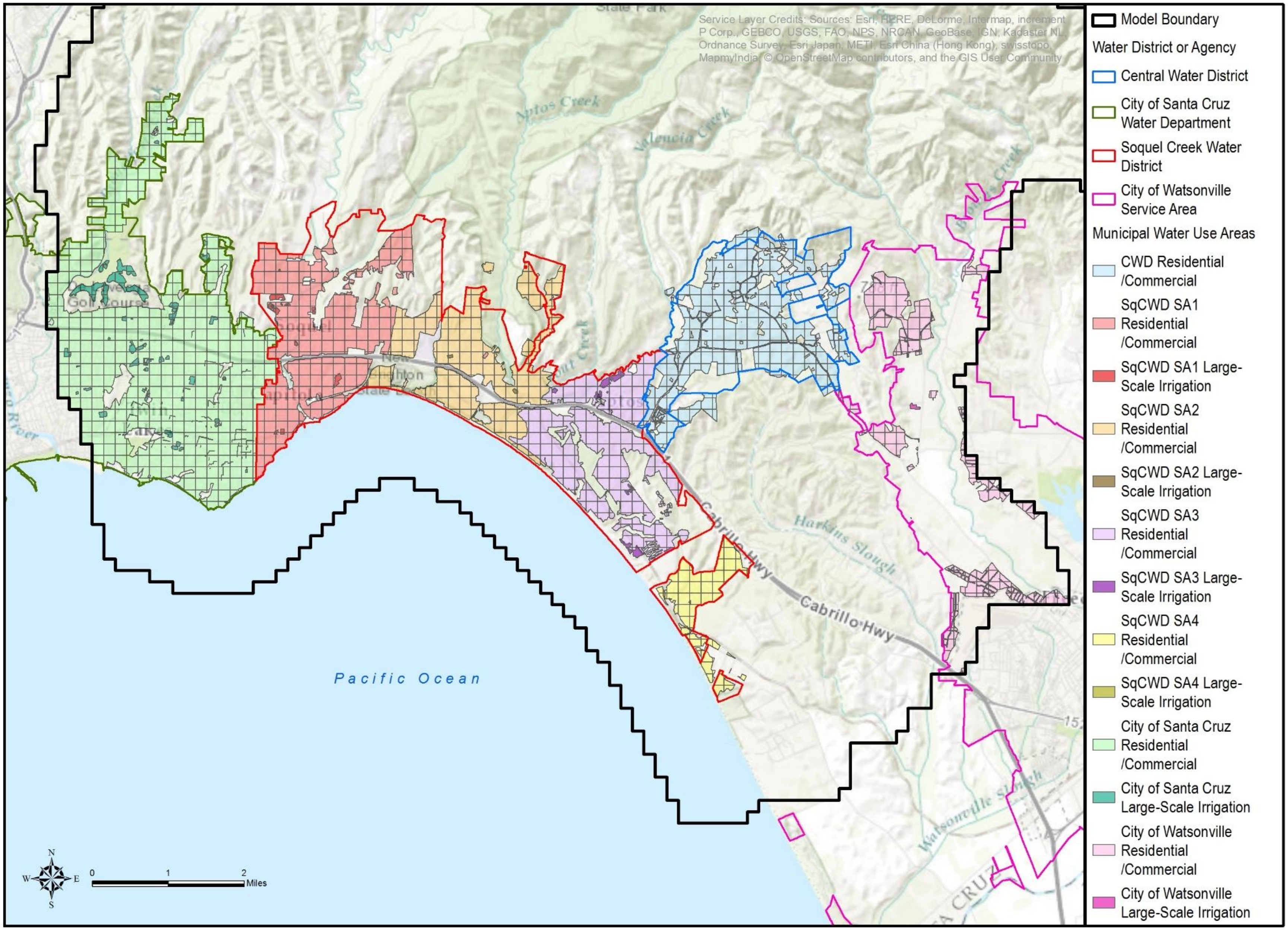


Figure 5: Residential/Commercial and Large-Scale Irrigation Areas within Municipal Service Area

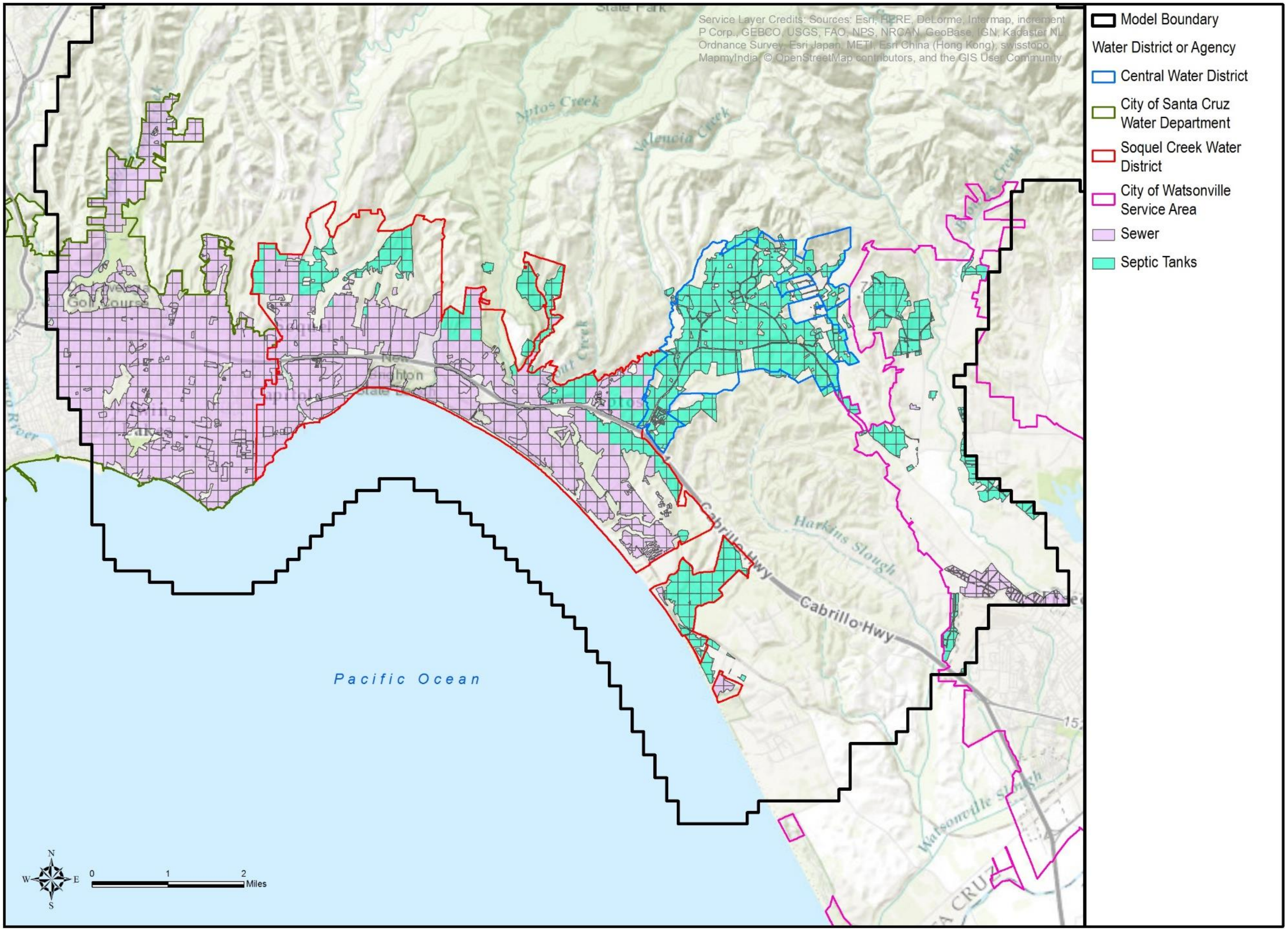


Figure 6: Municipal Sewered and Septic Tank Areas

Table 3: City of Watsonville Return Flow Estimates

Water Year	Water Supply to Service Area in Model, acre-feet	Return Flow in acre-feet						Percentage of Water Supply that Becomes Return Flow
		Water System Losses	Large-Scale Landscape Irrigation	Small-Scale Landscape Irrigation	Sewer Losses	Septic Systems	Total Return Flow	
1985	478.1	28.7	0.3	14.2	6.5	206.8	227.9	47.7%
1986	497.3	29.8	0.3	14.8	6.7	215.2	237.1	47.7%
1987	511.9	30.7	0.3	15.3	6.9	221.6	244.1	47.7%
1988	529.1	31.7	0.3	15.8	7.2	229.1	252.3	47.7%
1989	543.1	32.6	0.3	16.2	7.4	235.2	259.0	47.7%
1990	561.0	33.7	0.3	16.7	7.6	243.0	267.6	47.7%
1991	577.5	34.6	0.3	17.2	7.8	250.2	275.5	47.7%
1992	596.8	35.8	0.3	17.8	8.1	258.6	284.8	47.7%
1993	614.0	36.8	0.3	18.3	8.3	266.1	293.0	47.7%
1994	633.2	38.0	0.3	18.9	8.6	274.4	302.2	47.7%
1995	650.5	39.0	0.3	19.4	8.8	282.0	310.5	47.7%
1996	708.8	42.5	0.3	21.2	9.6	307.4	338.5	47.7%
1997	724.8	43.5	0.3	21.7	9.8	314.3	346.1	47.7%
1998	742.7	44.6	0.3	22.2	10.1	322.1	354.7	47.8%
1999	766.0	46.0	0.3	22.9	10.4	332.2	365.8	47.8%
2000	816.4	49.0	0.3	24.4	11.1	354.2	390.0	47.8%
2001	823.0	49.4	0.3	24.6	11.2	357.1	393.1	47.8%
2002	819.0	49.1	0.3	24.5	11.1	355.3	391.2	47.8%
2003	828.3	49.7	0.3	24.8	11.2	359.4	395.7	47.8%
2004	850.9	51.1	0.3	25.4	11.5	369.2	406.5	47.8%
2005	843.1	50.6	0.3	25.2	11.4	365.8	402.7	47.8%
2006	860.6	51.6	0.3	25.7	11.7	373.5	411.2	47.8%
2007	868.5	52.1	0.3	26.0	11.8	376.9	414.9	47.8%
2008	872.4	52.3	0.3	26.1	11.8	378.6	416.8	47.8%
2009	850.2	51.0	0.3	25.4	11.5	368.9	406.2	47.8%
2010	852.1	51.1	0.3	25.5	11.6	369.7	407.1	47.8%
2011	858.4	51.5	0.3	25.7	11.6	372.5	410.1	47.8%
2012	861.6	51.7	0.3	25.8	11.7	373.9	411.6	47.8%
2013	866.0	52.0	0.3	25.9	11.8	375.8	413.7	47.8%
2014	798.0	47.9	0.3	23.9	10.8	346.2	381.2	47.8%
2015	744.0	44.6	0.3	22.2	10.1	322.7	355.3	47.8%
Average	727.3	43.6	0.3	21.7	9.9	315.4	347.3	47.7%

Table 4: City of Santa Cruz Return Flow Estimates

Water Year	Water Supply to Service Area in Model, acre-feet	Return Flow in acre-feet					Percentage of Water Supply that Becomes Return Flow
		Water System Losses	Large-Scale Landscape Irrigation	Small-Scale Landscape Irrigation	Sewer Losses	Total Return Flow	
1985	6,593.7	461.6	72.1	162.3	238.6	934.6	14.2%
1986	6,663.3	466.4	68.7	165.3	243.0	943.4	14.2%
1987	6,941.7	485.9	84.4	168.3	247.4	986.1	14.2%
1988	6,258.3	438.1	77.5	151.3	222.5	889.4	14.2%
1989	5,749.4	402.5	61.8	141.9	208.6	814.7	14.2%
1990	5,209.9	364.7	55.0	126.8	186.4	732.9	14.1%
1991	4,891.0	342.4	53.1	120.3	176.8	692.6	14.2%
1992	5,419.7	379.4	57.6	133.7	196.5	767.2	14.2%
1993	5,455.4	381.9	47.1	137.9	202.8	769.7	14.1%
1994	5,648.9	395.4	47.4	143.2	210.5	796.4	14.1%
1995	5,777.5	404.4	47.1	147.0	216.1	814.6	14.1%
1996	6,143.6	430.1	51.7	155.8	229.0	866.6	14.1%
1997	6,633.3	464.3	64.7	165.5	243.2	937.7	14.1%
1998	5,887.4	412.1	43.9	151.0	221.9	828.9	14.1%
1999	6,192.2	433.5	52.4	156.9	230.7	873.4	14.1%
2000	6,183.4	432.8	51.5	157.0	230.7	872.0	14.1%
2001	6,255.6	437.9	63.6	155.4	228.4	885.2	14.2%
2002	6,072.7	425.1	62.4	150.5	221.3	859.4	14.2%
2003	6,072.7	425.1	69.6	148.4	218.2	861.4	14.2%
2004	6,191.6	433.4	75.0	150.1	220.6	879.2	14.2%
2005	5,780.4	404.6	58.0	143.7	211.3	817.6	14.1%
2006	5,579.3	390.6	62.6	136.8	201.0	790.9	14.2%
2007	5,477.2	383.4	54.7	136.3	200.4	774.8	14.1%
2008	5,537.2	387.6	60.7	136.1	200.1	784.6	14.2%
2009	4,840.5	338.8	44.0	121.7	178.9	683.5	14.1%
2010	4,764.2	333.5	41.4	120.4	177.0	672.4	14.1%
2011	4,569.3	319.8	36.8	116.4	171.1	644.2	14.1%
2012	4,870.7	341.0	47.2	121.7	178.8	688.7	14.1%
2013	5,078.7	355.5	54.5	125.3	184.1	719.4	14.2%
2014	4,083.1	285.8	35.7	103.1	151.6	576.3	14.1%
2015	3,837.2	268.6	42.4	94.3	138.6	543.9	14.2%
Average	5,634.2	394.4	56.3	140.1	206.0	796.8	14.1%

Table 5: Soquel Creek Water District Return Flow Estimates

Water Year	Water Supply to Service Area in Model, acre-feet	Return Flow in acre-feet						Percentage of Water Supply that Becomes Return Flow
		Water System Losses	Large-Scale Landscape Irrigation	Small-Scale Landscape Irrigation	Sewer Losses	Septic Systems	Total Return Flow	
1985	4,318.5	302.3	13.2	116.5	135.8	559.0	1,126.8	26.1%
1986	4,272.5	299.1	10.3	116.1	137.1	529.0	1,091.6	25.5%
1987	5,234.6	366.4	13.8	141.9	163.7	708.1	1,393.9	26.6%
1988	4,858.7	340.1	14.8	131.1	151.0	658.1	1,295.2	26.7%
1989	4,797.2	335.8	12.7	130.0	149.0	664.8	1,292.3	26.9%
1990	4,818.5	337.3	13.3	130.5	150.6	649.1	1,280.7	26.6%
1991	4,703.0	329.2	10.4	128.1	148.1	634.4	1,250.3	26.6%
1992	4,908.3	343.6	13.9	132.8	152.6	672.0	1,314.9	26.8%
1993	4,863.2	340.4	11.6	132.2	152.2	665.2	1,301.7	26.8%
1994	5,089.3	356.2	10.4	138.9	159.4	706.7	1,371.6	27.0%
1995	4,854.9	339.8	9.9	132.5	153.5	650.6	1,286.3	26.5%
1996	5,183.2	362.8	12.7	140.8	163.4	688.0	1,367.7	26.4%
1997	5,570.8	390.0	14.7	151.0	174.1	755.0	1,484.8	26.7%
1998	4,966.1	347.6	7.8	136.2	157.8	670.0	1,319.4	26.6%
1999	5,211.5	364.8	8.2	142.9	165.0	712.3	1,393.2	26.7%
2000	5,270.8	369.0	9.9	144.1	166.6	712.7	1,402.2	26.6%
2001	5,174.7	362.2	9.7	141.5	164.3	688.2	1,365.9	26.4%
2002	5,375.8	376.3	9.6	147.1	172.6	689.3	1,394.9	25.9%
2003	5,331.8	373.2	11.1	145.4	171.4	667.7	1,368.9	25.7%
2004	5,372.0	376.0	13.0	146.0	172.8	659.2	1,367.0	25.4%
2005	4,543.8	318.1	7.3	124.6	147.2	566.2	1,163.4	25.6%
2006	4,548.6	318.4	10.2	123.9	144.5	591.7	1,188.7	26.1%
2007	4,625.8	323.8	12.0	125.5	144.9	623.6	1,229.7	26.6%
2008	4,557.0	319.0	12.6	123.4	141.7	625.9	1,222.6	26.8%
2009	4,162.1	291.3	12.5	112.4	131.6	529.8	1,077.6	25.9%
2010	3,932.5	275.3	10.3	106.6	127.5	461.6	981.3	25.0%
2011	4,011.2	280.8	8.7	109.3	131.0	467.1	997.0	24.9%
2012	4,159.1	291.1	12.7	112.2	134.0	487.8	1,037.9	25.0%
2013	4,217.5	295.2	19.2	111.9	132.2	509.1	1,067.6	25.3%
2014	3,702.9	259.2	20.0	97.3	115.6	432.6	924.7	25.0%
2015	3,153.9	220.8	22.4	81.3	96.9	355.8	777.2	24.6%
Average	4,702.9	329.2	12.2	127.5	148.6	612.6	1,230.2	26.1%

Table 6: Central Water District Return Flow Estimates

Water Year	Water Supply to Service Area in Model*, acre-feet	Return Flow in acre-feet				Percentage of Water Supply that Becomes Return Flow
		Water System Losses	Small-Scale Landscape Irrigation	Septic Systems	Total Return Flow	
1985	352.9	27.5	9.8	205.0	242.3	68.7%
1986	363.0	28.3	10.0	210.9	249.2	68.7%
1987	399.4	31.1	11.1	232.1	274.2	68.6%
1988	393.2	30.6	10.9	228.4	270.0	68.6%
1989	363.2	28.4	10.0	210.9	249.4	68.7%
1990	387.1	30.1	10.7	224.9	265.7	68.6%
1991	383.9	29.8	10.6	223.1	263.5	68.6%
1992	417.5	32.7	11.5	242.5	286.7	68.7%
1993	429.6	33.7	11.9	249.4	295.0	68.7%
1994	431.2	33.7	11.9	250.4	296.1	68.7%
1995	409.5	32.2	11.3	237.7	281.2	68.7%
1996	469.4	36.8	13.0	272.5	322.3	68.7%
1997	539.5	42.3	14.9	313.2	370.4	68.7%
1998	476.0	37.4	13.2	276.3	326.9	68.7%
1999	479.9	37.7	13.3	278.6	329.6	68.7%
2000	489.2	38.3	13.5	284.1	335.9	68.7%
2001	496.7	39.0	13.7	288.4	341.1	68.7%
2002	529.1	41.5	14.6	307.2	363.3	68.7%
2003	519.3	40.8	14.4	301.5	356.7	68.7%
2004	565.6	44.3	15.6	328.4	388.4	68.7%
2005	456.9	36.0	12.6	265.2	313.8	68.7%
2006	483.1	38.1	13.3	280.3	331.8	68.7%
2007	532.3	41.7	14.7	309.1	365.5	68.7%
2008	520.0	40.9	14.4	301.9	357.1	68.7%
2009	530.4	41.6	14.7	307.9	364.2	68.7%
2010	428.8	33.6	11.9	248.9	294.4	68.7%
2011	434.4	34.1	12.0	252.2	298.3	68.7%
2012	479.3	37.5	13.3	278.4	329.1	68.7%
2013	501.2	39.1	13.9	291.1	344.1	68.7%
2014	452.3	35.0	12.5	262.9	310.4	68.6%
2015	352.7	27.4	9.8	204.9	242.1	68.6%
Average	453.8	35.5	12.5	263.5	311.6	68.7%

* This column is water supply for residential/commercial use only, and does not include water delivered for agricultural use.

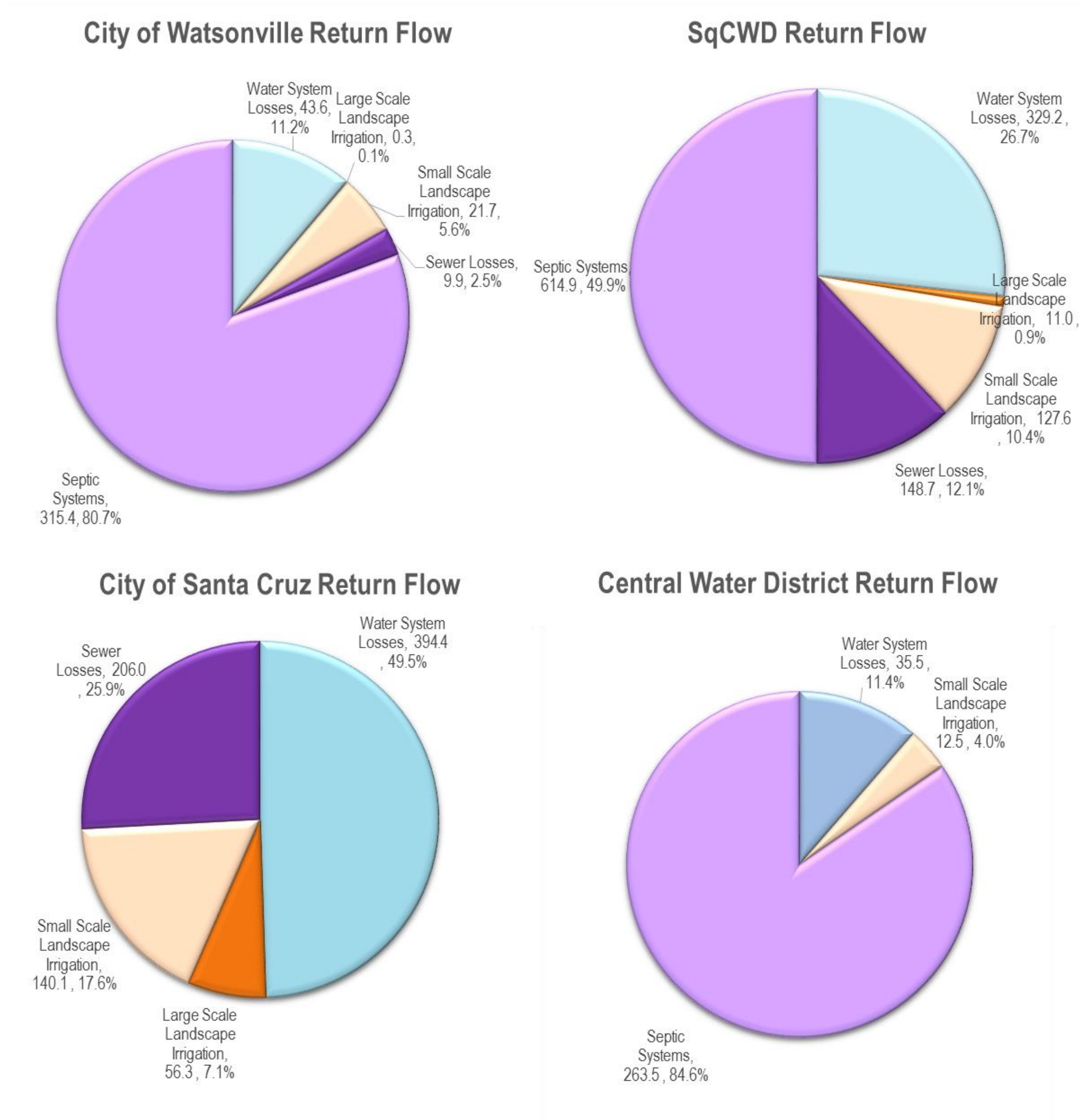
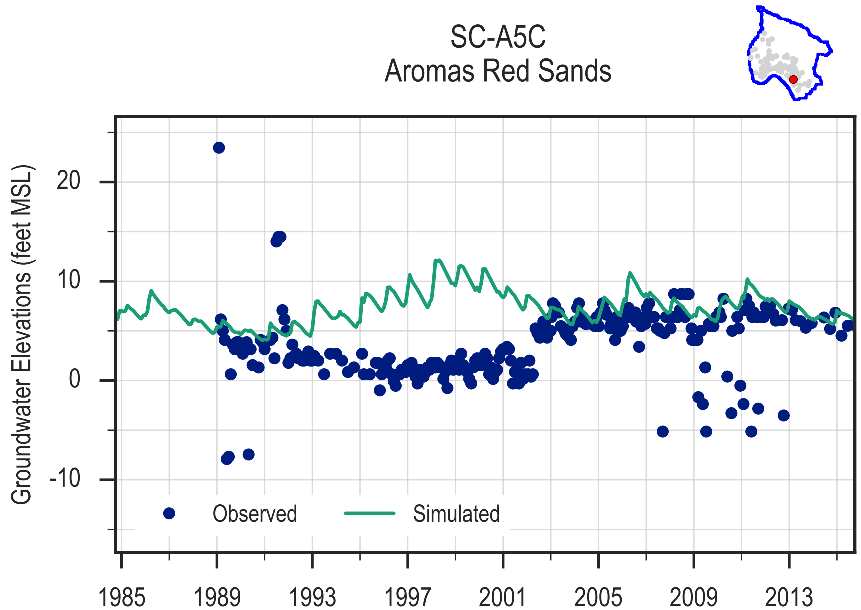


Figure 7: Municipal Return Flow Pie Charts (in acre-feet per year)

Appendix C

Selected Well Hydrographs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Aromas Red Sands
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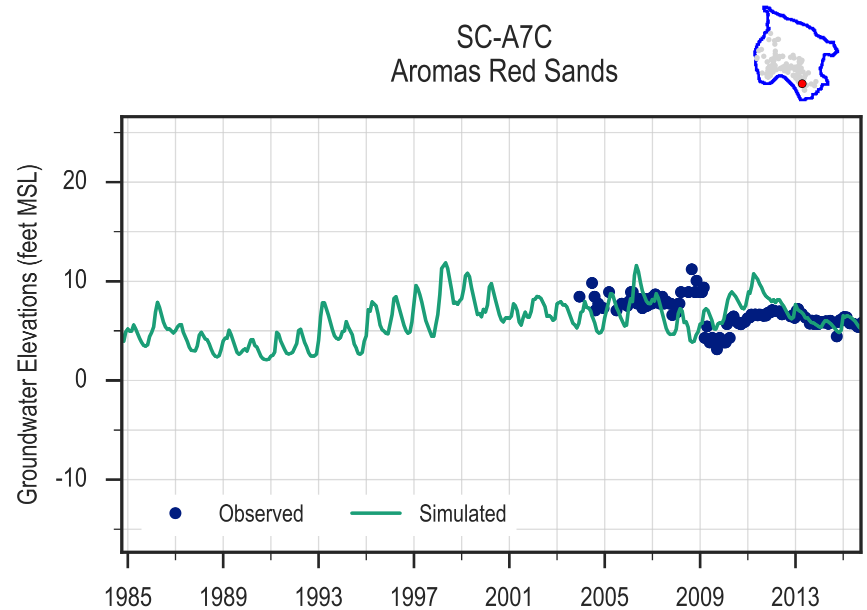
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


SC-A7C
Aromas Red Sands
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-10
Observed
Simulated
1985
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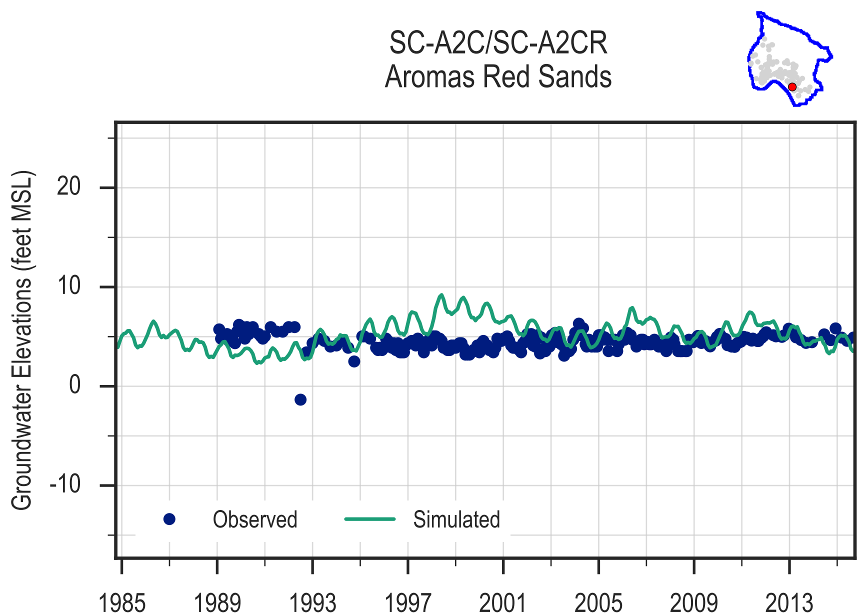
2009
2013


SC-A2C/SC-A2CR
Aromas Red Sands
Groundwater Elevations (feet MSL)
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Observed
Simulated
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1989
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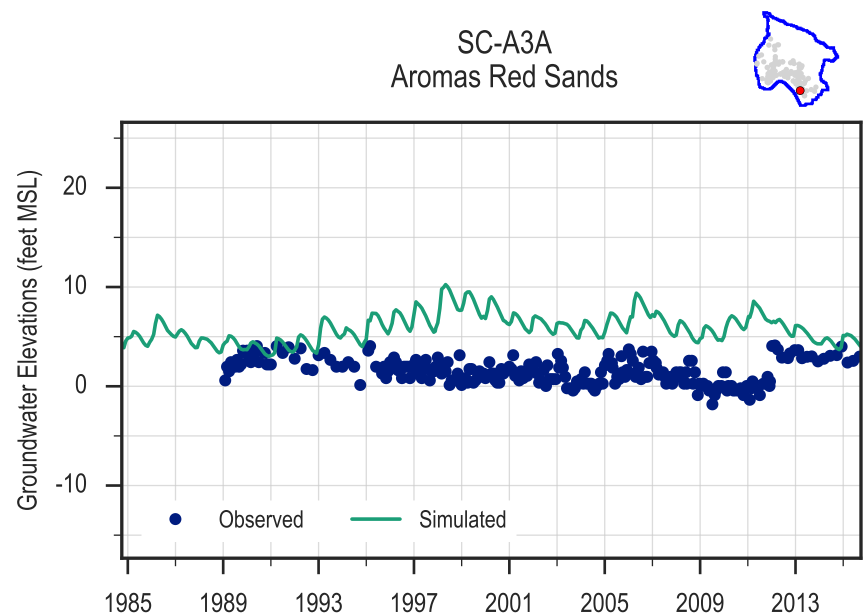
1997
2001
2005
2009
2013


SC-A3A
Aromas Red Sands
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Observed
Simulated
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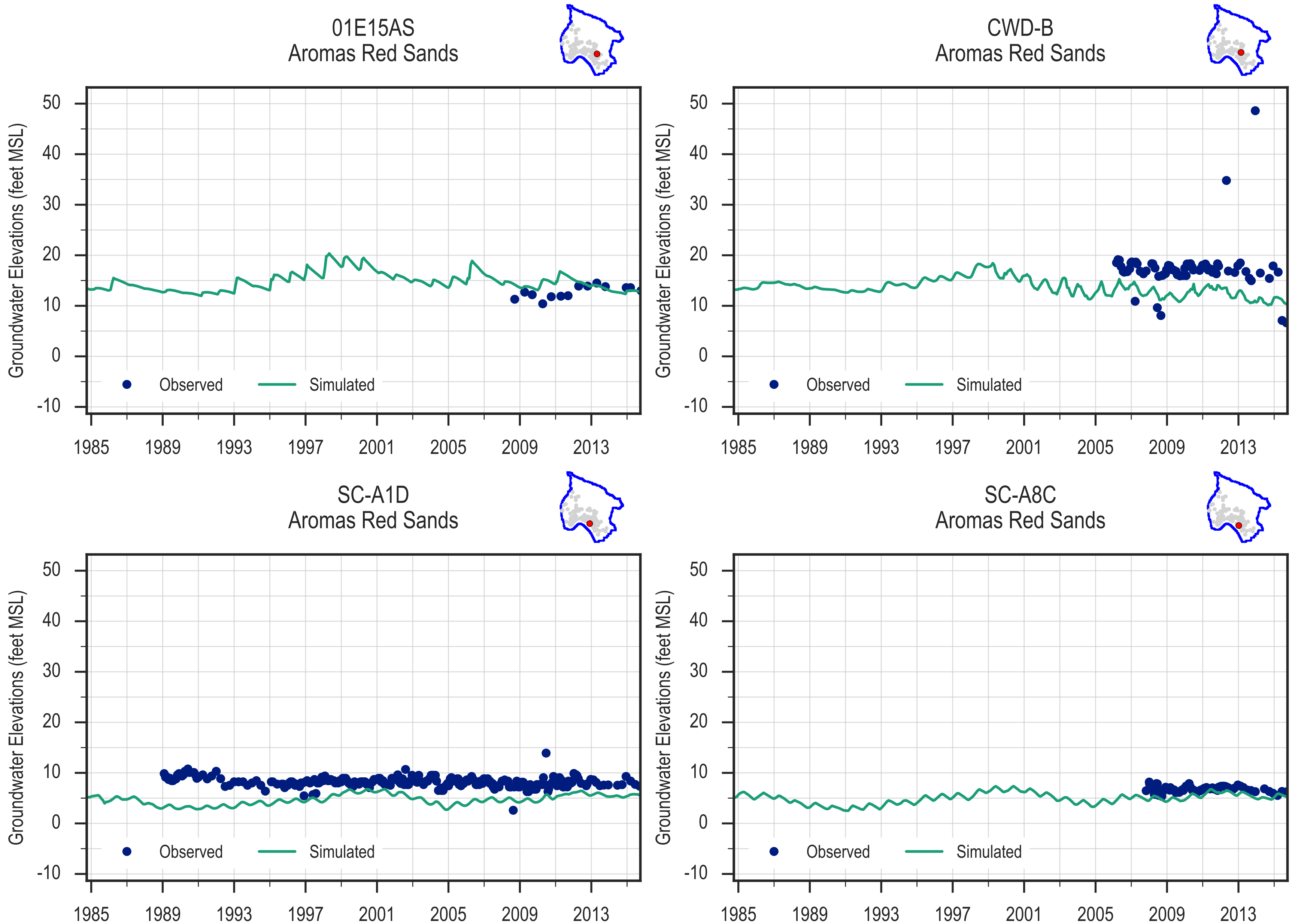
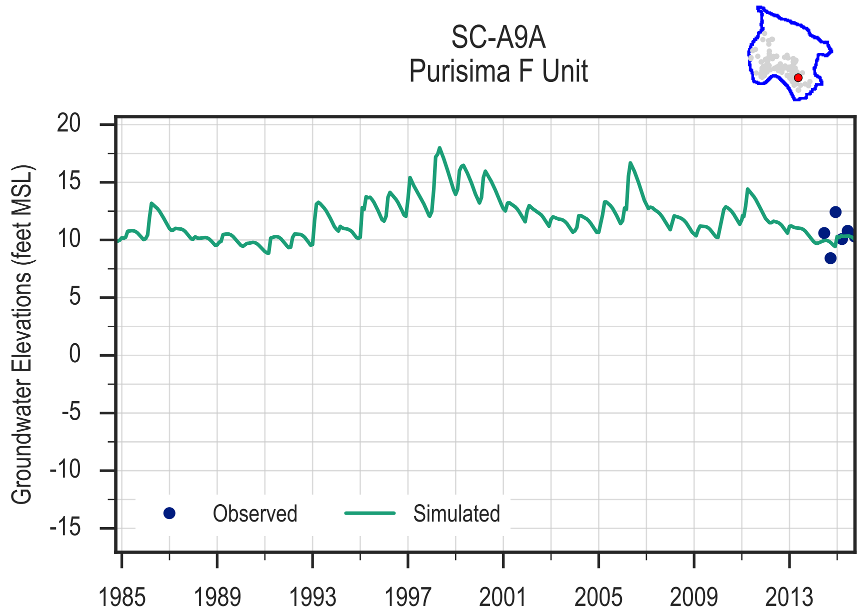
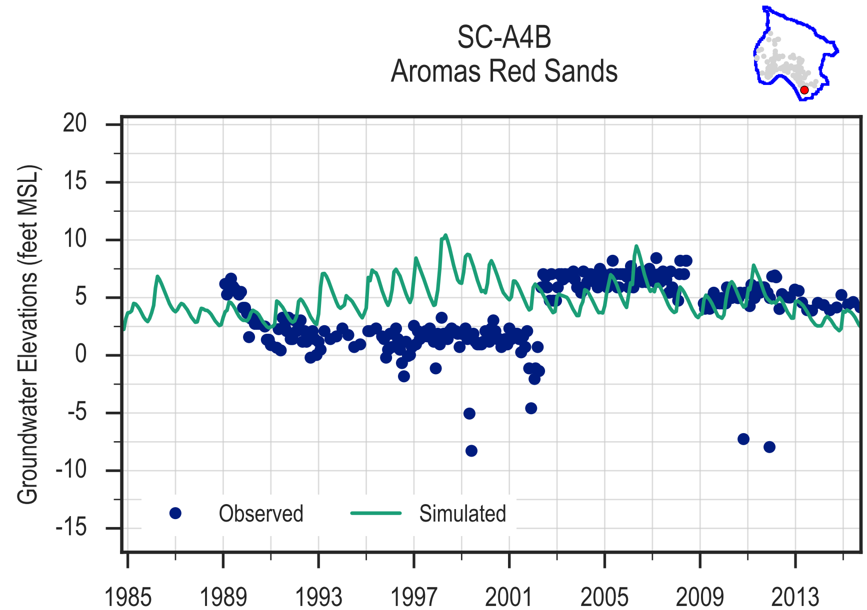
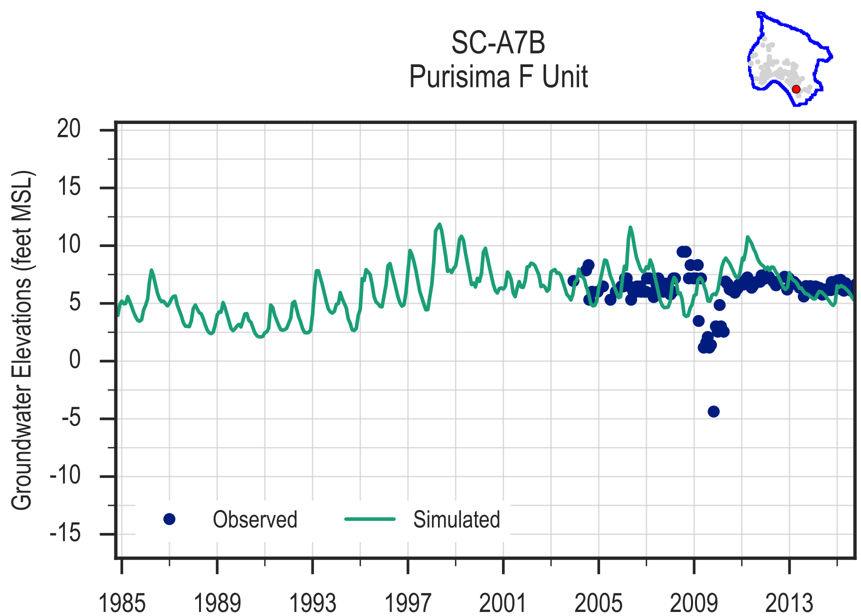
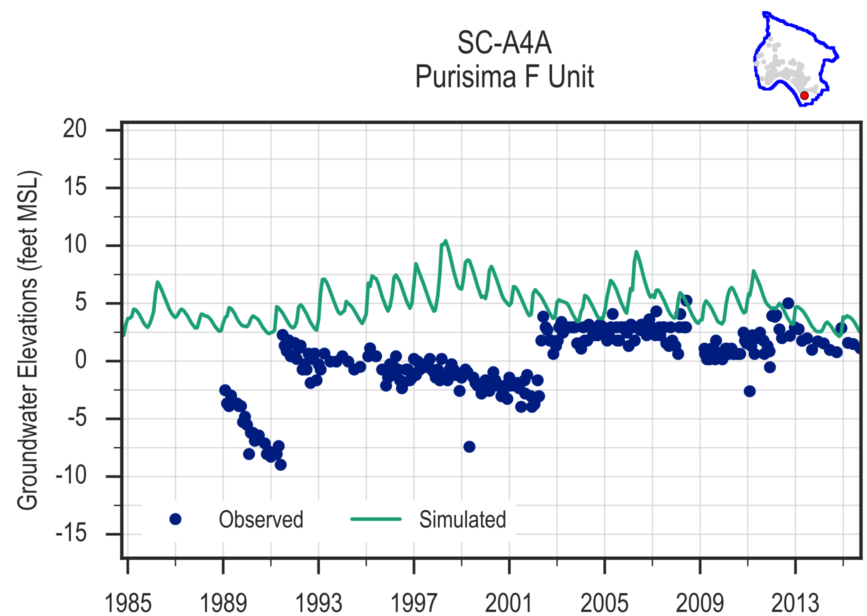
1989
1993
1997
2001
2005
2009
2013

