

# Sonoma County Groundwater Recharge Analysis

## Introduction

Developing accurate estimates of the spatial and temporal distribution of groundwater recharge is a key component of sustainable groundwater management. Efforts to quantify recharge are inherently difficult owing to the wide variability of controlling hydrologic processes, the wide range of available tools/methods for estimating recharge, and the difficulty in assessing the accuracy of estimates because direct measurement of recharge rates is, for the most part, infeasible.

Numerical modeling is a common approach for developing recharge estimates. Soil-water-balance modeling is one category of numerical models particularly well-suited for estimating recharge across large areas with modest data requirements. This study describes an application of the U.S. Geological Survey's (USGS) Soil Water Balance Model (SWB) (Westenbroek et al., 2010) to develop spatial and temporal distributions of groundwater recharge across Sonoma County. Hydrologically connected portions of Marin County, including the San Antonio Creek and Walker Creek watersheds, were also included in the model domain. This model operates on a daily timestep and calculates surface runoff based on the Natural Resources Conservation Service (NRCS) curve number method, actual evapotranspiration (AET), and recharge based on a modified Thornthwaite-Mather soil-water-balance approach (Westenbroek et al., 2010).

It is important to note that the SWB model focuses on surface and soil-zone processes and does not simulate the groundwater system or track groundwater storage over time. The model also does not simulate surface water/groundwater interaction or baseflow; thus, the runoff estimates represent only the surface runoff component of streamflow resulting from rainstorms and the recharge estimates represent only the infiltration recharge component (also referred to as diffuse recharge) of total recharge (stream-channel recharge is not simulated).

## Model Development

The model was developed using a 1 arc-second (90.8-ft) resolution rectangular grid. Water budget calculations were made on a daily time step. Key spatial inputs included a flow direction map developed from the USGS 1 arc-second resolution Digital Elevation Model (DEM), a land cover dataset derived from the Sonoma County Veg Map Lifeform dataset supplemented by the U.S. Forest Service (USFS) CALVEG dataset for portions of Marin County (Figure 1), a distribution of Hydrologic Soil Groups (A through D classification from lowest to highest runoff potential; Figure 2), and a distribution of Available Water Capacity (AWC) developed from the NRCS Soil Survey Geographic Database (SSURGO) (Figure 3).

A series of model parameters were assigned for each land cover type/soil group combination including a curve number, dormant and growing season interception storage values, and a rooting depth (Table 1). Curve numbers were assigned based on standard NRCS methods. Interception storage values and rooting depths were assigned based on literature values and



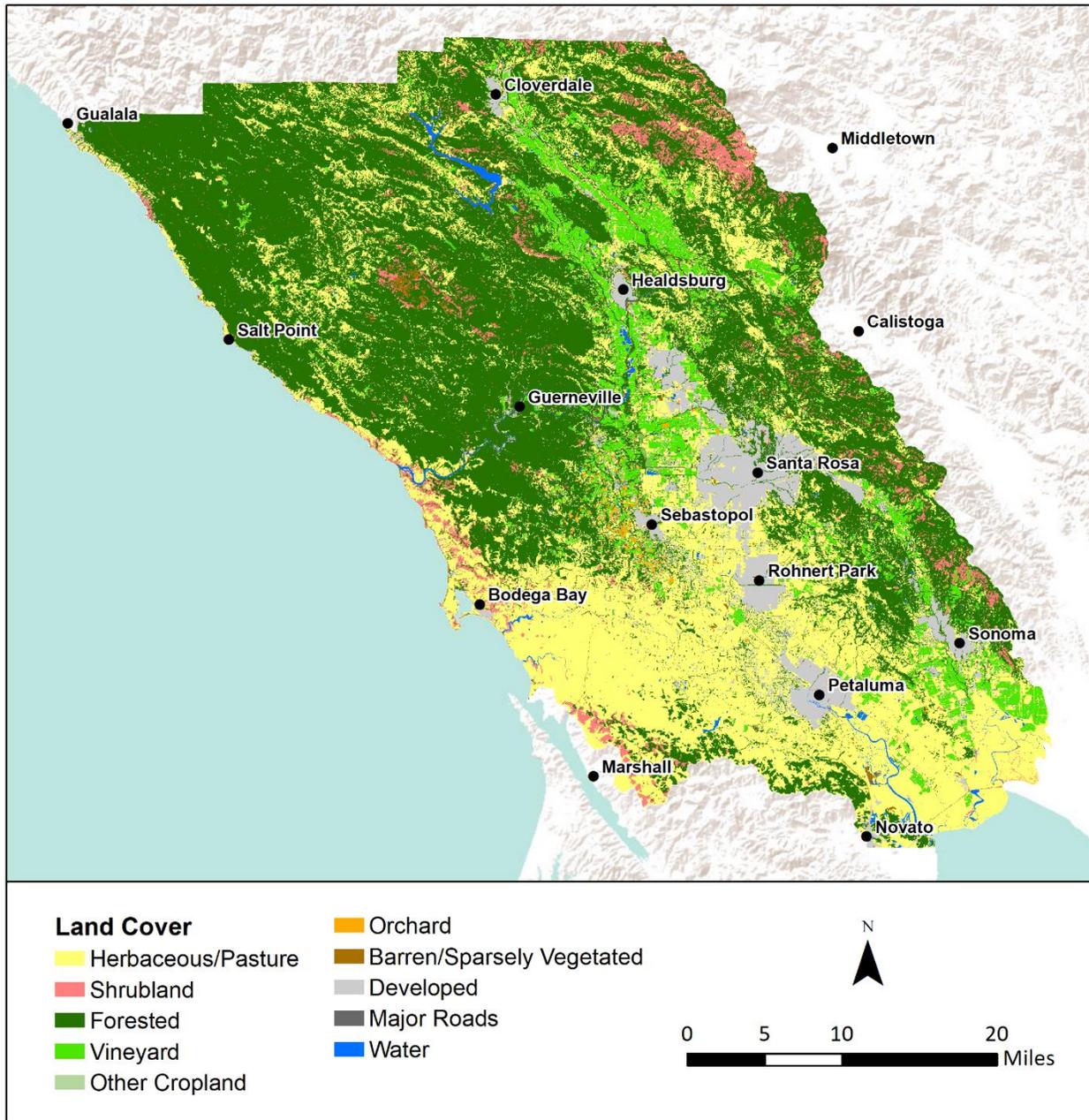


Figure 1: Land cover map used in the Sonoma County SWB model.

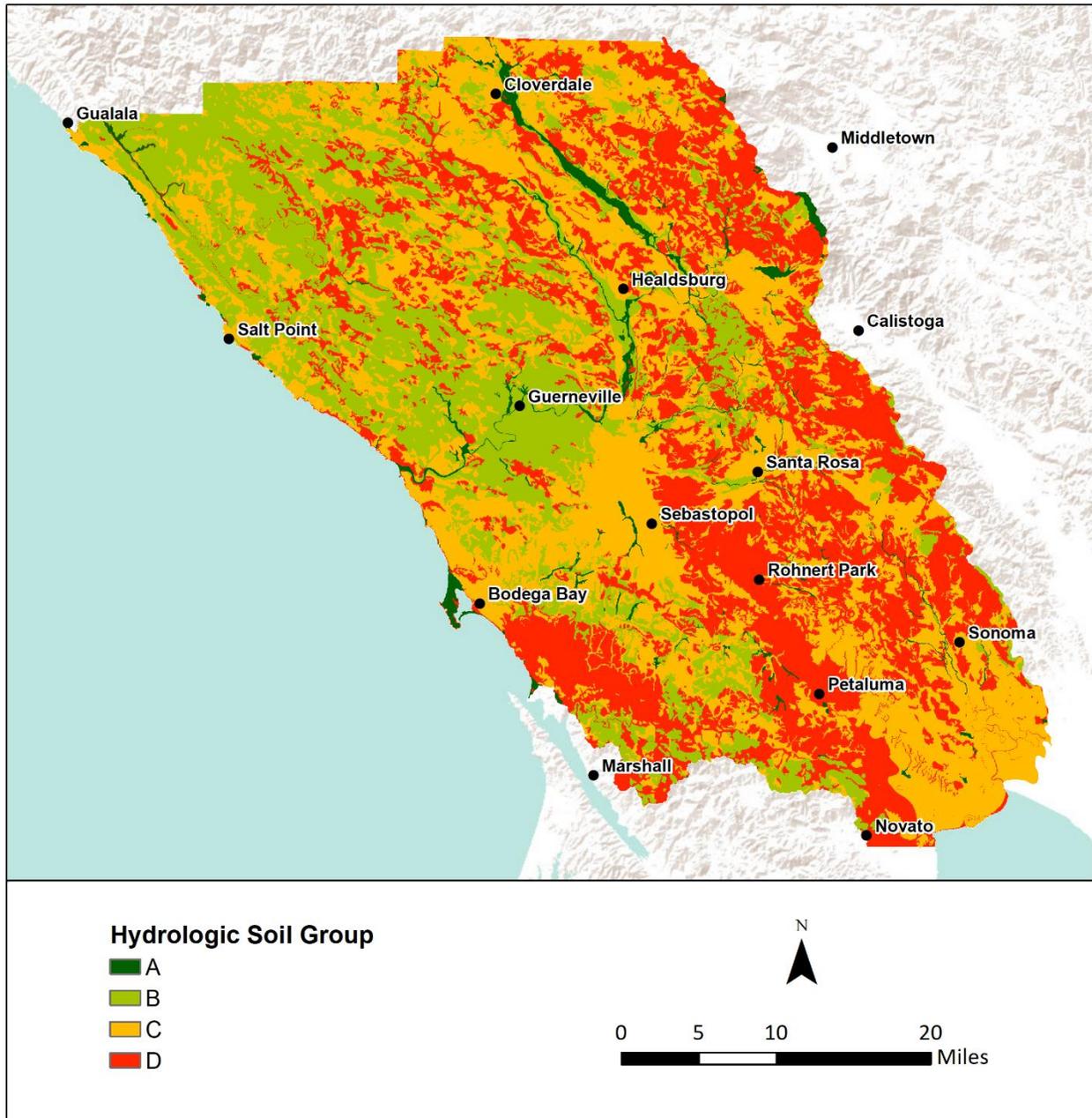


Figure 2: Hydrologic soil group map used in the Sonoma County SWB model.