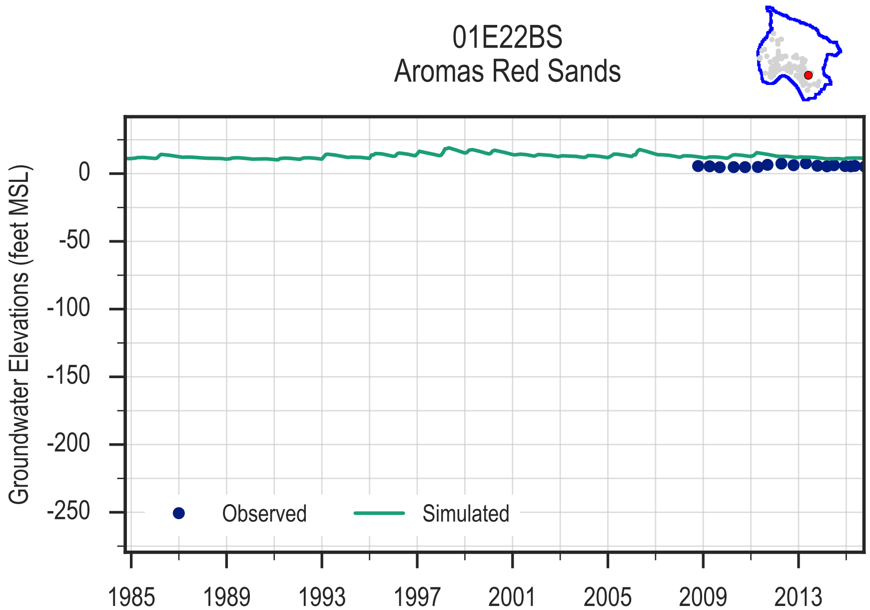

01E15AS
Aromas Red Sands
CWD-B
Aromas Red Sands
SC-A1D
Aromas Red Sands
SC-A8C
Aromas Red Sands
Groundwater Elevations (feet MSL)
50
40
30
20
10
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

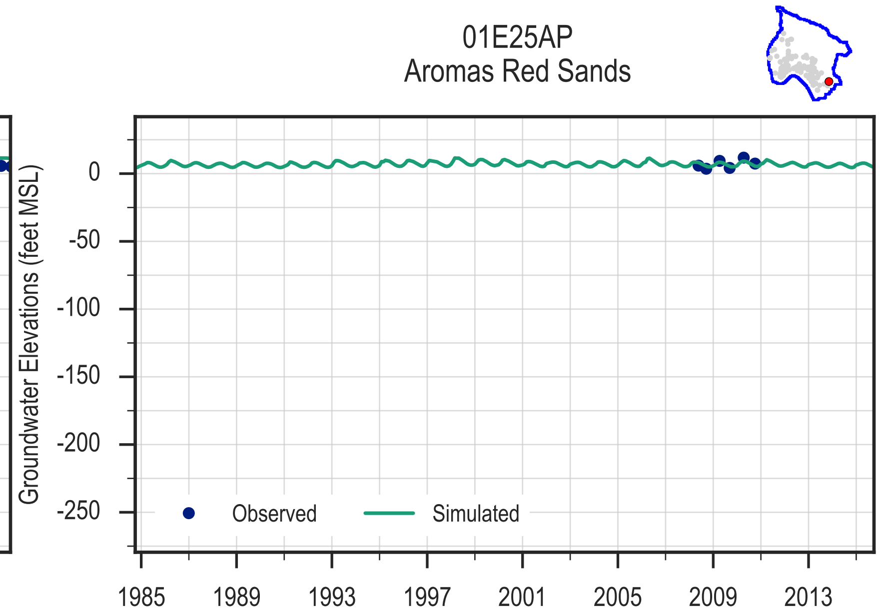

SC-A9A
Purisima F Unit
Groundwater Elevations (feet MSL)
Observed
Simulated

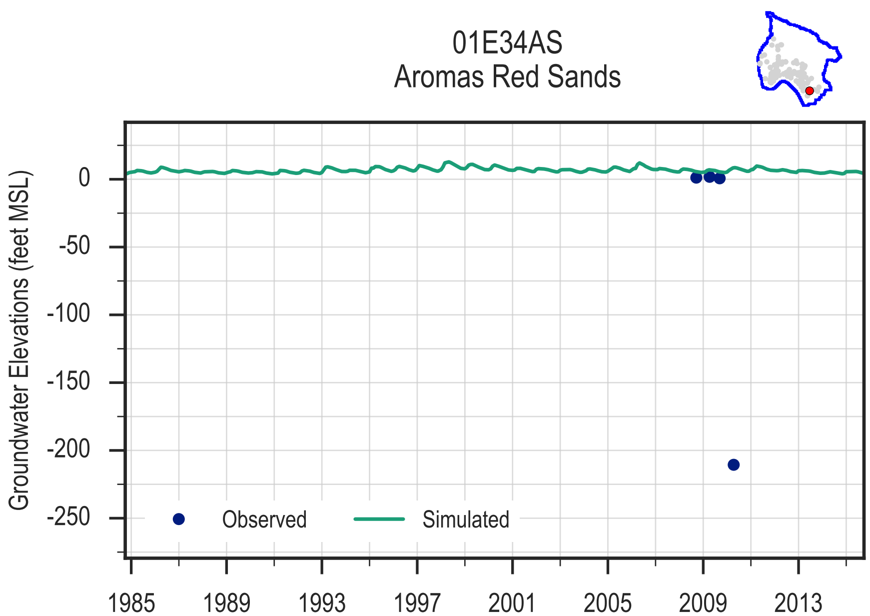

SC-A4B
Aromas Red Sands
Groundwater Elevations (feet MSL)
Observed
Simulated

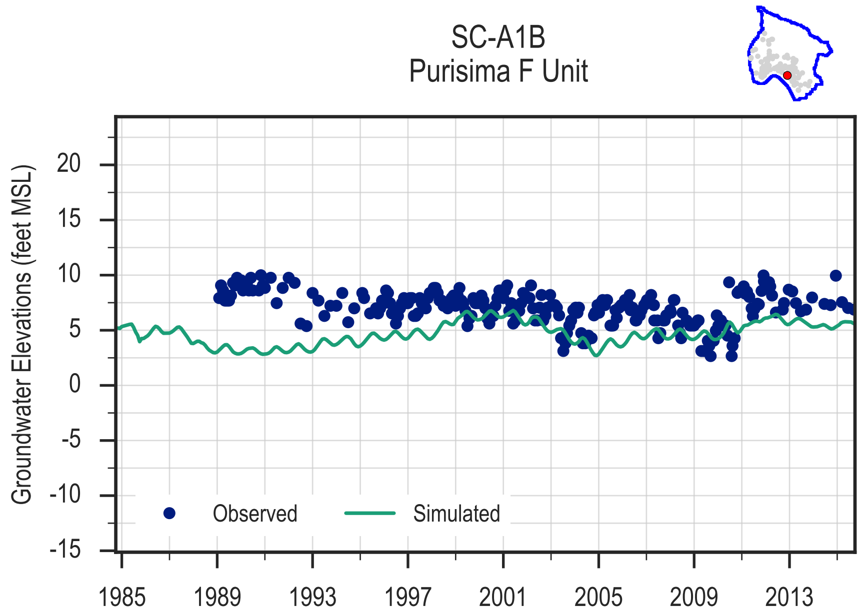

SC-A7B
Purisima F Unit
Groundwater Elevations (feet MSL)
Observed
Simulated

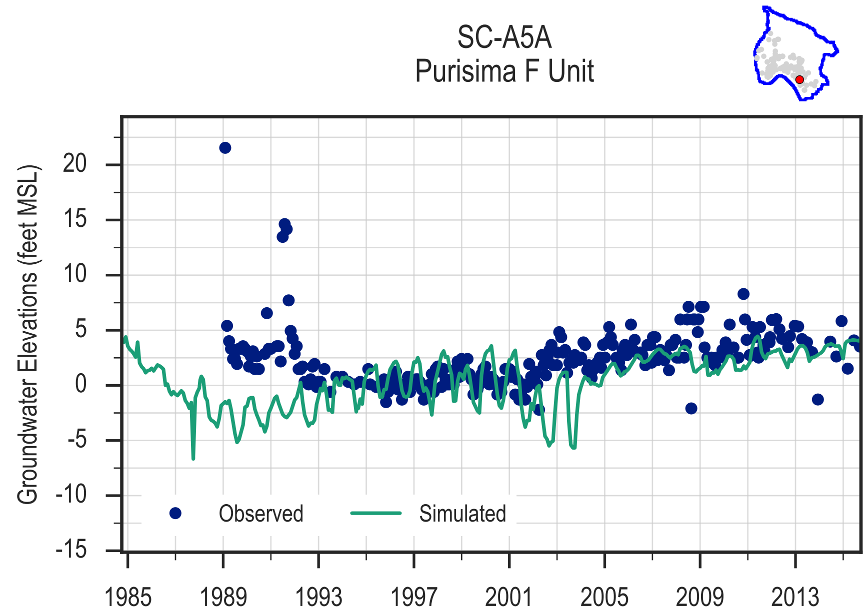

SC-A4A
Purisima F Unit
Groundwater Elevations (feet MSL)
Observed
Simulated

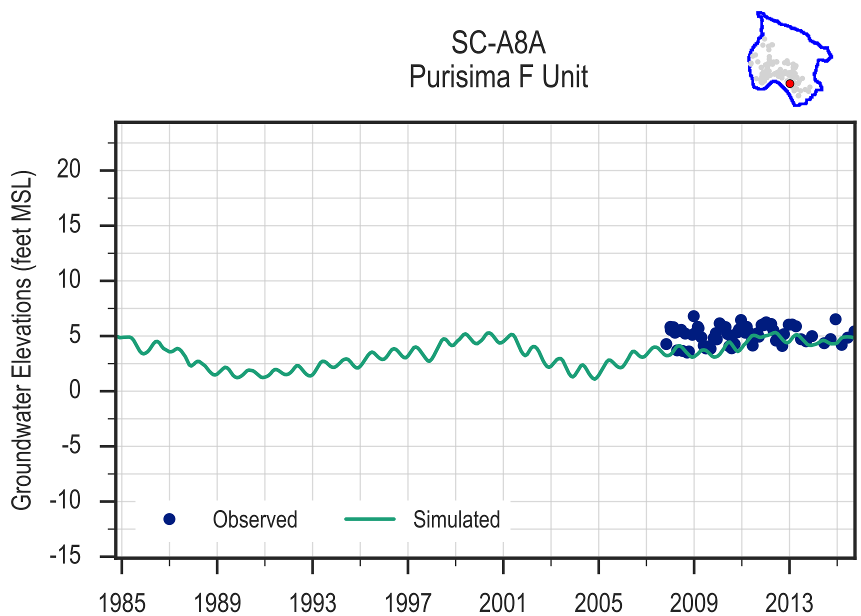

01E22BS
Aromas Red Sands
Groundwater Elevations (feet MSL)
0
-50
-100
-150
-200
-250
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

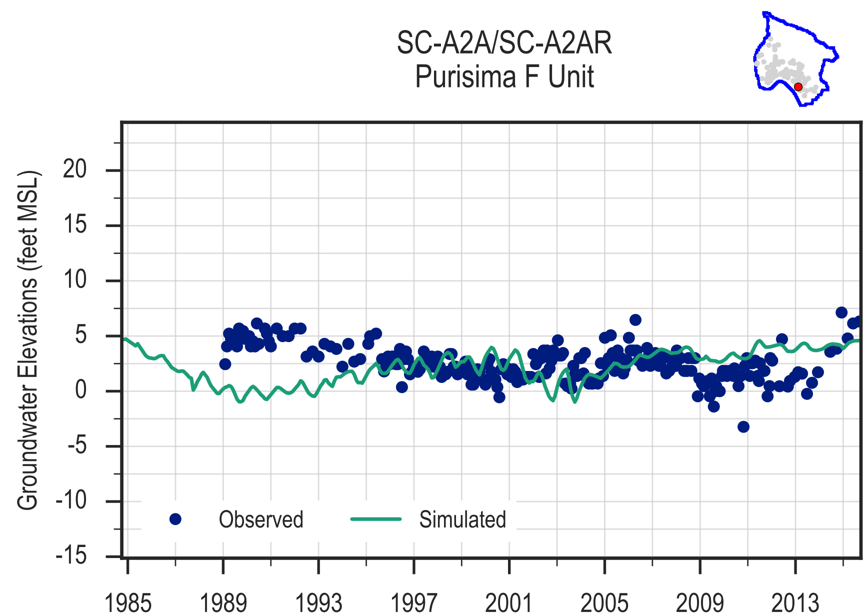

01E25AP
Aromas Red Sands
Groundwater Elevations (feet MSL)
0
-50
-100
-150
-200
-250
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

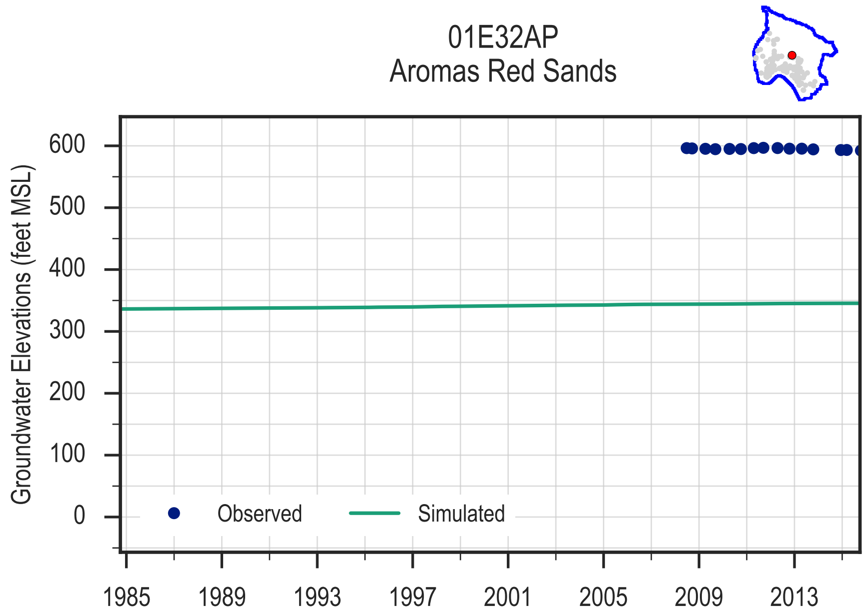

01E34AS
Aromas Red Sands
Groundwater Elevations (feet MSL)
0
-50
-100
-150
-200
-250
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

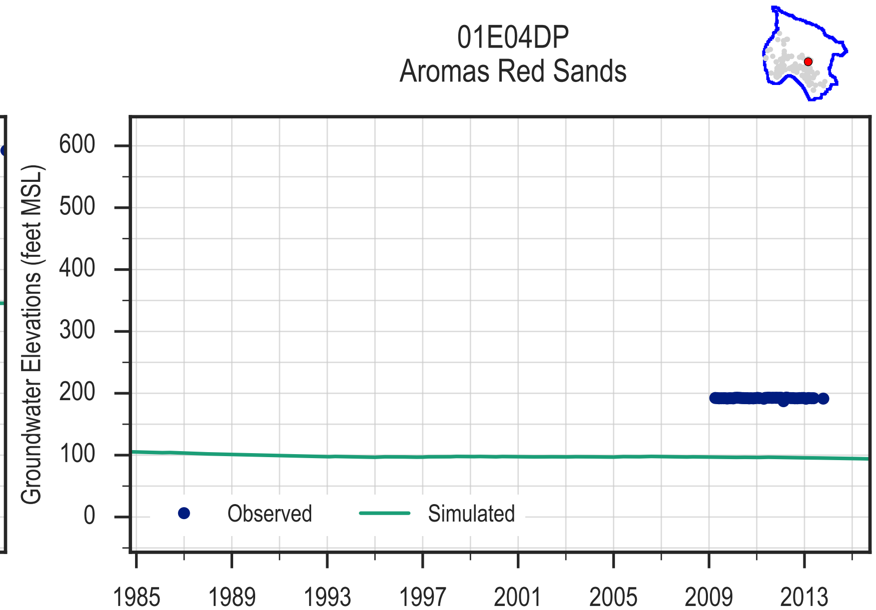

SC-A1B
Purisima F Unit
Groundwater Elevations (feet MSL)
20
15
10
5
0
-5
-10
-15
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

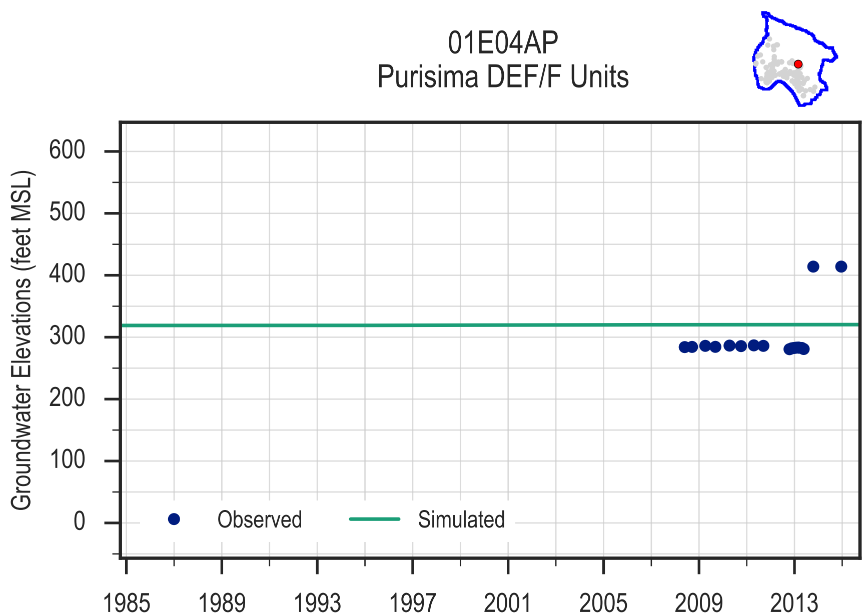

SC-A5A
Purisima F Unit
Groundwater Elevations (feet MSL)
20
15
10
5
0
-5
-10
-15
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

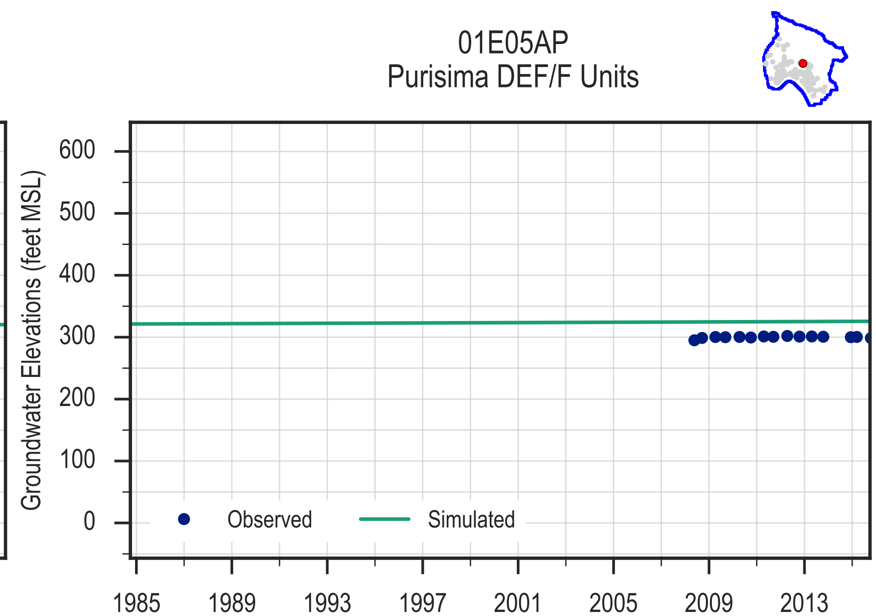

SC-A8A
Purisima F Unit
Groundwater Elevations (feet MSL)
20
15
10
5
0
-5
-10
-15
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

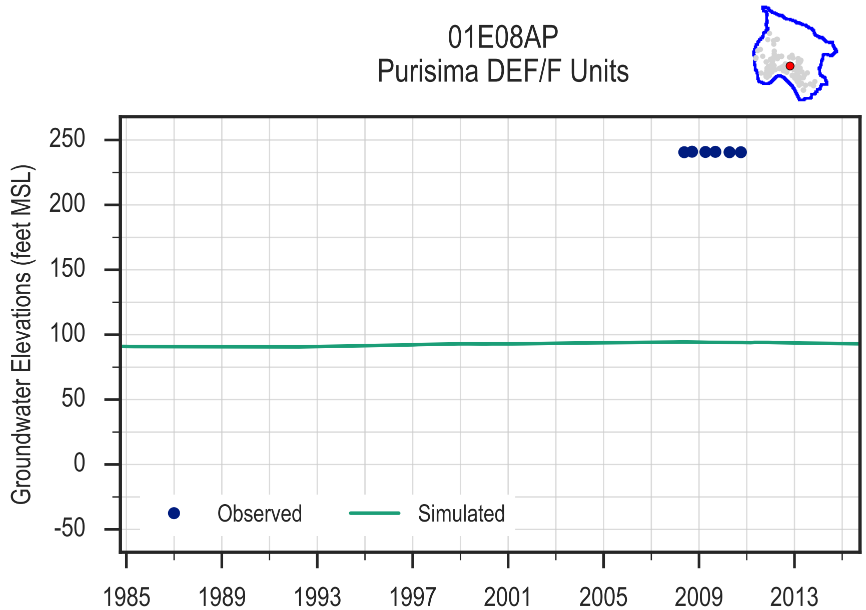

SC-A2A/SC-A2AR
Purisima F Unit
Groundwater Elevations (feet MSL)
20
15
10
5
0
-5
-10
-15
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

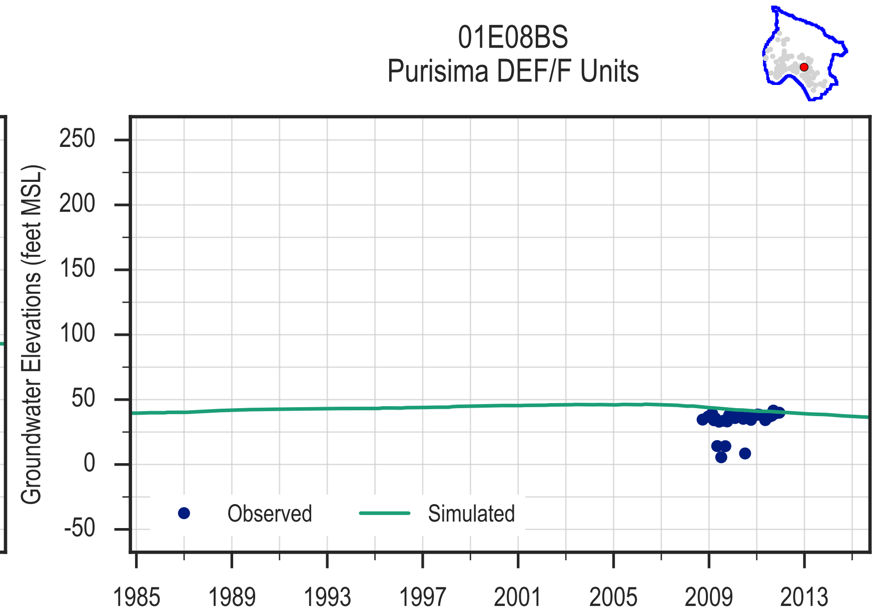

01E32AP
Aromas Red Sands
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

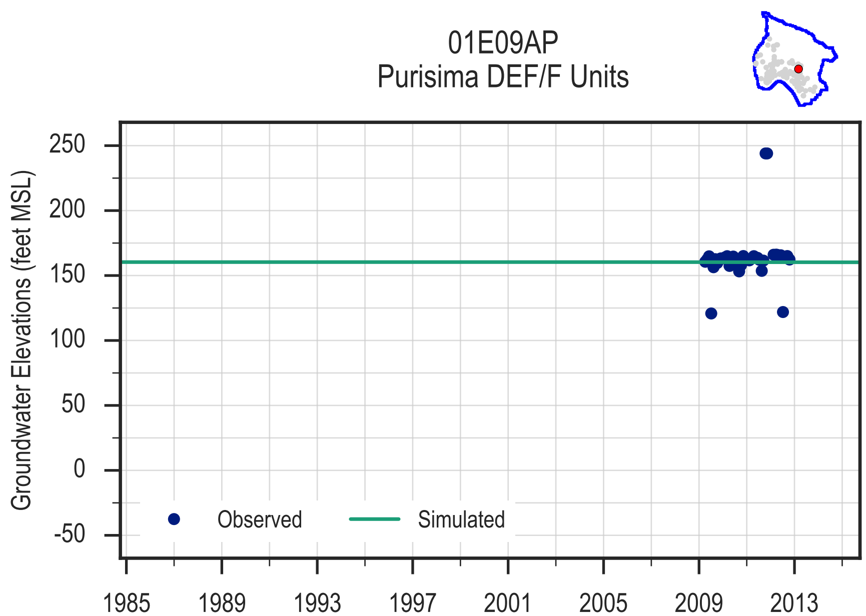

01E04DP
Aromas Red Sands
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

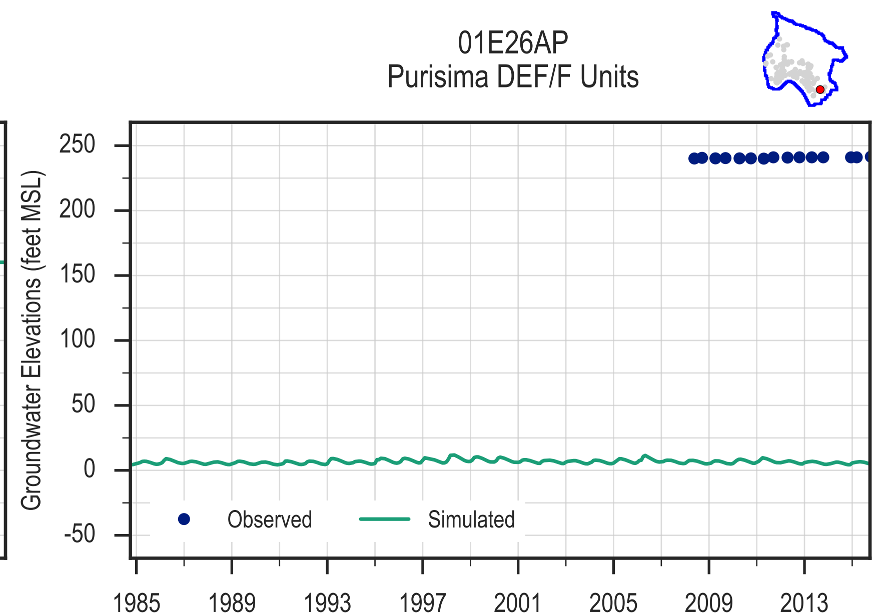

01E04AP
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

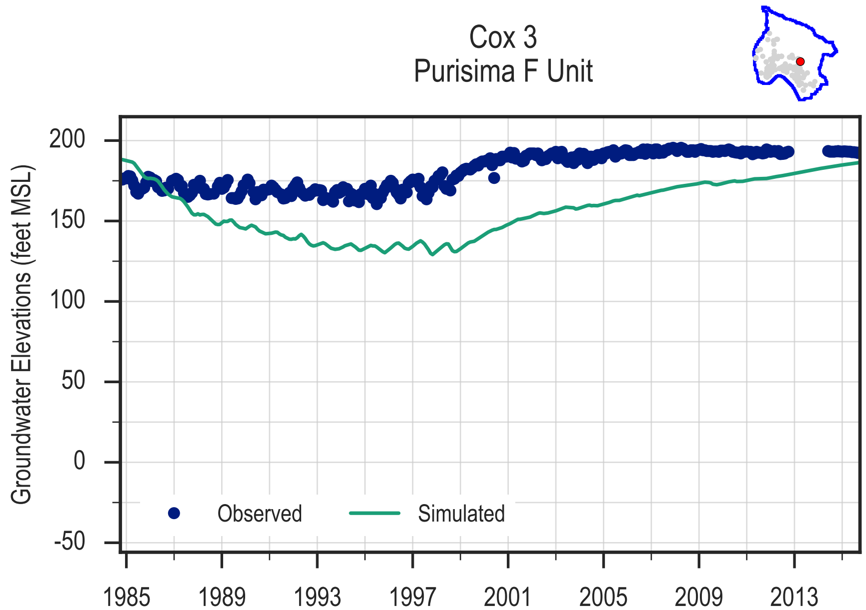

01E05AP
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

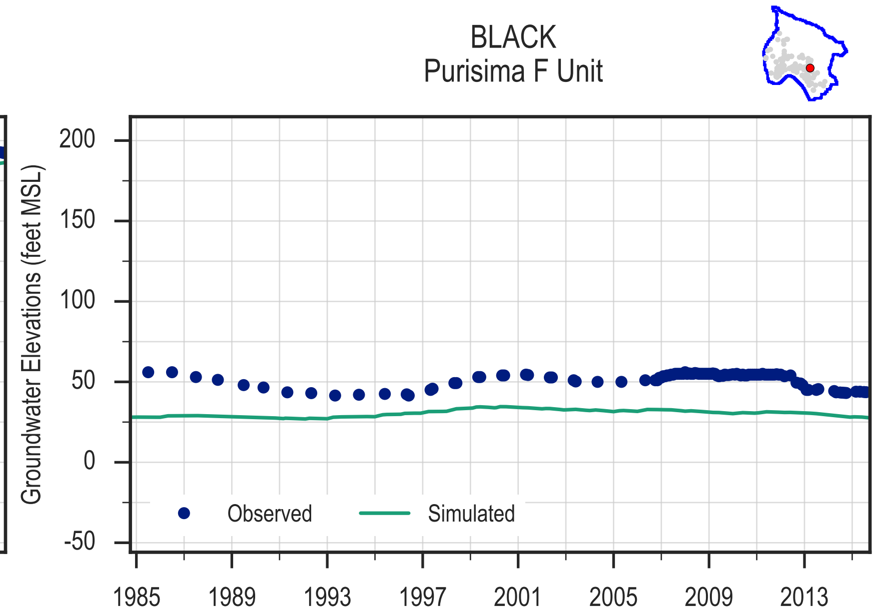

01E08AP
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
250
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

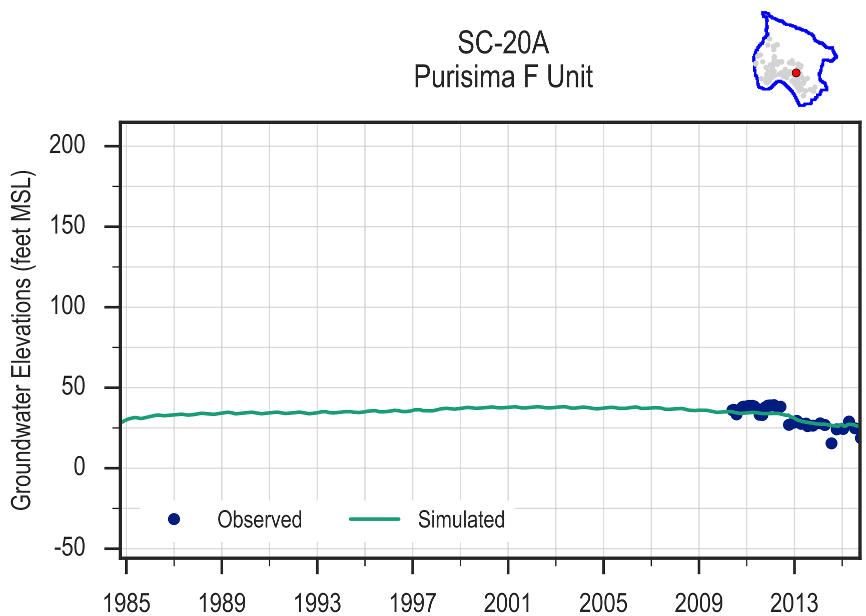

01E08BS
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
250
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

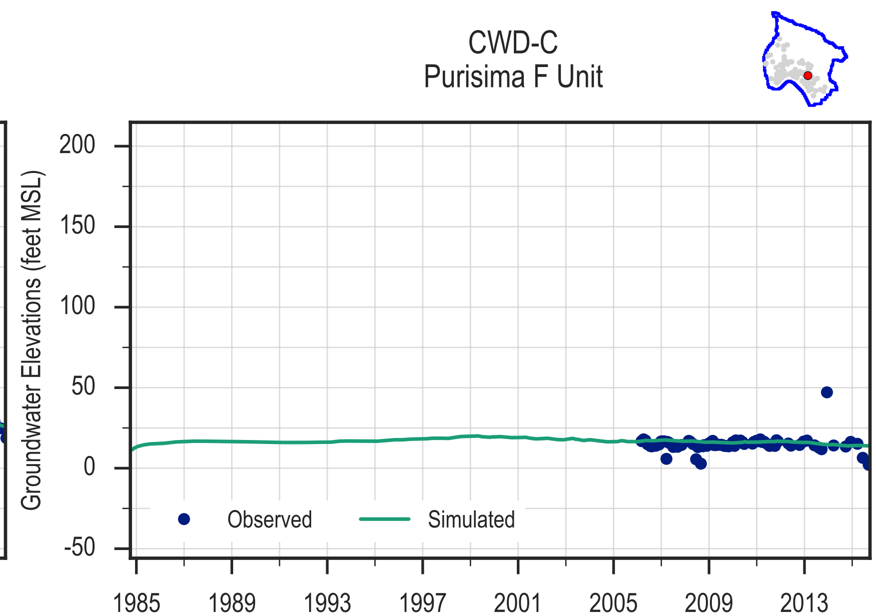

01E09AP
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
250
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

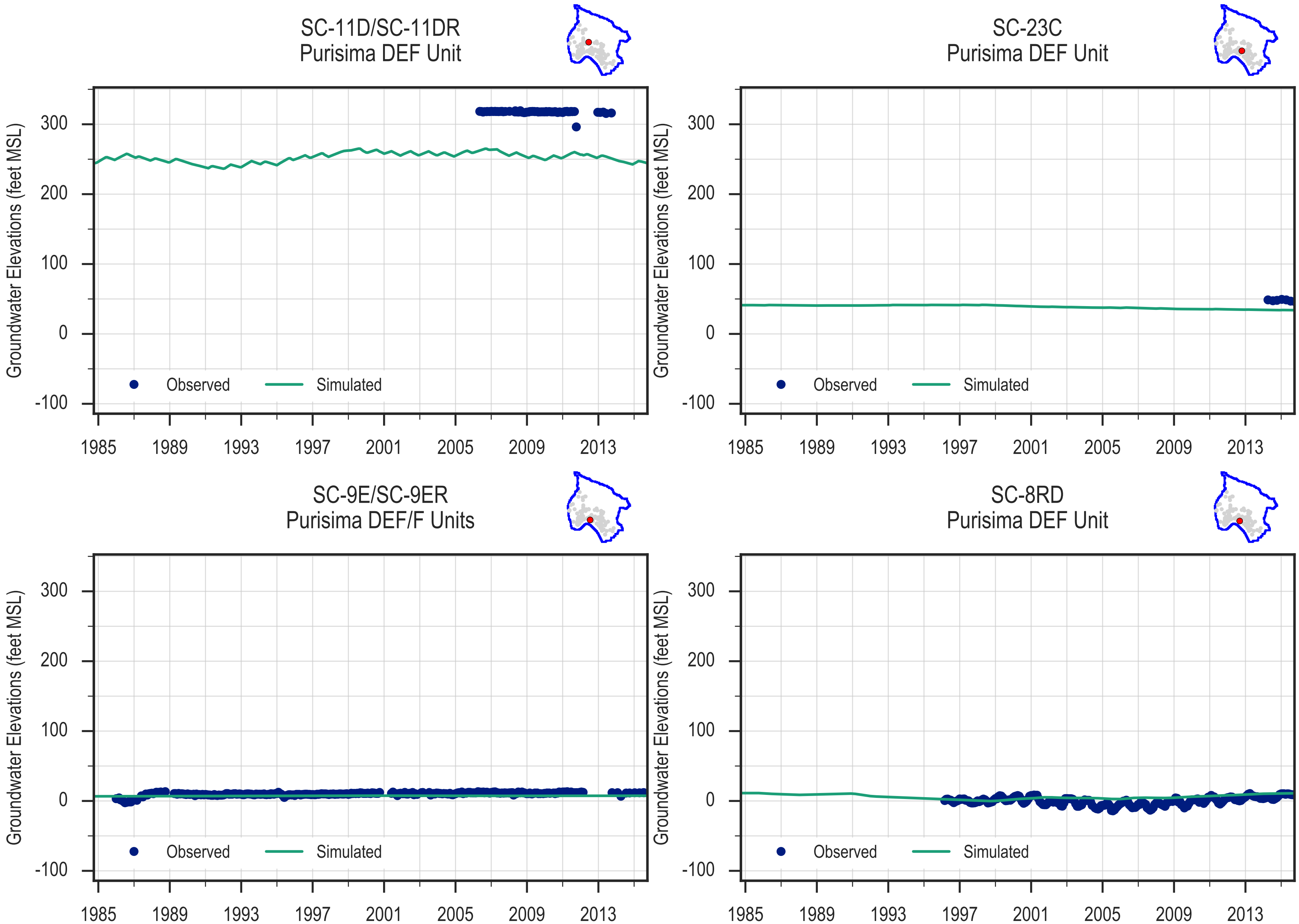

01E26AP
Purisima DEF/F Units
Groundwater Elevations (feet MSL)
250
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

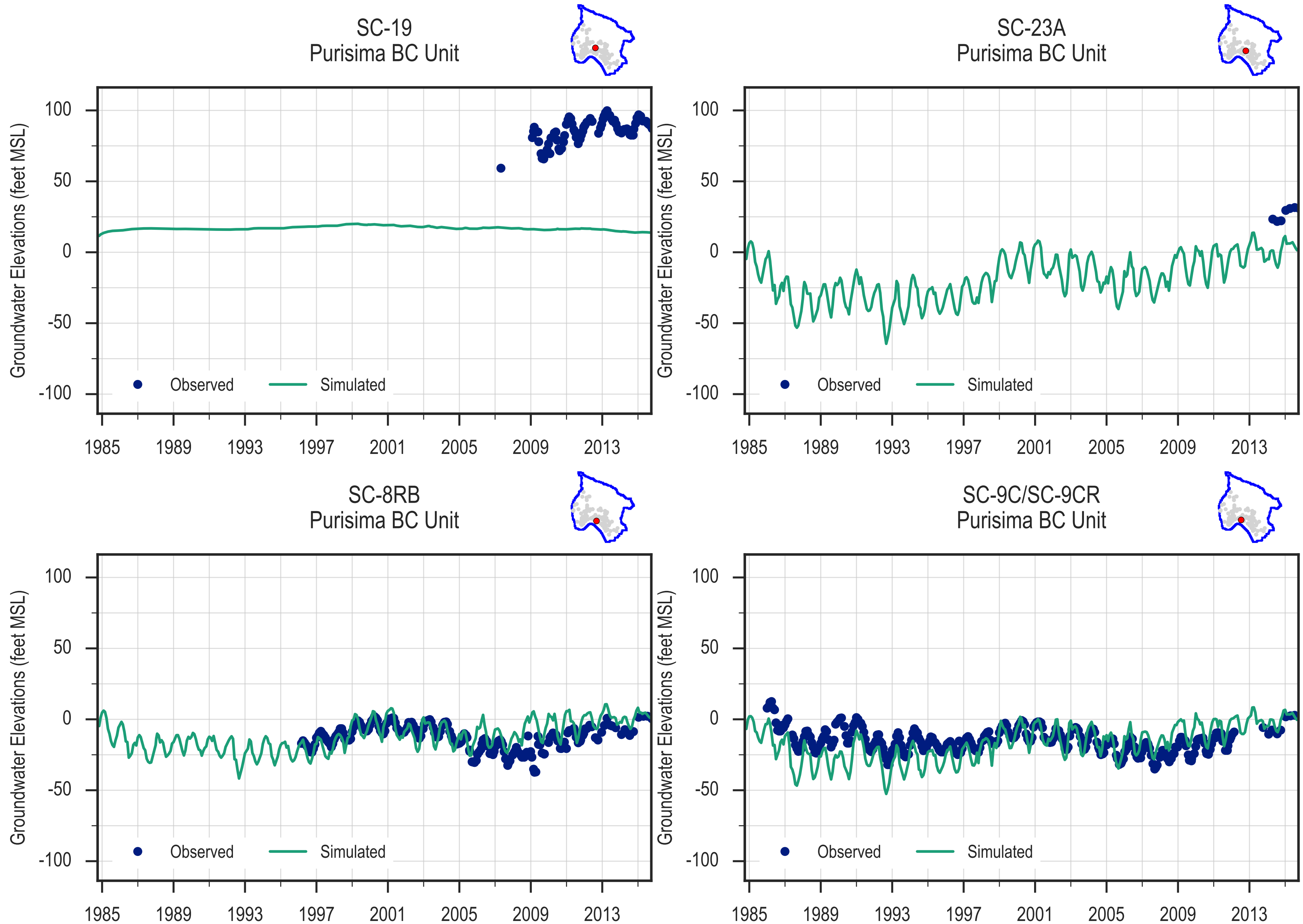

Cox 3
Purisima F Unit
Groundwater Elevations (feet MSL)
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

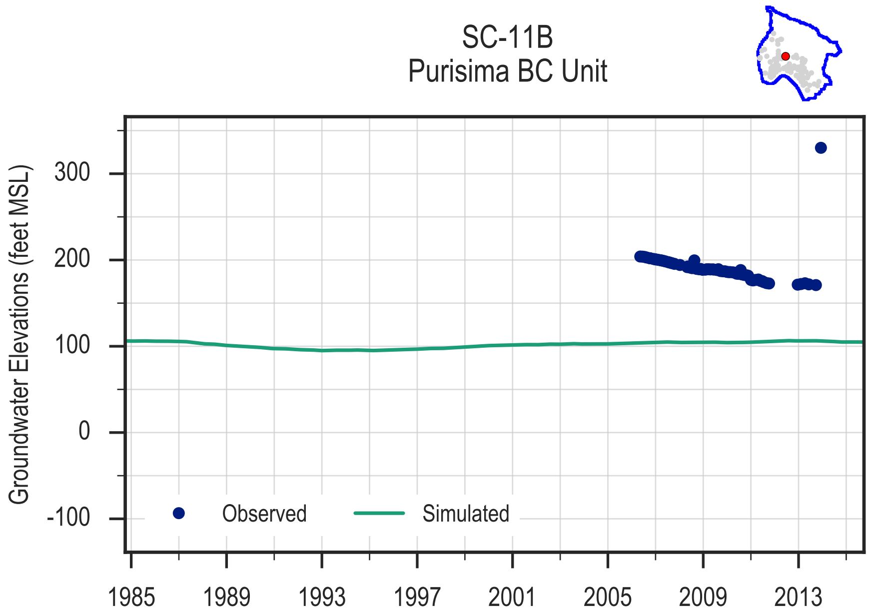

BLACK
Purisima F Unit
Groundwater Elevations (feet MSL)
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

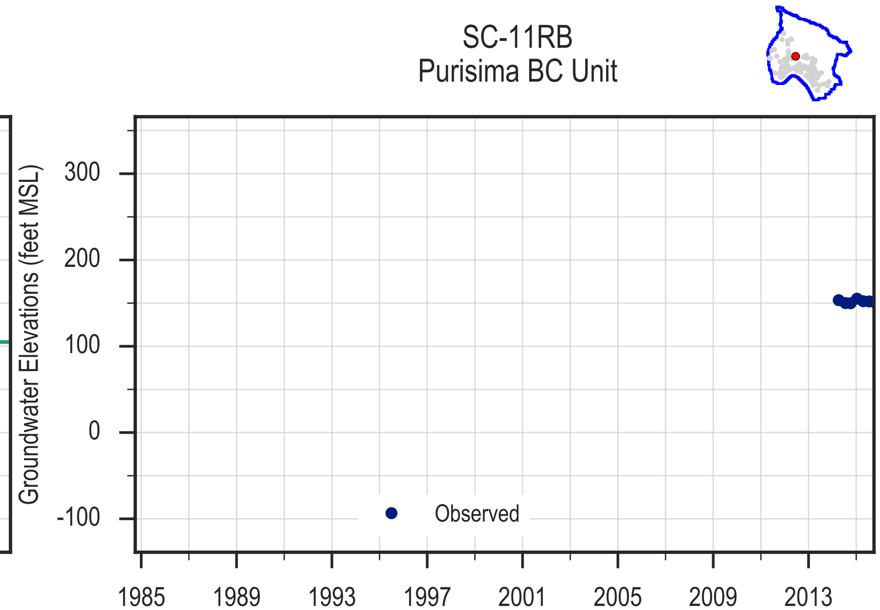

SC-20A
Purisima F Unit
Groundwater Elevations (feet MSL)
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

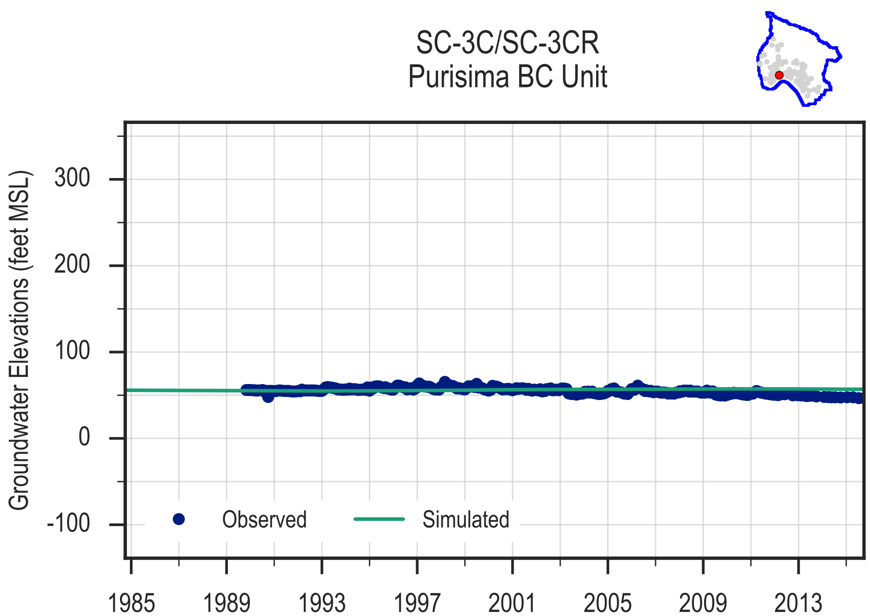

CWD-C
Purisima F Unit
Groundwater Elevations (feet MSL)
200
150
100
50
0
-50
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

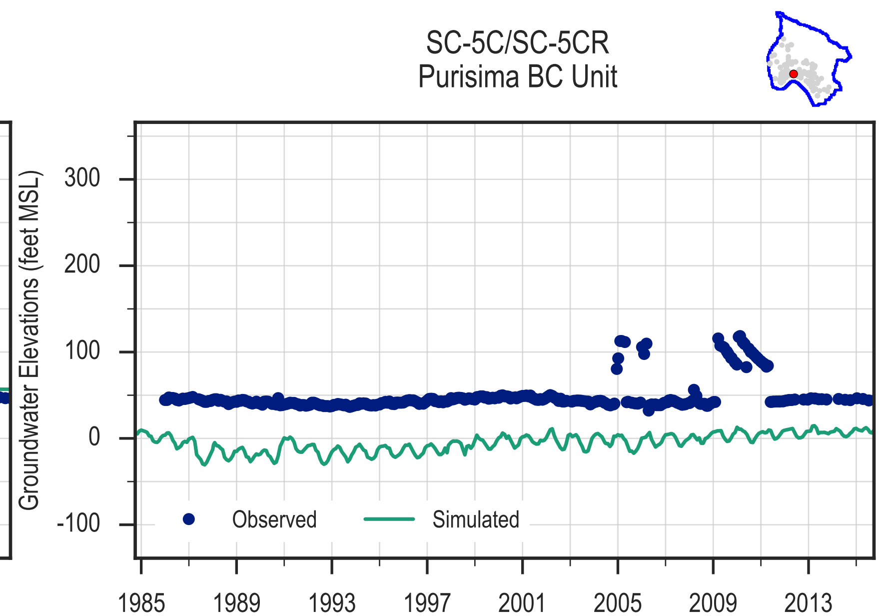

SC-11D/SC-11DR
Purisima DEF Unit
SC-23C
Purisima DEF Unit
SC-9E/SC-9ER
Purisima DEF/F Units
SC-8RD
Purisima DEF Unit
Groundwater Elevations (feet MSL)
300
200
100
0
-100
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

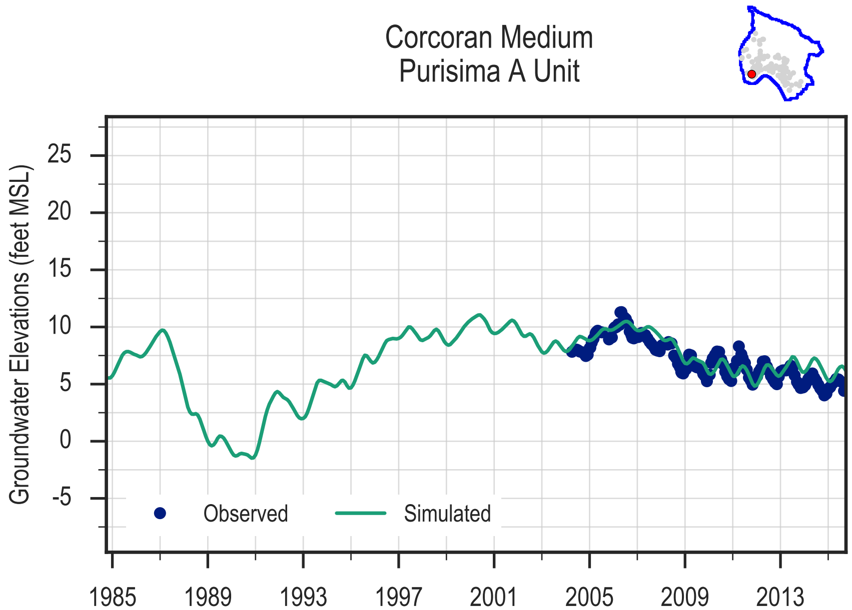

SC-19
Purisima BC Unit
SC-23A
Purisima BC Unit
SC-8RB
Purisima BC Unit
SC-9C/SC-9CR
Purisima BC Unit
Groundwater Elevations (feet MSL)
100
50
0
-50
-100
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

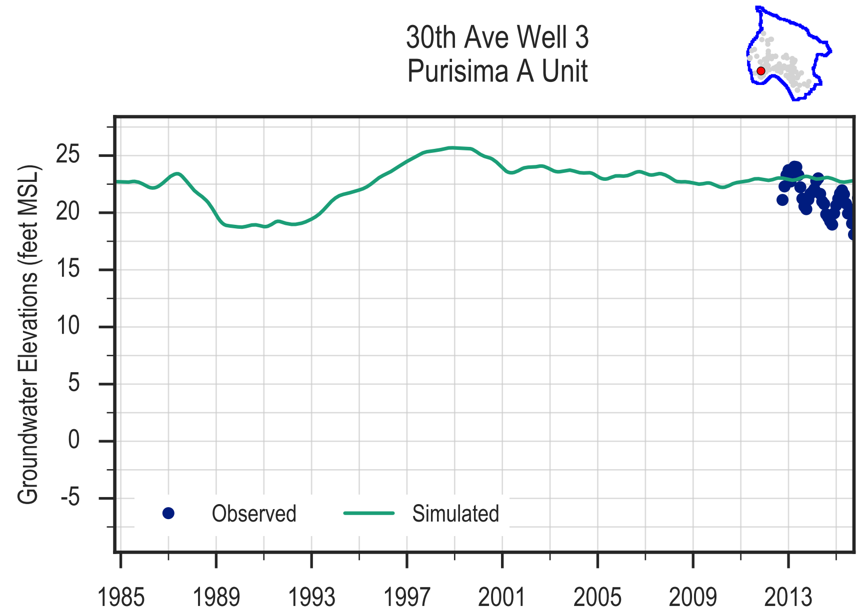

SC-11B
Purisima BC Unit
Groundwater Elevations (feet MSL)
300
200
100
0
-100
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

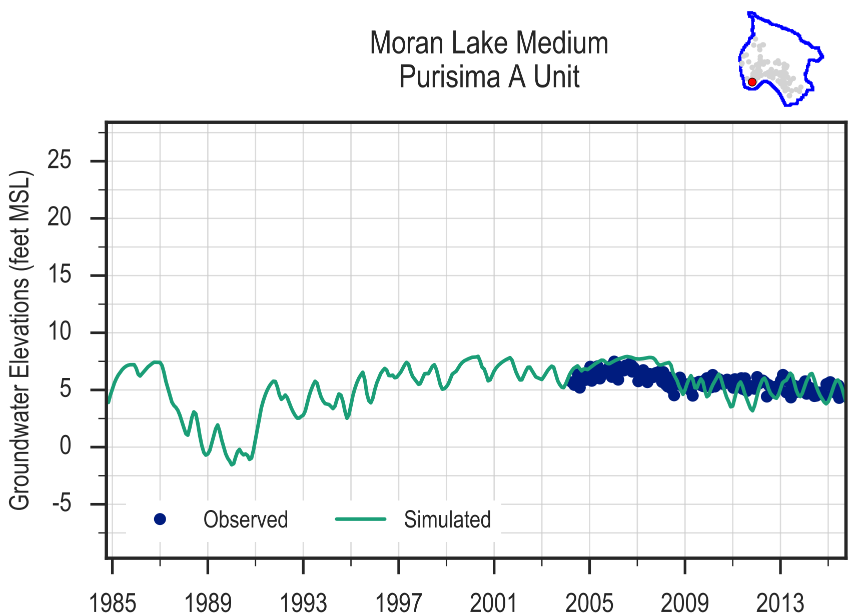

SC-11RB
Purisima BC Unit
Groundwater Elevations (feet MSL)
300
200
100
0
-100
Observed
1985
1989
1993
1997
2001
2005
2009
2013

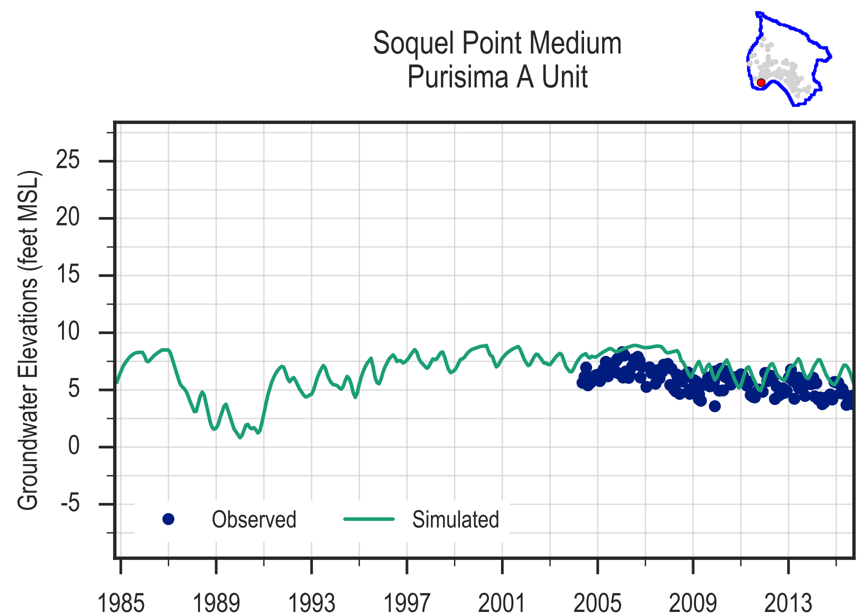

SC-3C/SC-3CR
Purisima BC Unit
Groundwater Elevations (feet MSL)
300
200
100
0
-100
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

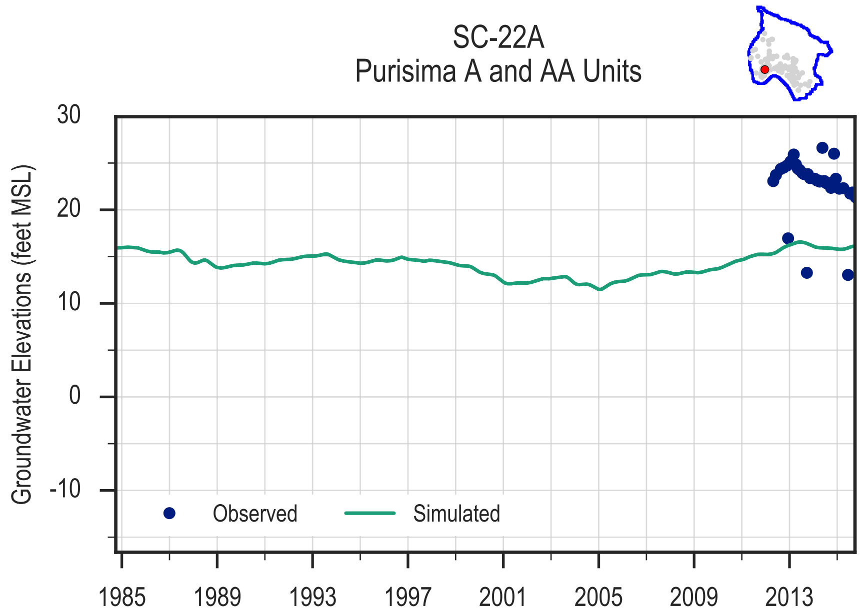

SC-5C/SC-5CR
Purisima BC Unit
Groundwater Elevations (feet MSL)
300
200
100
0
-100
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

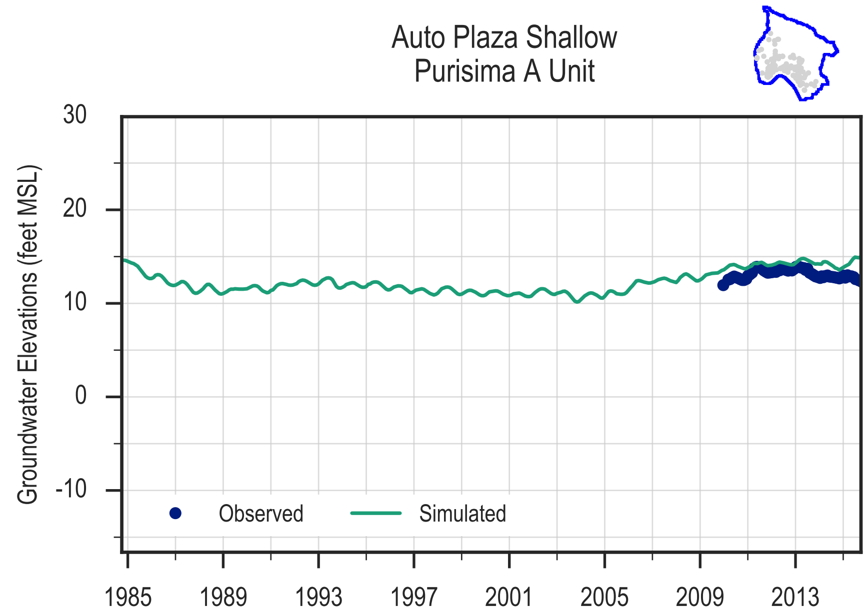

Corcoran Medium
Purisima A Unit
Groundwater Elevations (feet MSL)
25
20
15
10
5
0
-5
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

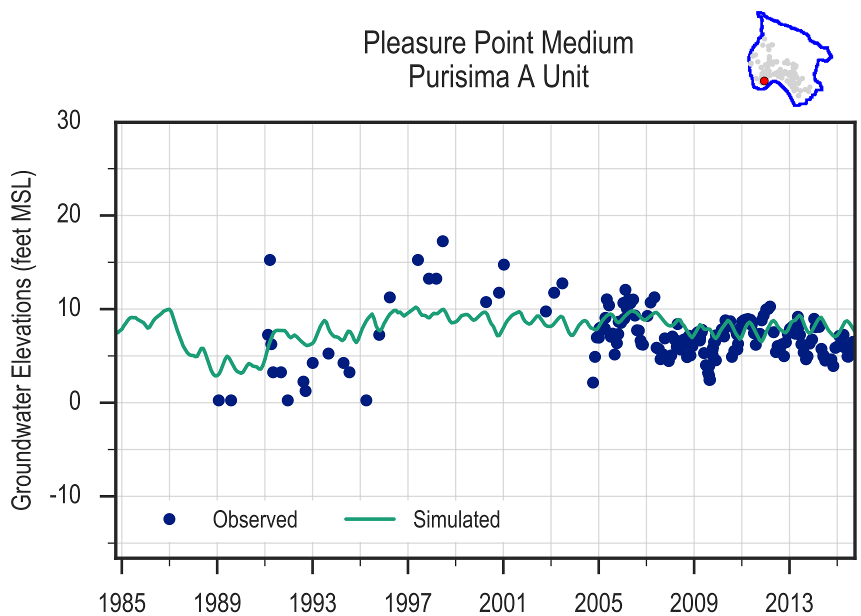

30th Ave Well 3
Purisima A Unit
Groundwater Elevations (feet MSL)
25
20
15
10
5
0
-5
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

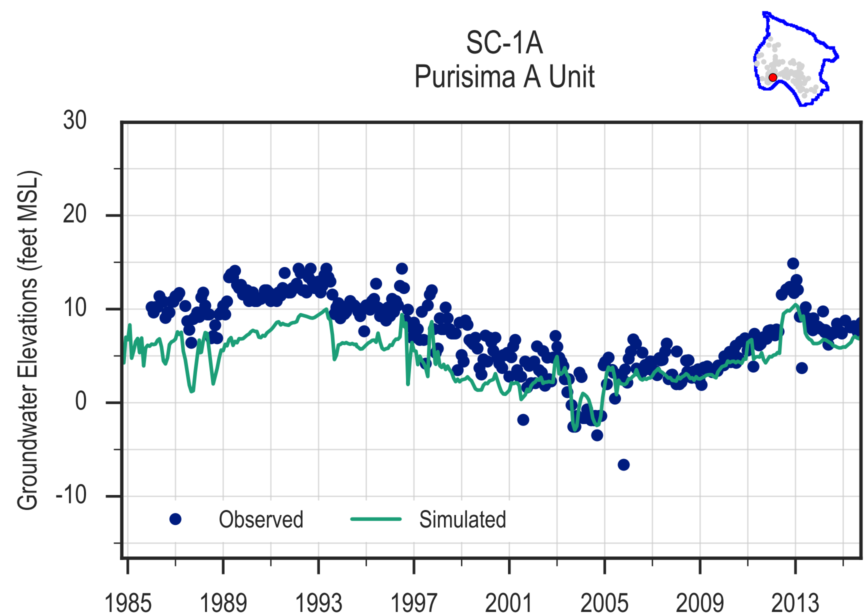

Moran Lake Medium
Purisima A Unit
Groundwater Elevations (feet MSL)
25
20
15
10
5
0
-5
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


Soquel Point Medium
Purisima A Unit
Groundwater Elevations (feet MSL)
25
20
15
10
5
0
-5
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

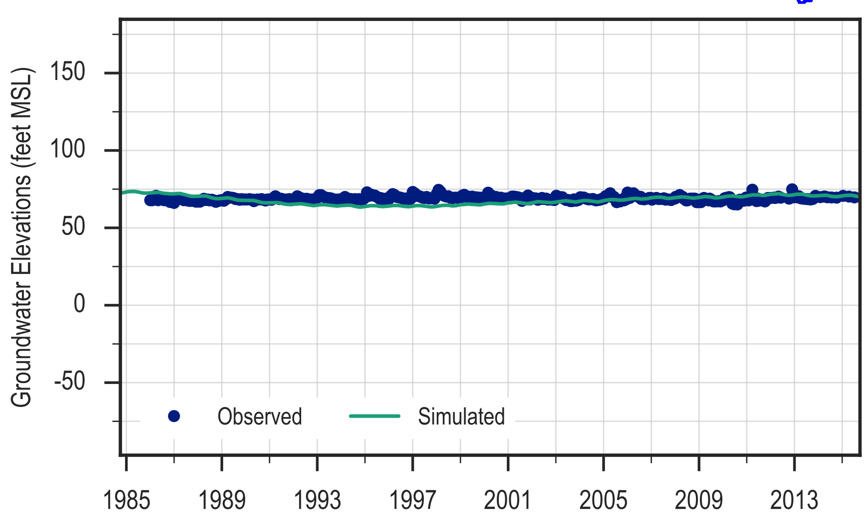

SC-22A
Purisima A and AA Units
Groundwater Elevations (feet MSL)
30
20
10
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


Auto Plaza Shallow
Purisima A Unit
Groundwater Elevations (feet MSL)
30
20
10
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

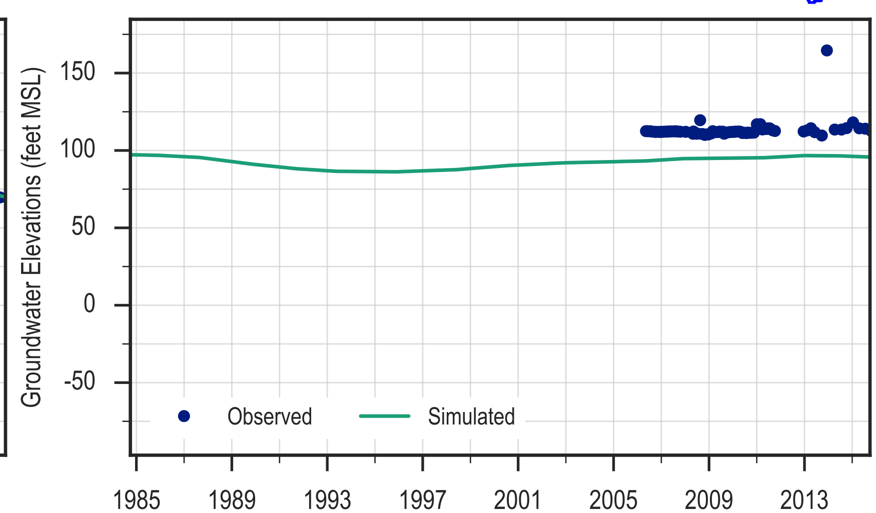

Pleasure Point Medium
Purisima A Unit
Groundwater Elevations (feet MSL)
30
20
10
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


SC-1A
Purisima A Unit
Groundwater Elevations (feet MSL)
30
20
10
0
-10
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