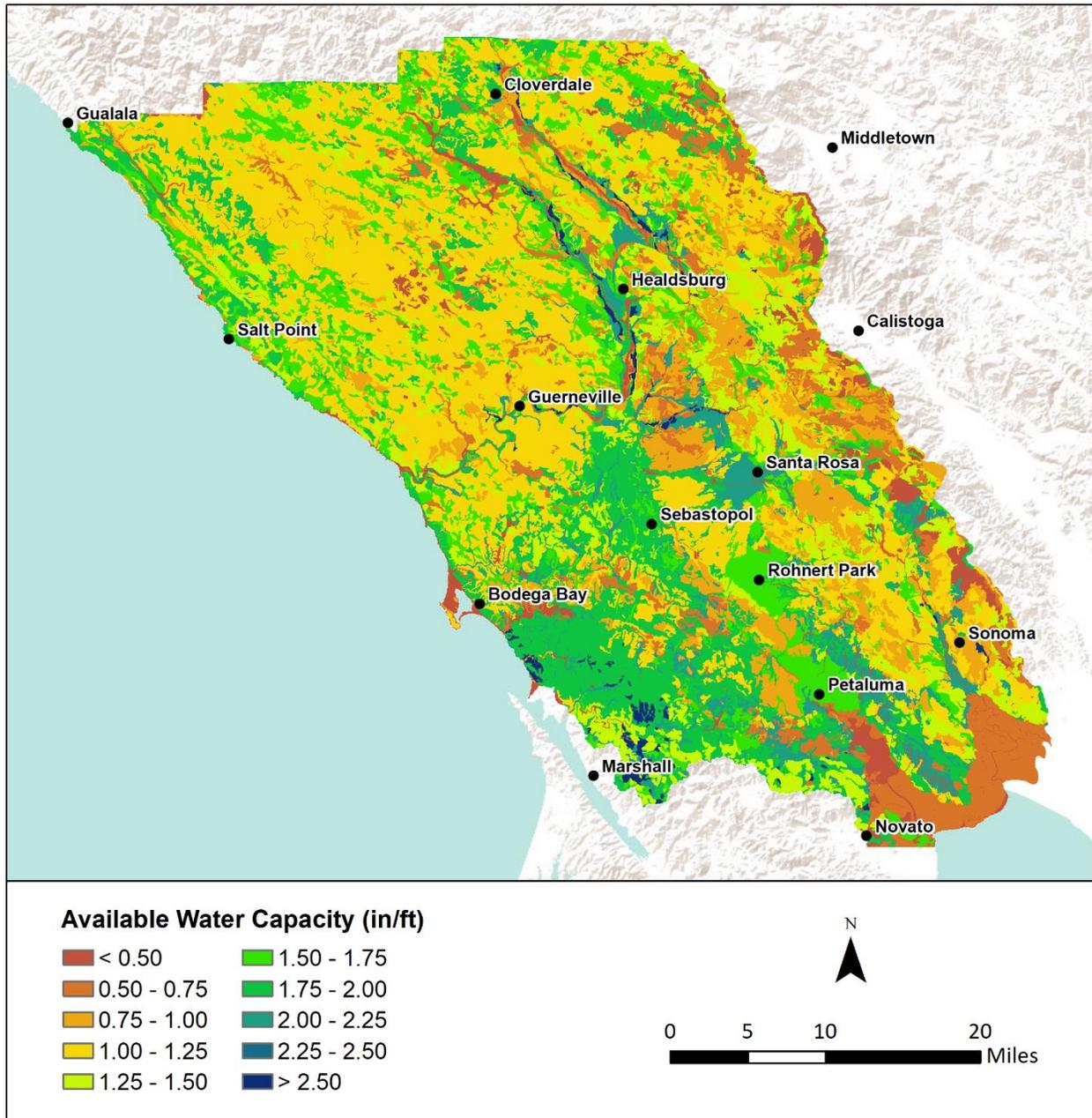


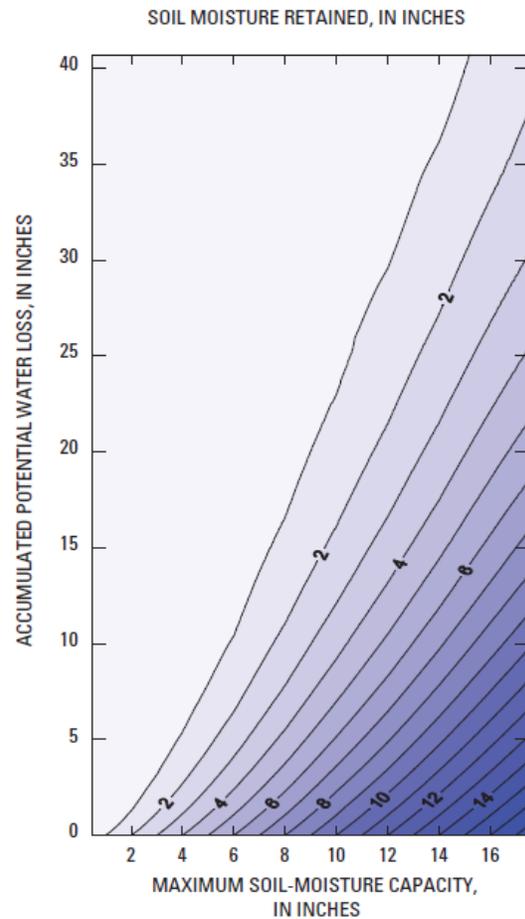
Figure 3: Available water capacity map used in the Sonoma County SWB model.

**Table 1: Soil and land cover properties used in the Sonoma County SWB model.**

Land Cover	Curve Number				Interception Storage Values		Rooting Depth (ft)			
	A Soils	B Soils	C Soils	D Soils	Growing Season	Dormant Season	A Soils	B Soils	C Soils	D Soils
	Herbaceous	30	58	71	78	0.005	0.004	1.3	1.1	1.0
Shrubland	30	48	65	73	0.080	0.015	3.2	2.8	2.7	2.6
Forested	30	55	70	77	0.050	0.020	5.9	5.1	4.9	4.7
Vineyard	38	61	75	81	0.080	0.015	2.2	2.1	2.0	1.9
Other Cropland	38	61	75	81	0.080	0.040	2.0	1.9	1.8	1.7
Orchard	38	61	75	81	0.050	0.015	3.2	2.8	2.7	2.6
Barren	77	86	91	94	0.000	0.000	0.7	0.6	0.5	0.4
Developed	61	75	83	87	0.005	0.002	2.3	2.1	2.0	1.8
Major Roads	77	85	90	92	0.005	0.002	0.7	0.6	0.5	0.4
Water	100	100	100	100	0.000	0.000	0.0	0.0	0.0	0.0

**Table 2: Infiltration rates for NRCS hydrologic soil groups (Cronshey et al., 1986).**

Soil Group	Infiltration Rate (in/hr)
A	> 0.3
B	0.15 - 0.3
C	0.05 - 0.15
D	<0.05



**Figure 4: Soil-moisture-retention table (Thornthwaite and Mather, 1957).**

previous modeling experience. Infiltration rates for hydrologic soil groups A through D were applied based on Cronshey et al. (1986) (Table 2) along with default soil-moisture-retention relationships based on Thornthwaite and Mather (1957) (Figure 4).

The SWB model utilizes daily precipitation and mean daily temperature data derived from climate stations. To account for the spatial variability of these parameters, daily precipitation and mean daily temperature were input as gridded time-series. The gridded precipitation time-series was created using data from 22 weather stations in Sonoma County, and the gridded mean temperature time-series was created using data from 10 stations (Table 3, Figures 5 & 6). These stations were selected based on completeness of the records and to provide station data across the range of climates experienced in the county. Temperature and precipitation data were obtained from the California Data Exchange Center (CDEC), the Western Regional Climate Center (WRCC), the National Climatic Data Center (NCDC), and data collected by O'Connor Environmental, Inc. from work on prior projects.

To create the gridded time-series, the model domain was divided into discrete areas represented by individual weather stations (Figures 7 and 8). This delineation was based on the USGS HUC-10 watersheds, local knowledge of climate variations across the county, and climate variations described by existing gridded mean annual (1981-2010) precipitation and temperature data (PRISM, 2010).

For the precipitation time-series, each area representing a weather station was subdivided into three to fifteen zones based on PRISM-derived 2-inch interval mean annual precipitation zones. The ratio of mean annual precipitation within a given zone and at a given gauge location was used to define scaling factors for each zone. The raw station data (daily precipitation) was then multiplied by the scaling factor to develop the final timeseries for each zone. The resulting gridded time-series is comprised of 215 individual time-series based on the scaled station data from the twenty-two stations.

The assignment of temperature stations was based on the understanding that the 10 available stations represent distinct climate zones in Sonoma County. Coastal climate conditions are best represented by the Fort Ross and Bodega Bay weather stations. The Occidental station is most representative of climate conditions in the coastal mountains of western Sonoma County, and the St. Helena station is most representative of conditions in the mountains of eastern Sonoma County. The remaining 6 stations all represent climate conditions in the inland valley bottom areas of the county. The temperature areas were not divided into additional zones for scaling because variations in temperatures within each representative area are expected to be relatively minor compared with the variations in precipitation; also the model sensitivity to temperature is expected to be small compared to the sensitivity to precipitation.

Missing and suspect data was encountered in the raw precipitation and temperature data from the weather stations used by the model. Values that were significantly outside the typical range and where similar outlying observations were not observed at nearby stations were removed from the datasets. These and missing values were filled using scaled data from other nearby

stations. Precipitation data was scaled using the ratio of the 1981 to 2010 mean annual precipitation (PRISM 2010) between the two stations. Temperature data was scaled using the ratio of the 1981 to 2010 mean monthly minimum and maximum temperatures (PRISM, 2010) between the two stations.

The current analysis focuses on a Water Year 2010 (October 1, 2009 – September 30, 2010). This year was selected because it represents a recent year with data available from most weather stations in the county, and the total annual rainfall was near long-term average conditions at most of the weather stations. Water year 2010 rainfall ranged from 83% of long-term average conditions at the Sonoma and Petaluma 10.1 W station to 137% at the Fort Ross station based on a comparison between the station data and the 1981-2010 average precipitation from PRISM (2010) (Table 3).

**Table 3: Weather stations used in the Sonoma County SWB model.**

Climate Zone	Station	Data Source	Data Used	1981 - 2010 Mean Annual Precip (in)	WY 2010 Precip (in)	WY 2010 Precip (% Avg.)
<b>Coastal</b>	Bodega Bay 6 WSW	NOAA accessed via NCDC	Precip. & Temp.	34.06	37.11	109%
	Fort Ross	NOAA accessed via WRCC	Precip. & Temp.	35.10	48.01	137%
<b>Western Mountains</b>	Francini Creek	OEI Project Data	Precip. Only	46.99	59.71	127%
	Geyserville 10.6 WNW	NOAA accessed via NCDC	Precip. Only	52.34	52.97	101%
	Monte Rio	NOAA accessed via NCDC	Precip. Only	48.44	51.01	105%
	Occidental	NOAA accessed via WRCC	Precip. & Temp.	55.37	57.02	103%
	Petaluma 10.1 W	NOAA accessed via NCDC	Precip. Only	37.90	31.57	83%
	SF Fuller Creek	OEI Project Data	Precip. Only	56.49	60.89	108%
	Venado	CA DWR accessed via CDEC	Precip. Only	60.14	66.01	110%
<b>Valleys</b>	Cloverdale	NOAA accessed via WRCC	Precip. & Temp.	42.63	52.65	123%
	Glen Ellen 1.5 N	NOAA accessed via NCDC	Precip. Only	36.14	46.74	129%
	Graton	NOAA from WRCC	Precip. & Temp.	41.07	45.00	110%
	Healdsburg	NOAA accessed via WRCC	Precip. Only	40.95	47.65	116%
	Petaluma River Airport	NOAA accessed via WRCC	Precip. & Temp.	26.60	26.92	101%
	Rohnert Park 0.9 SW	NOAA accessed via NCDC	Precip. Only	33.36	34.73	104%
	Santa Rosa	CAL Fire accessed via CDEC	Precip. & Temp.	31.90	39.55	124%
	Sonoma	NOAA accessed via WRCC	Precip. & Temp.	31.77	26.35	83%
	Calistoga	NOAA accessed via WRCC	Temp. Only	na	na	na
	Warm Springs Dam	USACE accessed via CDEC	Precip. Only	43.44	53.29	123%
<b>Eastern Mountains</b>	Calistoga 4.6 WSW	NOAA accessed via NCDC	Precip. Only	39.64	44.85	113%
	Glen Ellen 1.9 WNW	NOAA accessed via NCDC	Precip. Only	49.16	46.32	94%
	Hawkeye	NOAA accessed via WRCC	Precip. Only	45.57	51.06	112%
	St. Helena 4 WSW	CA DWR accessed via CDEC	Precip. & Temp.	49.12	47.88	97%

Notes: NOAA – National Oceanic and Atmospheric Administration; CA DWR – California Department of Water Resources; NCDC- National Climate Data Center; USACE – United States Army Corps of Engineers; WRCC – Western Regional Climate Center; CDEC – California Data Exchange Center

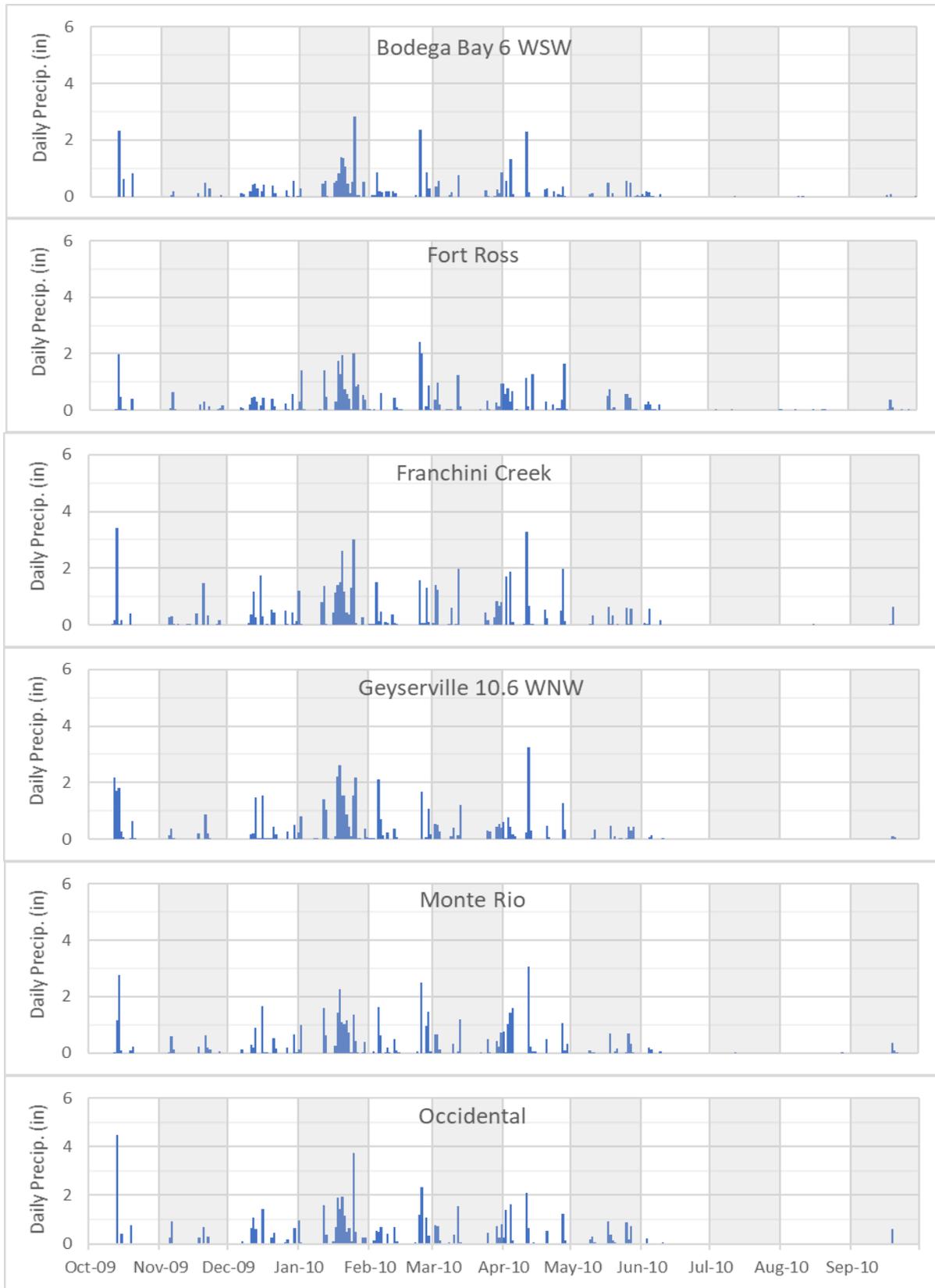


Figure 5: Daily precipitation data used in the Sonoma County SWB model.

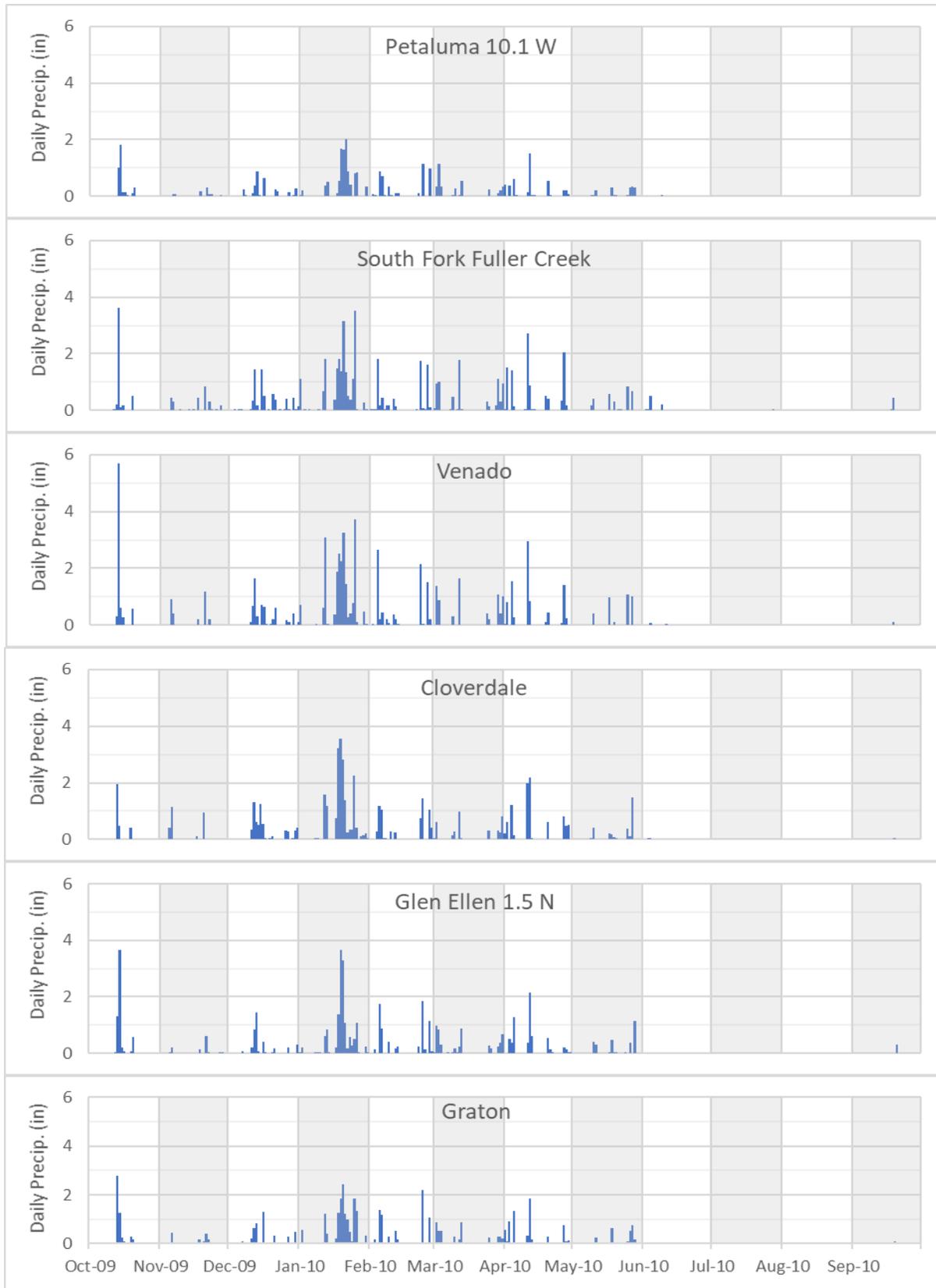


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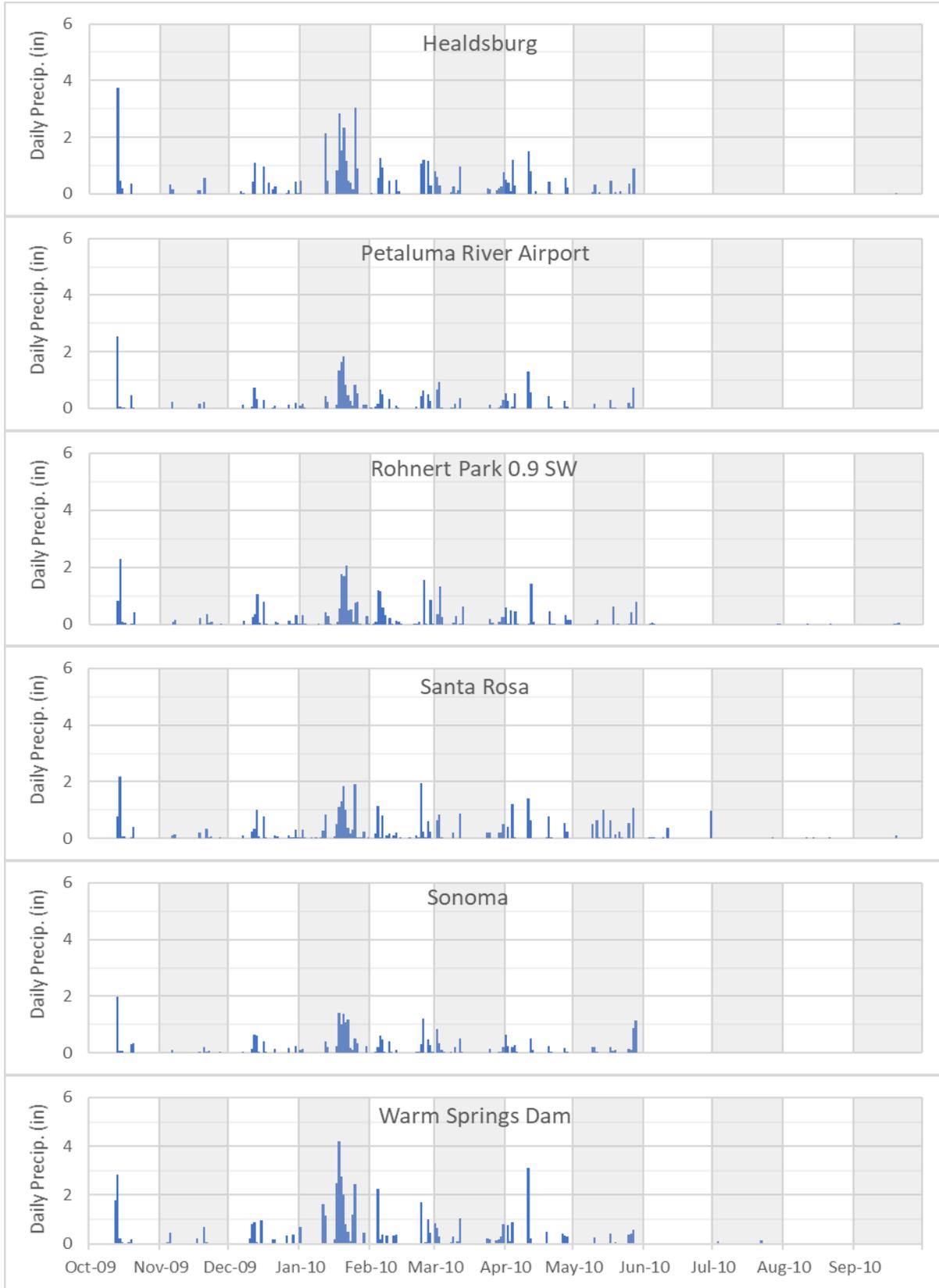