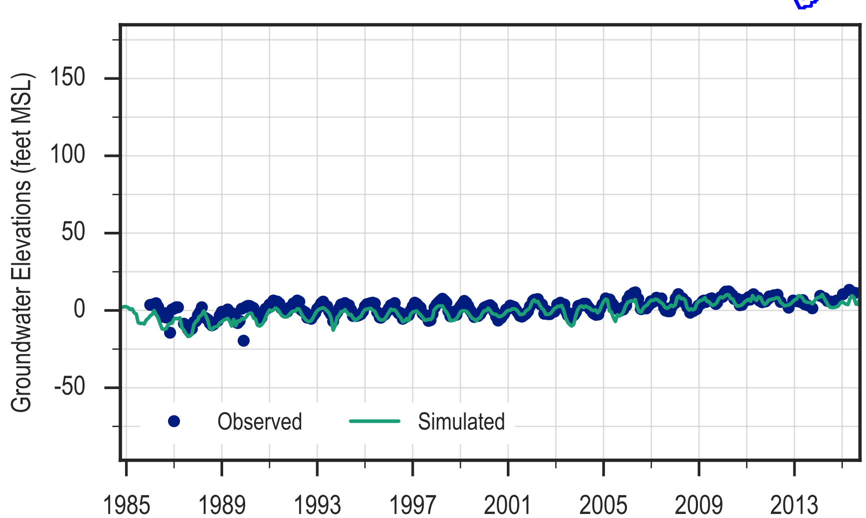
SC-10A/SC-10AR
Purisima A Unit



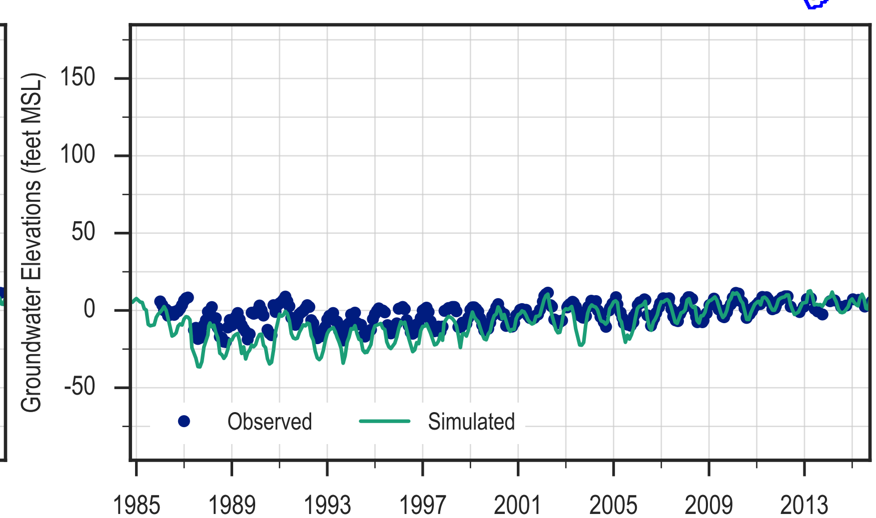
SC-11A/SC-11AR
Purisima A Unit



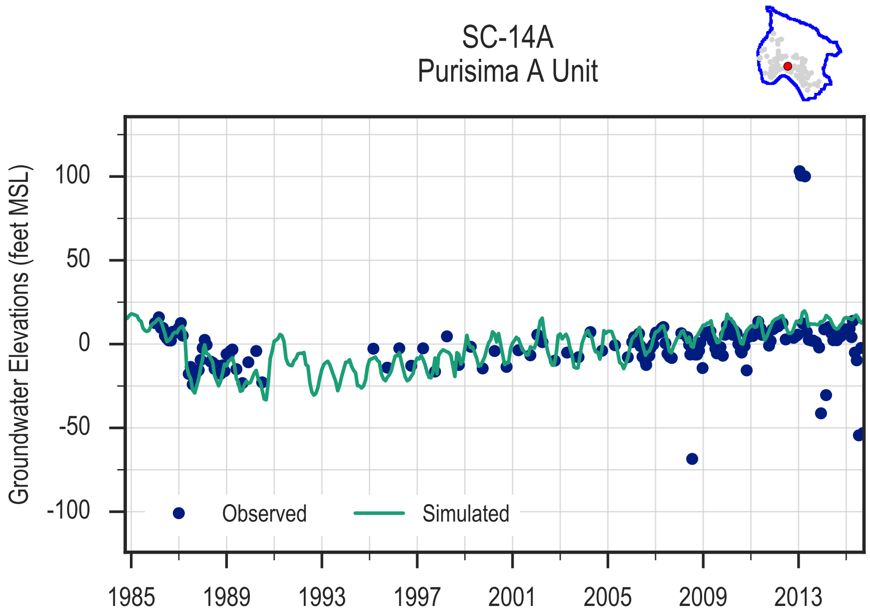
SC-3A/SC-3AR
Purisima A Unit



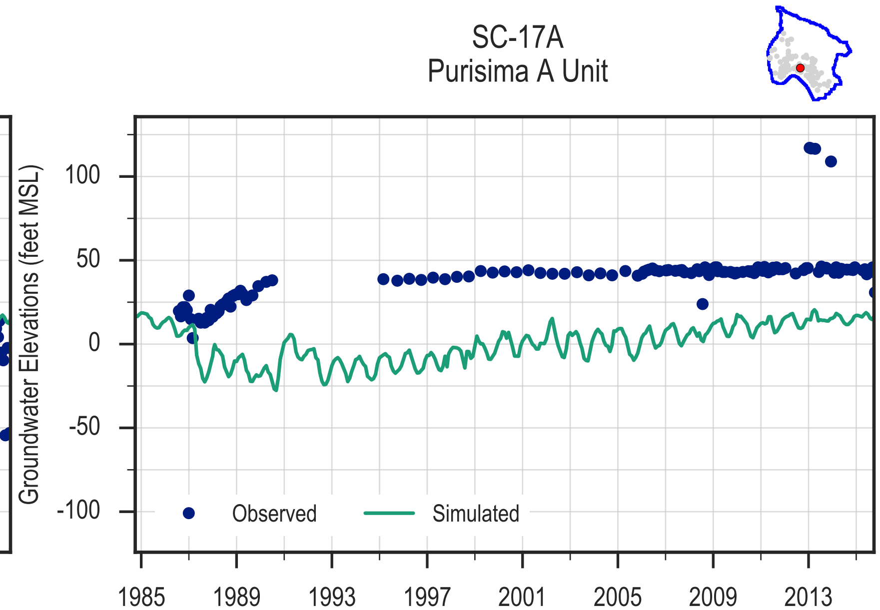
SC-5A/SC-5AR
Purisima A Unit



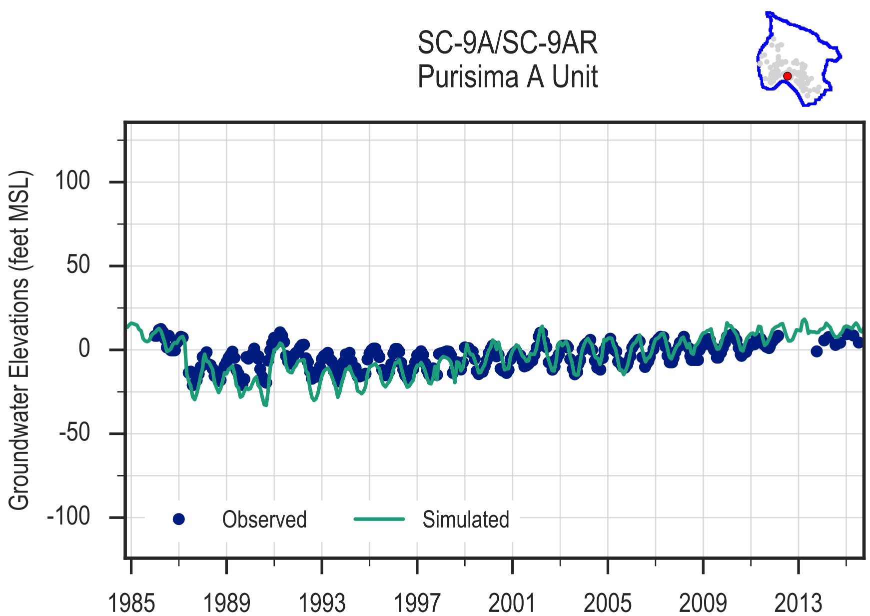
SC-14A
Purisima A Unit



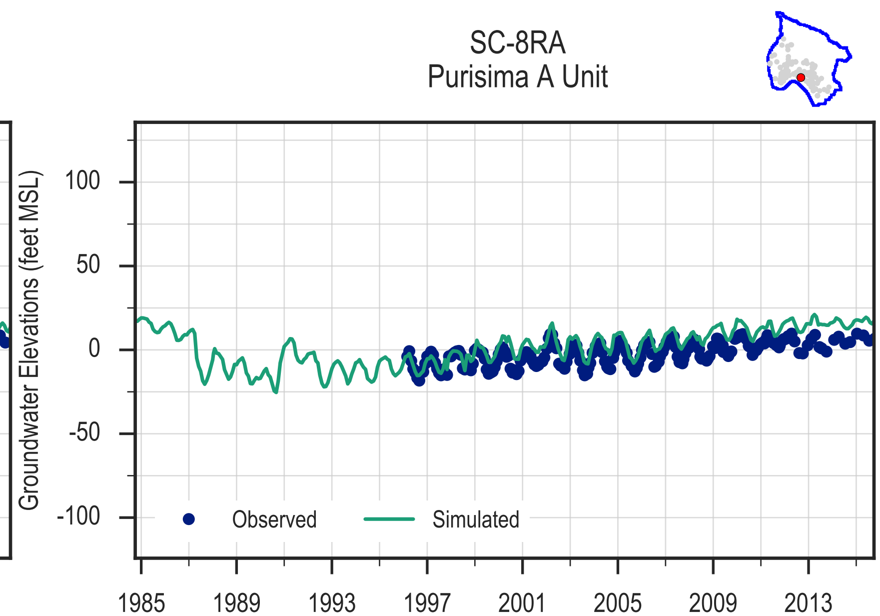
SC-17A
Purisima A Unit



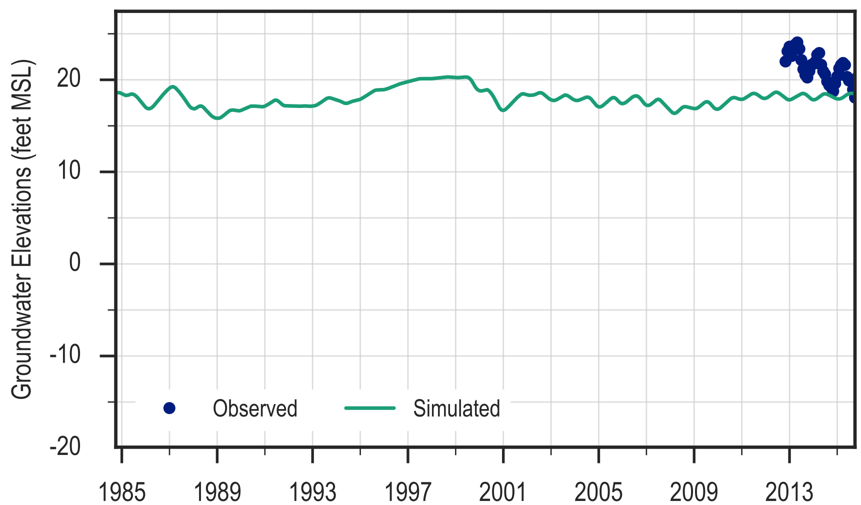
SC-9A/SC-9AR
Purisima A Unit



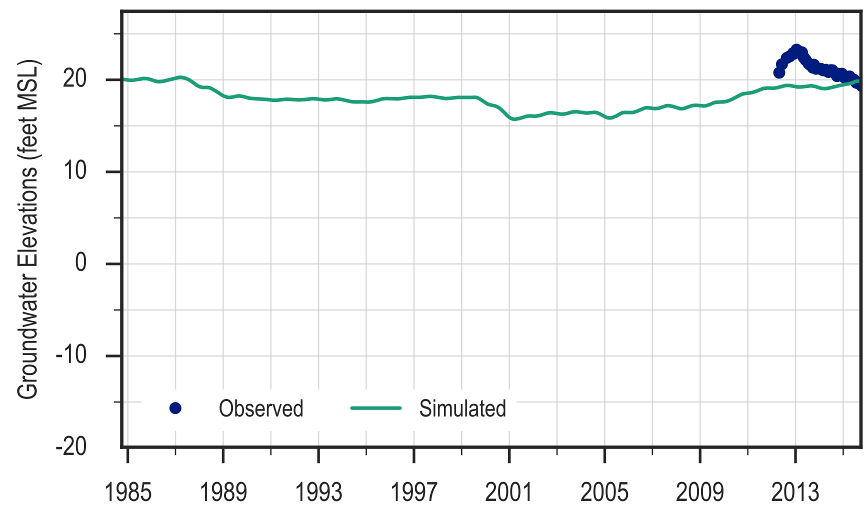
SC-8RA
Purisima A Unit



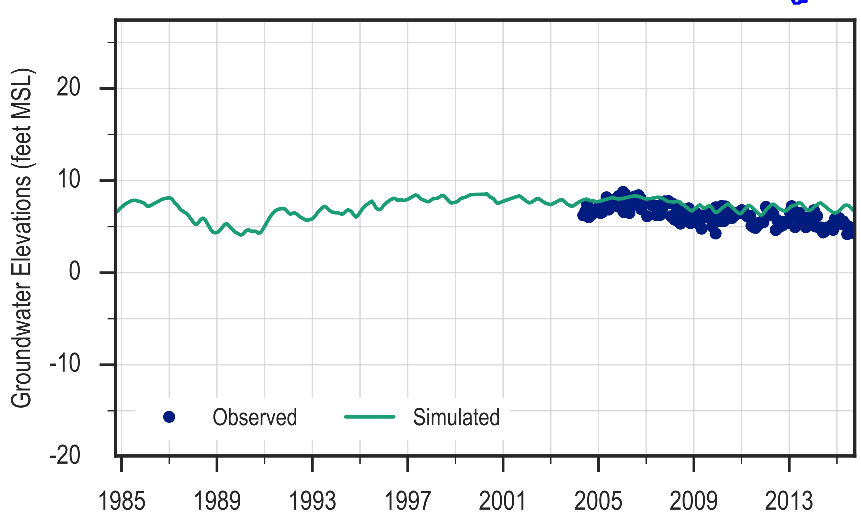
30th Ave Well 2
Purisima AA Unit



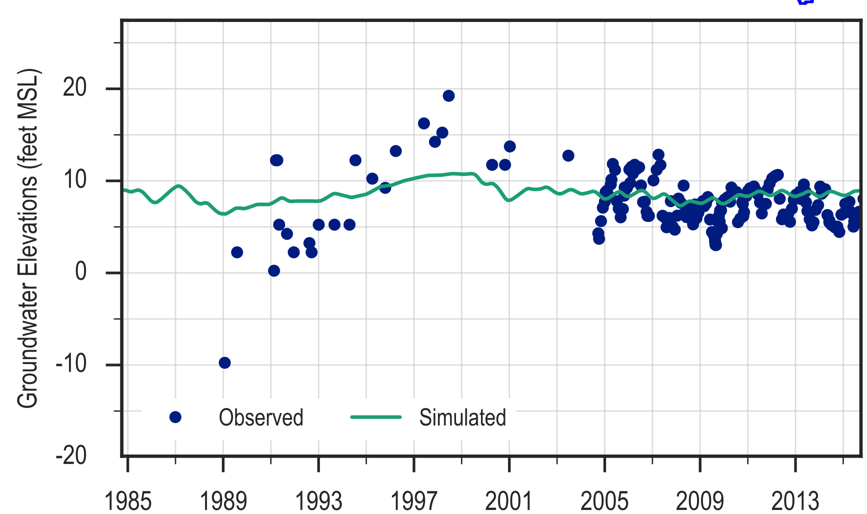
SC-22AA
Purisima AA Unit

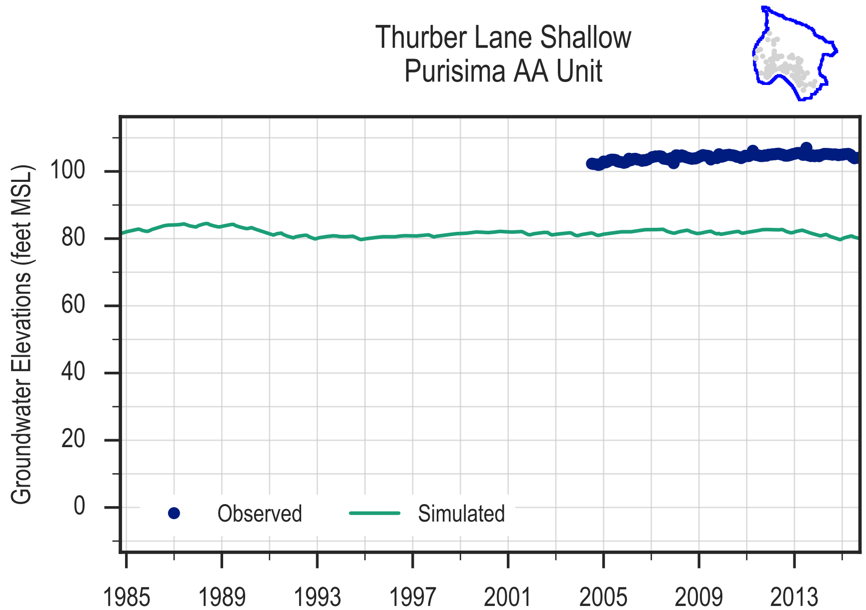


Soquel Point Deep
Purisima AA Unit

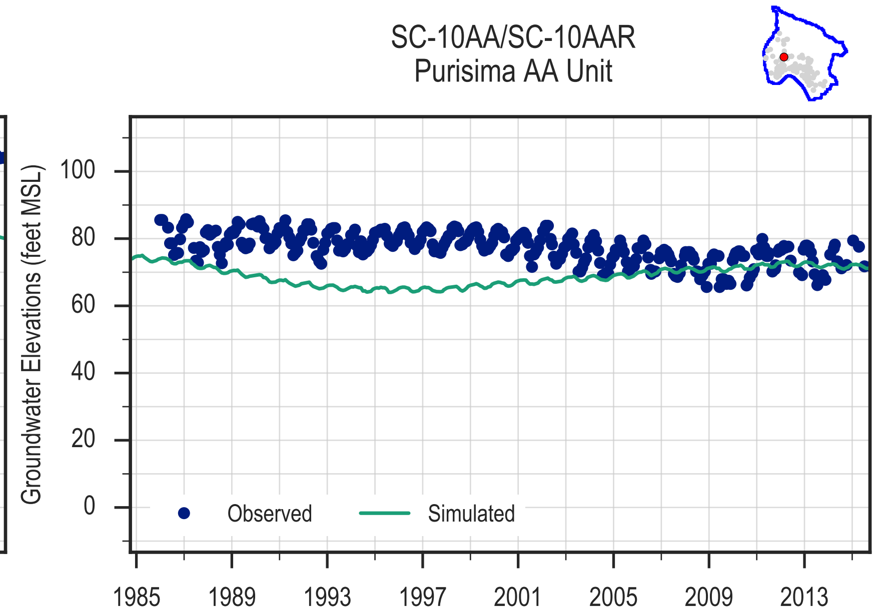


Pleasure Point Deep
Purisima AA Unit

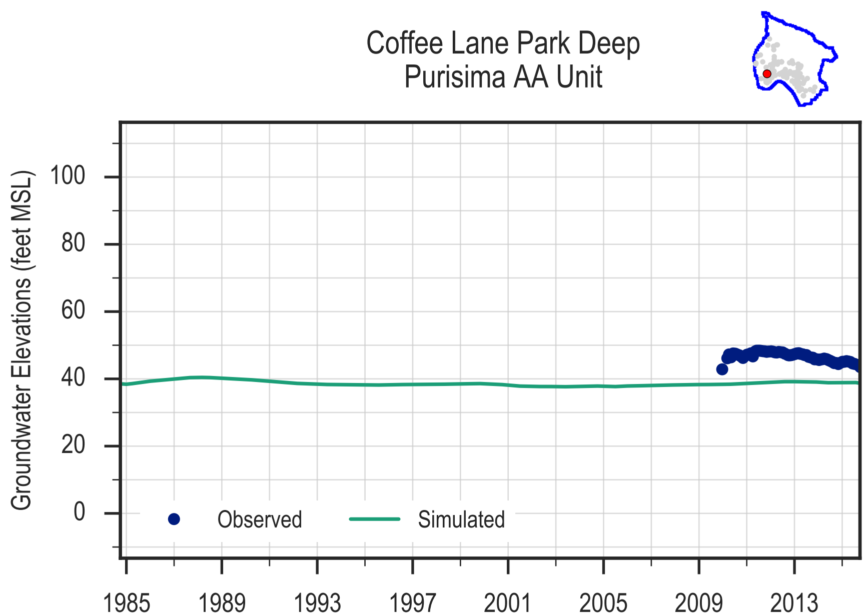




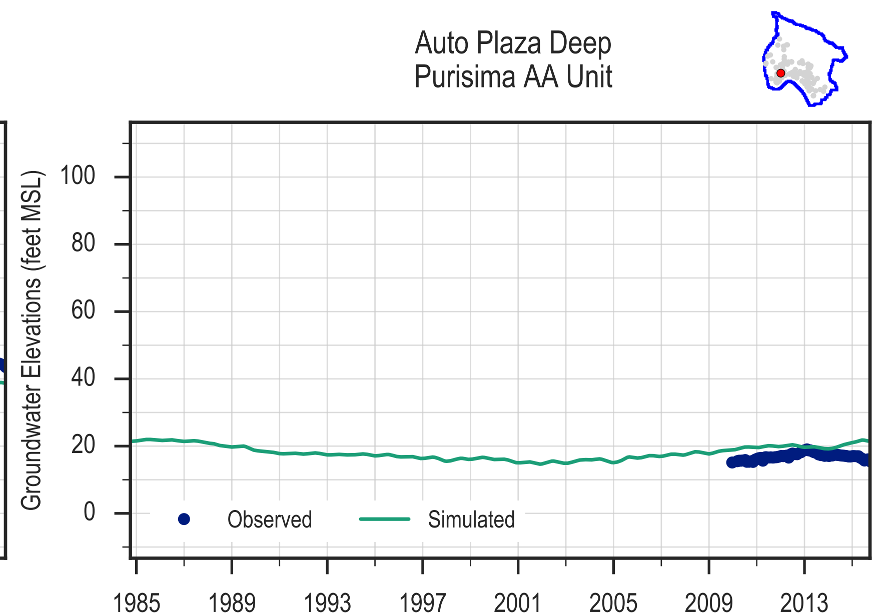
Thurber Lane Shallow
Purisima AA Unit
Groundwater Elevations (feet MSL)
0
20
40
60
80
100
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated



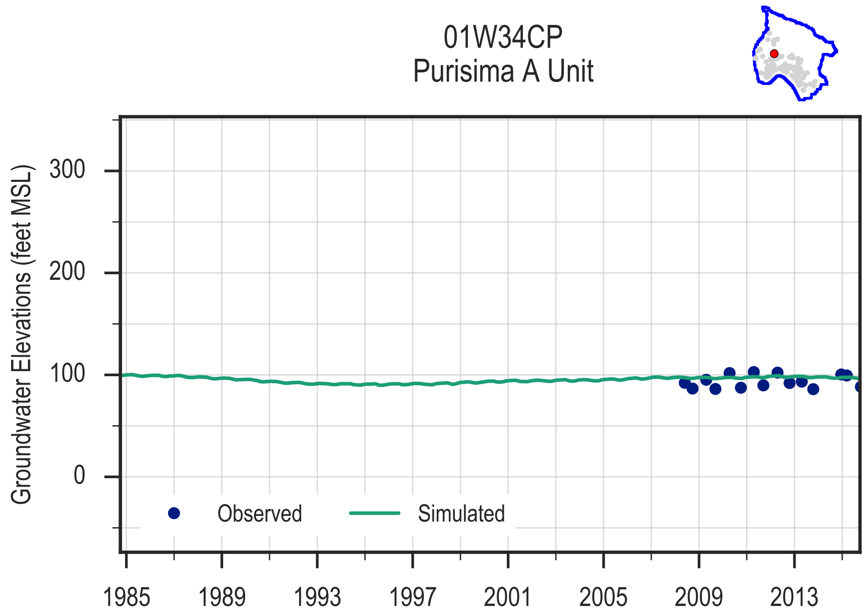
SC-10AA/SC-10AAR
Purisima AA Unit
Groundwater Elevations (feet MSL)
0
20
40
60
80
100
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

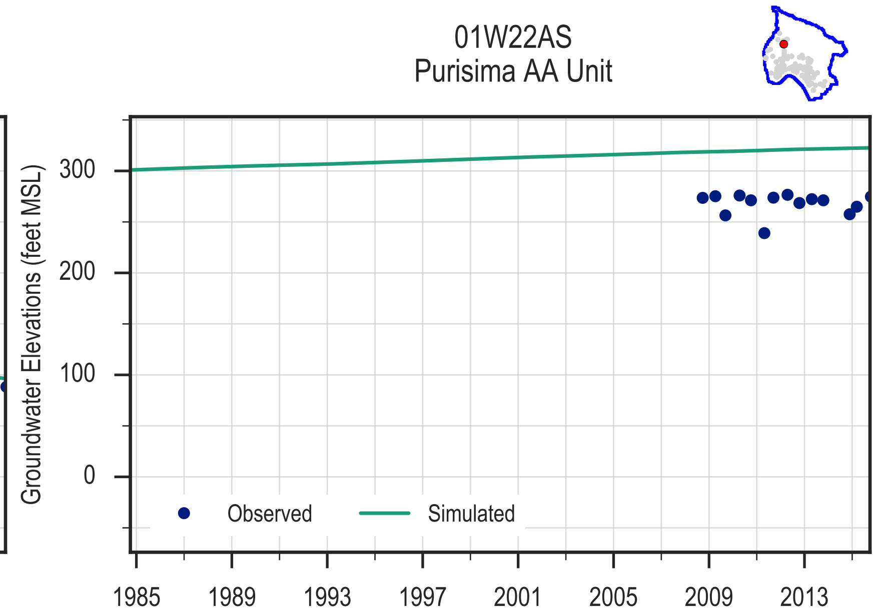


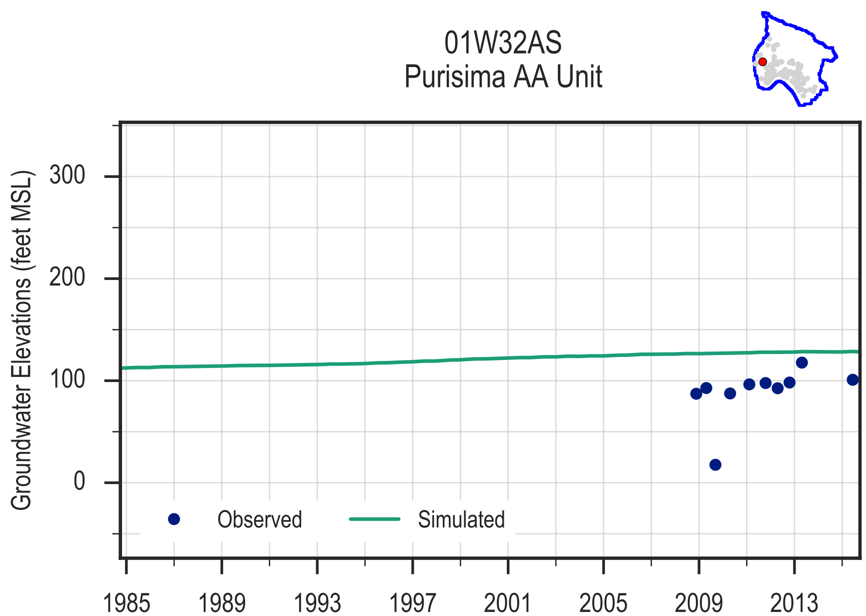
Coffee Lane Park Deep
Purisima AA Unit
Groundwater Elevations (feet MSL)
0
20
40
60
80
100
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

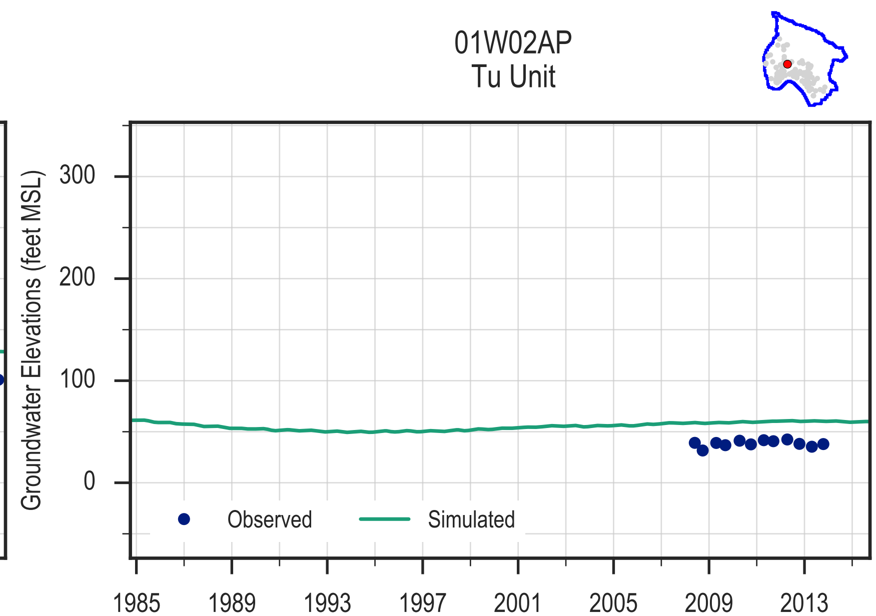


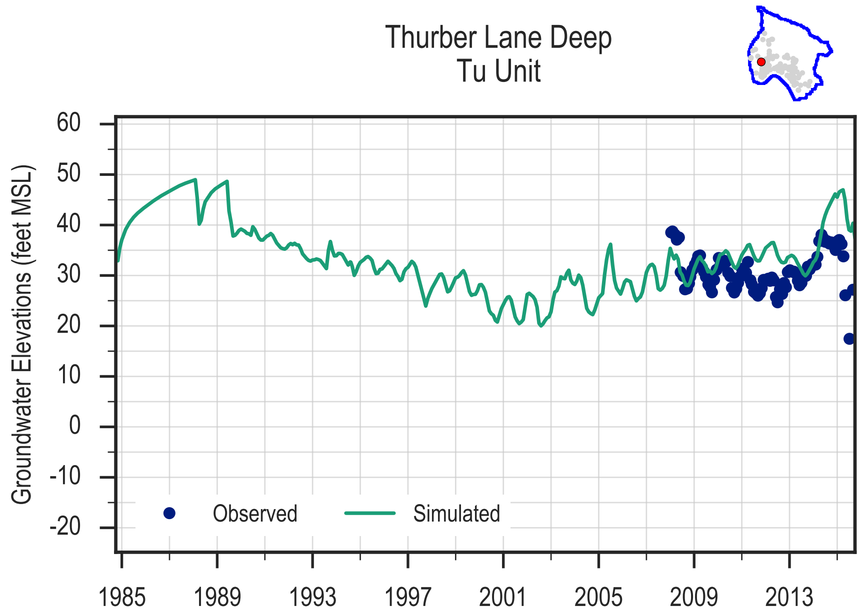
Auto Plaza Deep
Purisima AA Unit
Groundwater Elevations (feet MSL)
0
20
40
60
80
100
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

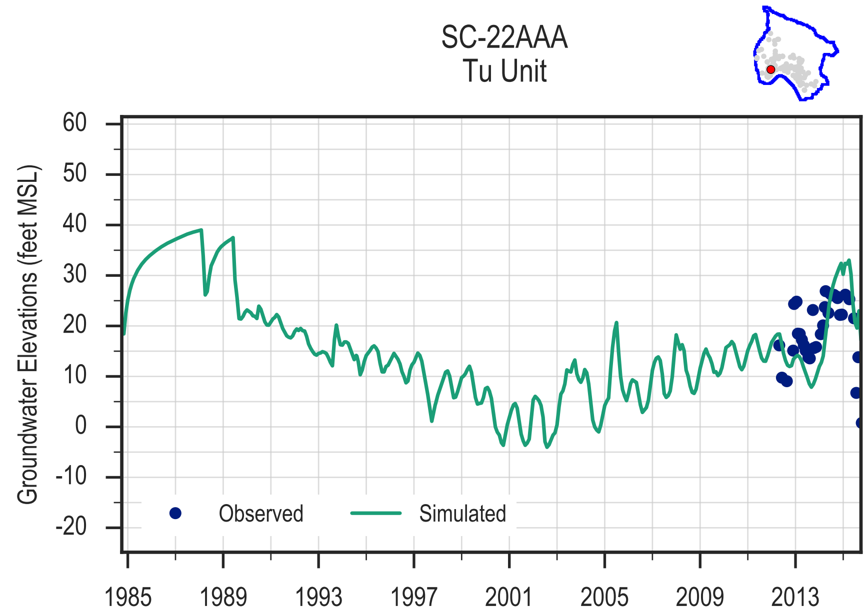

01W34CP
Purisima A Unit
Groundwater Elevations (feet MSL)
300
200
100
0
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

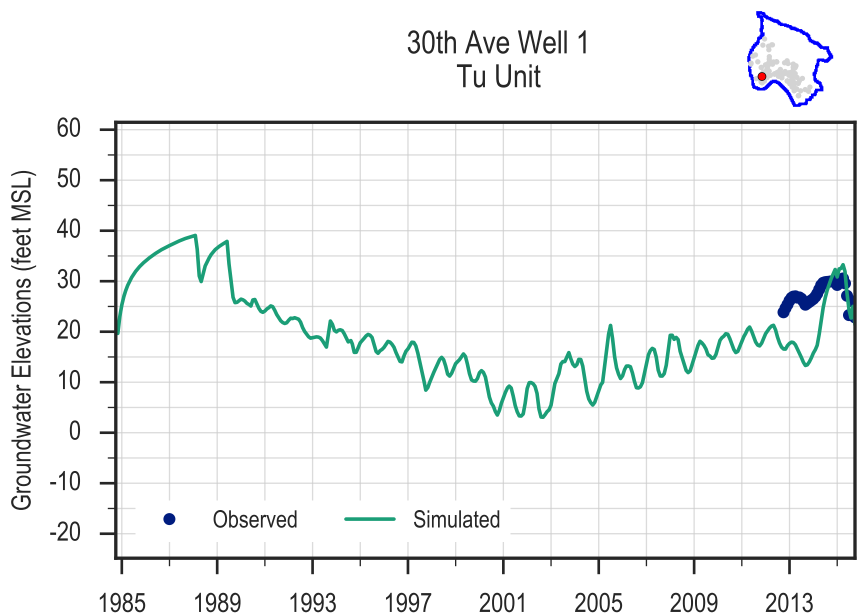

01W22AS
Purisima AA Unit
Groundwater Elevations (feet MSL)
300
200
100
0
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

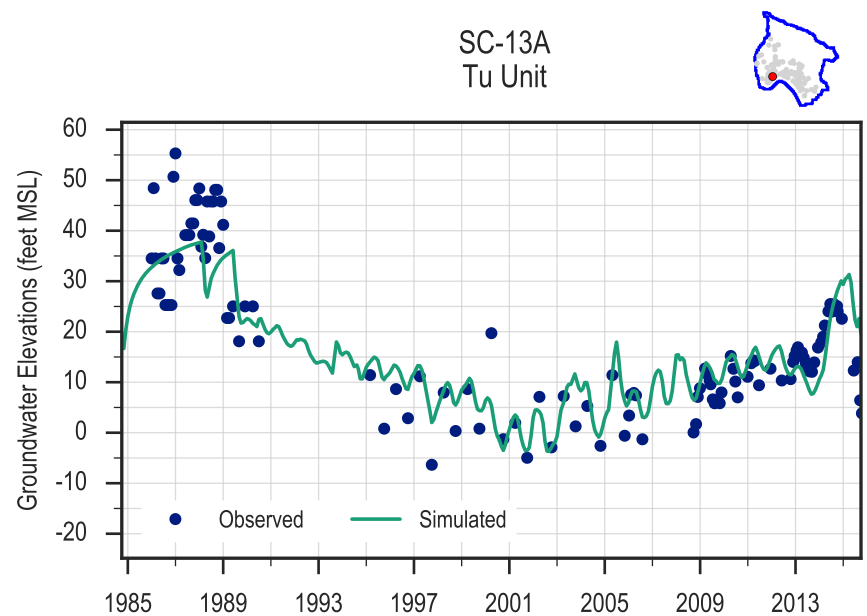

01W32AS
Purisima AA Unit
Groundwater Elevations (feet MSL)
300
200
100
0
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

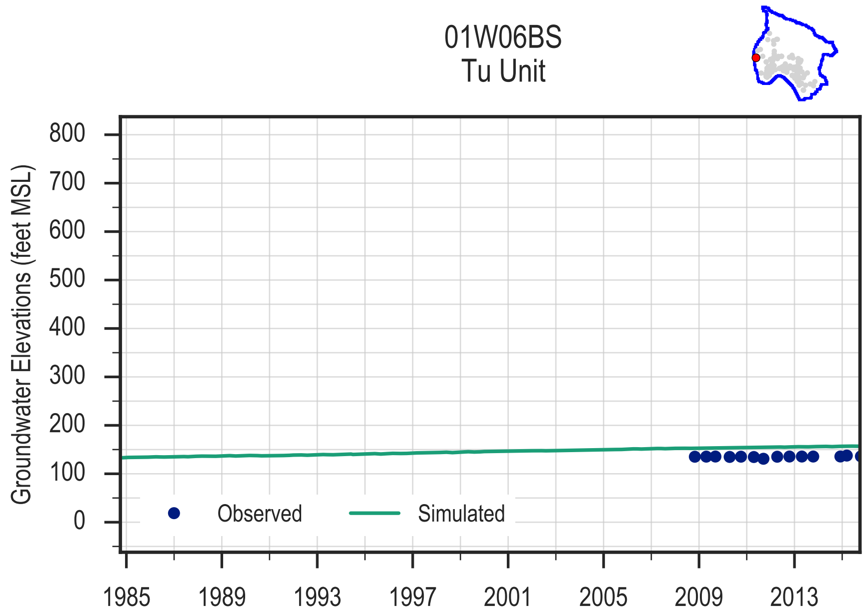

01W02AP
Tu Unit
Groundwater Elevations (feet MSL)
300
200
100
0
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


Thurber Lane Deep
Tu Unit
Groundwater Elevations (feet MSL)
60
50
40
30
20
10
0
-10
-20
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

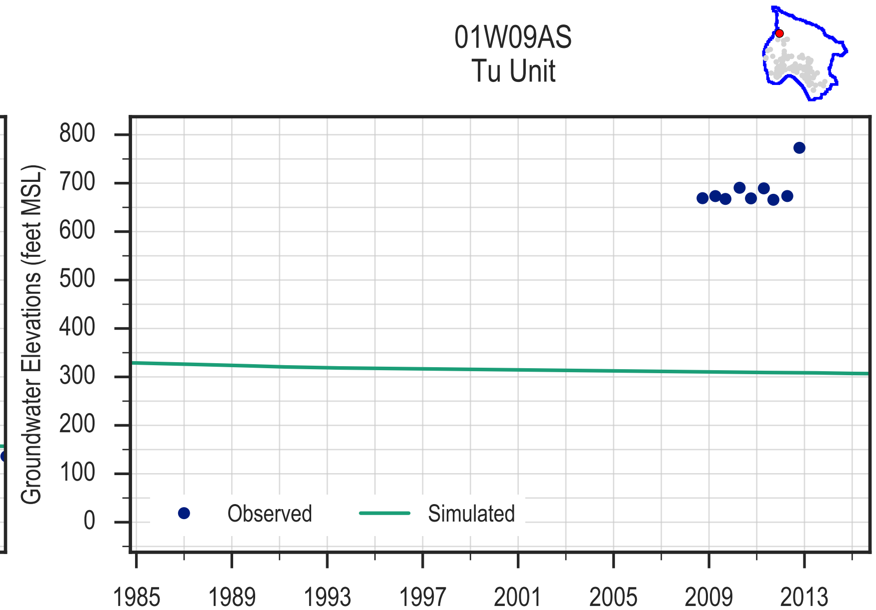

SC-22AAA
Tu Unit
Groundwater Elevations (feet MSL)
60
50
40
30
20
10
0
-10
-20
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


30th Ave Well 1
Tu Unit
Groundwater Elevations (feet MSL)
60
50
40
30
20
10
0
-10
-20
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

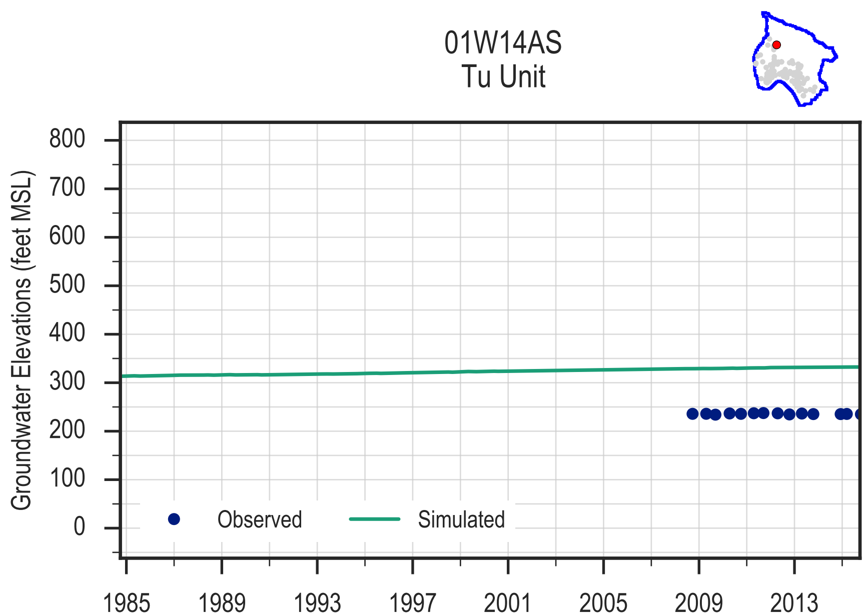

SC-13A
Tu Unit
Groundwater Elevations (feet MSL)
60
50
40
30
20
10
0
-10
-20
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013



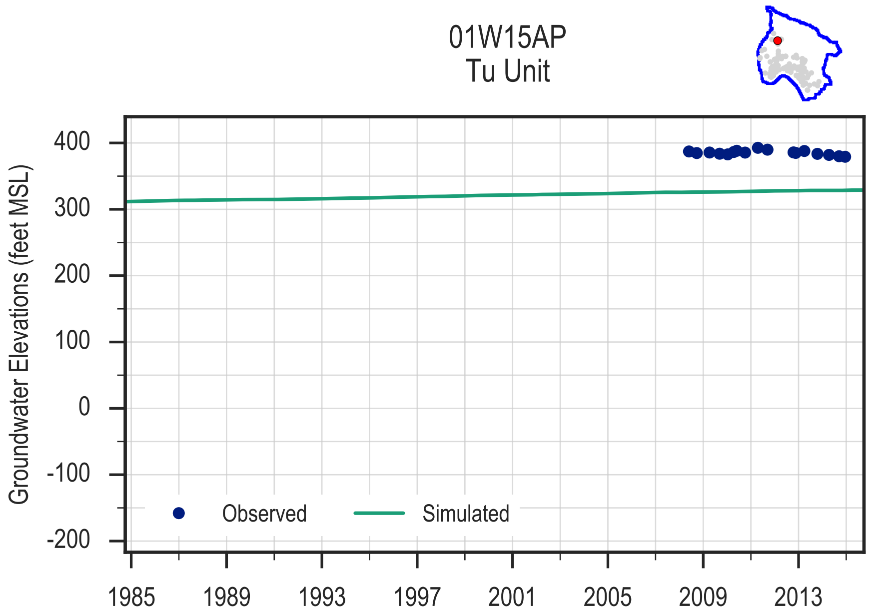
01W06BS
Tu Unit
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
700
800
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated

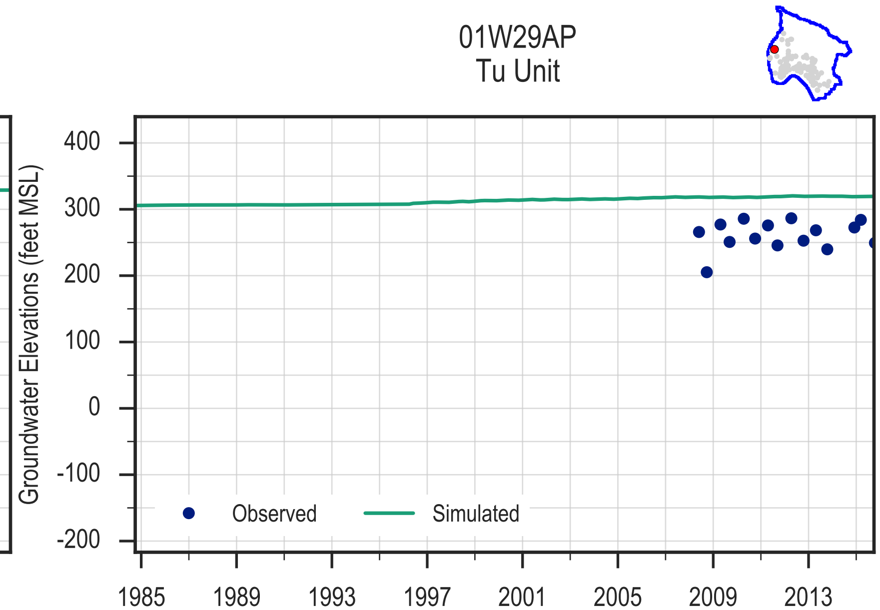


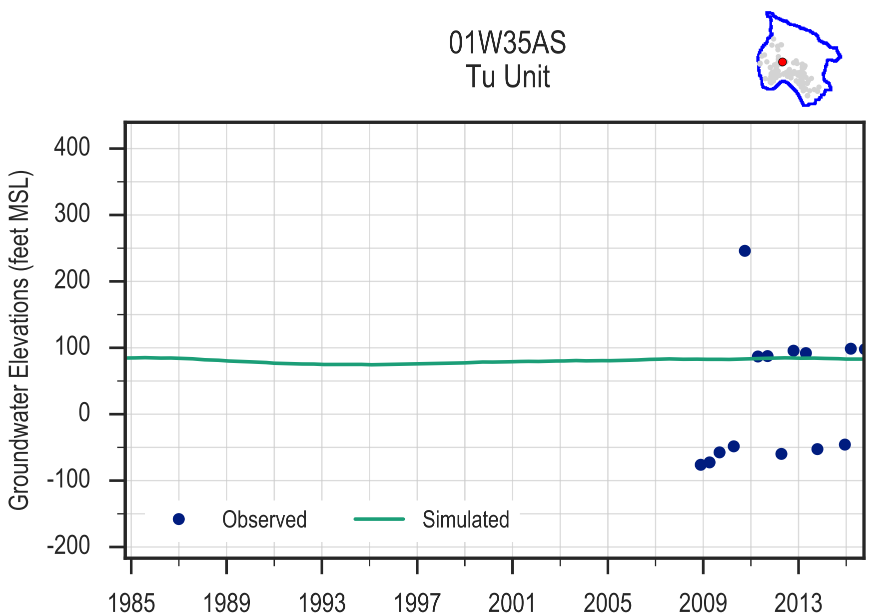
01W09AS
Tu Unit
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
700
800
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated



01W14AS
Tu Unit
Groundwater Elevations (feet MSL)
0
100
200
300
400
500
600
700
800
1985
1989
1993
1997
2001
2005
2009
2013
Observed
Simulated


01W15AP
Tu Unit
Groundwater Elevations (feet MSL)
400
300
200
100
0
-100
-200
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


01W29AP
Tu Unit
Groundwater Elevations (feet MSL)
400
300
200
100
0
-100
-200
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013


01W35AS
Tu Unit
Groundwater Elevations (feet MSL)
400
300
200
100
0
-100
-200
Observed
Simulated
1985
1989
1993
1997
2001
2005
2009
2013