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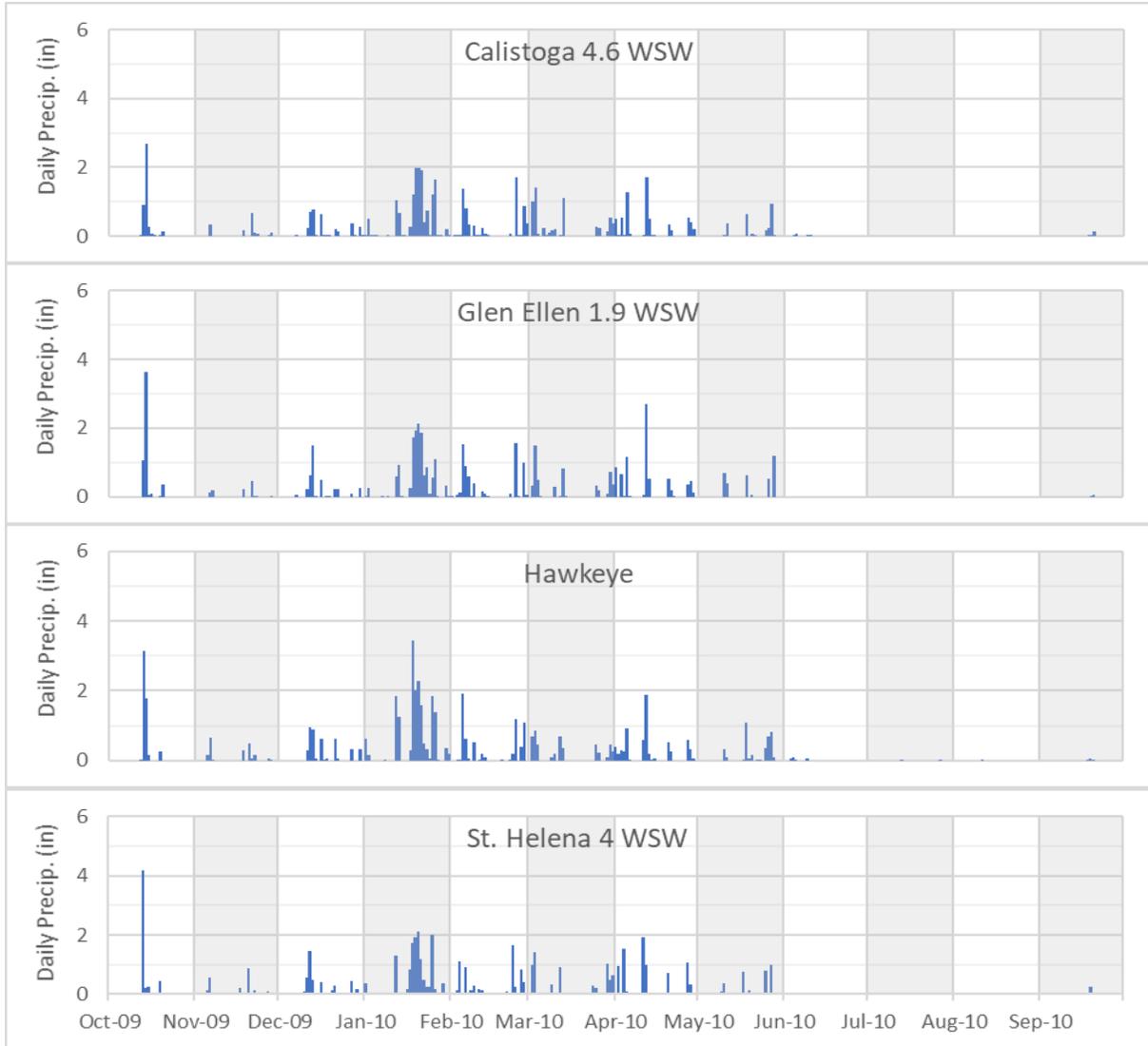


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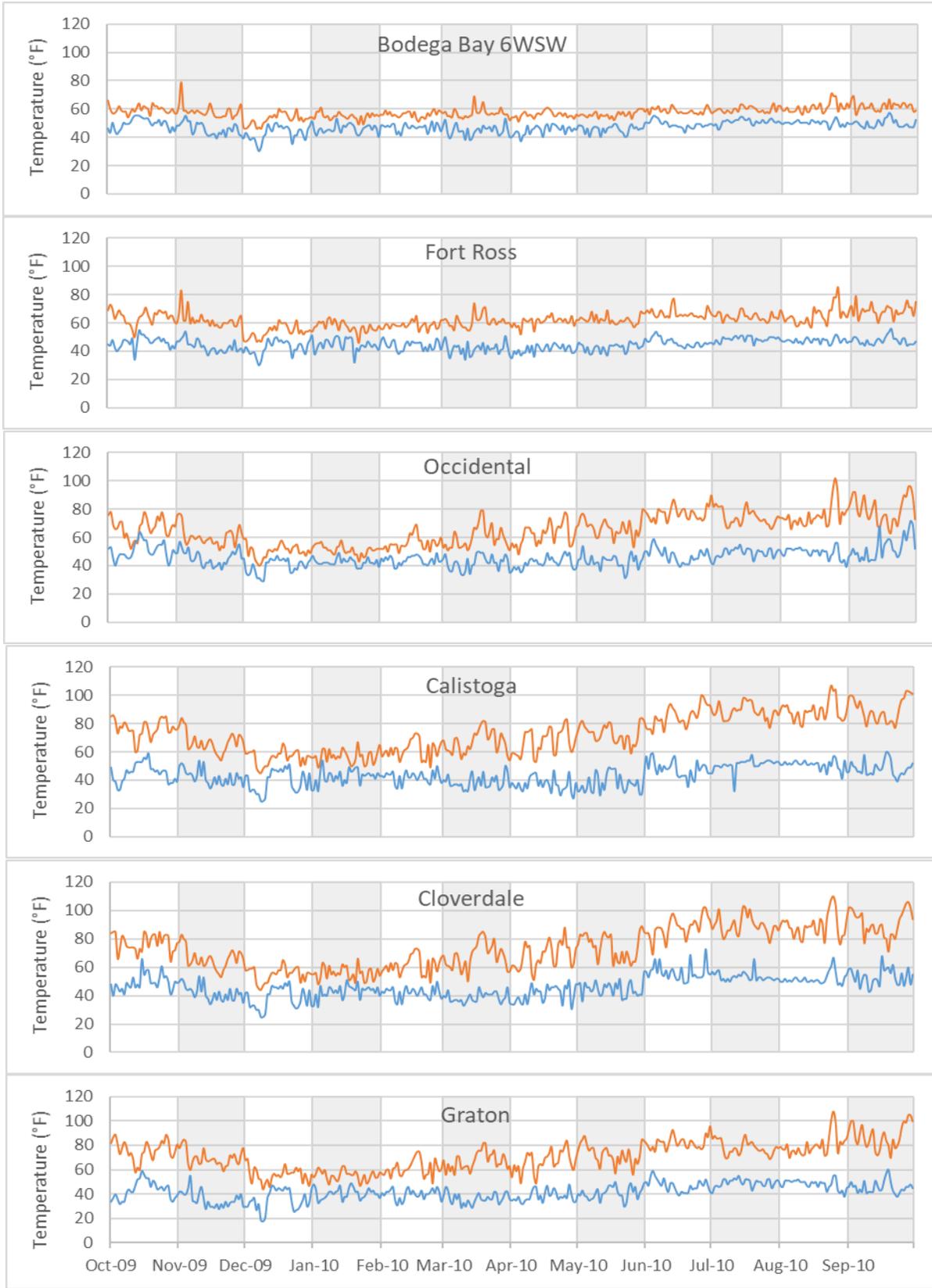


Figure 6: Daily minimum and maximum temperature data used in the Sonoma County SWB model.