Appendix B

Comparison of Model Parameters to Parameters Estimated by Pumping Tests

		Thickness [ft]				Horizontal Hydraulic Conductivity [ft/day]						Transmissivity [ft^2/day]						Vertical Hydraulic Conductivity [ft/day]					
Well_Name_Data_Type	**Aquifer(s)**	**b_rcl**	**b_min**	**b_max**	**b_am**	**Kx_rcl**	**Kx_min**	**Kx_max**	**Kx_hm**	**Kx_gm**	**Kx_am**	**T_rcl**	**T_min**	**T_max**	**T_hm**	**T_gm**	**T_am**	**Kz_rcl**	**Kz_min**	**Kz_max**	**Kz_hm**	**Kz_gm**	**Kz_am**
Aptos Jr High 2 [aquif. tests]	F		246	246	246		9.0	9.0	9.0	9.0	9.0		2,203	2,203	2,203	2,203	2,203		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Aptos Jr High 2 [L3]	F	879	599	1169	832	0.90	0.06	6.5	0.40	0.7	1.1	787	38	5,179	293	579	896	2.7E-02	3.6E-05	1.1E+00	7.9E-04	2.6E-02	1.6E-01
Beltz 07 [aquif. tests]	A/AA		100	100	100		2.5	2.5	2.5	2.5	2.5		125	125	125	125	125		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Beltz 07 [L7]	A	110	7	239	134	10.4	1.0	10	4.8	5.2	5.5	1,154	34	2,067	322	561	783	2.3E-03	1.0E-04	1.8E-02	2.4E-03	3.7E-03	4.6E-03
Beltz 07 [L8]	AA	403	332	406	383	1.67	0.36	24	1.0	1.7	3.5	676	137	8,665	401	633	1,301	1.2E-03	8.4E-04	2.6E-02	1.8E-03	2.3E-03	3.6E-03
Beltz 08 [aquif. tests]	A		90	100	93		37	108	66	70	74	729	3,650	9,690	6,133	6,449	6,767		3.0E-03	5.4E+00	1.5E-02	4.1E-01	1.6E+00
Beltz 08 [L7]	A	163	13	216	145	4.5	3.2	29	5.5	5.9	6.7	838	66	5,769	480	745	1,082		1.1E-03	2.4E-02	3.2E-03	3.7E-03	4.7E-03
Beltz 09 [aquif. tests]	A	A	90	110	100	26	26	68	42	44	47	4,418	2,370	6,830	4,158	4,418	4,658	1.5E-01	1.5E-01	1.5E-01	1.5E-01	1.5E-01	1.5E-01
Beltz 09 [L7]	A	161	39	266	178	5.2	3.2	12.7	6.0	6.4	6.9	838	199	3,350	790	1,046	1,327	2.6E-03	1.6E-03	3.0E-01	3.5E-03	4.9E-03	1.4E-02
Beltz 12 [aquif. tests]	AA/Tu		0	0	#DIV/0!		0.00	0.00	#N/A	#NUM!	#DIV/0!		2,470	2,470	2,470	2,470	2,470		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Beltz 12 [L8]	AA	382	189	428	346	1.37	0.43	4.11	1.17	1.38	1.63	522	163	1,516	397	474	569	5.8E-02	3.8E-03	1.2E-01	1.8E-02	3.2E-02	4.7E-02
Beltz 12 [L9]	Tu	213	124	318	196	5.21	2.44	8.85	4.61	4.81	5.00	1,111	510	1,339	896	916	934	1.0E-07	1.0E-07	1.0E-07	1.0E-07	1.0E-07	1.0E-07
Bonita [aquif. tests]	F/Aromas		475	475	475		15	15	15	15	15		7,200	7,200	7,200	7,200	7,200		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Bonita [L2]	Aromas	361	224	616	406	16.2	8.5	114	18	26	40	5,842	2,189	66,971	6,251	10,010	17,370	1.03	0.40	1.07	0.94	0.95	0.96
Bonita [L3]	F	880	737	1041	876	3.93	0.63	11	2.6	3.8	5.1	3,458	563	8,743	2,341	3,273	4,267	1.1E-01	1.0E-02	6.8E-01	3.9E-02	9.5E-02	2.2E-01
Cox #3 [aquif. tests]	DEF/F		143	143	143		3.3000	3.400	3.349	3.350	3.350		470	488	479	479	479						
Cox #3 [L3]	DEF/F	1232	789	1675	1237	0.0525	0.0033	0.071	0.016	0.021	0.027	65	4	85	19	26	35	5.3E-04	7.6E-05	5.7E-03	1.8E-04	2.9E-04	6.5E-04
Estates [aquif. tests]	A/BC		415	615	515		3.90	5.70	4.63	4.71	4.80		2,380	2,400	2,390	2,390	2,390		4.0E-02	4.0E-02	4.0E-02	4.0E-02	4.0E-02
Estates [L5]	BC	190	190	190	190	10.68	0.21	12.54	1.07	1.78	3.26	2,030	40	2,382	203	338	620	3.7E-03	9.6E-04	1.2E-02	2.2E-03	2.5E-03	2.9E-03
Estates [L7]	A	307	266	307	299	4.66	0.55	10.00	1.90	2.76	3.89	1,428	163	3,061	570	825	1,164	7.0E-05	1.4E-05	3.3E-03	7.4E-05	2.6E-04	7.3E-04
Garnet [aquif. tests]	A		200	200	200		17.00	19.00	17.62	17.64	17.67		3,350	4,480	3,673	3,705	3,740		4.0E-01	5.0E-01	4.4E-01	4.5E-01	4.5E-01
Garnet [L7]	A	199	93	255	192	5.07	1.83	47.98	4.90	5.99	8.41	1,007	412	9,975	894	1,123	1,674	1.8E-03	6.0E-05	1.1E-01	5.4E-04	2.7E-03	1.2E-02
Granite Way [aquif. tests]	DEF												238	238	238	238	238						
Granite Way [L3]	DEF	593	335	1067	597	0.301	0.048	0.78	0.15	0.20	0.26	178	24	548	88	112	142	1.6E-04	1.1E-05	4.4E-02	8.7E-05	4.5E-04	4.6E-03
Ledyard [aquif. tests]	BC		215	215	215		1.80	1.80	1.80	1.80	1.80		300	300	300	300	300		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Ledyard [L5]	BC	190	190	190	190	17.10	0.34	17.10	1.34	2.08	3.61	3,248	64	3,248	255	394	685	2.0E-03	1.1E-03	3.7E-03	1.9E-03	2.0E-03	2.0E-03
Madeline [aquif. tests]	BC		160	230	195		1.40	1.50	1.45	1.45	1.45		240	300	267	268	270		2.0E-02	2.0E-02	2.0E-02	2.0E-02	2.0E-02
Madeline [L5]	BC	190	190	190	190	5.48	0.11	17.10	0.74	1.69	3.61	1,040	21	3,248	140	321	686	1.7E-03	9.6E-04	1.2E-02	2.1E-03	2.3E-03	2.8E-03
Main St [aquif. tests]	AA/Tu		172	600	399		3.28	14.90	8.70	9.24	9.67		563	4,600	3,040	3,530	3,728		2.0E-03	8.0E-01	1.0E-02	3.2E-02	1.3E-01
Main St [L8]	AA	369	335	404	358	2.33	1.07	4.11	1.79	1.90	2.02	858	378	1,516	636	678	729	2.3E-02	3.1E-03	8.9E-02	1.5E-02	2.2E-02	3.2E-02
Main St [L9]	Tu	110	59	184	116	7.78	0.09	8.85	0.64	1.91	3.71	853	11	1,129	69	215	455	1.0E-07	1.0E-07	1.0E-07	1.0E-07	1.0E-07	1.0E-07
Rosedale [aquif. tests]	A		350	350	350		14.00	14.00	14.00	14.00	14.00		4,800	4,800	4,800	4,800	4,800		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Rosedale [L7]	A	255	72	281	223	6.04	1.91	7.64	4.33	4.59	4.84	1,541	194	1,932	845	989	1,102	2.1E-03	1.6E-05	1.1E-01	2.2E-04	3.0E-03	1.8E-02
Rosedale [L8]	AA	345	324	411	360	2.10	1.22	4.11	1.74	1.83	1.94	724	411	1,516	624	658	702	7.9E-03	6.8E-04	8.9E-02	3.5E-03	7.1E-03	1.5E-02
San Andreas [aquif. tests]	F/Aromas		350	450	400		13.00	14.00	13.48	13.49	13.50		4,700	6,300	5,384	5,442	5,500		2.4E+00	2.4E+00	2.4E+00	2.4E+00	2.4E+00
San Andreas [L2]	Aromas	346	215	651	432	9.34	8.47	100.18	13.43	16.64	23.33	3,234	2,061	56,958	5,143	6,978	11,128	1.0	0.8	1.1	1.0	1.0	1.0
San Andreas [L3]	F	886	738	1050	882	6.07	0.99	11.14	3.67	4.70	5.81	5,383	889	8,743	3,369	4,129	4,887	2.0E-01	8.0E-03	6.2E-01	3.3E-02	7.6E-02	1.8E-01
Seascape [aquif. tests]	F/Aromas		420	420	420		29.00	29.00	29.00	29.00	29.00		12,000	12,000	12,000	12,000	12,000		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Seascape [L2]	Aromas	464	198	599	404	10.00	8.47	18.12	9.90	9.97	10.06	4,644	1,982	10,136	3,778	3,928	4,097	1.0	0.5	1.0	0.9	0.9	0.9
Seascape [L3]	F	808	666	964	808	8.90	1.17	11.14	4.86	5.79	6.55	7,186	869	8,743	3,853	4,656	5,266	4.0E-02	7.4E-03	5.6E-01	1.9E-02	3.5E-02	1.0E-01
Sells [aquif. tests]	F/Aromas		330	330	330		210.00	210.00	210.00	210.00	210.00		66,800	73,500	69,990	70,070	70,150		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Sells [L2]	Aromas	478	342	735	503	9.80	9.07	29.95	10.65	10.93	11.34	4,684	3,422	17,716	5,075	5,405	5,928	0.6	0.3	1.1	0.7	0.7	0.8
Sells [L3]	F	769	634	955	777	1.58	0.88	8.24	1.57	1.89	2.40	1,218	557	7,142	1,153	1,457	1,954	9.4E-03	7.5E-03	1.8E-02	9.6E-03	9.7E-03	9.8E-03
Tannery II [aquif. tests]	A		235	235	235		8.80	10.00	9.36	9.38	9.40		2,020	2,060	2,040	2,040	2,040		7.0E-01	7.0E-01	7.0E-01	7.0E-01	7.0E-01
Tannery II [L7]	A	265	231	305	264	5.05	0.55	7.64	2.82	3.61	4.22	1,337	163	1,932	776	950	1,086	2.5E-04	1.2E-05	1.2E-02	7.5E-05	5.5E-04	2.1E-03

Notes:
"Well-Name [aquif. Tests]" denotes parameter summary stats for pumping well based on pumping test results
"Well-Name [LX]" denotes averaged model paramters around each well based on averaging grid cells in Layer X that are within 3200 feet radial distance (4 grid cells) of the grid cell containing the well.
rcl = value at the well grid cell (at row=r, col=c, layer=l)
min = minimum value
max = maximum value
hm = harmonic mean
gm - geometric mean
am = arithmetic mean

		Specifc Storage [1/ft]						Storativity [ft/ft]						Hydraulic Diffusivity (K/Ss) [ft^2/day]					
Well_Name_Data_Type	Aquifer(s)	Ss_rcl	Ss_min	Ss_max	Ss_hm	Ss_gm	Ss_am	S_rcl	S_min	S_max	S_hm	S_gm	S_am	D_rcl	D_min	D_max	D_hm	D_gm	D_am
Aptos Jr High 2 [aquif. tests]	F		1.7E-06	1.7E-06	1.7E-06	1.7E-06	1.7E-06		4.3E-04	4.3E-04	4.3E-04	4.3E-04	4.3E-04		5.1E+06	5.1E+06	5.1E+06	5.1E+06	5.1E+06
Aptos Jr High 2 [L3]	F	9.5E-05	9.0E-05	9.9E-04	1.3E-04	1.3E-04	1.6E-04	8.31E-02	6.9E-02	6.1E-01	9.8E-02	1.1E-01	1.3E-01	9.5E+03	6.3E+01	6.5E+04	1.1E+03	5.4E+03	1.1E+04
Beltz 07 [aquif. tests]	A/AA		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Beltz 07 [L7]	A	9.2E-04	9.2E-06	9.2E-04	2.4E-04	2.4E-04	3.6E-04	1.01E-01	5.0E-04	1.2E-01	1.1E-02	2.6E-02	4.0E-02	1.1E+04	3.7E+03	5.7E+05	1.4E+04	2.2E+04	4.5E+04
Beltz 07 [L8]	AA	8.6E-05	6.7E-05	1.1E-04	8.8E-05	8.8E-05	8.9E-05	3.48E-02	2.4E-02	4.3E-02	3.3E-02	3.4E-02	3.4E-02	1.9E+04	5.3E+03	2.5E+05	1.2E+04	1.9E+04	3.7E+04
Beltz 08 [aquif. tests]	A		1.8E-06	4.9E-05	3.7E-06	6.2E-06	1.3E-05		1.6E-04	4.4E-03	3.5E-04	5.8E-04	1.2E-03		1.5E+06	5.6E+07	5.6E+06	1.1E+07	1.9E+07
Beltz 08 [L7]	A	2.7E-04	7.8E-07	9.2E-04	8.6E-05	8.6E-05	2.7E-04	4.43E-02	1.5E-04	1.2E-01	1.8E-03	1.1E-02	3.0E-02	1.6E+04	3.7E+03	8.2E+06	1.8E+04	6.9E+04	8.3E+05
Beltz 09 [aquif. tests]	A	1.3E-04	1.3E-04	1.3E-04	1.3E-04	1.3E-04	1.3E-04	1.40E-02	1.4E-02	1.4E-02	1.4E-02	1.4E-02	1.4E-02	0.0E+00	3.1E+05	3.1E+05	3.1E+05	3.1E+05	3.1E+05
Beltz 09 [L7]	A	5.4E-04	4.3E-05	9.2E-04	2.8E-04	2.8E-04	3.7E-04	8.76E-02	8.7E-03	2.0E-01	3.6E-02	4.6E-02	5.8E-02	9.6E+03	3.7E+03	2.0E+05	1.6E+04	2.3E+04	3.5E+04
Beltz 12 [aquif. tests]	AA/Tu		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03		2.5E+06	2.5E+06	2.5E+06	2.5E+06	2.5E+06
Beltz 12 [L8]	AA	1.0E-04	7.4E-05	1.0E-04	9.3E-05	9.3E-05	9.3E-05	3.90E-02	1.9E-02	3.9E-02	3.1E-02	3.2E-02	3.2E-02	1.3E+04	5.8E+03	4.4E+04	1.3E+04	1.5E+04	1.7E+04
Beltz 12 [L9]	Tu	4.2E-06	2.7E-06	8.0E-06	4.4E-06	4.4E-06	4.6E-06	8.92E-04	6.5E-04	1.2E-03	8.4E-04	8.4E-04	8.5E-04	1.2E+06	5.8E+05	1.6E+06	1.1E+06	1.1E+06	1.1E+06
Bonita [aquif. tests]	F/Aromas		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Bonita [L2]	Aromas	1.0E-05	9.6E-06	1.2E-05	1.0E-05	1.0E-05	1.0E-05	3.61E-03	2.2E-03	7.5E-03	3.8E-03	3.9E-03	4.1E-03	1.6E+06	8.5E+05	1.2E+07	1.8E+06	2.6E+06	4.0E+06
Bonita [L3]	F	1.0E-04	9.8E-05	1.0E-04	1.0E-04	1.0E-04	1.0E-04	8.80E-02	7.4E-02	1.0E-01	8.7E-02	8.7E-02	8.8E-02	3.9E+04	6.3E+03	1.1E+05	2.6E+04	3.8E+04	5.1E+04
Cox #3 [aquif. tests]	DEF/F		7.0E-07	1.7E-06	1.0E-06	1.1E-06	1.2E-06		1.0E-04	2.5E-04	1.4E-04	1.6E-04	1.8E-04		2.0E+06	4.7E+06	2.8E+06	3.0E+06	3.3E+06
Cox #3 [L3]	DEF/F	1.6E-04	1.5E-04	1.1E-03	3.9E-04	3.9E-04	5.0E-04	1.93E-01	1.9E-01	1.5E+00	4.0E-01	4.8E-01	5.8E-01	3.3E+02	3.5E+00	4.5E+02	2.3E+01	5.4E+01	1.2E+02
Estates [aquif. tests]	A/BC		4.8E-07	4.8E-07	4.8E-07	4.8E-07	4.8E-07		2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04		1.2E+07	1.2E+07	1.2E+07	1.2E+07	1.2E+07
Estates [L5]	BC	5.7E-07	2.0E-07	5.0E-06	7.9E-07	7.9E-07	1.2E-06	1.08E-04	3.8E-05	9.5E-04	1.1E-04	1.5E-04	2.2E-04	1.9E+07	1.0E+05	4.5E+07	9.0E+05	2.3E+06	5.0E+06
Estates [L7]	A	3.4E-07	6.1E-08	3.4E-05	7.7E-07	7.7E-07	3.1E-06	1.03E-04	1.8E-05	1.0E-02	1.0E-04	2.3E-04	9.3E-04	1.4E+07	2.0E+04	1.5E+08	3.6E+05	3.6E+06	1.4E+07
Garnet [aquif. tests]	A		1.0E-06	8.0E-06	1.8E-06	2.8E-06	4.5E-06		2.0E-04	1.6E-03	3.6E-04	5.7E-04	9.0E-04		2.1E+06	1.7E+07	3.8E+06	6.0E+06	9.4E+06
Garnet [L7]	A	7.8E-07	2.0E-07	2.7E-04	3.3E-06	3.3E-06	2.1E-05	1.55E-04	4.6E-05	4.4E-02	2.0E-04	6.2E-04	3.3E-03	6.5E+06	1.6E+04	6.0E+07	2.3E+05	1.8E+06	7.5E+06
Granite Way [aquif. tests]	DEF																		
Granite Way [L3]	DEF	1.8E-04	1.2E-04	9.9E-04	3.3E-04	3.3E-04	3.9E-04	1.04E-01	8.1E-02	6.1E-01	1.7E-01	1.9E-01	2.2E-01	1.7E+03	6.3E+01	6.4E+03	3.6E+02	6.0E+02	9.4E+02
Ledyard [aquif. tests]	BC		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Ledyard [L5]	BC	2.0E-06	2.0E-07	6.4E-06	8.8E-07	8.8E-07	1.1E-06	3.86E-04	3.8E-05	1.2E-03	1.4E-04	1.7E-04	2.1E-04	8.4E+06	1.4E+05	4.5E+07	1.3E+06	2.4E+06	4.7E+06
Madeline [aquif. tests]	BC		2.8E-05	2.8E-05	2.8E-05	2.8E-05	2.8E-05		4.5E-03	4.5E-03	4.5E-03	4.5E-03	4.5E-03		5.3E+04	5.3E+04	5.3E+04	5.3E+04	5.3E+04
Madeline [L5]	BC	6.5E-07	2.0E-07	5.0E-06	8.8E-07	8.8E-07	1.2E-06	1.23E-04	3.8E-05	9.5E-04	1.2E-04	1.7E-04	2.3E-04	8.4E+06	1.0E+05	4.5E+07	7.0E+05	1.9E+06	5.1E+06
Main St [aquif. tests]	AA/Tu		1.1E-07	1.3E-03	7.6E-07	4.6E-06	8.2E-05		3.9E-05	2.3E-01	2.4E-04	1.4E-03	1.5E-02		2.4E+03	1.1E+08	4.5E+04	2.4E+06	1.7E+07
Main St [L8]	AA	9.5E-05	3.1E-05	1.0E-04	8.1E-05	8.1E-05	8.5E-05	3.51E-02	1.1E-02	4.1E-02	2.7E-02	2.9E-02	3.0E-02	2.4E+04	1.4E+04	4.4E+04	2.2E+04	2.3E+04	2.4E+04
Main St [L9]	Tu	8.0E-06	4.4E-06	2.1E-05	8.9E-06	8.9E-06	9.9E-06	8.75E-04	5.8E-04	1.9E-03	9.7E-04	1.0E-03	1.0E-03	9.7E+05	7.0E+03	1.2E+06	5.4E+04	2.1E+05	5.1E+05
Rosedale [aquif. tests]	A		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!		0.0E+00	0.0E+00	#N/A	#NUM!	#DIV/0!
Rosedale [L7]	A	4.1E-06	4.3E-07	1.0E-04	6.2E-06	6.2E-06	2.0E-05	1.05E-03	1.0E-04	1.5E-02	5.0E-04	1.3E-03	3.3E-03	1.5E+06	2.3E+04	1.0E+07	1.7E+05	7.4E+05	2.7E+06
Rosedale [L8]	AA	9.9E-05	6.6E-05	1.1E-04	9.4E-05	9.4E-05	9.4E-05	3.41E-02	2.3E-02	4.1E-02	3.4E-02	3.4E-02	3.4E-02	2.1E+04	1.1E+04	4.4E+04	1.8E+04	1.9E+04	2.1E+04
San Andreas [aquif. tests]	F/Aromas		2.9E-06	2.9E-06	2.9E-06	2.9E-06	2.9E-06		1.0E-03	1.0E-03	1.0E-03	1.0E-03	1.0E-03		4.7E+06	4.7E+06	4.7E+06	4.7E+06	4.7E+06
San Andreas [L2]	Aromas	1.0E-05	9.6E-06	1.1E-05	1.0E-05	1.0E-05	1.0E-05	3.46E-03	2.2E-03	7.3E-03	4.1E-03	4.2E-03	4.3E-03	9.3E+05	8.5E+05	9.7E+06	1.3E+06	1.7E+06	2.3E+06
San Andreas [L3]	F	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	8.86E-02	7.4E-02	1.0E-01	8.7E-02	8.8E-02	8.8E-02	6.1E+04	9.9E+03	1.1E+05	3.7E+04	4.7E+04	5.8E+04
Seascape [aquif. tests]	F/Aromas		4.8E-07	4.8E-07	4.8E-07	4.8E-07	4.8E-07		2.0E-04	2.0E-04	2.0E-04	2.0E-04	2.0E-04		6.0E+07	6.0E+07	6.0E+07	6.0E+07	6.0E+07
Seascape [L2]	Aromas	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	4.64E-03	2.0E-03	6.0E-03	3.8E-03	3.9E-03	4.0E-03	1.0E+06	8.5E+05	1.8E+06	9.9E+05	1.0E+06	1.0E+06
Seascape [L3]	F	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	8.08E-02	6.7E-02	9.6E-02	8.0E-02	8.0E-02	8.1E-02	8.9E+04	1.2E+04	1.1E+05	4.9E+04	5.8E+04	6.5E+04
Sells [aquif. tests]	F/Aromas		2.4E-06	2.4E-06	2.4E-06	2.4E-06	2.4E-06		8.0E-04	8.0E-04	8.0E-04	8.0E-04	8.0E-04		8.4E+07	9.2E+07	8.7E+07	8.8E+07	8.8E+07
Sells [L2]	Aromas	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	4.78E-03	3.4E-03	7.4E-03	4.9E-03	4.9E-03	5.0E-03	9.8E+05	9.1E+05	3.0E+06	1.1E+06	1.1E+06	1.1E+06
Sells [L3]	F	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	1.0E-04	7.69E-02	6.3E-02	9.5E-02	7.7E-02	7.7E-02	7.8E-02	1.6E+04	8.8E+03	8.2E+04	1.6E+04	1.9E+04	2.4E+04
Tannery II [aquif. tests]	A		2.3E-06	2.3E-06	2.3E-06	2.3E-06	2.3E-06		5.5E-04	5.5E-04	5.5E-04	5.5E-04	5.5E-04		3.7E+06	3.7E+06	3.7E+06	3.7E+06	3.7E+06
Tannery II [L7]	A	1.7E-06	1.6E-07	3.2E-05	1.9E-06	1.9E-06	4.8E-06	4.43E-04	4.8E-05	8.0E-03	2.5E-04	5.1E-04	1.3E-03	3.0E+06	1.2E+05	1.1E+07	7.0E+05	1.9E+06	4.1E+06

Notes:

"Well-Name [aquif. Tests]" denotes parameter summary stats for pumping well based on pumping test results

"Well-Name [LX]" denotes averaged model paramters around each well based on averaging grid cells in Layer X that are within 3200 feet radial distance (4 grid cells) of the grid cell containing the well.

rcl = value at the well grid cell (at row=r, col=c, layer=l)

min = minimum value

max = maximum value

hm = harmonic mean

gm - geometric mean

am = arithmetic mean

Appendix D

Water Budgets by Model Layer

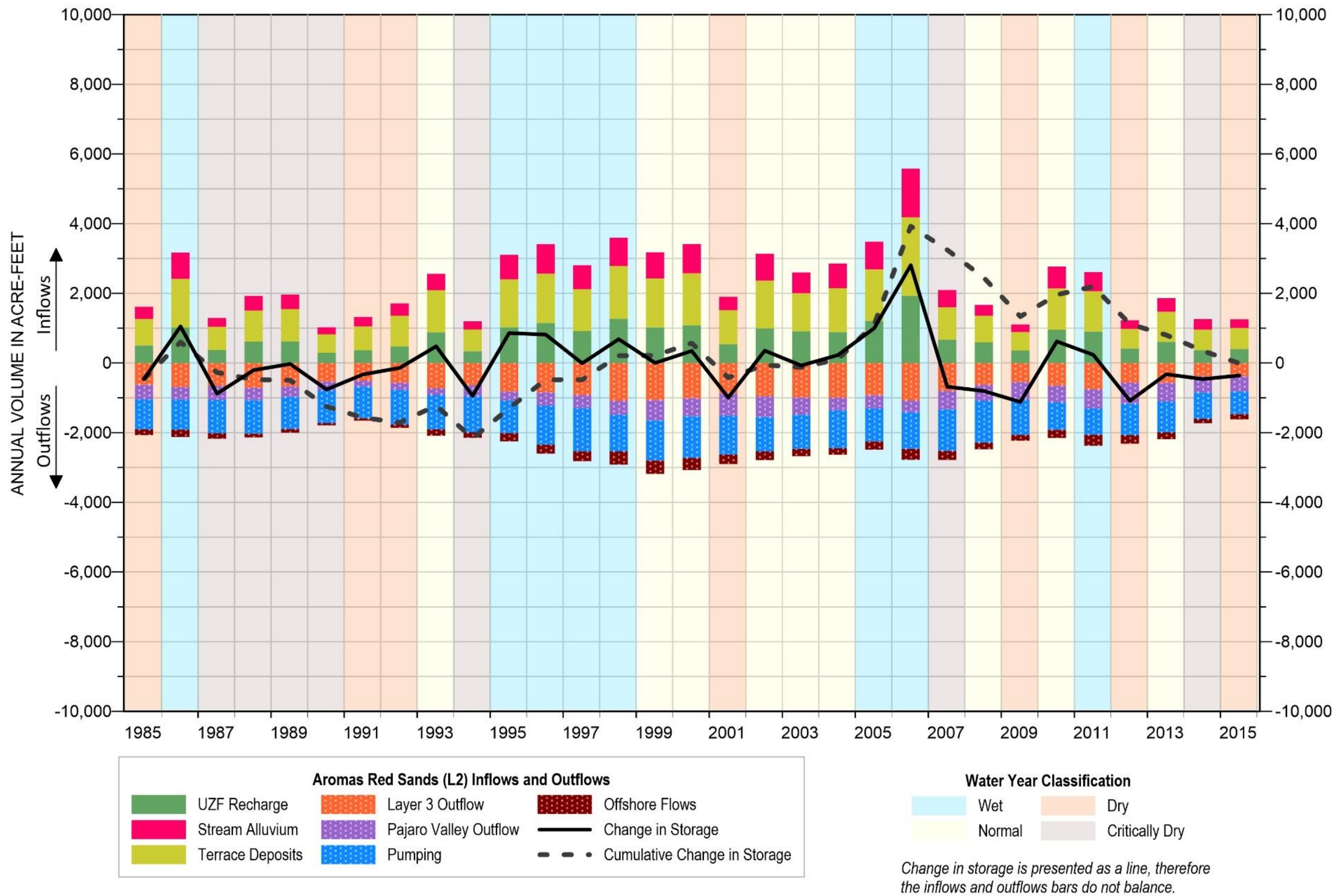


Figure C-1: Detailed Annual Water Budget for Layer 2 (Aromas Red Sands) in Mid-County Basin

MONTGOMERY & ASSOCIATES

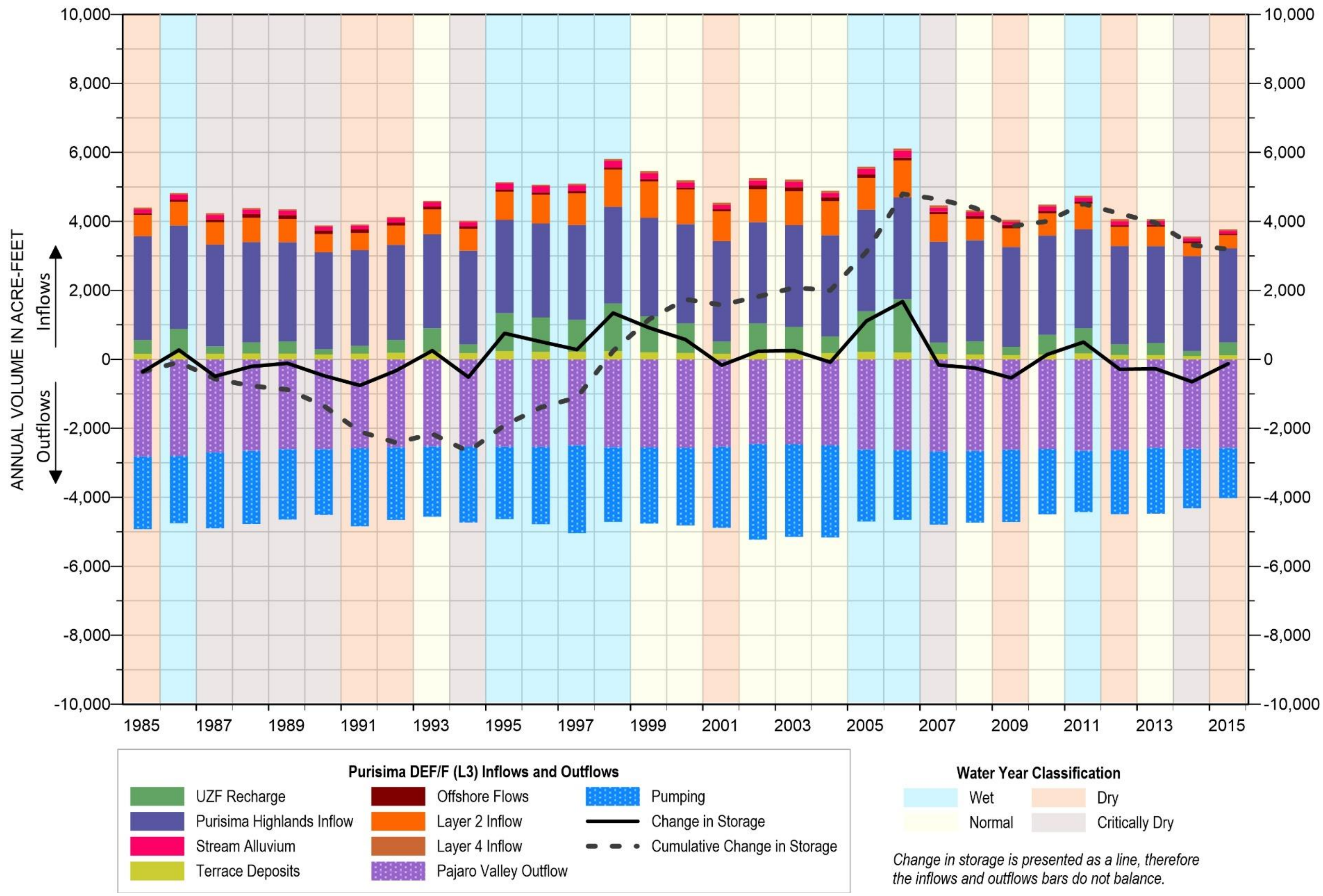


Figure C-2: Detailed Annual Water Budget for Layer 3 (Purisima F/DEF) in Mid-County Basin

MONTGOMERY & ASSOCIATES

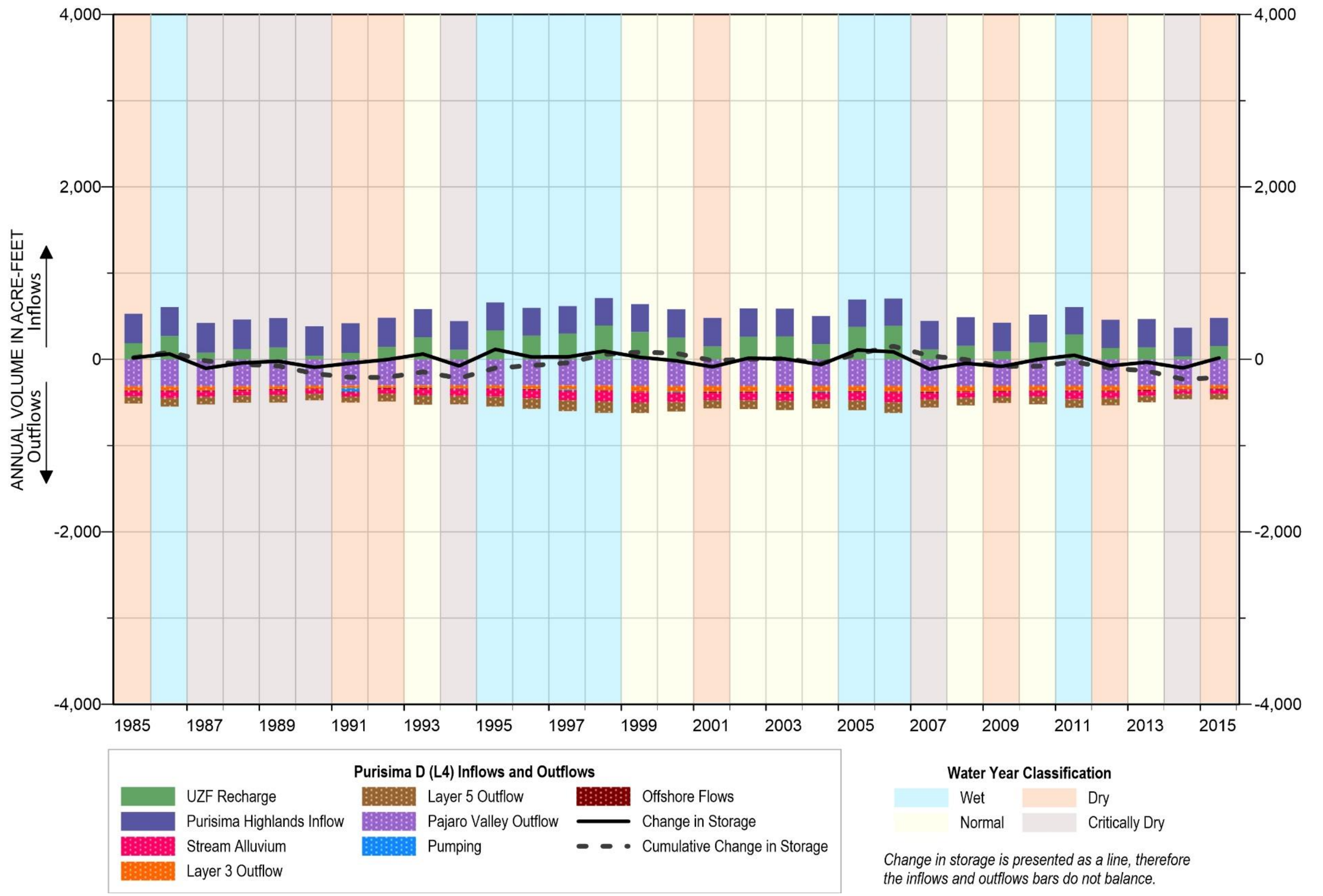


Figure C-3: Detailed Annual Water Budget for Layer 4 (Purisima D) in Mid-County Basin

MONTGOMERY & ASSOCIATES

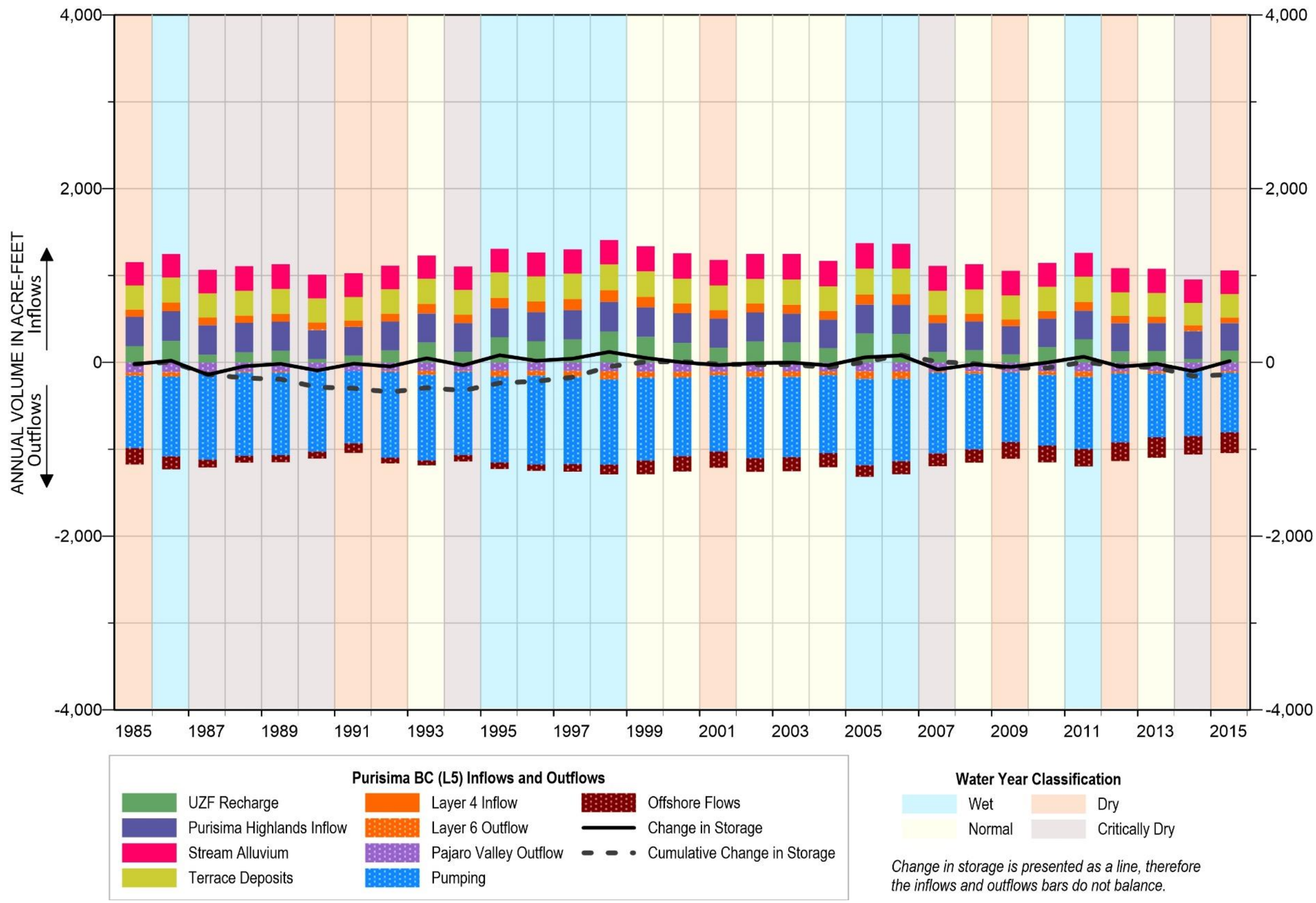


Figure C-4: Detailed Annual Water Budget for Layer 5 (Purisima BC) in Mid-County Basin