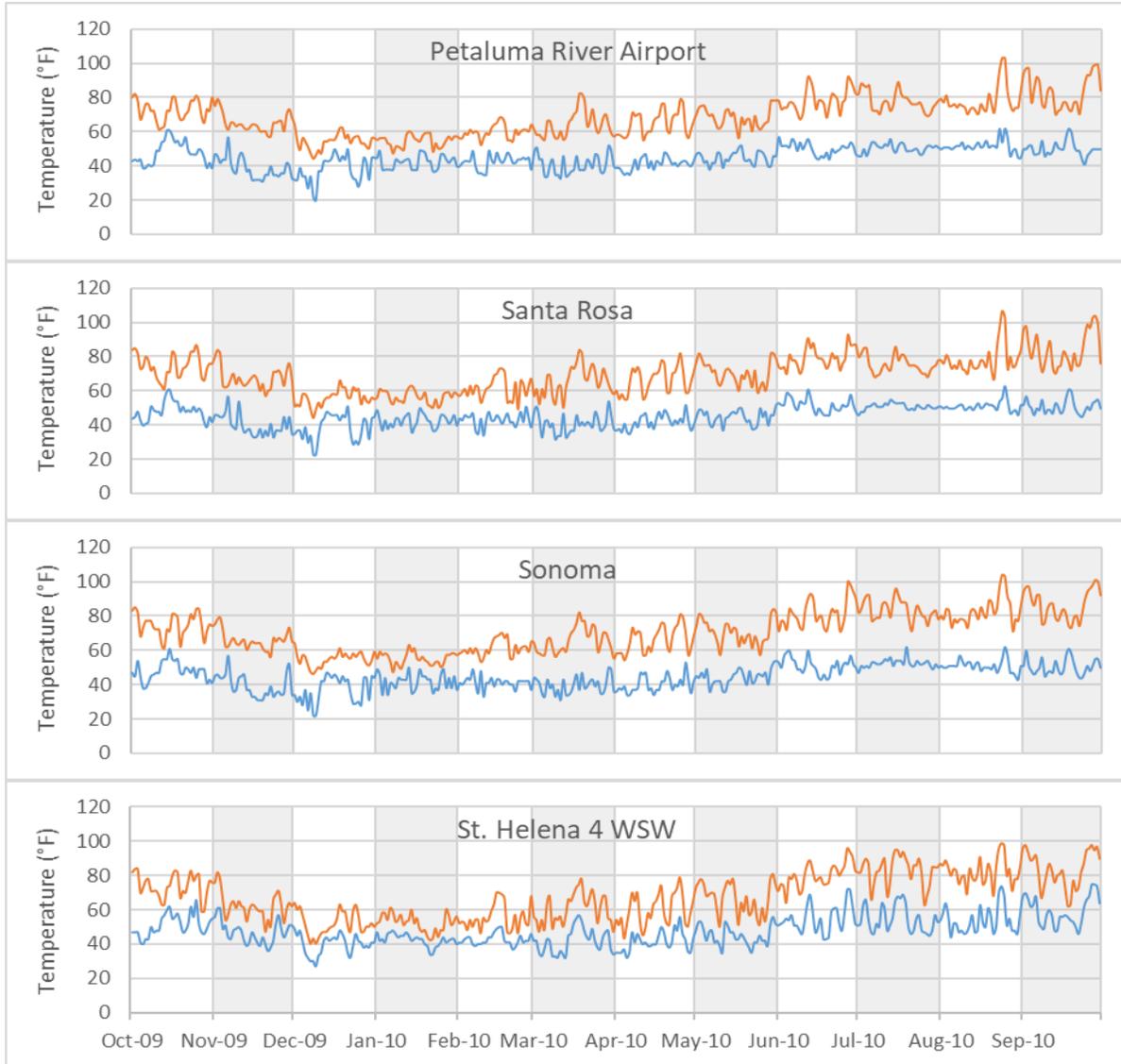


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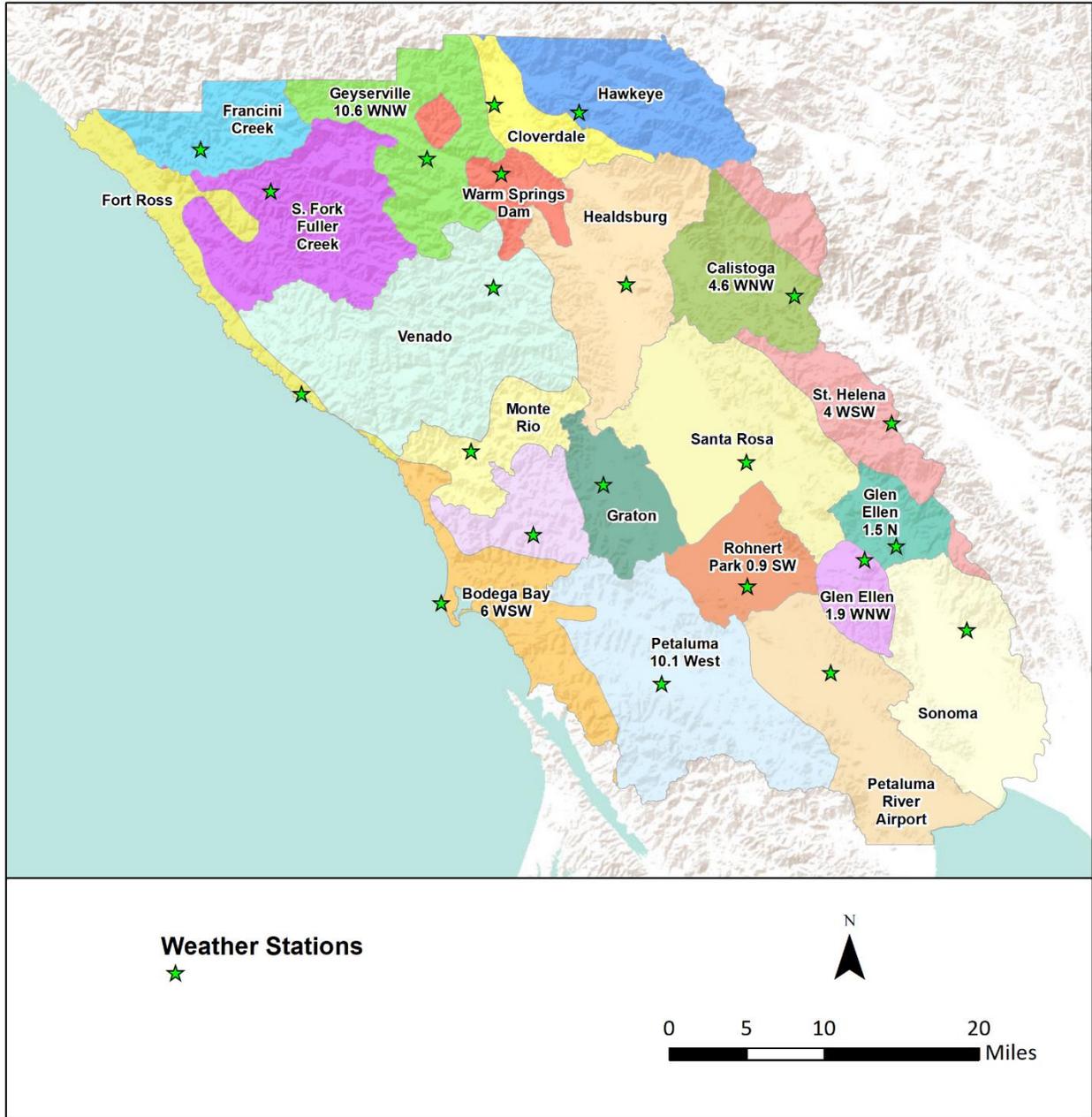


Figure 7: Precipitation zones used in the Sonoma County SWB model.

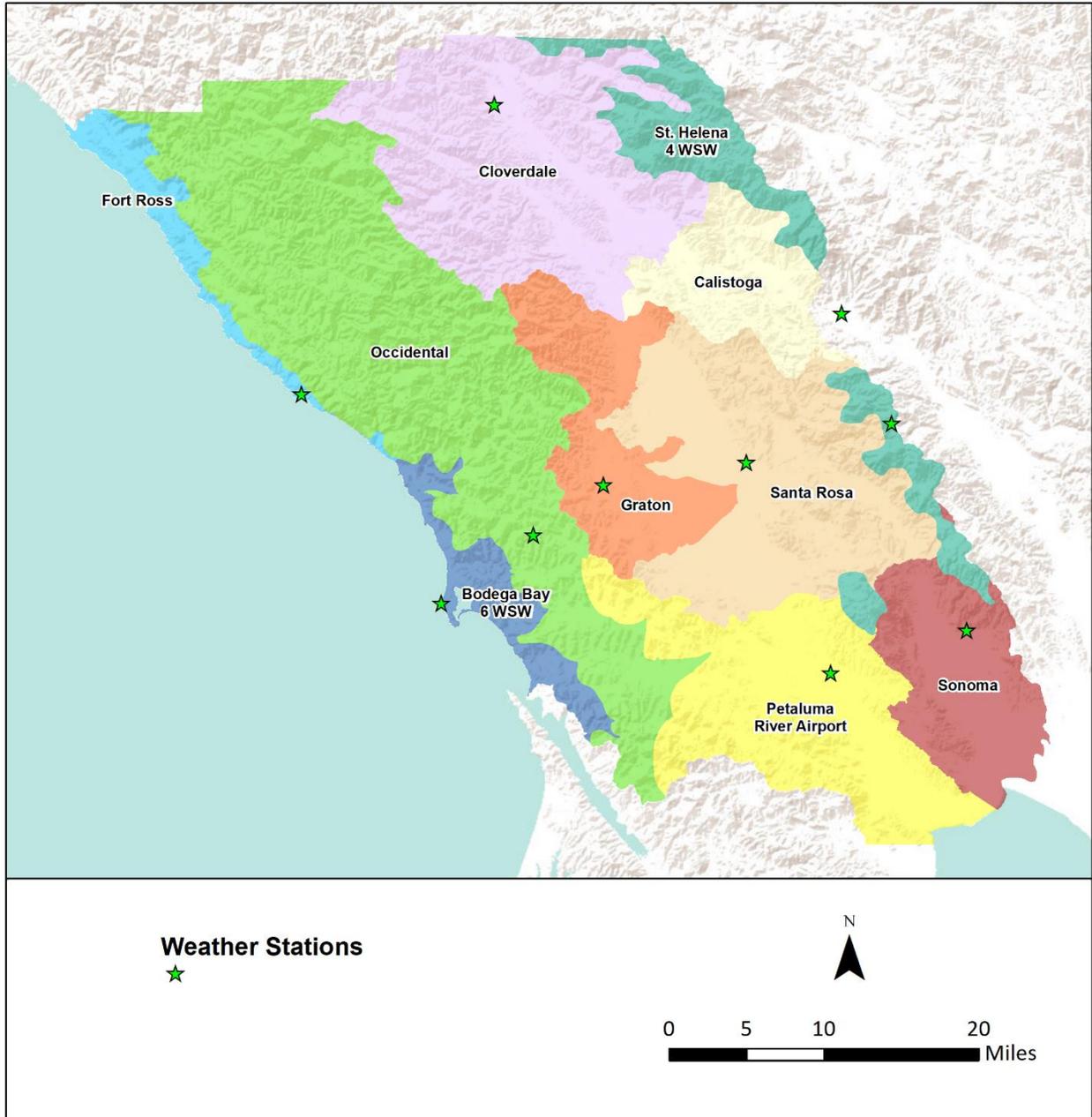


Figure 8: Temperature zones used in the Sonoma County SWB model.

## Model Calibration

To provide a means of calibrating the Sonoma County SWB model, streamflow data was compiled from five gauges with available data for water year 2010 (Figure 9, Table 4). These gauges were selected because they represent relatively small watersheds without significant urbanization, diversions, groundwater abstraction, reservoir impoundments, or large alluvial bodies where significant exchanges between surface water and groundwater may be expected. These attributes are desirable because the hydrographs can more readily be separated into surface runoff and baseflow components and the surface runoff pattern is more directly comparable to the SWB simulated surface runoff which does not account for water use, reservoir operations, or surface water/groundwater exchange. An overview of hydrograph separation methods may be found in Healy (2010, pp. 85-90).

We utilized the web-based Hydrograph Analysis Tool (Lim et al., 2005) to perform baseflow separations on the gauge records using the recursive digital filter method (Eckhardt, 2005) and default filter parameters for perennial streams with hard rock aquifers. Total monthly surface runoff volumes were compiled for each gauge and compared to the mean monthly surface runoff volumes predicted by SWB within each corresponding watershed area. SWB utilizes a simplified routing scheme whereby surface runoff is routed to downslope cells or out of the model domain on the same day in which it originates as rainfall, thus it is not capable of accurately estimating streamflow over short-time frames. The use of the total monthly surface runoff volumes provides a means of calibrating the model to measured surface runoff data within the limitations of the model's routing scheme.

The model successfully reproduced the seasonal variations in surface runoff at all five gauge locations (Figure 10). Monthly Mean Errors (ME) ranged from -0.2 to 0.4 inches with a mean value of 0.1 inches (Table 5). Monthly Root Mean Square Errors (RMSE) ranged from 0.5 to 1.5 inches with a mean value of 1.0 inches. Annual surface runoff totals ranged from an under-prediction of approximately 10% at Franchini Creek to an over-prediction of approximately 19% at Buckeye Creek, with a mean over-prediction of approximately 6% across the five stations (Table 5). These results indicate that the SWB model was able to reproduce monthly surface runoff volumes with a reasonable degree of accuracy and that the model tends to over-predict surface runoff somewhat, suggesting that the model may generate a low-range estimate of recharge.