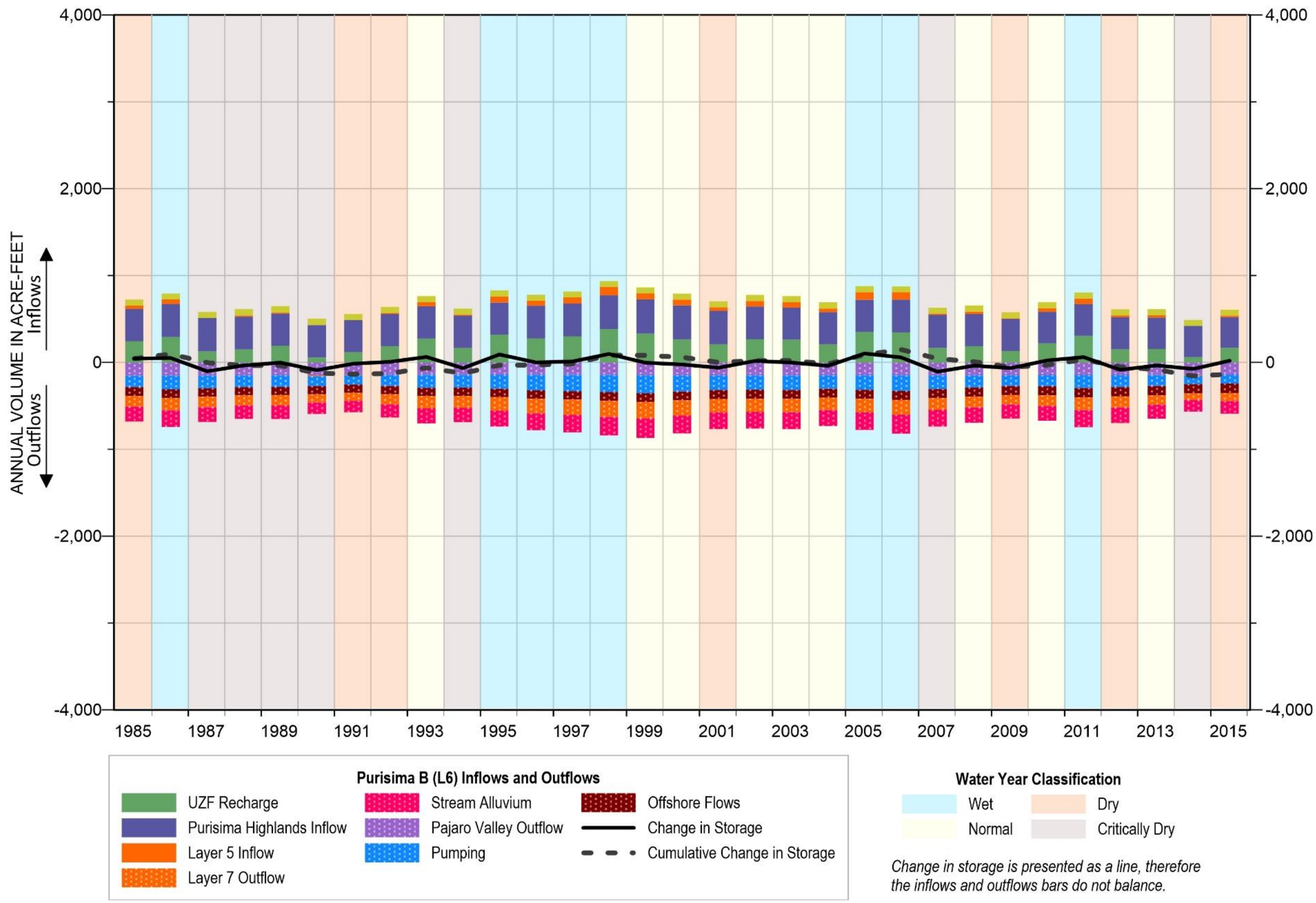


Figure C-5: Detailed Annual Water Budget for Layer 6 (Purisima B) in Mid-County Basin

MONTGOMERY & ASSOCIATES

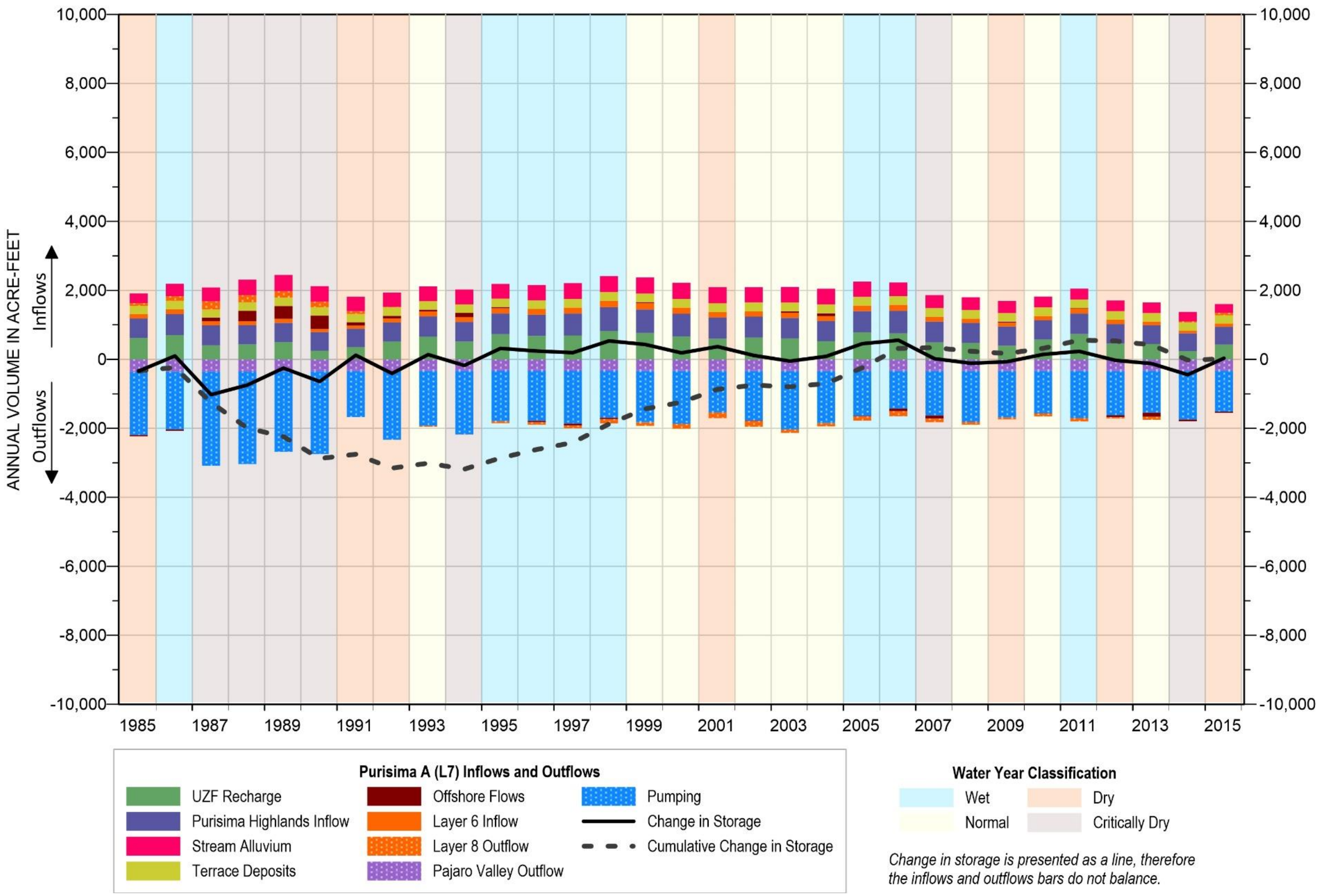


Figure C-6: Detailed Annual Water Budget for Layer 7 (Purisima A) in Mid-County Basin

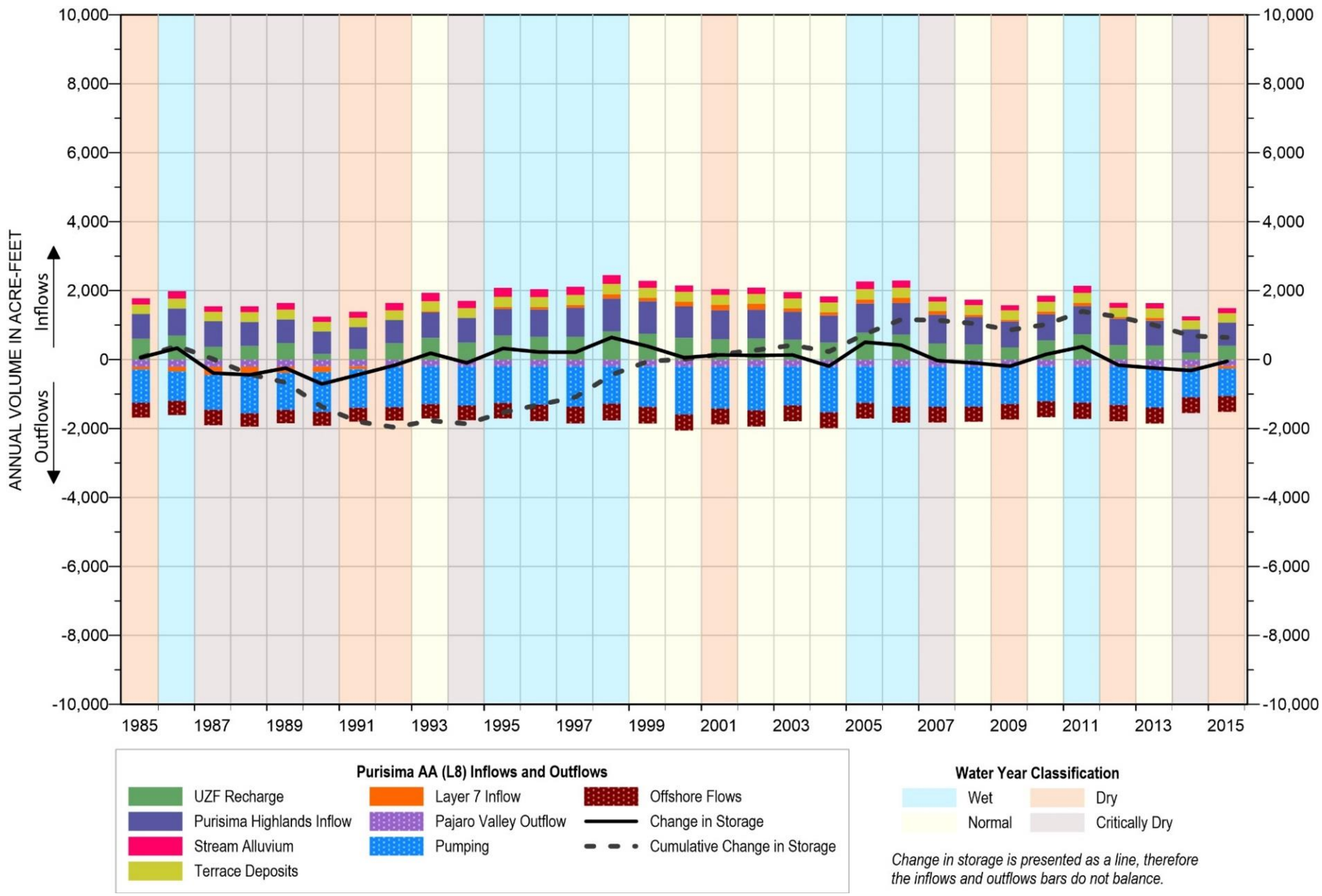


Figure C-7: Detailed Annual Water Budget for Layer 8 (Purisima AA) in Mid-County Basin

MONTGOMERY & ASSOCIATES

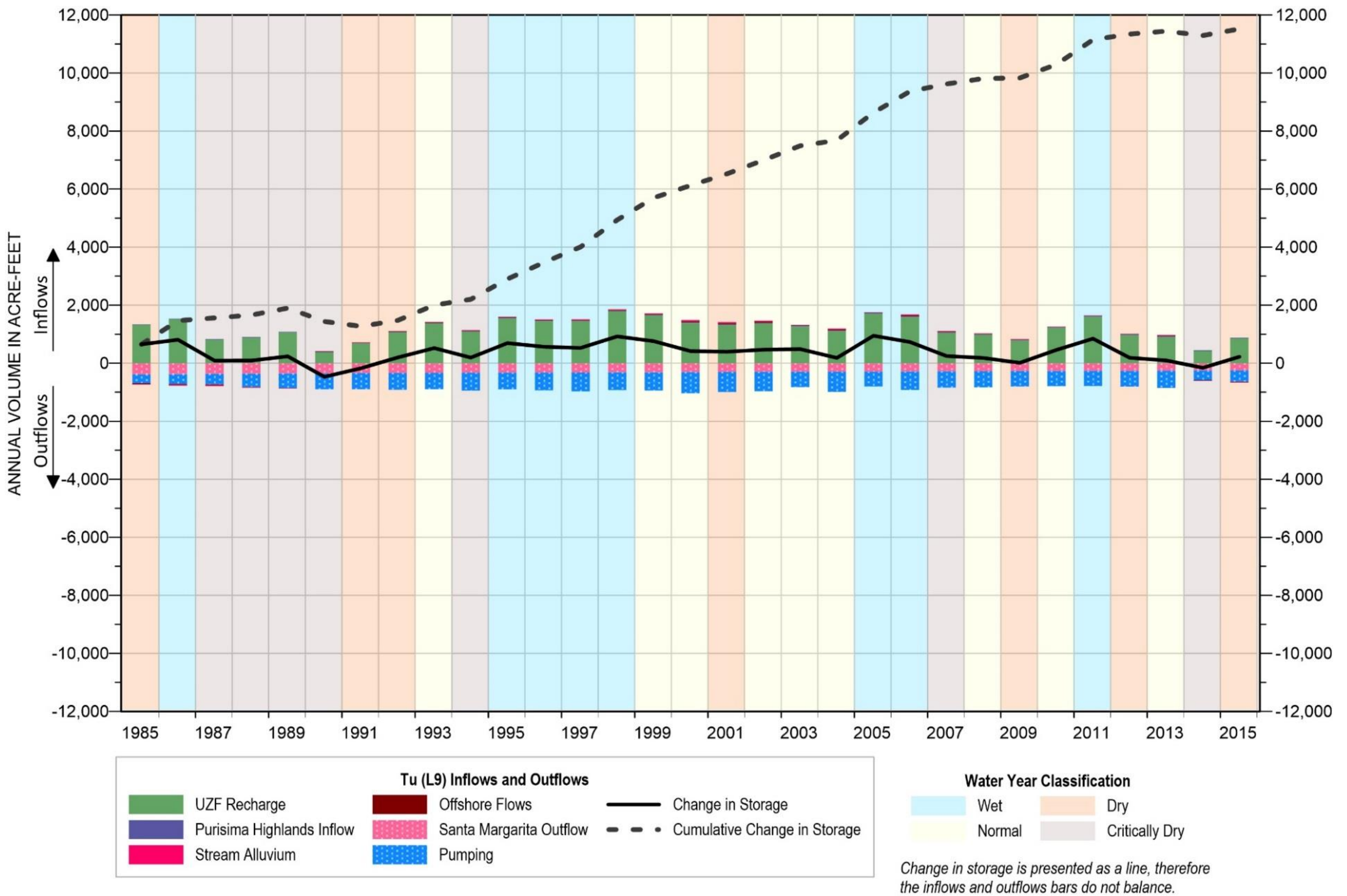


Figure C-8: Detailed Annual Water Budget for Layer 9 (Tu) in Mid-County Basin

APPENDIX 2-G

SANTA CRUZ MID-COUNTY GROUNDWATER FLOW MODEL: FUTURE CLIMATE FOR MODEL SIMULATIONS (TASK 5) MEMORANDUM

1814 Franklin St, Suite 501
Oakland, CA 94612

TECHNICAL MEMORANDUM

To: Mid-County Groundwater Agency Executive Staff

From: Georgina King and Cameron Tana

Date: August 17, 2017

Subject: Santa Cruz Mid-County Basin Groundwater Flow Model: Future Climate for Model Simulations (Task 5)

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Appendix A: Santa Cruz Coop Station Exceedance Probabilities with Year Type Classification

Appendix B: Proposed Climate Scenarios

1.0 INTRODUCTION

This technical memorandum documents our approach for developing an initial future climate scenario to be implemented with simulations using the GSFLOW model of the Santa Cruz Mid-County Groundwater Basin currently under development, and presents two proposed climate scenarios. Climate data used in GSFLOW includes minimum and maximum temperature, and precipitation at the Santa Cruz Co-op and Watsonville Waterworks stations.

The objective of this subtask is to develop a reasonable climate scenario that adequately represents the warmer temperatures that are being predicted due to global climate change. At the August 24, 2016 TAC meeting, Prof. Andrew Fisher suggested using a catalog of historical annual climate instead of one of the multitude of General Circulation Models (GCM) available for future climate scenarios. The premise of this approach is that we use actual historical climate data representing the warmest years on record and not modeled climate data such as GCM. This approach is appropriate because to retain integrity of the climate data, the future climate scenario must have temperature data that corresponds to precipitation data, which is ensured by using historical data. A similar approach using historical data instead of using future climate predictions is used by Metropolitan Water District of Southern California to evaluate its region's future water supply reliability (MWD, 2016).

As discussed in our revised scope of work for fiscal year 2016-2017 approved by the MGA Board, downscaling one or more GCM scenarios to develop additional climate change scenarios has been re-prioritized for implementation in 2017. This is still recommended because the GCMs predict temperatures warmer than even the warmest years on record.

2.0 CLIMATE DATASETS

2.1 SANTA CRUZ CO-OP STATION

The Santa Cruz Co-op station has climate data available from January 1893 through present. Figure 1 shows the average annual temperature ranges and overall average for Water Years 1894 through 2016. It is visually evident that minimum temperatures have been higher since 1977. Maximum temperatures do not show the same trend, perhaps because of the moderating influence of the ocean. Expectedly, average annual temperatures also show an increase but of a lower magnitude than the minimum temperature increase due to more stable maximum temperatures. Water Years 2013 through 2016 have four of the five hottest average annual temperatures in the record. Table 1 illustrates that post-1977, average annual temperatures at the Santa Cruz Co-op station are 1.3° F warmer than before 1977. The 1985-2015 average for the model calibration period is also shown.

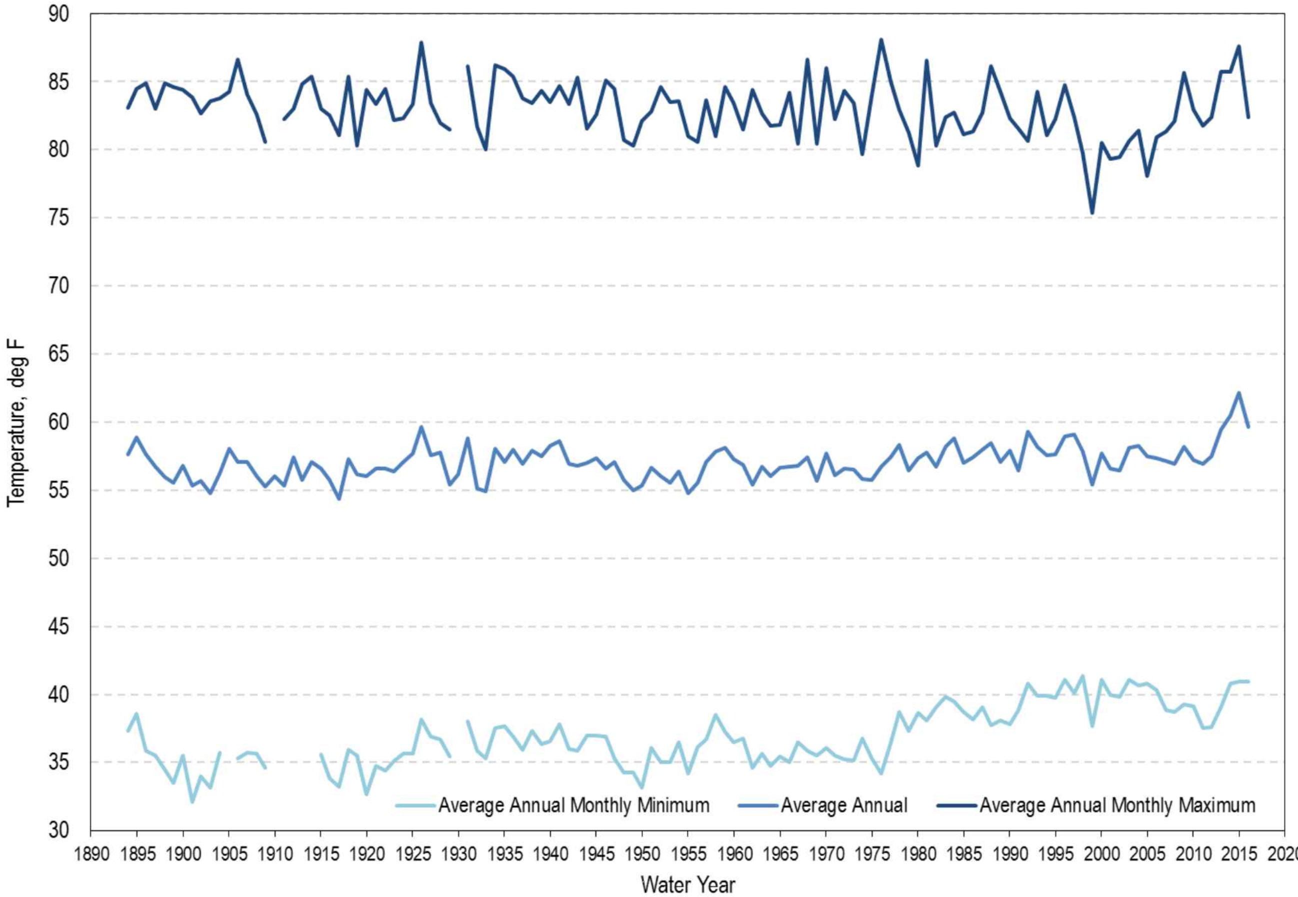


Figure 1: Measured Minimum, Maximum, and Average Annual Temperatures at the Santa Cruz Co-op Station

Table 1: Santa Cruz Co-op Station Average Annual Temperatures for Selected Periods

Annual Temperature, °F	
1985-2015 Average	57.9
1977-2016 Average	57.9
Pre-1977 Average	56.6
1894-2016 Average	57.0

Figure 2 presents the annual precipitation recorded at the Santa Cruz Co-op station. The average annual precipitation for various periods of interest are provided in Table 2. Although the chart on Figure 2 does not show any discernible trends, the averages in Table 2 indicate that pre-1977 precipitation was very slightly lower than that experienced from 1977 onwards. In general however, the data do not show a trend that is visually evident like temperature.

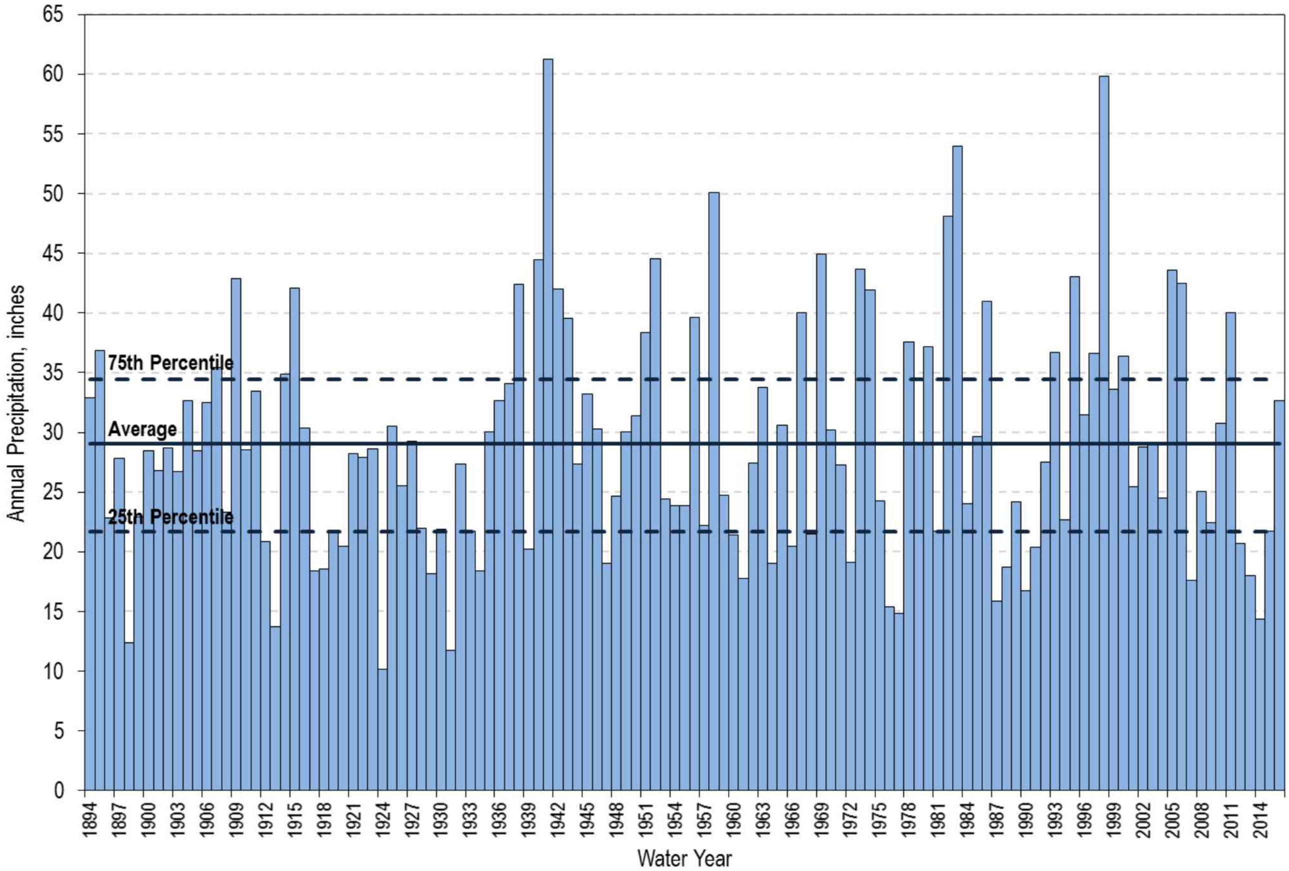


Figure 2: Annual Precipitation at the Santa Cruz Co-op Station

Table 2: Santa Cruz Co-op Station Average Precipitation for Selected Periods

Annual Precipitation, inches	
1985-2015 Average	29.0
1977-2016 Average	30.0
Pre-1977 Average	28.7
1894-2016 Average	29.1

2.2 WATSONVILLE WATERWORKS STATION

The Watsonville Waterworks station has climate data available from January 1908 through present. Figure 3 shows average annual temperature ranges and overall average for Water Years 1909 through 2016; note there were a number of missing records in the monthly data used to generate the annual averages; therefore those years are not included on the chart. The line showing minimum temperatures has a clear increasing trend over the period of record, with a slight jump in temperatures from 1977 onwards where minimum temperatures mostly remain consistently above pre-1977 temperatures. At this station, maximum temperatures also show an increasing trend like minimum temperatures but they are more muted. The Watsonville Waterworks station is 4.5 miles from the ocean compared to the Santa Cruz Co-op station which is two miles from the ocean, and has less effects from the ocean. Average annual temperatures also show a noticeable increase after 1977. Table 4 illustrates that post-1977, average annual temperatures at the Watsonville Waterworks station are 1.7 °F warmer than before 1977.

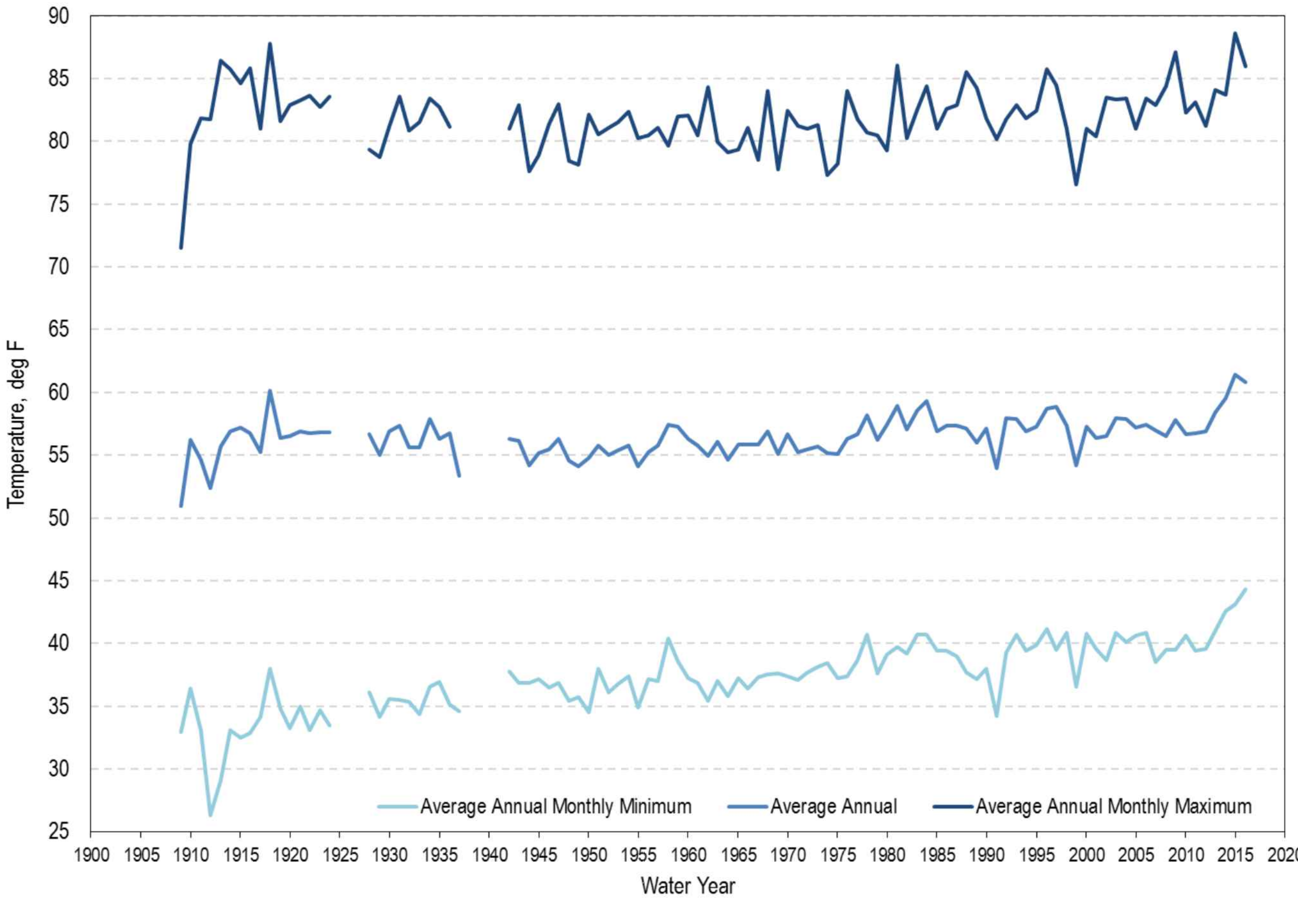


Figure 3: Measured Minimum, Maximum, and Average Annual Temperatures at the Watsonville Waterworks Station

Table 3: Watsonville Waterworks Station Average Annual Temperatures for Selected Periods

Annual Temperature, °F	
1985-2015 Average	57.3
1977-2016 Average	57.5
Pre-1977 Average	55.8
1894-2016 Average	56.5

Figure 4 presents the annual precipitation recorded at the Watsonville Waterworks station. The average annual precipitation for various periods of interest are provided in Table 4. The data suggest that since the 1980s, there has been an increase in the amount of precipitation at this station. This is confirmed in Table 4 where post-1977 precipitation is 2.8 inches more than before 1977.

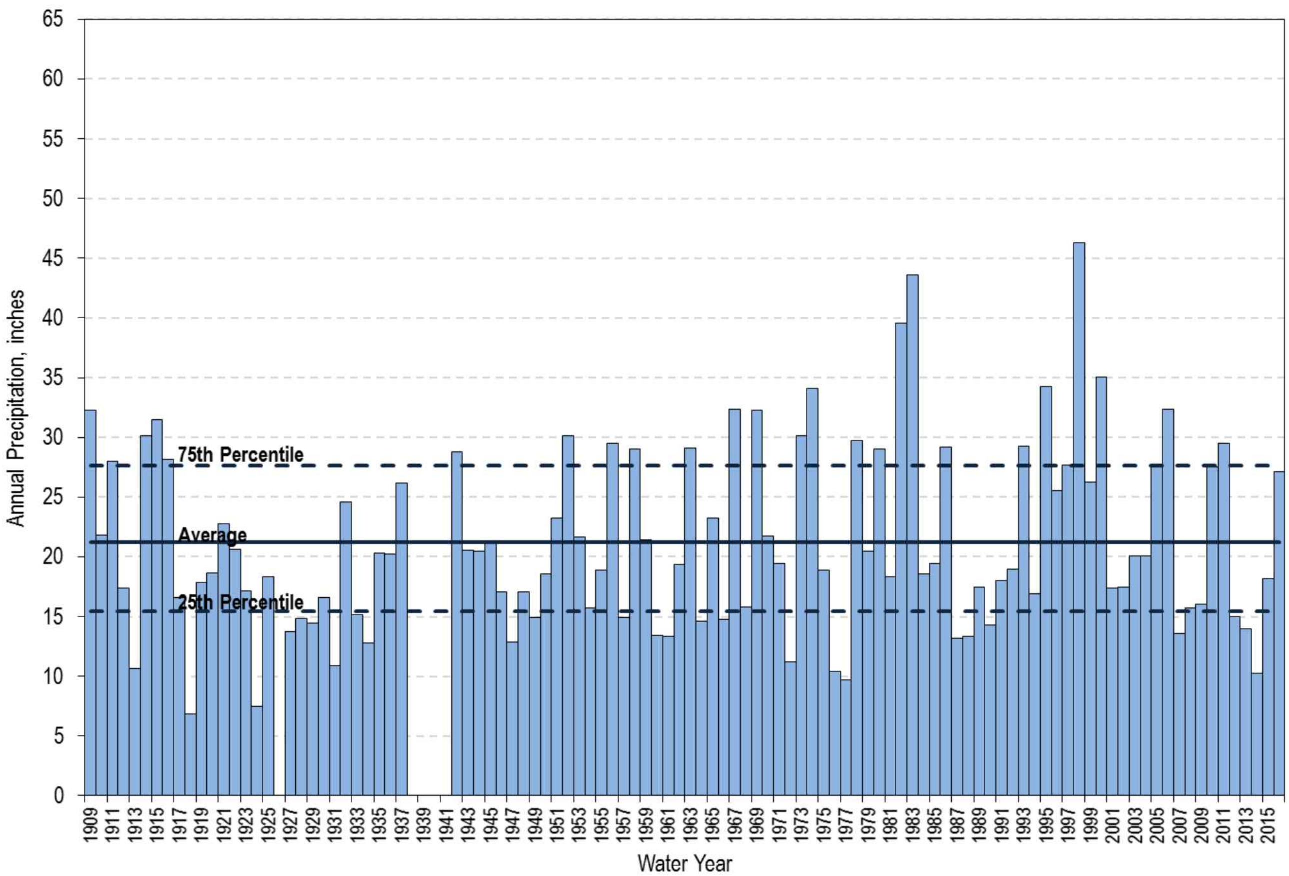


Figure 4: Annual Precipitation at the Watsonville Waterworks Station

Table 4: Watsonville Waterworks Station Average Precipitation for Selected Periods

Annual Precipitation, inches	
1985-2015 Average	21.9
1977-2015 Average	22.9
Pre-1977 Average	20.1
1909-2015 Average	21.2

3.0 APPROACH

3.1 CLIMATE CATALOG

Using the general method for creating a catalog of each historical year suggested by Prof. Andrew Fisher (Young, 2016), exceedance probabilities (p) for both temperature and precipitation are calculated using the following equation for the full dataset on record for the climate station:

$$p = \frac{m}{n+1}$$

where m is the rank based on total precipitation or temperature (from largest to smallest), and n is the total number of years in the dataset. A chart of exceedance probabilities for temperature and precipitation at the Santa Cruz Co-op station is provided on Figure 5. The catalog is based on the Santa Cruz Co-op station because the majority of model cells are assigned to it for rainfall distribution in PRMS, the watershed component of the GSFLOW model.

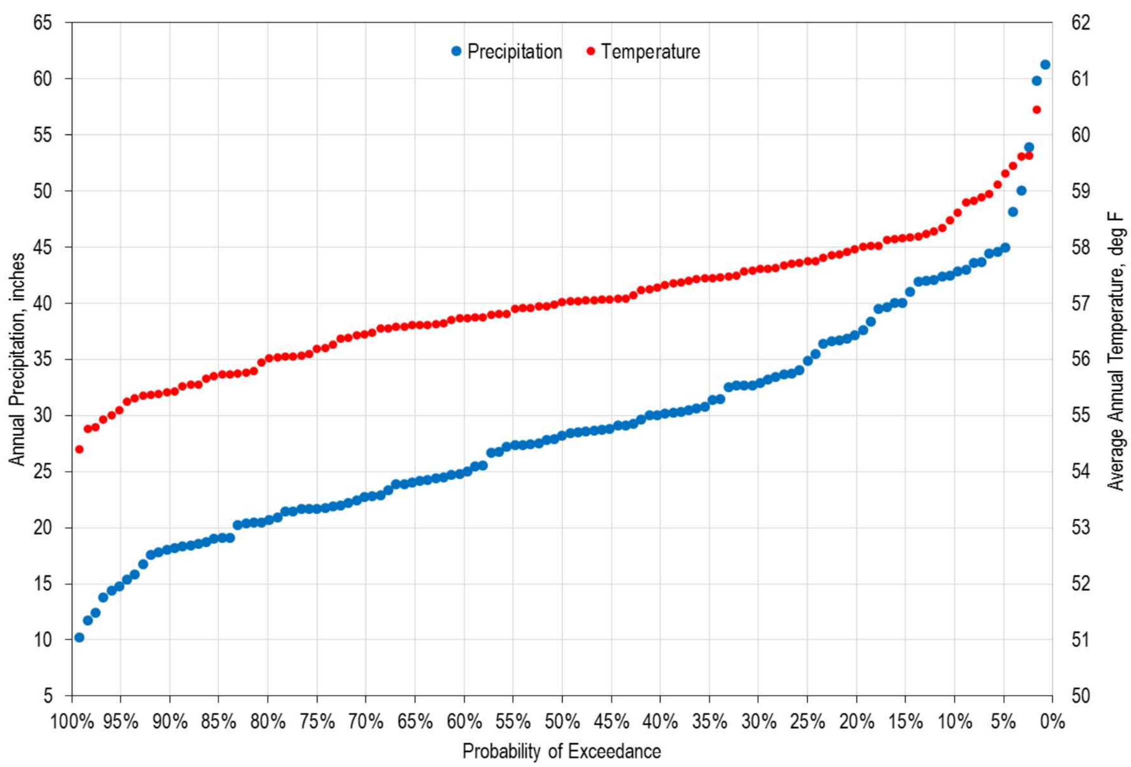


Figure 5: Probability of Exceedance for Annual Precipitation and Average Annual Temperature, Santa Cruz Co-op Station

Figure 6 and Figure 7 graphically show consecutive water years' probabilities of exceedance for temperature and precipitation at the Santa Cruz Co-op Station, respectively. Figure 6, similar to Figure 1, shows that since 1977, there has been an increased number of years that have less than a 50% probability of exceedance, i.e., warmer than the rest of the record. Figure 7 shows no visual trend towards either decreasing or increasing precipitation over time like temperature does.

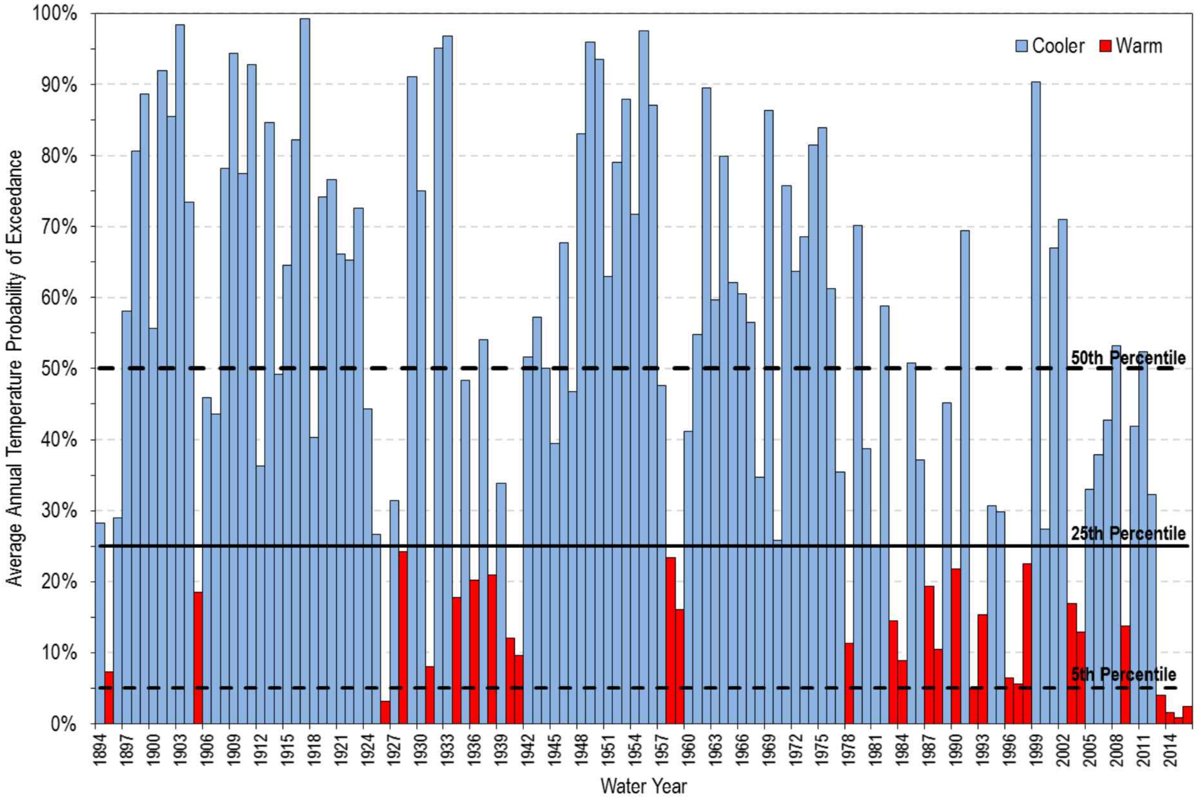


Figure 6: Average Annual Temperature Probability of Exceedance for the Santa Cruz Co-op Station

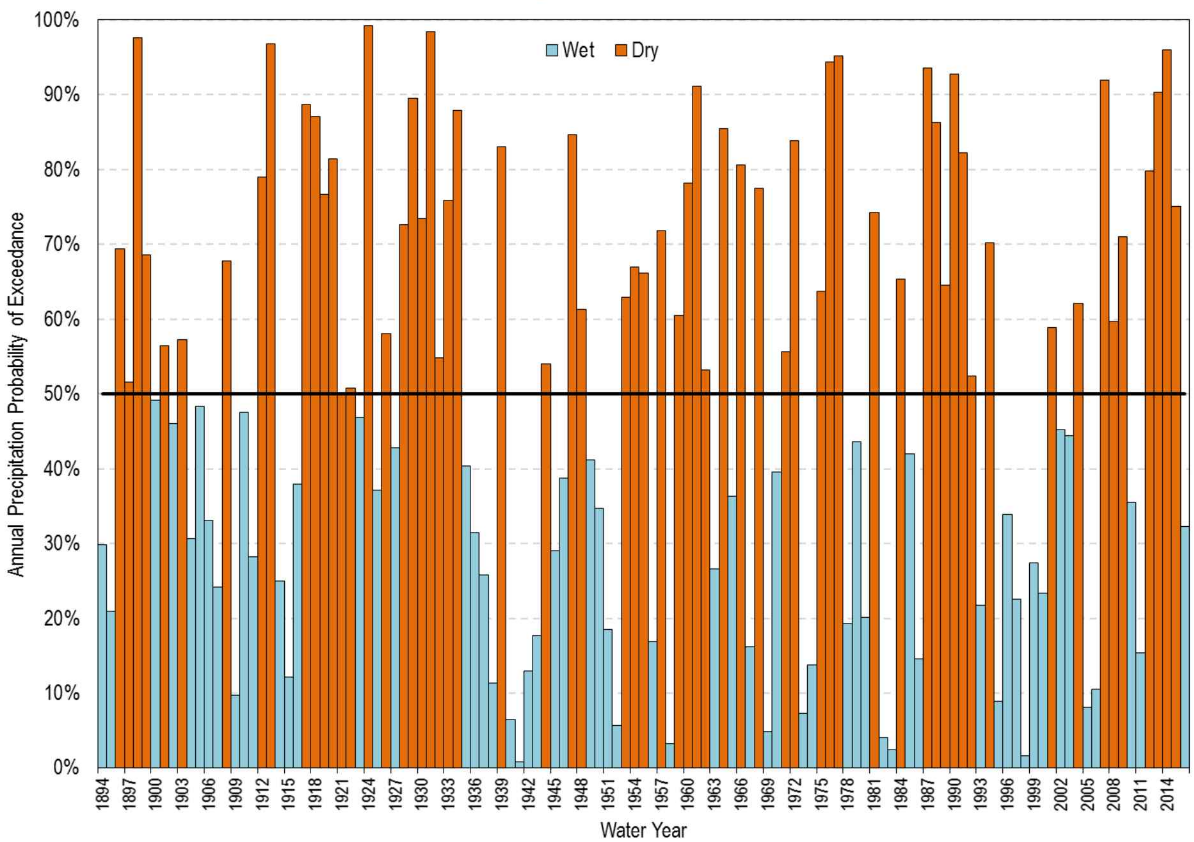


Figure 7: Annual Precipitation Probability of Exceedance for the Santa Cruz Co-op Station

Another way to visualize the climate data based on probabilities of exceedance is to classify each water year according to a combination of temperature and precipitation probabilities shown in Table 5. Appendix A provides the probabilities for all water years on record for the Santa Cruz Co-op Station, and Figure 8 presents the historical data color-coded by classification plotted against precipitation.

Table 5: Classification of Probabilities

Probability of Exceedance		Category
Precipitation	**Average Temperature**	
>= 50%	< 25%	Warm and Dry
< 50%	< 25%	Warm and Wet
< 50%	>= 25%	Cooler and Wet
>= 50%	>= 25%	Cooler and Dry

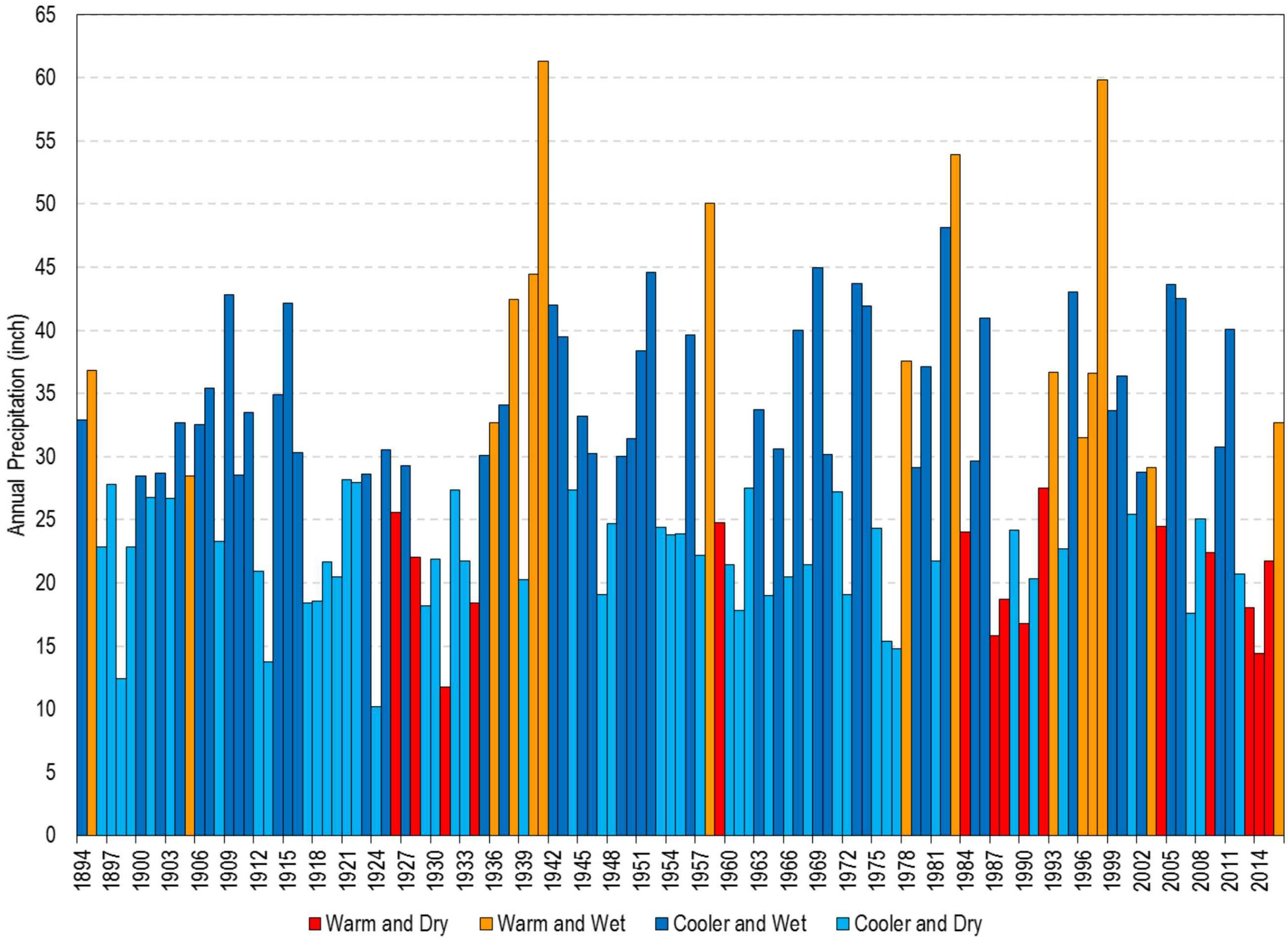


Figure 8: Santa Cruz Co-op Station Classification of Historical Water Years

3.2 FUTURE CLIMATE SCENARIO GENERATION

The future climate scenario will cover Water Years 2016-2069. This time span is selected to meet the requirement in California Department of Water Resources regulations for Groundwater Sustainability Plans (GSP) to evaluate sustainability for future climate over fifty years. Fifty years after the 2020 GSP deadline for the critically overdrafted Santa Cruz Mid-County Groundwater Basin goes through Water Year 2069. Water Year 2016 will be simulated based on recorded climate data using initial conditions from the end of the calibrated model run of Water Years 1985-2015. The 53 water years 2017-2069 will be simulated using the approach described below.

As temperature shows a much more evident trend than precipitation, the catalog of annual average temperature at the Santa Cruz Co-op station is used to generate one future climate scenario. First, a subset of historic climate is selected to form a catalog from which to generate the future climate scenario. The catalog of years selected are all the years from 1977 to 2016 representing the most recent period where warming has been observed, plus six additional years from 1909[1] to 1977 that have a temperature probability of exceedance of 25% or less, i.e., the warmest years and that don't have entire months of missing temperature data in the Watsonville Waterworks station record. See bold records in Appendix A for those years included in the catalog.

The catalog is then randomly ordered using the Random Number Generator in Excel to generate the scenario. The Random Number Generator uses weights applied to each water year to ensure a pre-determined distribution of temperature exceedance probabilities results from the process. Weights are assigned by categories of exceedance probabilities for temperature shown in Table 6. For example, the warmest category (<5% exceedance probability) is given a 50% weight and includes Water Years 1992, and 2013-2016. Warmer years are given greater weights than cooler years to ensure an overall warmer scenario is generated.

[1] Water Year 1909 was selected because this is the first water year for the Watsonville Waterworks station climate records. If we used prior years, there would be no climate data for the Watsonville Waterworks station for the future climate scenario for those years.

Table 6: Weights Assigned to Catalog of Water Years Based on Temperature Exceedance Probabilities

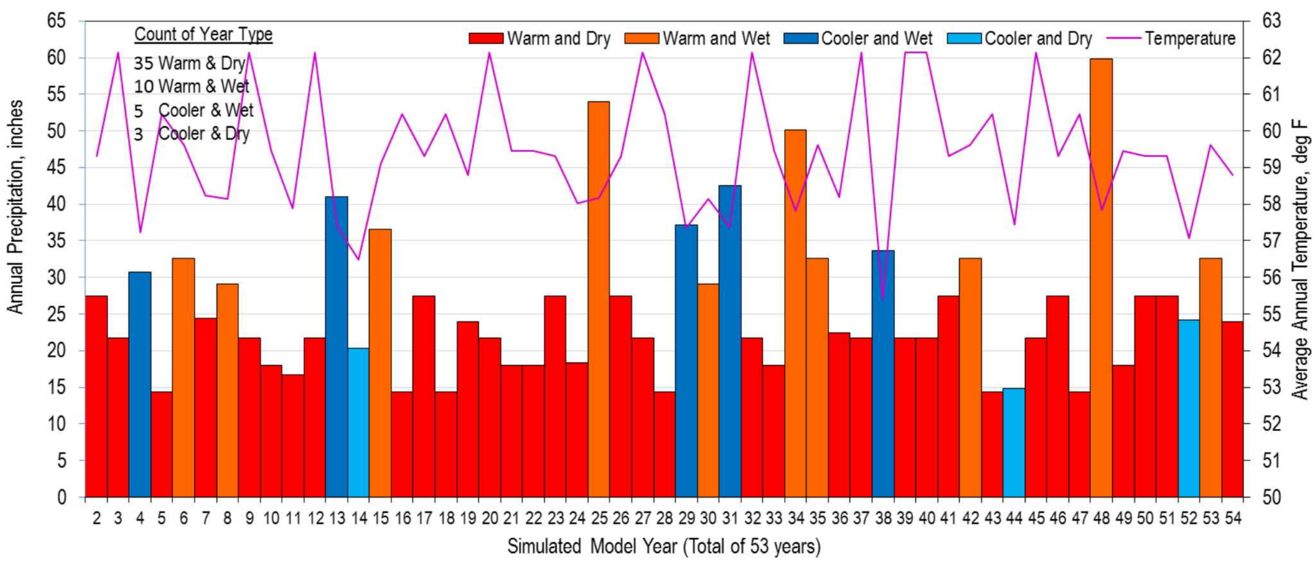
Exceedance Probability Category	Weight
< 5%	0.5
5 – 25%	0.3
>=25 – 50%	0.1
> = 50%	0.1

After the water year sequence is selected based on the Santa Cruz Co-op temperature data, climate data for the future climate scenario for the Watsonville Waterworks station is selected based on the same water year sequence. Climate data for both the Santa Cruz Co-op and Watsonville Waterworks stations are input into the GSFLOW model.

4.0 Proposed Climate Scenarios

4.1 Temperature Weighted

The first scenario is generated using the temperature weights shown in Table 6 and the Random Number Generator to arrive at a sequence of 53 water years with an average temperature that is as high as we could get without manually selecting the warmest years. Figure 9 shows the color-coded distribution of water years for the Santa Cruz Co-op station representing a potential future climate scenario that is on average 2.4 °F warmer than the long-term average and 1.6 °F warmer than the average annual temperature from 1977-2016. The scenario also has 3.1 inches less precipitation per year than the long-term historical average as 4 of the 5 hottest years used for 50% of the scenario are dry years. Appendix B provides a list of the randomly selected historic years generated for this scenario.

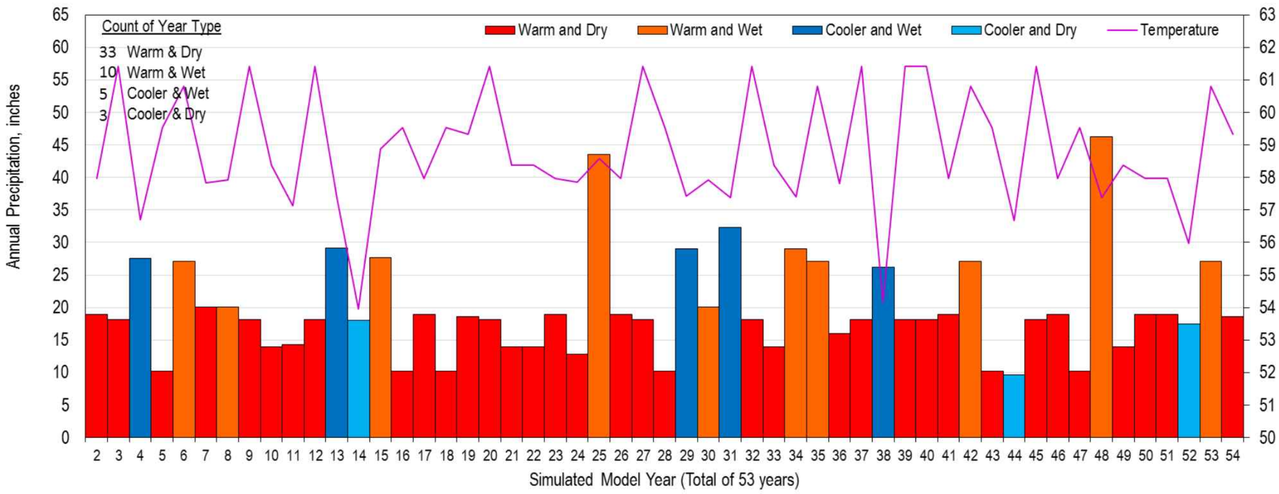


Annual Temperature, deg F	
Scenario Average	59.4
1985-2015 Average	57.9
1977-2016 Average	57.8
Pre-1977 Average	56.6
1894-2016 Average	57.0

Annual Precipitation, inches	
Scenario Average	26.0
1985-2015 Average	29.0
1977-2016 Average	29.9
Pre-1977 Average	28.7
1894-2016 Average	29.1

Figure 9: Temperature Weighted Climate Scenario for Santa Cruz Co-op Station

Using the same sequence of 53 water years used for the Santa Cruz Co-op station temperature weighted climate scenario. Figure 10 shows a potential future climate scenario for the Watsonville Waterworks station that is on average 2.4 °F warmer than the long-term average and 1.4°F warmer than the average annual temperature from 1977-2016. The scenario also has 1.3 inches less precipitation per year than the long-term historical average.



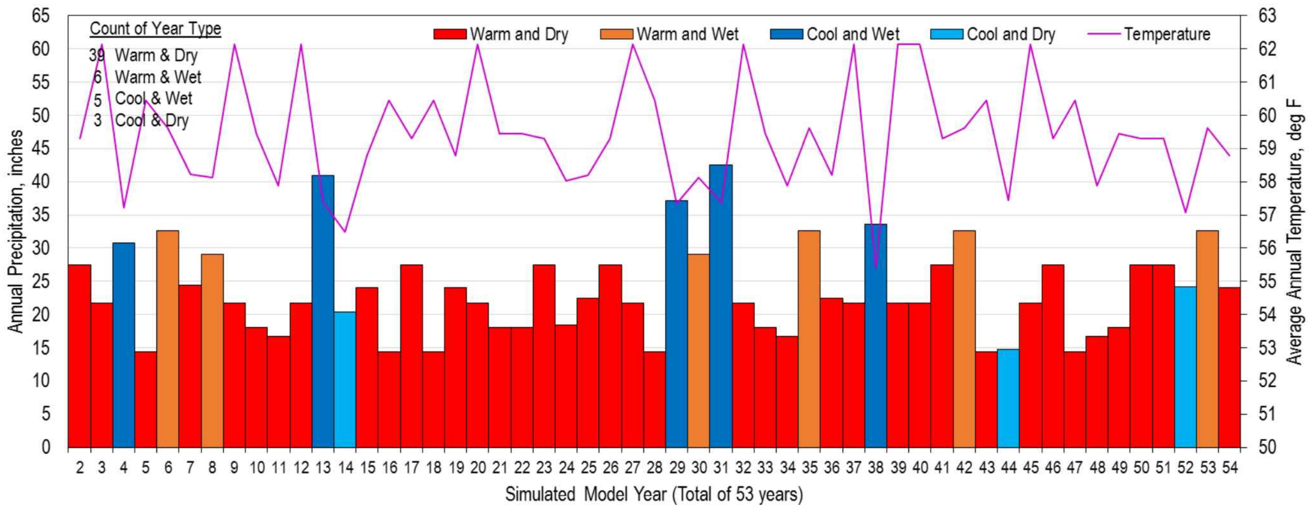
Annual Temperature, deg F	
Scenario Average	58.8
1985-2015 Average	57.3
1977-2016 Average	57.4
Pre-1977 Average	55.8
1894-2016 Average	56.4

Annual Precipitation, inches	
Scenario Average	19.8
1985-2015 Average	21.9
1977-2016 Average	22.8
Pre-1977 Average	20.1
1894-2016 Average	21.1

Figure 10: Temperature Weighted Climate Scenario for Watsonville Waterworks Station

4.2 TEMPERATURE WEIGHTED AND PRECIPITATION ADJUSTED

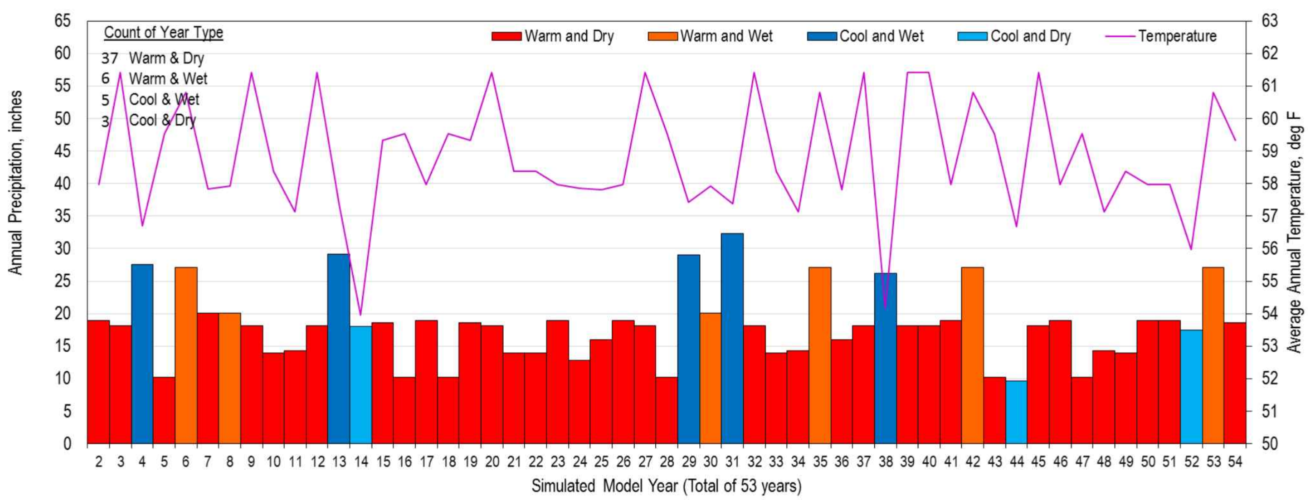
Although there is no trend of decreased precipitation in the Santa Cruz area, a drier scenario than that generated by weighting temperature only is also generated for consideration. We avoided randomly generating a new dataset based on both temperature and precipitation weights as we want a scenario that we can compare with the temperature weighted climate scenario. To arrive at this scenario, we start with the temperature weighted scenario and then adjust the four wettest "Warm and Wet" years to "Warm and Dry" by substituting the "Warm and Wet" years with "Warm and Dry" years with similar temperatures but less precipitation. Figure 11 shows the color-coded distribution of water years for the Santa Cruz Co-op station representing a potential future climate scenario that has the same average temperature as the temperature weighted scenario but has 5.4 inches less precipitation per year than the long-term average. Appendix B provides a list of the randomly selected historic years generated for this scenario. Figure 12 shows this potential future climate scenario applied to the Watsonville Waterworks station that results in the same average temperature as the temperature weighted scenario but has 2.9 inches less precipitation per year than the long-term average.



Annual Temperature, deg F	
Scenario Average	59.4
1985-2015 Average	57.9
1977-2016 Average	57.8
Pre-1977 Average	56.6
1894-2016 Average	57.0

Annual Precipitation, inches	
Scenario Average	23.7
1985-2015 Average	29.0
1977-2016 Average	29.9
Pre-1977 Average	28.7
1894-2016 Average	29.1

Figure 11: Temperature Weighted Climate Scenario for Santa Cruz Co-op Station with Decreased Precipitation Adjustment



Annual Temperature, deg F	
Scenario Average	58.8
1985-2015 Average	57.3
1977-2016 Average	57.4
Pre-1977 Average	55.8
1894-2016 Average	56.4

Annual Precipitation, inches	
Scenario Average	18.2
1985-2015 Average	21.9
1977-2016 Average	22.8
Pre-1977 Average	20.1
1894-2016 Average	21.1

Figure 12: Temperature Weighted Climate Scenario for Watsonville Waterworks with Decreased Precipitation Adjustment

5.0 DISCUSSION AND LIMITATIONS

One of the two scenarios presented in this memo will be selected to run simulations using the GSFLOW model. The selection will be made based on input from MGA member agency staff, the model Technical Advisory Committee, and possibly the MGA Board.

This approach of using historical climate allows us to generate climate scenarios that are warmer than the past 40 years but it does not increase temperatures to the degree that some of the GCMs predict global warming. For example, GCMs (Flint and Flint, 2014) have been downscaled to the San Lorenzo-Soquel Basin, which includes the Santa Cruz Mid-County Groundwater Basin. The downscaled predictions include warming of up to 4.1 °F (GFDL A2, a moderately warmer, drier future) and 6.2°F (MIROC-esm RCP 8.5, the warmest, driest future) over our simulated model period (54 years from Water Year 2016 – 2069). It is important to note that these GCM predicted temperatures are for minimum temperatures which, as shown above, tend to have a greater increase than average temperatures. We used average temperature in our analysis. Additionally, the GCM downscaled predictions are for the entire San Lorenzo-Soquel Basin which extends much farther inland than the Santa Cruz Co-op and Watsonville Waterworks stations.

Assigning lower weights to the "Cooler and dry" and "Cooler and wet" classifications will raise the scenario's average temperature slightly but still not as high as those in the GCMs described above because the hottest years in the historical record are not as hot as what is projected by the GCMs.

Simulating GCM projections will require downscaling GCM results to the Santa Cruz Co-op and Watsonville Waterworks stations for distribution to the model grid by the PRMS watershed component of GSFLOW. The USGS has recommended that the Jensen-Haise formulation for potential evapotranspiration used in the model be changed to Priestly-Taylor or Penman-Monteith when using hotter GCM projections. The Priestly-Taylor and Penman-Monteith evapotranspiration formulations have only recently been added to PRMS so will take additional work to implement with the likelihood of issues implementing new capabilities. Therefore, we will use one of the scenarios described in this memo to represent future climate to perform the initial evaluation of groundwater management alternatives. Implementation of downscaled GCM projections has been re-prioritized to 2017.

This approach also does not project trends for temporal precipitation patterns as previously evaluated by Daniels (2014)[2]. Daniels identified long-term trends in storm intensity, duration, and pauses between storms and assessed effects on groundwater recharge and streamflow of those trends projected into the future. Since those projections are not part of the historical record, they are not part of the climate scenario described in this memo. However, 83% of historical years randomly selected for the future climate scenario in this memo are from 1990-2016, so the historical trends for these patterns are reflected in the scenario.

[2] Dr. Bruce Daniels is Board President of Soquel Creek Water District, a member of the Santa Cruz Mid-County Agency that is funding development of this GSFLOW model. Dr. Daniels also serves on the Technical Advisory Committee for this model.

6.0 REFERENCES

Daniels, B.K. 2014. *Hydrologic response to climate change in California: observational and modeling studies.* Ph.D. dissertation, University of California, Santa Cruz. December.

Flint L.E. and A.L. Flint. 2014. *California basin characterization model: a dataset of historical and future hydrologic response to climate change*, U.S. Geological Survey Data Release, doi:10.5066/F76T0JPB

Metropolitan Water District of Southern California (MWD). 2016. *Integrated Water Resources Plan, 2015 Update*. Report No. 1518. January.

Young, K. 2016. *A high-resolution, regional-scale analysis of stormwater runoff in the San Lorenzo river basin for managed aquifer recharge decision making*. Masters of Science Thesis, University of California, Santa Cruz. June.

Appendix A

Santa Cruz Co-op Station Exceedance Probabilities with Year Type Classification

Water Year	Temperature			Precipitation			Classification
	Average (°F)	Rank	Probability of Exceedance	Total (inches)	Rank	Probability of Exceedance	1 = Warm & dry 2 = Warm & wet 3 = Cooler & dry 4 = Cooler & wet
1894	57.6	35	28.2%	32.9	37	29.8%	3
1895	58.9	9	7.3%	36.8	26	21.0%	2
1896	57.6	36	29.0%	22.9	86	69.4%	4
1897	56.8	72	58.1%	27.8	64	51.6%	4
1898	55.9	100	80.6%	12.4	121	97.6%	4
1899	55.5	110	88.7%	22.9	85	68.5%	4
1900	56.8	69	55.6%	28.4	61	49.2%	3
1901	55.4	114	91.9%	26.8	70	56.5%	4
1902	55.7	106	85.5%	28.7	57	46.0%	3
1903	54.8	122	98.4%	26.7	71	57.3%	4
1904	56.3	91	73.4%	32.7	38	30.6%	3
1905	58.0	23	18.5%	28.5	60	48.4%	2
1906	57.1	57	46.0%	32.5	41	33.1%	3
1907	57.1	54	43.5%	35.5	30	24.2%	3
1908	56.0	97	78.2%	23.3	84	67.7%	4
1909	55.2	117	94.4%	42.9	12	9.7%	3
1910	56.1	96	77.4%	28.6	59	47.6%	3
1911	55.3	115	92.7%	33.5	35	28.2%	3
1912	57.4	45	36.3%	20.9	98	79.0%	4
1913	55.7	105	84.7%	13.8	120	96.8%	4
1914	57.0	61	49.2%	34.9	31	25.0%	3
1915	56.6	80	64.5%	42.1	15	12.1%	3
1916	55.8	102	82.3%	30.4	47	37.9%	3
1917	54.4	123	99.2%	18.4	110	88.7%	4
1918	57.3	50	40.3%	18.6	108	87.1%	4
1919	56.2	92	74.2%	21.7	95	76.6%	4
1920	56.1	95	76.6%	20.5	101	81.5%	4
1921	56.6	82	66.1%	28.2	62	50.0%	4
1922	56.6	81	65.3%	27.9	63	50.8%	4
1923	56.4	90	72.6%	28.6	58	46.8%	3
1924	57.1	55	44.4%	10.2	123	99.2%	4
1925	57.7	33	26.6%	30.5	46	37.1%	3
1926	59.6	4	3.2%	25.6	72	58.1%	1
1927	57.6	39	31.5%	29.3	53	42.7%	3

	Temperature			Precipitation			Classification
Water Year	Average (°F)	Rank	Probability of Exceedance	Total (inches)	Rank	Probability of Exceedance	1 = Warm & dry 2 = Warm & wet 3 = Cooler & dry 4 = Cooler & wet
1928	**57.8**	**30**	**24.2%**	**22.0**	**90**	**72.6%**	1
1929	55.4	113	91.1%	18.2	111	89.5%	4
1930	56.2	93	75.0%	21.9	91	73.4%	4
1931	**58.8**	**10**	**8.1%**	**11.7**	**122**	**98.4%**	1
1932	55.1	118	95.2%	27.4	68	54.8%	4
1933	54.9	120	96.8%	21.7	94	75.8%	4
1934	**58.0**	**22**	**17.7%**	**18.4**	**109**	**87.9%**	1
1935	57.0	60	48.4%	30.1	50	40.3%	3
1936	**58.0**	**25**	**20.2%**	**32.7**	**39**	**31.5%**	2
1937	56.9	67	54.0%	34.1	32	25.8%	3
1938	57.9	26	21.0%	42.4	14	11.3%	2
1939	57.5	42	33.9%	20.2	103	83.1%	4
1940	58.3	15	12.1%	44.5	8	6.5%	2
1941	58.6	12	9.7%	61.3	1	0.8%	2
1942	57.0	64	51.6%	42.0	16	12.9%	3
1943	56.8	71	57.3%	39.5	22	17.7%	3
1944	57.0	62	50.0%	27.4	67	54.0%	4
1945	57.3	49	39.5%	33.2	36	29.0%	3
1946	56.6	84	67.7%	30.3	48	38.7%	3
1947	57.1	58	46.8%	19.1	105	84.7%	4
1948	55.7	103	83.1%	24.7	76	61.3%	4
1949	55.0	119	96.0%	30.0	51	41.1%	3
1950	55.3	116	93.5%	31.4	43	34.7%	3
1951	56.6	78	62.9%	38.4	23	18.5%	3
1952	56.0	98	79.0%	44.6	7	5.6%	3
1953	55.6	109	87.9%	24.4	78	62.9%	4
1954	56.4	89	71.8%	23.8	83	66.9%	4
1955	54.8	121	97.6%	23.9	82	66.1%	4
1956	55.6	108	87.1%	39.7	21	16.9%	3
1957	57.0	59	47.6%	22.2	89	71.8%	4
1958	**57.8**	**29**	**23.4%**	**50.1**	**4**	**3.2%**	2
1959	**58.1**	**20**	**16.1%**	**24.8**	**75**	**60.5%**	1
1960	57.3	51	41.1%	21.4	97	78.2%	4
1961	56.9	68	54.8%	17.8	113	91.1%	4
1962	55.4	111	89.5%	27.5	66	53.2%	4
1963	56.7	74	59.7%	33.7	33	26.6%	3
1964	56.0	99	79.8%	19.0	106	85.5%	4
1965	56.6	77	62.1%	30.6	45	36.3%	3
1966	56.7	75	60.5%	20.5	100	80.6%	4
1967	56.8	70	56.5%	40.0	20	16.1%	3

Water Year	Temperature Average (°F)	Temperature Rank	Temperature Probability of Exceedance	Precipitation Total (inches)	Precipitation Rank	Precipitation Probability of Exceedance	Classification 1 = Warm & dry 2 = Warm & wet 3 = Cooler & dry 4 = Cooler & wet
1968	57.4	43	34.7%	21.5	96	77.4%	4
1969	55.7	107	86.3%	44.9	6	4.8%	3
1970	57.7	32	25.8%	30.2	49	39.5%	3
1971	56.1	94	75.8%	27.2	69	55.6%	4
1972	56.6	79	63.7%	19.1	104	83.9%	4
1973	56.5	85	68.5%	43.7	9	7.3%	3
1974	55.8	101	81.5%	42.0	17	13.7%	3
1975	55.7	104	83.9%	24.3	79	63.7%	4
1976	56.7	76	61.3%	15.4	117	94.4%	4
1977	**57.4**	**44**	**35.5%**	**14.8**	**118**	**95.2%**	**4**
1978	**58.3**	**14**	**11.3%**	**37.6**	**24**	**19.4%**	**2**
1979	**56.5**	**87**	**70.2%**	**29.2**	**54**	**43.5%**	**3**
1980	**57.4**	**48**	**38.7%**	**37.1**	**25**	**20.2%**	**3**
1981	**57.7**	**31**	**25.0%**	**21.7**	**92**	**74.2%**	**4**
1982	**56.7**	**73**	**58.9%**	**48.1**	**5**	**4.0%**	**3**
1983	**58.2**	**18**	**14.5%**	**53.9**	**3**	**2.4%**	**2**
1984	**58.8**	**11**	**8.9%**	**24.0**	**81**	**65.3%**	**1**
1985	**57.0**	**63**	**50.8%**	**29.7**	**52**	**41.9%**	**3**
1986	**57.4**	**46**	**37.1%**	**41.0**	**18**	**14.5%**	**3**
1987	**58.0**	**24**	**19.4%**	**15.9**	**116**	**93.5%**	**1**
1988	**58.5**	**13**	**10.5%**	**18.7**	**107**	**86.3%**	**1**
1989	**57.1**	**56**	**45.2%**	**24.2**	**80**	**64.5%**	**4**
1990	**57.9**	**27**	**21.8%**	**16.8**	**115**	**92.7%**	**1**
1991	**56.5**	**86**	**69.4%**	**20.4**	**102**	**82.3%**	**4**
1992	**59.3**	**6**	**4.8%**	**27.5**	**65**	**52.4%**	**1**
1993	**58.2**	**19**	**15.3%**	**36.7**	**27**	**21.8%**	**2**
1994	**57.6**	**38**	**30.6%**	**22.7**	**87**	**70.2%**	**4**
1995	**57.6**	**37**	**29.8%**	**43.0**	**11**	**8.9%**	**3**
1996	**59.0**	**8**	**6.5%**	**31.5**	**42**	**33.9%**	**2**
1997	**59.1**	**7**	**5.6%**	**36.6**	**28**	**22.6%**	**2**
1998	**57.9**	**28**	**22.6%**	**59.8**	**2**	**1.6%**	**2**
1999	**55.4**	**112**	**90.3%**	**33.7**	**34**	**27.4%**	**3**
2000	**57.7**	**34**	**27.4%**	**36.4**	**29**	**23.4%**	**3**
2001	**56.6**	**83**	**66.9%**	**25.5**	**73**	**58.9%**	**4**
2002	**56.4**	**88**	**71.0%**	**28.8**	**56**	**45.2%**	**3**
2003	**58.1**	**21**	**16.9%**	**29.1**	**55**	**44.4%**	**2**
2004	**58.2**	**16**	**12.9%**	**24.5**	**77**	**62.1%**	**1**
2005	**57.5**	**41**	**33.1%**	**43.6**	**10**	**8.1%**	**3**
2006	**57.4**	**47**	**37.9%**	**42.5**	**13**	**10.5%**	**3**
2007	**57.1**	**53**	**42.7%**	**17.6**	**114**	**91.9%**	**4**

Water Year	Temperature			Precipitation			Classification 1 = Warm & dry 2 = Warm & wet 3 = Cooler & dry 4 = Cooler & wet
	Average (°F)	Rank	Probability of Exceedance	Total (inches)	Rank	Probability of Exceedance	
2008	**56.9**	**66**	**53.2%**	**25.0**	**74**	**59.7%**	**4**
2009	**58.2**	**17**	**13.7%**	**22.4**	**88**	**71.0%**	**1**
2010	**57.2**	**52**	**41.9%**	**30.8**	**44**	**35.5%**	**3**
2011	**57.0**	**65**	**52.4%**	**40.1**	**19**	**15.3%**	**3**
2012	**57.5**	**40**	**32.3%**	**20.7**	**99**	**79.8%**	**4**
2013	**59.4**	**5**	**4.0%**	**18.0**	**112**	**90.3%**	**1**
2014	**60.5**	**2**	**1.6%**	**14.4**	**119**	**96.0%**	**1**
2015	**62.2**	**1**	**0.8%**	**21.7**	**93**	**75.0%**	**1**
2016	**59.6**	**3**	**2.4%**	**32.6**	**40**	**32.3%**	**2**

Bold records denote water years included in the catalog for future climate scenario generation

Appendix B

Proposed Climate Scenarios

The Weighted Temperature Scenario with Precipitation Adjustment columns only show those water years where records are manually adjusted to be drier. For the remaining years, data from the Weighted Temperature Scenario apply.