**Table 4: Overview of the streamflow gauges used for calibrating the Sonoma County SWB model.**

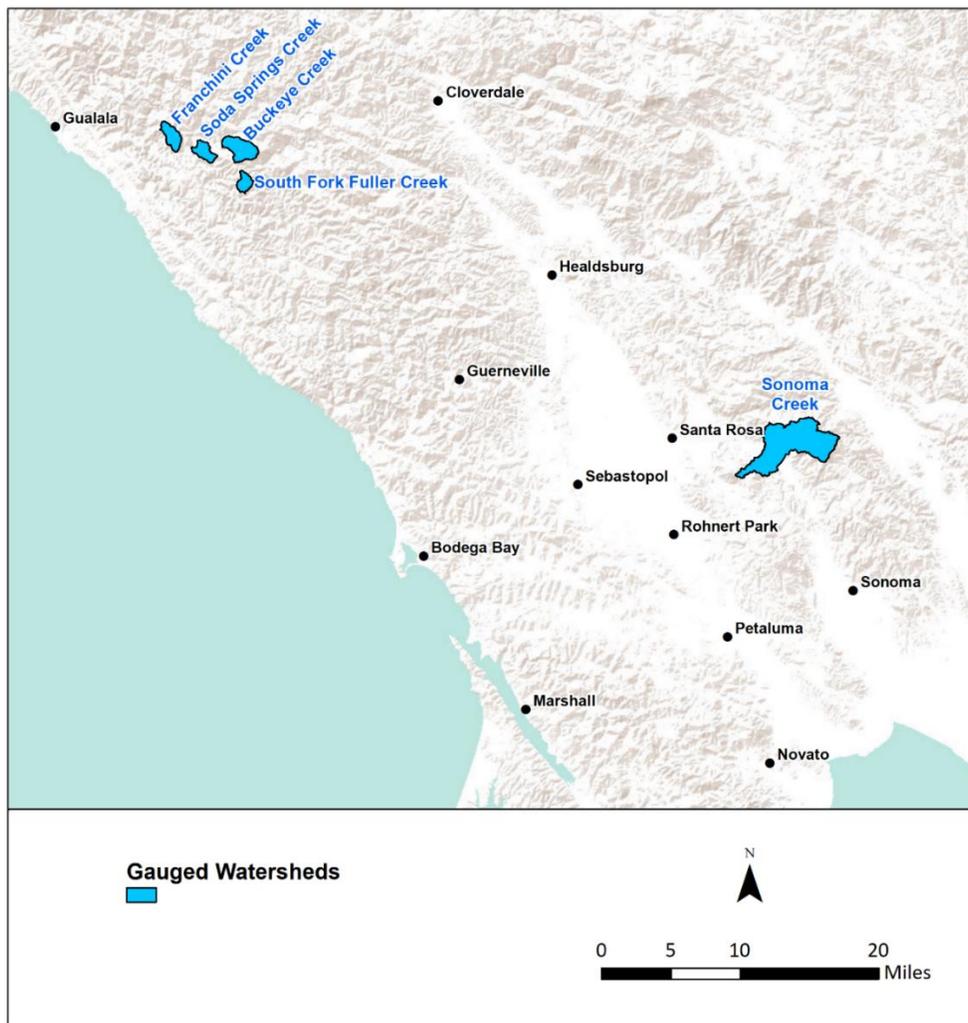
	Operated By	Drainage Area (mi <sup>2</sup> )	Period of Record
Sonoma Creek at Kenwood, CA (#11458433)	USGS	14.3	Oct 2008 - present
Buckeye Creek	OEI	3.1	Dec 2005 - Sept. 2012
Franchini Creek	OEI	1.8	Dec 2005 - Sept. 2012
South Fork Fuller Creek	OEI	1.2	Mar 2006 - Sept. 2012
Soda Springs Creek	OEI	1.5	Dec 2005 - Sept. 2012

Notes: USGS - U.S. Geological Survey, OEI - O'Connor Environmental, Inc.

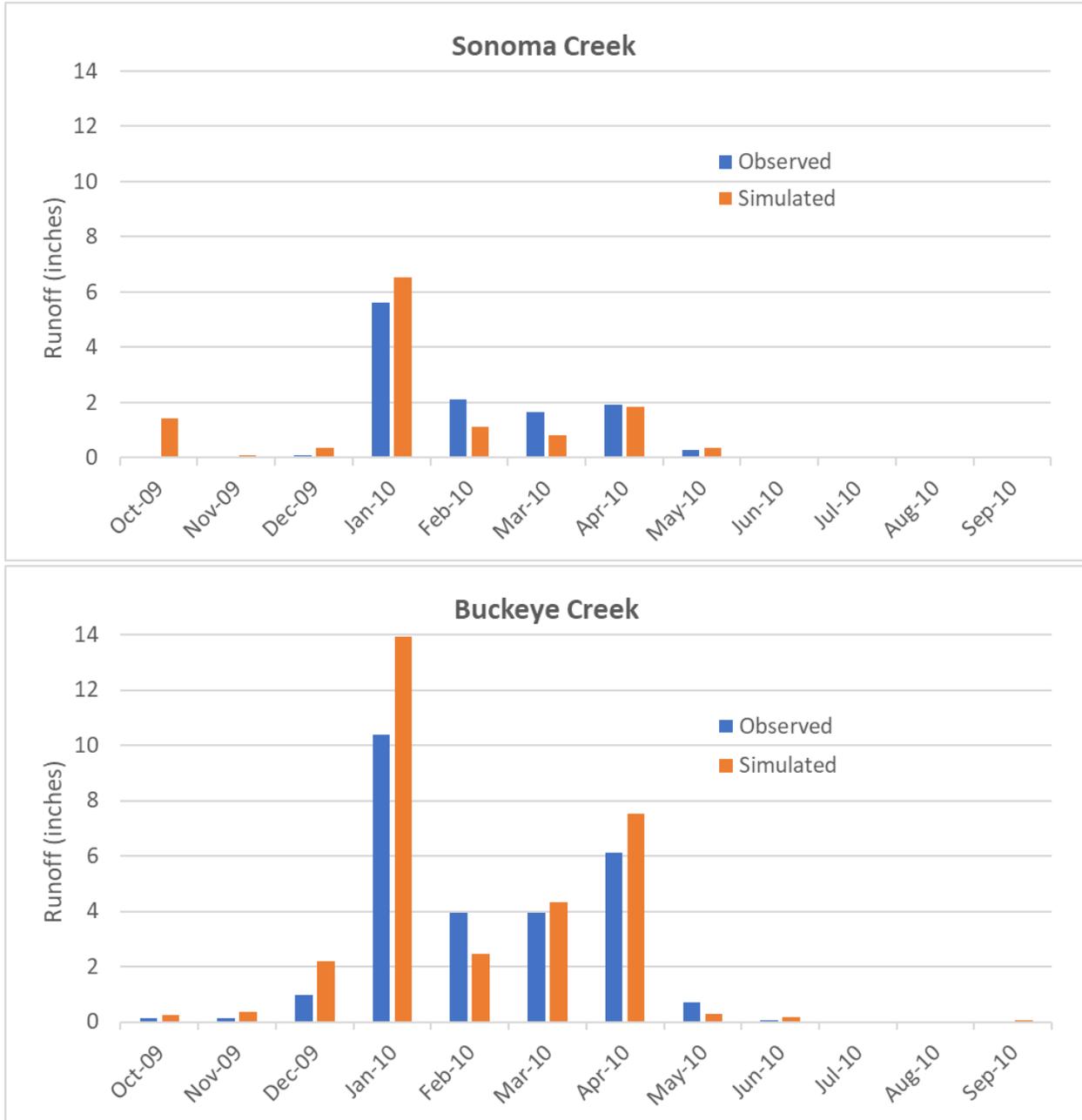
**Table 5: Calibration statistics for the Sonoma County SWB model calibration.**

	Annual Simulated Surface Runoff (in)	Annual Observed Surface Runoff (in)	Annual PE	Monthly ME (in)	Monthly RMSE (in)
Sonoma Creek	12.7	11.7	8.1%	0.1	0.6
Buckeye Creek	31.6	26.5	19.2%	0.4	1.2
Franchini Creek	22.1	24.5	-9.6%	-0.2	1.0
South Fork Fuller Creek	24.1	21.9	10.2%	0.2	1.5
Soda Springs Creek	24.2	24.1	0.6%	0.0	0.5
<b>MEAN</b>	<b>23.0</b>	<b>21.7</b>	<b>5.7%</b>	<b>0.1</b>	<b>1.0</b>

Notes: PE - Percent Error, ME - Mean Error, RMSE – Root Mean Square Error



**Figure 9: Gauged watersheds used to calibrate the Sonoma County SWB model.**



**Figure 10: Comparison between monthly surface runoff computed from hydrograph separation at streamflow gauges and monthly surface runoff simulated with the Sonoma County SWB model.**

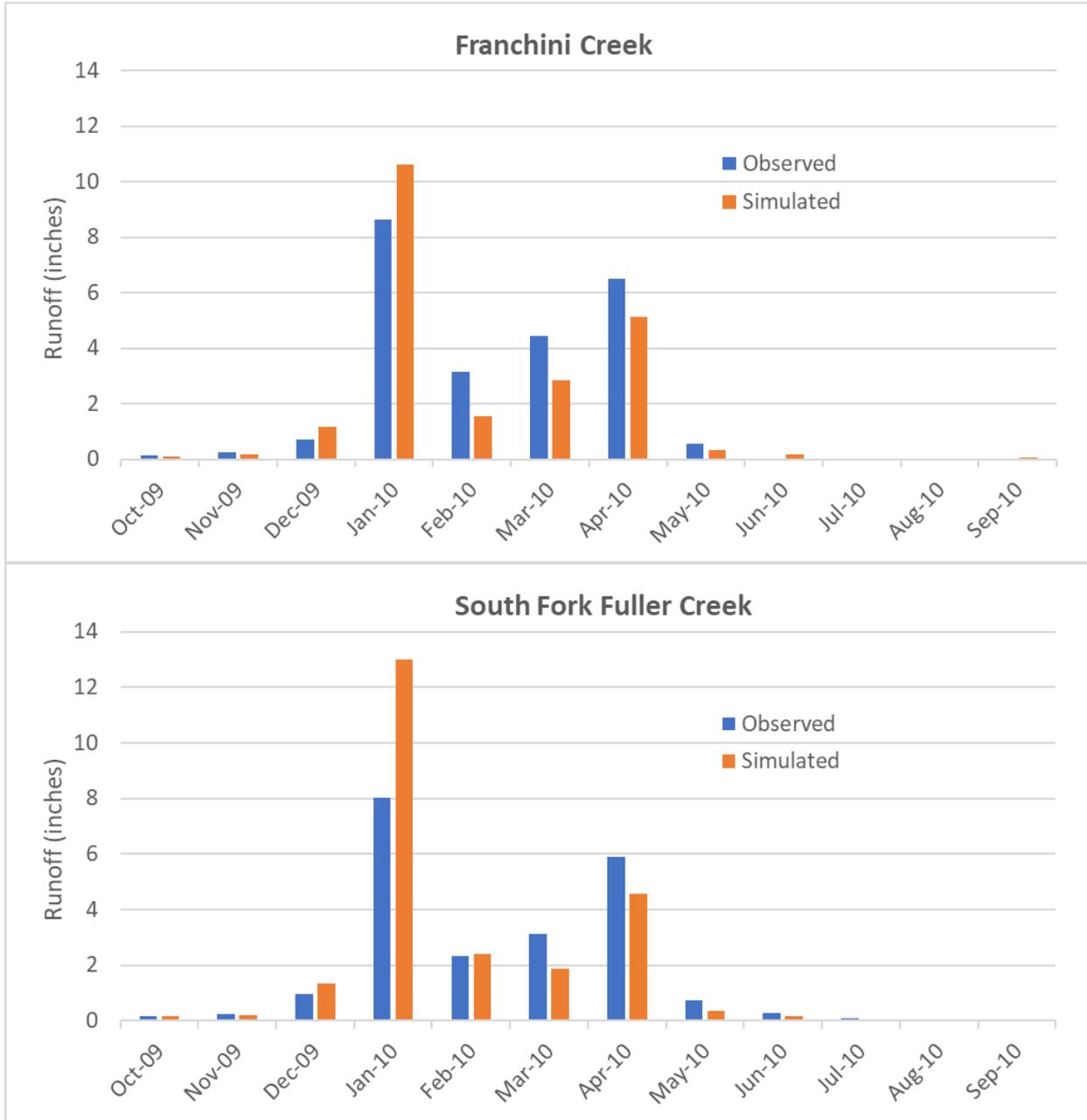


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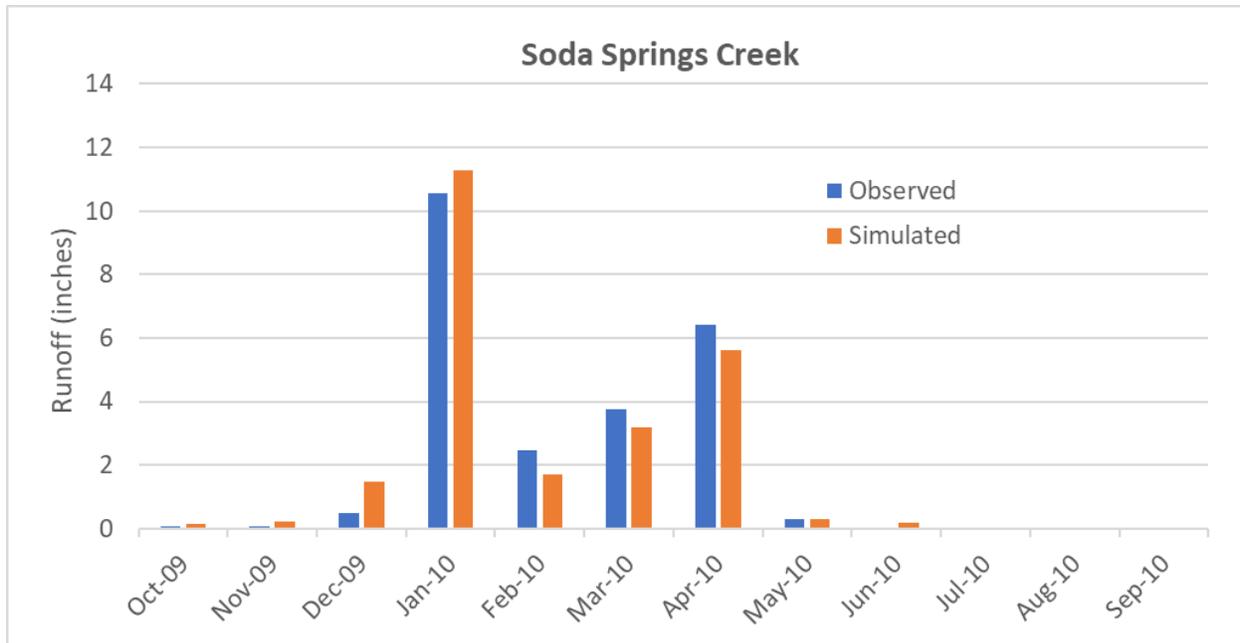


Figure 10 (continued)

### Model Results

The principal elements of the annual water budget simulated with the Sonoma County SWB model for water year 2010 are shown in map form in Figures 12 through 16 and in tabular form (sorted by total annual precipitation) for 23 major watershed areas in the county in Table 6. The watershed areas are a modified version of the USGS HUC-10 watersheds and are named for the stream which comprises the largest proportion of the area; although in many cases the areas consist of multiple tributary streams (Figure 11).

Water year 2010 precipitation varied from 26.1 inches in the Lower Sonoma Creek watershed to 70.7 inches in the Austin Creek watershed (Table 6, Figure 12). Actual evapotranspiration (AET) ranged from 17.9 inches in the San Antonio Creek watershed to 29.5 inches in the Pena Creek watershed (Table 6, Figure 13). Surface runoff ranged from 4.0 inches in the Lower Sonoma Creek watershed to 28.1 inches in the Austin Creek watershed (Table 6, Figure 14). Recharge ranged from 5.0 inches in the Lower Sonoma Creek watershed to 16.4 inches in the Austin Creek watershed (Table 6, Figure 15). Small decreases in soil moisture storage (up to 0.8 inches) occurred in 16 of the 23 watersheds and small increases (up to 0.8 inches) occurred in the remaining watersheds (Table 6, Figure 16).

When expressed as a percentage of the annual precipitation, AET ranged from 37% in the Austin Creek watershed to 69% in the Lower Sonoma Creek watershed (Table 7). Surface runoff ranged from 15% of precipitation in the Lower Sonoma Creek watershed to 40% in the Austin Creek watershed. The variations in recharge as a percentage of precipitation is relatively narrow ranging from 19% in the Lower Sonoma Creek watershed to 27% in the Salmon Creek watershed (Table 7).

**Table 6: Water budgets simulated with the Sonoma County SWB model for water year 2010  
(see Figure 11 for locations).**

Watershed	Drainage		AET (in)	Surface Runoff (in)	Recharge (in)	Soil Moisture Change (in)
	Area (sq. mi.)	Precipitation (in)				
Lower Sonoma Creek	120	26.1	18.0	4.0	5.0	-0.8
San Antonio Creek	79	29.6	17.9	6.0	6.4	-0.7
Petaluma River	76	31.4	19.3	5.9	6.9	-0.7
Chileno Creek	145	33.3	19.1	7.0	7.9	-0.6
Upper Laguna De Santa Rosa	62	36.2	21.6	8.0	7.5	-0.8
Mark West Creek	161	43.3	26.6	8.7	8.5	-0.5
Lower Laguna De Santa Rosa	31	43.6	25.8	9.6	9.0	-0.8
Upper Sonoma Creek	45	46.4	24.1	13.4	9.4	-0.4
Sausal Creek	46	47.8	24.3	13.4	10.8	-0.8
Maacama Creek	97	47.9	25.4	12.6	10.6	-0.7
Salmon Creek	53	48.7	22.3	13.2	13.1	0.2
Atascadero Creek	38	50.2	28.1	12.7	10.0	-0.6
Big Sulphur Creek	130	52.6	26.2	16.5	10.5	-0.5
Lower Dry Creek	42	53.5	26.4	17.2	10.7	-0.7
Willow Creek	24	53.9	22.8	18.2	12.7	0.2
Mill Creek	53	55.4	27.7	17.1	11.3	-0.6
Upper Dry Creek	89	57.4	27.0	20.0	10.9	-0.5
Dutch Bill Creek	55	57.7	25.2	18.6	13.7	0.1
Wheatfield Fork Gualala River	145	61.4	26.0	20.9	14.0	0.5
Pena Creek	23	63.0	29.5	21.6	12.5	-0.5
Buckeye Creek	60	65.7	26.4	24.0	14.4	0.8
South Fork Gualala River	65	68.2	25.7	26.2	16.1	0.1
Austin Creek	70	70.7	26.1	28.1	16.4	0.0

**Table 7: Water budgets simulated with the Sonoma County SWB model for water year 2010 expressed as a percentage of annual precipitation (see Figure 11 for locations).**

Watershed	Drainage		AET (%)	Surface	
	Area (sq. mi.)	Precipitation (in)		Runoff (%)	Recharge (%)
Lower Sonoma Creek	120	26.1	69%	15%	19%
San Antonio Creek	79	29.6	60%	20%	22%
Petaluma River	76	31.4	62%	19%	22%
Chileno Creek	145	33.3	57%	21%	24%
Upper Laguna De Santa Rosa	62	36.2	59%	22%	21%
Mark West Creek	161	43.3	61%	20%	20%
Lower Laguna De Santa Rosa	31	43.6	59%	22%	21%
Upper Sonoma Creek	45	46.4	52%	29%	20%
Sausal Creek	46	47.8	51%	28%	23%
Maacama Creek	97	47.9	53%	26%	22%
Salmon Creek	53	48.7	46%	27%	27%
Atascadero Creek	38	50.2	56%	25%	20%
Big Sulphur Creek	130	52.6	50%	31%	20%
Lower Dry Creek	42	53.5	49%	32%	20%
Willow Creek	24	53.9	42%	34%	24%
Mill Creek	53	55.4	50%	31%	20%
Upper Dry Creek	89	57.4	47%	35%	19%
Dutch Bill Creek	55	57.7	44%	32%	24%
Wheatfield Fork Gualala River	145	61.4	42%	34%	23%
Pena Creek	23	63.0	47%	34%	20%
Buckeye Creek	60	65.7	40%	37%	22%
South Fork Gualala River	65	68.2	38%	38%	24%
Austin Creek	70	70.7	37%	40%	23%

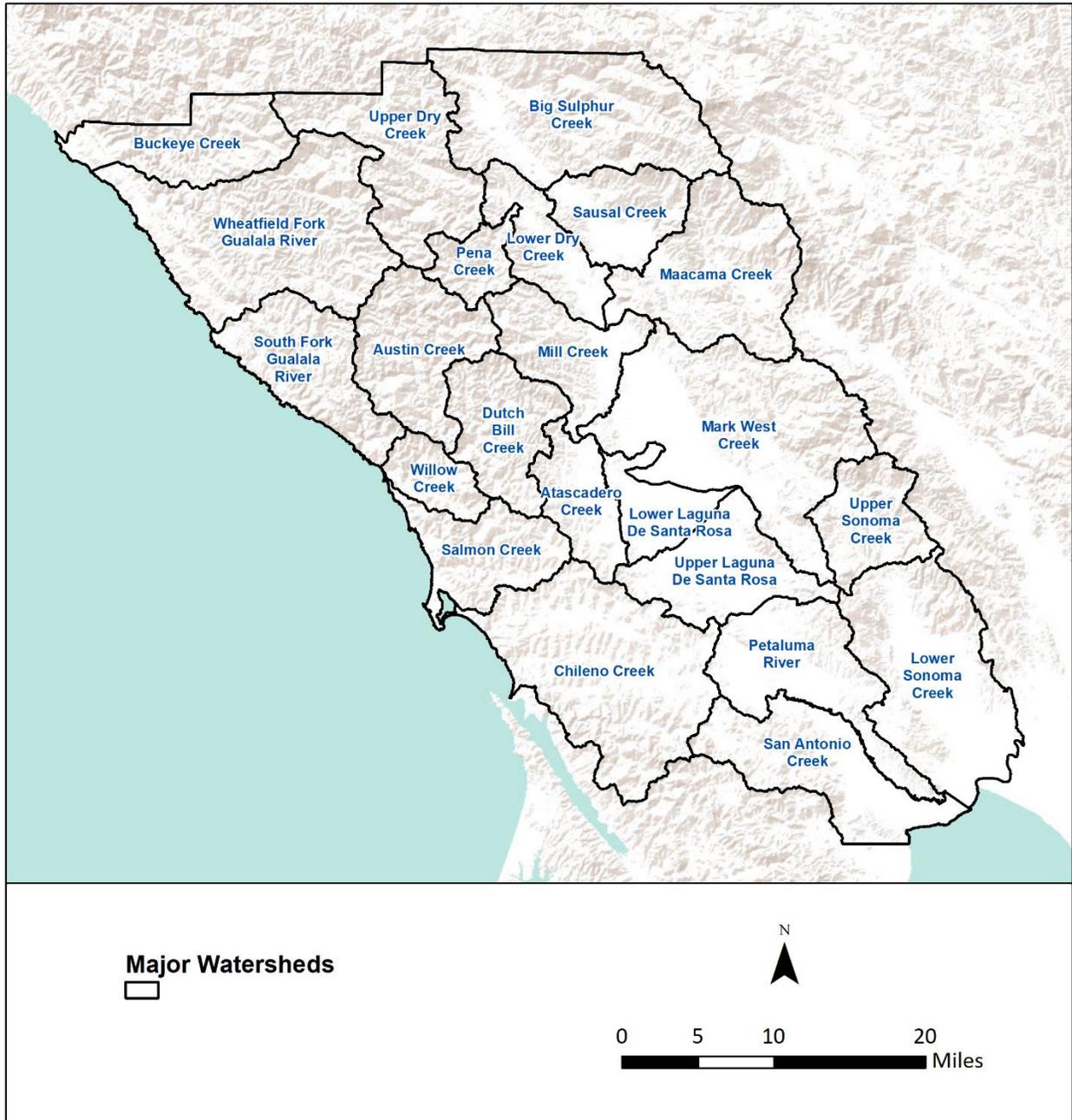


Figure 11: Major watersheds areas used to summarize water budget information in Tables 6 & 7).