	Weighted Temperature Scenario					Weighted Temperature Scenario with Precipitation Adjustment (Drier)				
		Temperature		Precipitation			Temperature		Precipitation	
Model Water Year	Historic Water Year	Average (°F)	Probability of Exceedance	Average (inches)	Probability of Exceedance	Historic Year if changed	Average (°F)	Probability of Exceedance	Average (inches)	Probability of Exceedance
1	2016	59.6	2.4%	32.6	32.3%					
2	1992	59.3	4.8%	27.5	52.4%					
3	2015	62.2	0.8%	21.7	75.0%					
4	2010	57.2	41.9%	30.8	35.5%					
5	2014	60.5	1.6%	14.4	96.0%					
6	2016	59.6	2.4%	32.6	32.3%					
7	2004	58.2	12.9%	24.5	62.1%					
8	2003	58.1	16.9%	29.1	44.4%					
9	2015	62.2	0.8%	21.7	75.0%					
10	2013	59.4	4.0%	18.0	90.3%					
11	1990	57.9	21.8%	16.8	92.7%					
12	2015	62.2	0.8%	21.7	75.0%					
13	1986	57.4	37.1%	41.0	14.5%					
14	1991	56.5	69.4%	20.4	82.3%					
15	1997	59.1	5.6%	36.6	22.6%	1984	58.8	8.9%	24.0	65.3%
16	2014	60.5	1.6%	14.4	96.0%					
17	1992	59.3	4.8%	27.5	52.4%					
18	2014	60.5	1.6%	14.4	96.0%					
19	1984	58.8	8.9%	24.0	65.3%					
20	2015	62.2	0.8%	21.7	75.0%					
21	2013	59.4	4.0%	18.0	90.3%					
22	2013	59.4	4.0%	18.0	90.3%					
23	1992	59.3	4.8%	27.5	52.4%					
24	1934	58.0	17.7%	18.4	87.9%					
25	1983	58.2	14.5%	53.9	2.4%	2009	58.2	13.7%	22.4	71.0%
26	1992	59.3	4.8%	27.5	52.4%					
27	2015	62.2	0.8%	21.7	75.0%					
28	2014	60.5	1.6%	14.4	96.0%					

Model Water Year	Weighted Temperature Scenario					Weighted Temperature Scenario with Precipitation Adjustment (Drier)				
		Temperature		Precipitation			Temperature		Precipitation	
	Historic Water Year	Average (°F)	Probability of Exceedance	Average (inches)	Probability of Exceedance	Historic Year if changed	Average (°F)	Probability of Exceedance	Average (inches)	Probability of Exceedance
29	1980	57.4	38.7%	37.1	20.2%					
30	2003	58.1	16.9%	29.1	44.4%					
31	2006	57.4	37.9%	42.5	10.5%					
32	2015	62.2	0.8%	21.7	75.0%					
33	2013	59.4	4.0%	18.0	90.3%					
34	1958	57.8	23.4%	50.1	3.2%	1990	57.9	21.8%	16.8	92.7%
35	2016	59.6	2.4%	32.6	32.3%					
36	2009	58.2	13.7%	22.4	71.0%					
37	2015	62.2	0.8%	21.7	75.0%					
38	1999	55.4	90.3%	33.7	27.4%					
39	2015	62.2	0.8%	21.7	75.0%					
40	2015	62.2	0.8%	21.7	75.0%					
41	1992	59.3	4.8%	27.5	52.4%					
42	2016	59.6	2.4%	32.6	32.3%					
43	2014	60.5	1.6%	14.4	96.0%					
44	1977	57.4	35.5%	14.8	95.2%					
45	2015	62.2	0.8%	21.7	75.0%					
46	1992	59.3	4.8%	27.5	52.4%					
47	2014	60.5	1.6%	14.4	96.0%					
48	1998	57.9	22.6%	59.8	1.6%	1990	57.9	21.8%	16.8	92.7%
49	2013	59.4	4.0%	18.0	90.3%					
50	1992	59.3	4.8%	27.5	52.4%					
51	1992	59.3	4.8%	27.5	52.4%					
52	1989	57.1	45.2%	24.2	64.5%					
53	2016	59.6	2.4%	32.6	32.3%					
54	1984	58.8	8.9%	24.0	65.3%					

APPENDIX 2-H
COMPARISON OF CLIMATE CHANGE SCENARIOS MEMORANDUM

TECHNICAL MEMORANDUM

DATE: July 17, 2018

TO: Ron Duncan, Santa Cruz Mid-County Groundwater Agency

FROM: Georgina King, John Mejia, and Cameron Tana

PROJECT: Santa Cruz Mid-County Basin Groundwater Model

SUBJECT: Comparison of Climate Change Scenarios

1. BACKGROUND

For the Santa Cruz Mid-County Basin (Basin) Groundwater Flow Model using GSFLOW, we plan to run predictive simulations of groundwater management alternatives for the Santa Cruz Mid-County Groundwater Agency (MGA) using future climate change scenarios. One future climate change scenario based on a catalog of historical climate years has already been developed for the MGA (HydroMetrics WRI, 2016) but we are scoped to also run simulations using projections of climate change downscaled to the Basin. Simulations based on climate change projections are considered important for planning because projections generally have warmer temperatures than the historical record which could have a significant effect on the water resources of the Basin. There are a number of options available for climate change projections. This technical memorandum compares the suite of projections available.

Climate change projections are made primarily on the basis of coupled atmosphere-ocean Global Circulation Model (GCM) simulations under a range of future emission scenarios. Currently, climate projections used in climate change analysis are based on climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The predecessor to CMIP5 was CMIP3.

Climate models in the CMIP5 use a set of emission scenarios called representative concentration pathways (RCPs) to reflect possible trajectories of greenhouse gas (GHG) emissions throughout this century. Each RCP defines a specific emissions trajectory and subsequent radiative forcing (a radiative forcing measures the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system).

For purposes of quantifying benefits or adverse impacts that could result from water storage projects proposed for the Water Storage Investment Program (WSIP) in California (California Water Commission, 2016), technical assistance included recommendations for the use of climate change projections. Twenty climate scenario-model combinations were selected based on recommendations by the California Department of Water Resources' (DWR) Climate Change Technical Advisory Group that they are the most appropriate for California water resources. The climate scenario-model combinations compose 10 global circulation models run with two emission scenarios: one optimistic (RCP 4.5) that stabilizes shortly after 2100 and one pessimistic (RCP 8.5) that is characterized by continuing increased GHG emissions over time.

Included in our comparison is the City of Santa Cruz's (City) climate change projection. The City, since 2008, uses CMIP3 GCM data adopted and made available by the CalAdapt program as the basis for their hydrologic and climate change modeling (Stratus, 2015). Specifically, they have selected the GFDL2.1 GCM for the A2 emissions scenario, which is the worst-case climate change dataset in the CalAdapt dataset. Under a subcontract to Pueblo Water Resources Inc., we have performed bias corrected spatial downscaling (Mejia et al., 2012) of the GFDL2.1-A2 projections to the climate stations in the Basin for use as input to represent climate for Water Years 2020-2069. We are currently using this climate input to simulate City of Santa Cruz Aquifer Storage and Recovery (ASR) preliminary alternatives.

A comparison of climate change projections will lead to a decision on what GCM projections should be used by the MGA for its simulations, including those simulations to guide the Basin's Groundwater Sustainability Plan (GSP). One option is the GFDL2.1-A2, which has already been downscaled to the Basin. If different GCM(s) are deemed appropriate, downscaling of those GCM(s) to climate stations in the Basin will be required to use with the Basin GSFLOW model.

2. COMPARISON OF DATASETS

Downscaling is commonly used to refine the coarse scale of GCM data to local regions. The CMIP5 ensemble of CGMs area available as downscaled projections using local constructed analogs (LOCA) for California on a 6 kilometer grid (Pierce, Cayan, and Dehann, 2016). WSIP used these downscaled projections for its set of 20 climate scenario-model combinations. Although further downscaling from LOCA, similar to what has been done for the GFDL2.1-A2 projection used by the City of Santa Cruz, will be required for the Basin GSFLOW model, we evaluated data from the LOCA cell in which the Santa Cruz Co-Op climate station is located, to compare climate change projections for the Basin region (Figure 1).

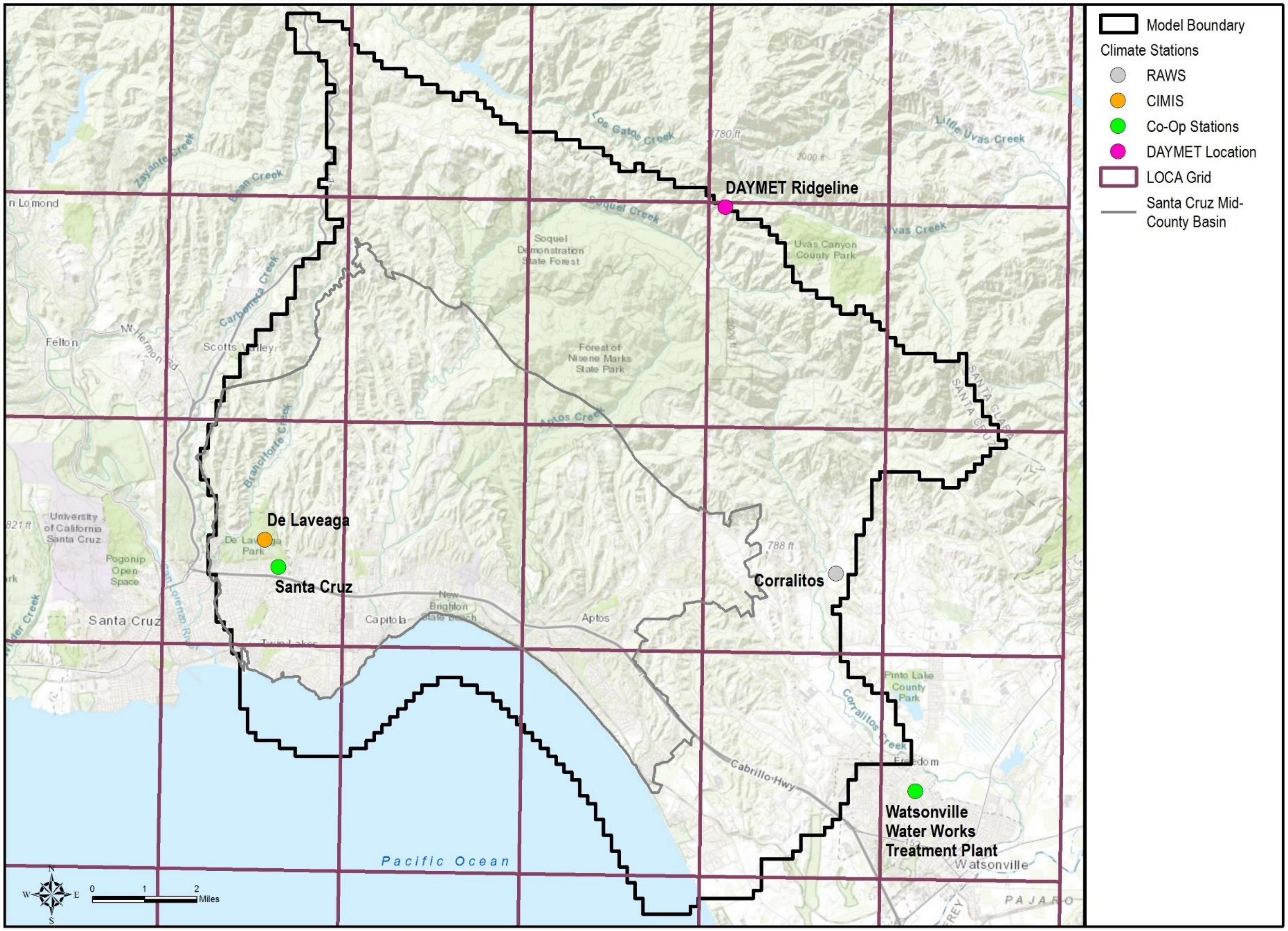


Figure 1. LOCA Grids in the Santa Cruz Area

Our comparison includes all available CMIP5 scenarios. The two different RCPs are compared separately, as are the 20 WSIP emission scenarios. Change in average precipitation, and minimum and maximum temperatures comparisons are summarized in Table 1. The values in the table represent changes between average projected 2020-2069 GCM climate and average reference historical 1984-2015 GCM climate for the grid cell. Comparing modeled results for these time periods are meant to represent the expected change in downscaled climate for a future period versus the Basin GSFLOW model calibration period of 1985-2015. Figure 2 plots the individual scenarios with a line connecting the average minimum and maximum temperature changes against a percentage change in average precipitation for each emission scenario.

Table 1: Climate Change 2020-2069 Compared to Reference Historical 1984-2015 Period

Scenario	Average Precipitation (%)	Average Minimum Temperature (°F)	Average Maximum Temperature (°F)
CMIP5 all	3.16	2.68	2.59
CMIP5 all RCP4.5	1.68	2.35	2.26
CMIP5 all RCP8.5	4.66	3.02	2.91
CMIP5 WSIP	1.79	2.82	2.74
CMIP5 WSIP RCP4.5	0.47	2.48	2.45
CMIP5 WSIP RCP8.5	3.11	3.16	3.04
CMIP3-GFDL-CM-A2 downscaled at Santa Cruz Co-op Station	-1.46	1.2	2.2
Catalog at Santa Cruz Co-op Station	-10.2	0.78	2.29

Notes: Historical Reference for CMIP5 is GCM results for 1984-2015
Historical reference for GFDL and Catalog is 1984-2015 dataset at Santa Cruz Co-op station.

The California Department of Water Resources (DWR) has stated they will use the ensemble of WSIP scenarios as the basis for climate change projections provided to local Groundwater Sustainability Agencies for sustainable groundwater management planning (Hatch, 2017). Personal communication with Tyler Hatch of DWR’s Sustainable Groundwater Management Branch, indicated that for sustainable groundwater planning, DWR will accept a climate change scenario that was more conservative than the WSIP ensemble, i.e., hotter and drier.

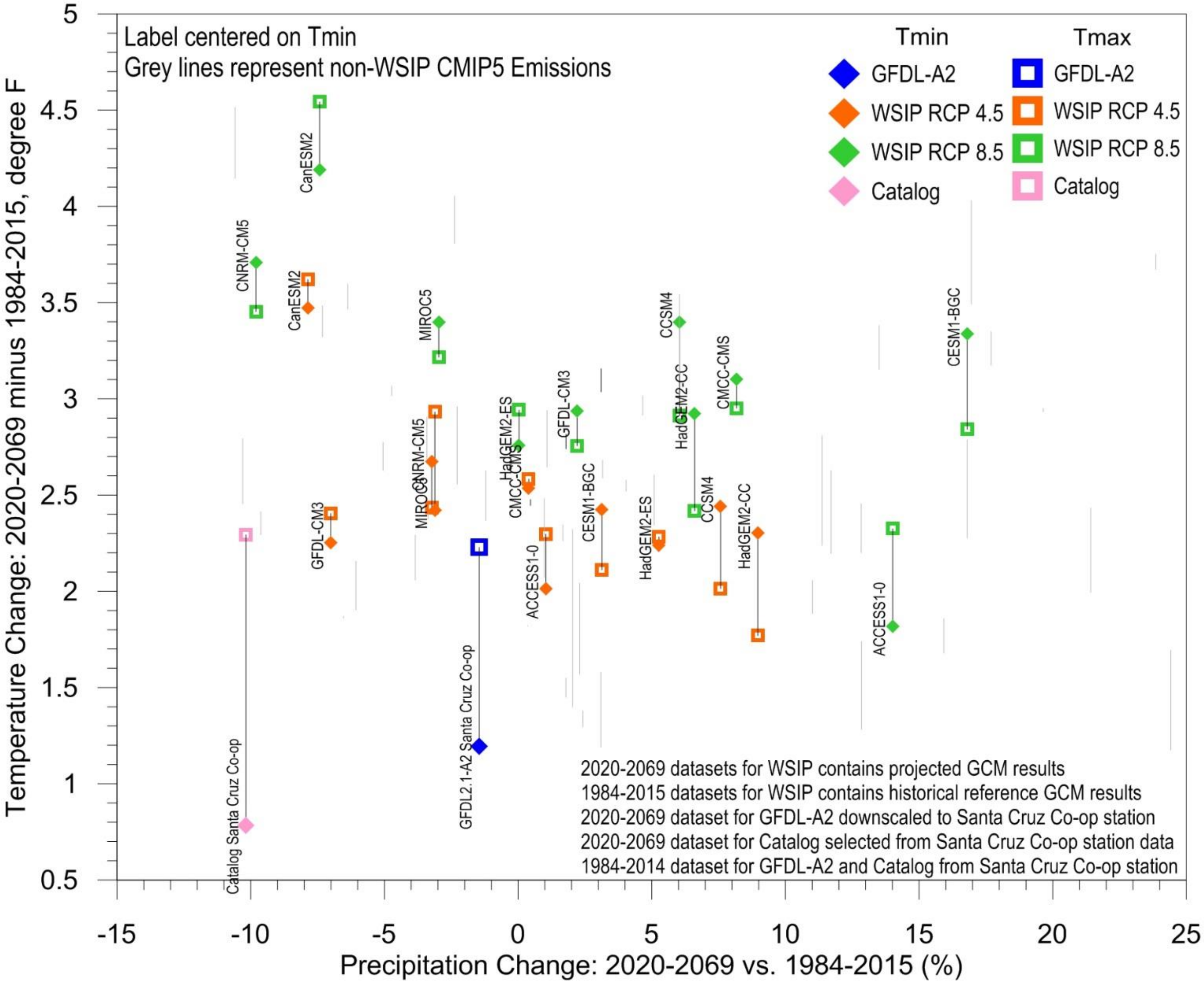


Figure 2. Climate Change 2020-2069 with Respect to Reference Period 1984-2015 for All CMIP5 Emissions

2.1. Precipitation Comparison

Average precipitation increases over 1984 – 2015 precipitation in all groups of CMIP5 scenarios (Table 1). The RCP 4.5 scenarios have lower precipitation increases than the RCP 8.5 scenarios. The WSIP scenarios have lower precipitation increases than the combined CMIP5 scenarios. Median daily precipitation plotted for each year (Figure 3) shows an increasing trend in the precipitation to 2069. Monthly averages of precipitation changes between 2020-2069 and 1984-2015 show only little change or increases every month for medians of all groups of CMIP5 scenarios. December through March precipitation increases in the WSIP scenarios is generally higher than the combined CMIP5 scenarios (Figure 4). The other months have similar daily precipitation changes.

Daily precipitation from the City's GFDL-A2 scenario compared to the full combination of WSIP scenarios is slightly wetter, with 2.04% more precipitation than 1984-2015 reference precipitation (Table 1). There is a notable reduction in precipitation after 2069, which is after our planned GSFLOW model period (Figure 3). GFDL-A2 precipitation from March through May has less precipitation than the reference historical period and less than the CMIP5 scenarios, however September, October, and February precipitation has greater increases than the CMIP5 scenarios (Figure 4).

2.2. Minimum Temperature Comparison

As expected, all RCP 8.5 scenarios are warmer than RCP 4.5 scenarios because of the projected increasing emissions that characterize those scenarios. The combined 20 WSIP scenarios' minimum temperature increases are overall greater than the full complement of CMIP5 scenarios, and more noticeably so in the RCP 8.5 group (Table 1). Figure 5 shows that the median RCP 8.5 minimum temperatures depart from temperatures in the other groups of scenarios around 2056 with an increasing trend.

GFDL-A2 average annual projections of minimum temperature are lower than median CMIP5 temperatures around 2038 and 2060 (Figure 5). Overall, this results in average minimum temperature increases than are lower than all other CMIP5 groups of scenarios (Table 1). Monthly averages for minimum temperatures are higher in all months for median RCP 8.5 emission scenarios than median RCP 4.5 emission scenarios. The average monthly minimum temperatures show less temperature increase in the GFDL-A2 scenario than the CMIP5 scenarios, except from May to August where they are more comparable to the RCP 4.5 scenarios (Figure 6).

2.3. Maximum Temperature Comparison

Similar to minimum temperatures, the combined 20 WSIP scenarios' maximum temperatures are overall slightly warmer than the full complement of CMIP5 maximum temperatures (Table 1). The months of June through October are when the WSIP scenario maximum temperature increases are noticeably greater than the combined CMIP5 scenarios (Figure 8).

Figure 7 shows that the GFDL-A2 scenario maximum temperatures follows the general trend of the WSIP RCP 8.5 emission scenarios better than other scenarios. However, similar to minimum temperature, around 2038 and 2060, the projection of maximum temperature falls below most CMIP5 scenarios (Figure 7). Overall, the average maximum temperature increases for the GFDL-A2 scenario are lower than the WSIP maximum temperatures increases. Monthly averages for maximum temperatures are higher in all months for median RCP 8.5 emission scenarios than median RCP 4.5 emission scenarios. The monthly distribution of average maximum monthly temperatures also show higher temperature increases in the GFDL-A2 scenario than the CMIP5 scenarios from May through August, and generally lower temperature increases in the other months (Figure 8).

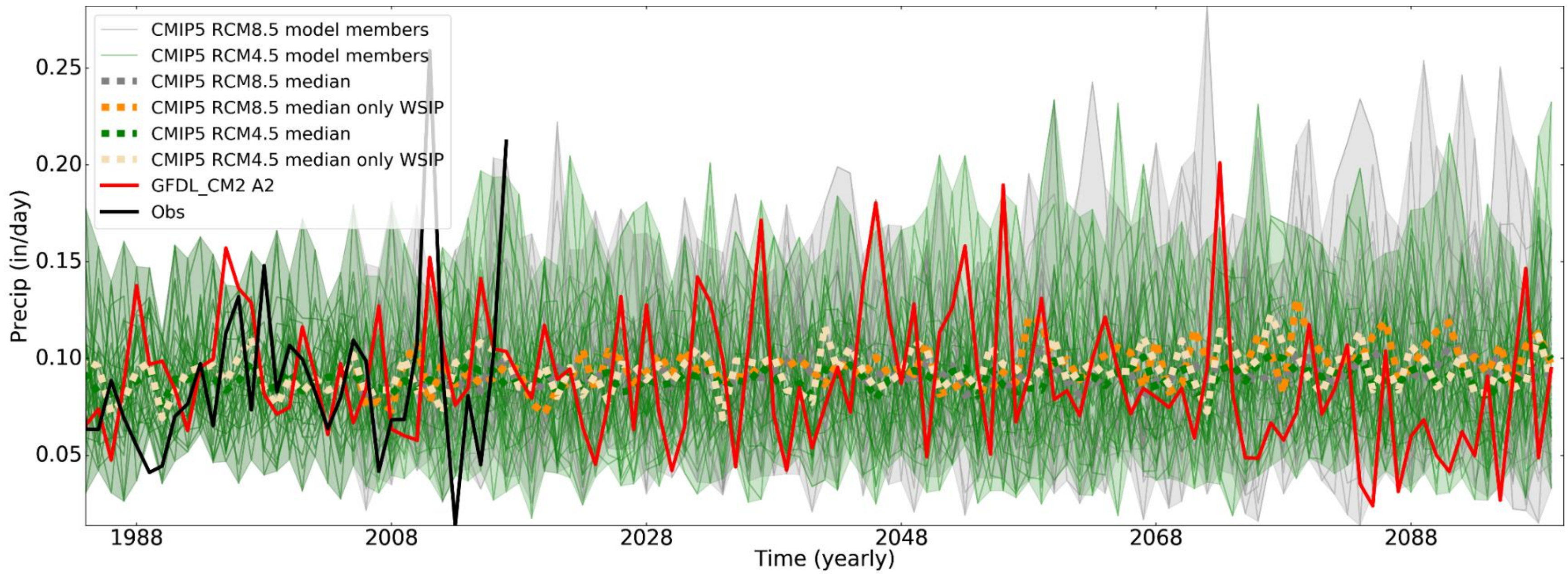


Figure 3. Average Annual Daily Projections for Precipitation

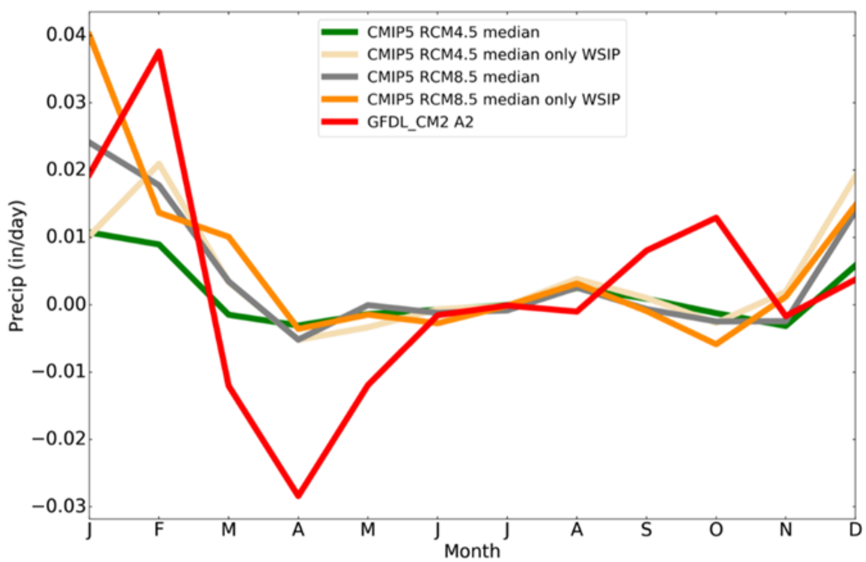


Figure 4. Average Monthly Projections for Precipitation Changes between 2020-2069 and 1985-2015

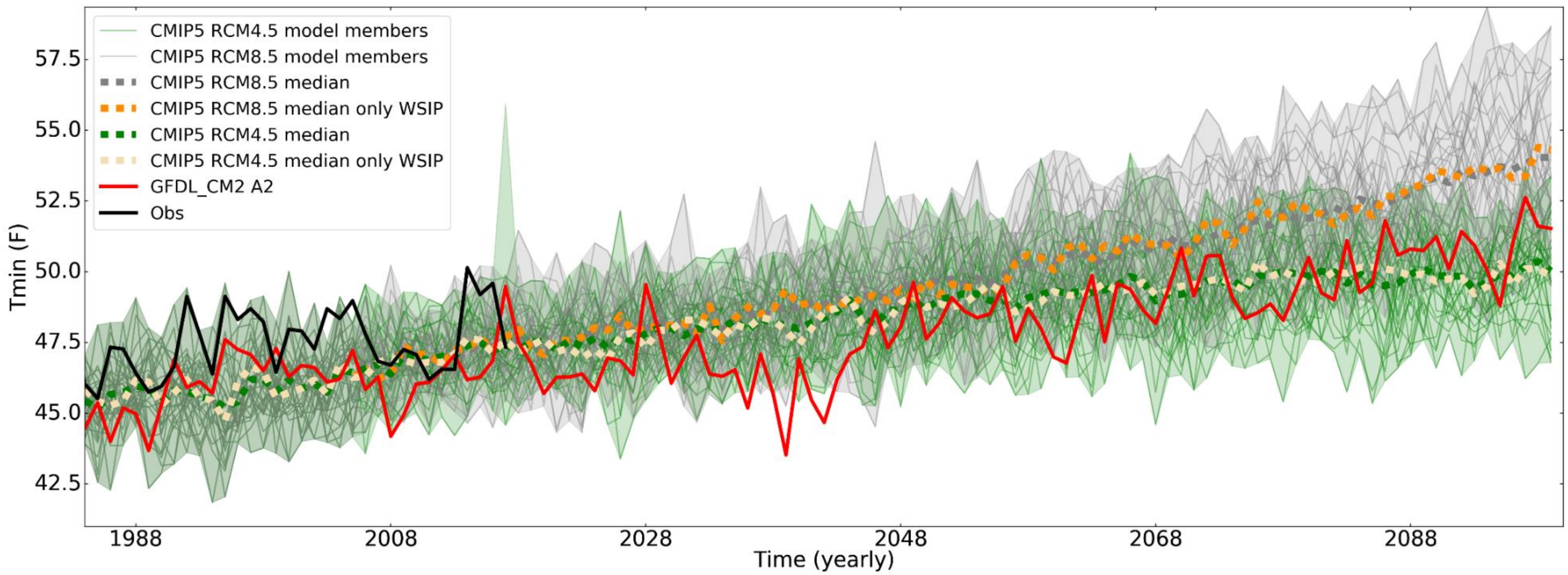


Figure 5. Average Annual Daily Projections for Minimum Temperature (Tmin)

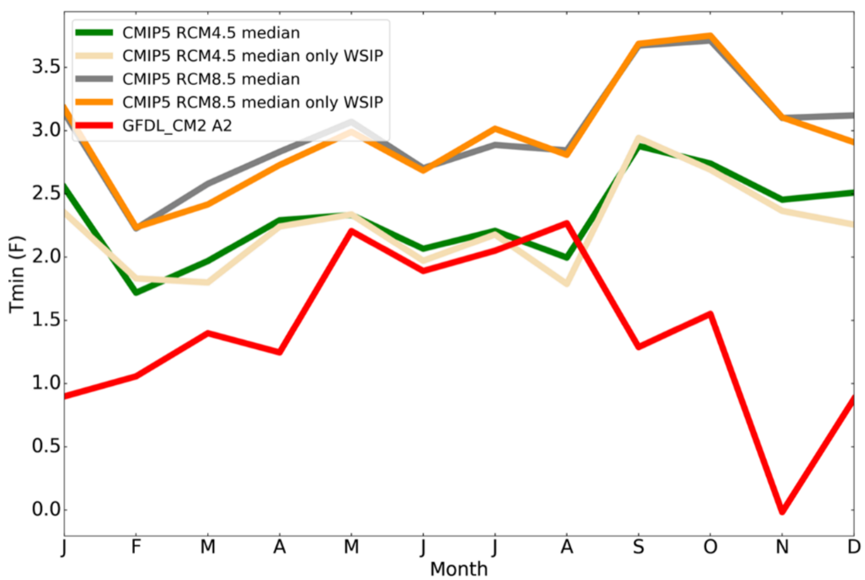


Figure 6. Average Monthly Projections for Minimum Temperature (Tmin) Changes between 2020-2069 and 1985-2015

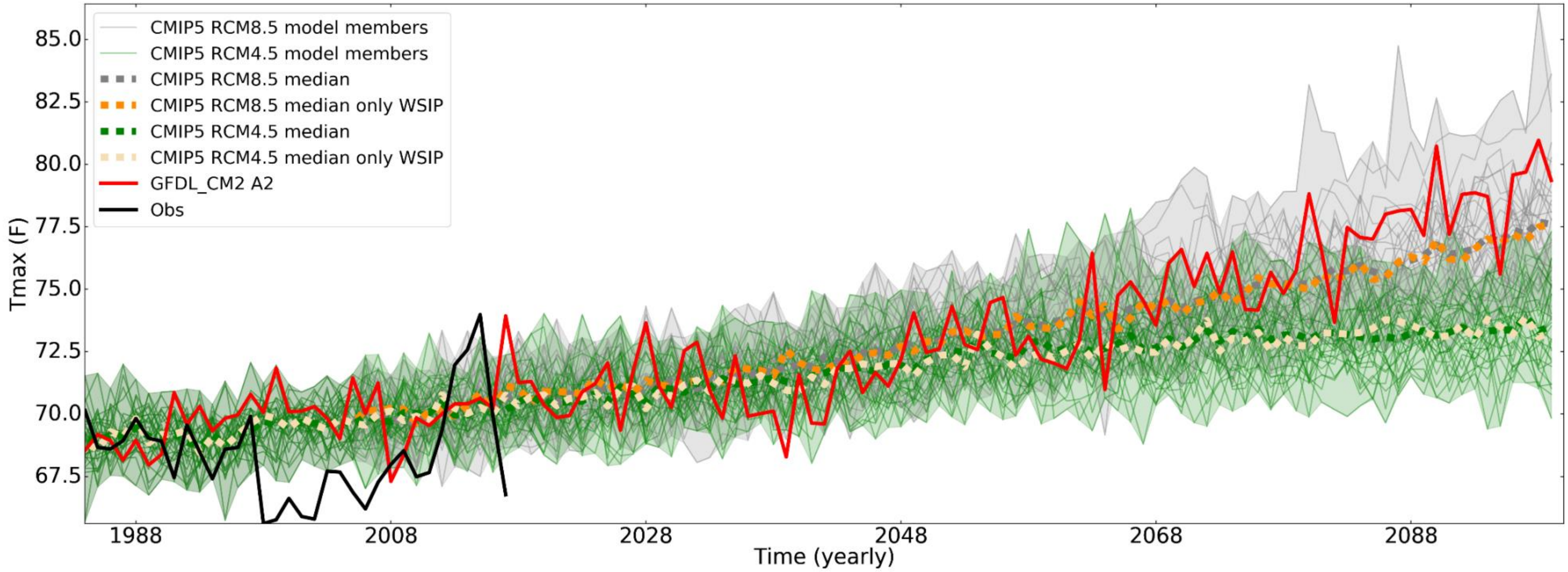


Figure 7. Average Annual Daily Projections for Maximum Temperature (Tmax)

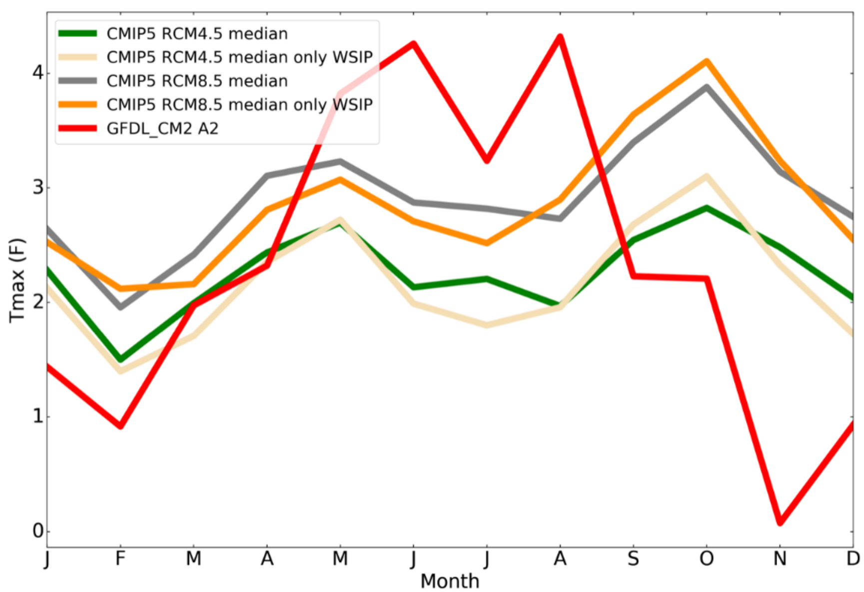


Figure 8. Average Monthly Projections for Maximum Temperature (Tmax) Changes between 2020-2069 and 1985-2015

3. CONCLUSIONS AND RECOMMENDATIONS

3.1. Conclusions

1. All projected average scenario ensembles (CMIP5 and WSIP) are wetter than the reference historical period.
2. The WSIP emission scenarios are drier and warmer than the combined CMIP5 scenarios.
3. The City's GFDL-A2 scenario is both wetter and cooler than many WSIP scenarios, although its maximum temperatures are warmer than WSIP RCP 4.5 scenarios.

3.2. Recommendations

It is expected that for groundwater sustainability planning, DWR will accept a climate change scenario that is more conservative than the WSIP ensemble, i.e., hotter and drier. Since the City's GFDL-A2 scenario does not fulfill this condition, a potential alternative needs to be selected. Although most projections show an increase in precipitation, we recommend selecting a projection that shows a decrease in precipitation. This will contribute to the robustness of groundwater sustainability planning by taking into account the possibility that water supply is reduced. Any projection that shows higher than average increases in temperature than the WSIP ensemble should also meet the requirements for groundwater sustainability planning.

We recommend selecting a scenario from the one of the 20 WSIP scenarios. WISP scenarios that are potential candidates are: MIROC5 RCP 8.5, CanESM2 RCP 4.5, CanESM2 RCP 8.5, and CNRM-CM5 RCP 8.5. These are shown on to have lower projected average precipitation than the reference historical period and higher temperatures than most other CMIP5 scenarios.

- CanESM2 RCP 8.5, CanESM2 RCP 4.5, and CNRM-CM5 RCP 8.5 are extreme scenarios that have over 7% less precipitation and some of the highest temperatures of all projections (Figure 2); such an extreme selection may not be justified.
- A fourth less extreme option is MIROC5 RCP 8.5 has 3% less precipitation than the reference historical period, and average temperatures that are higher than the majority of other scenarios.

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APPENDIX 2-I

IMPLEMENTATION AND ANALYSIS OF PROJECTS AND MANAGEMENT ACTIONS IN MODEL SENARIOS AS PART OF GROUNDWATER SUSTAINABILITY PLAN DEVELOPMENT

November 15, 2019

Implementation and Analysis of Projects and Management Actions in Model Scenarios as Part of Groundwater Sustainability Plan Development

Prepared for:

Santa Cruz Mid-County Groundwater Agency

Prepared by:

Montgomery & Associates

1970 Broadway, Oakland, California

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