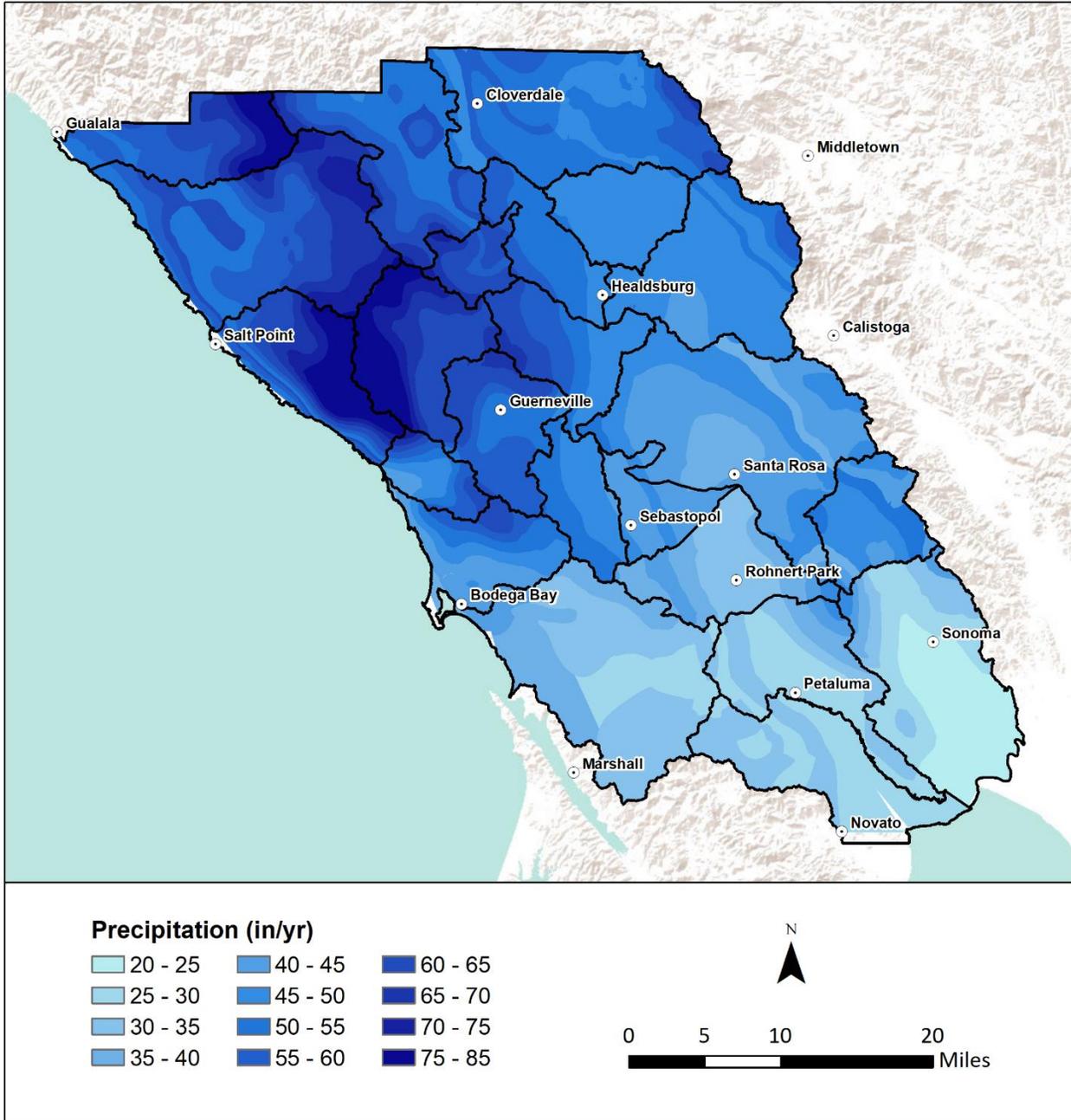


Figure 12: Water year 2010 Precipitation simulated with the Sonoma County SWB model.

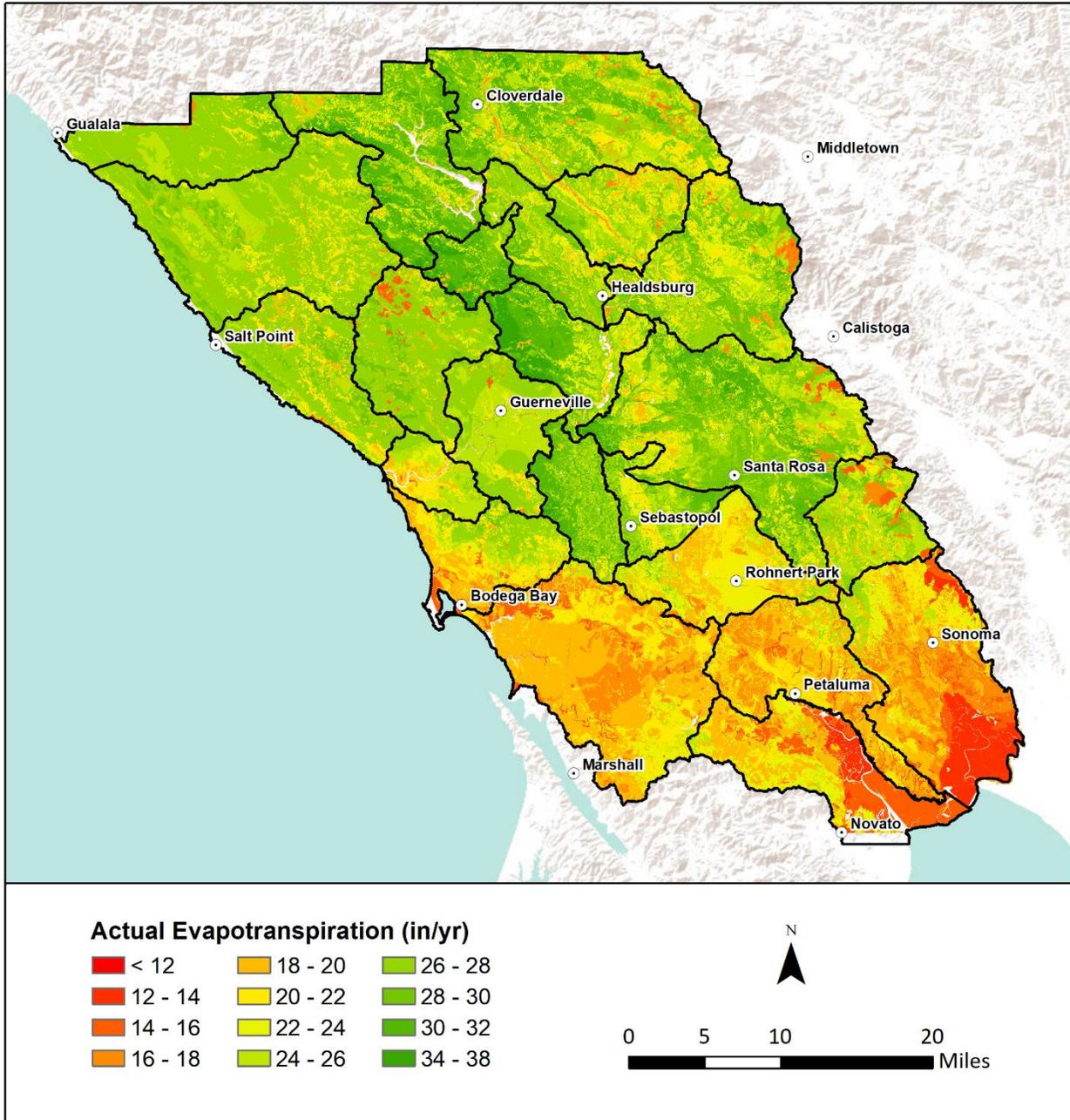


Figure 13: Water year 2010 Actual Evapotranspiration (AET) simulated with the Sonoma County SWB model.

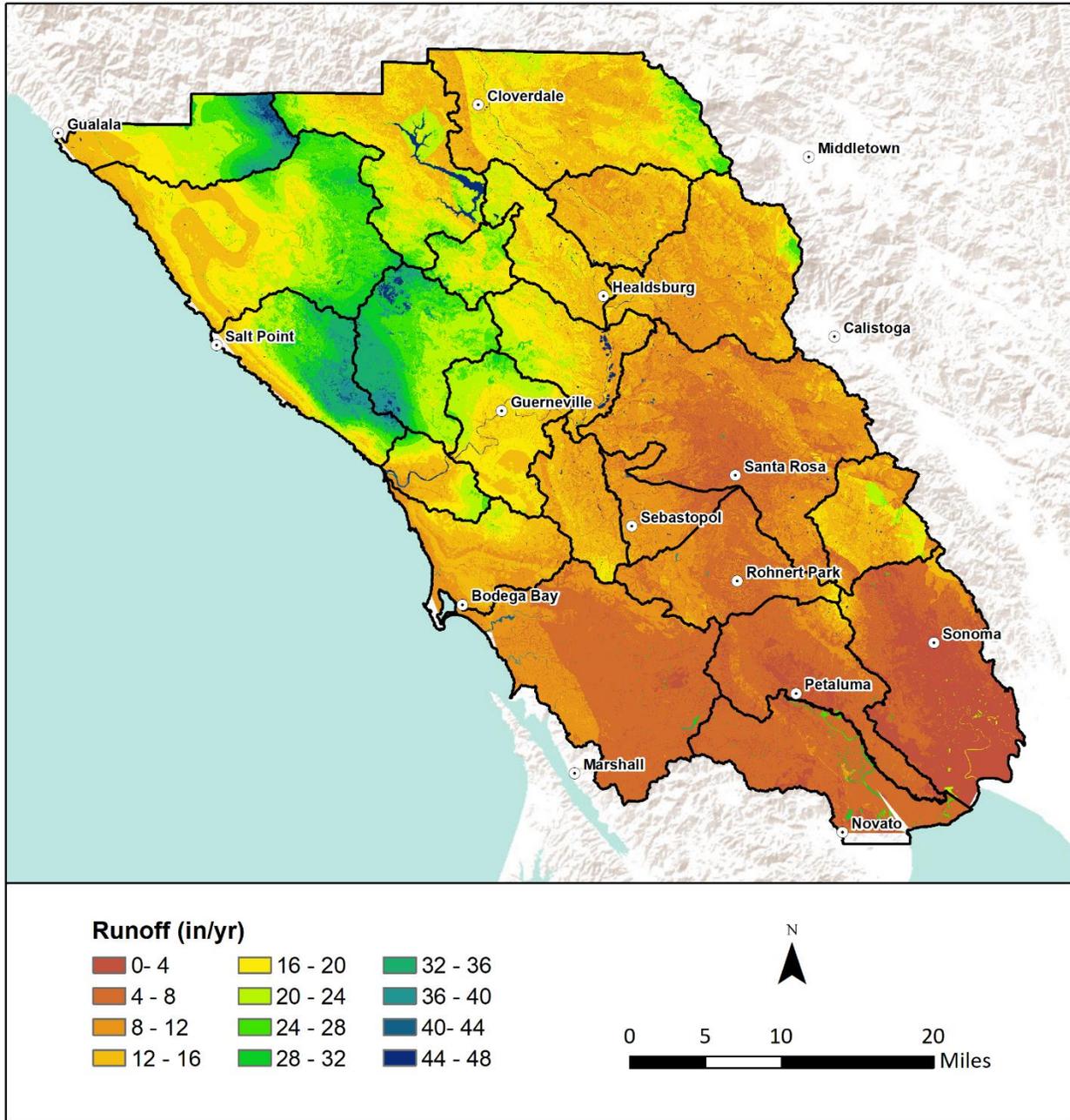


Figure 14: Water year 2010 Surface runoff simulated with the Sonoma County SWB model.

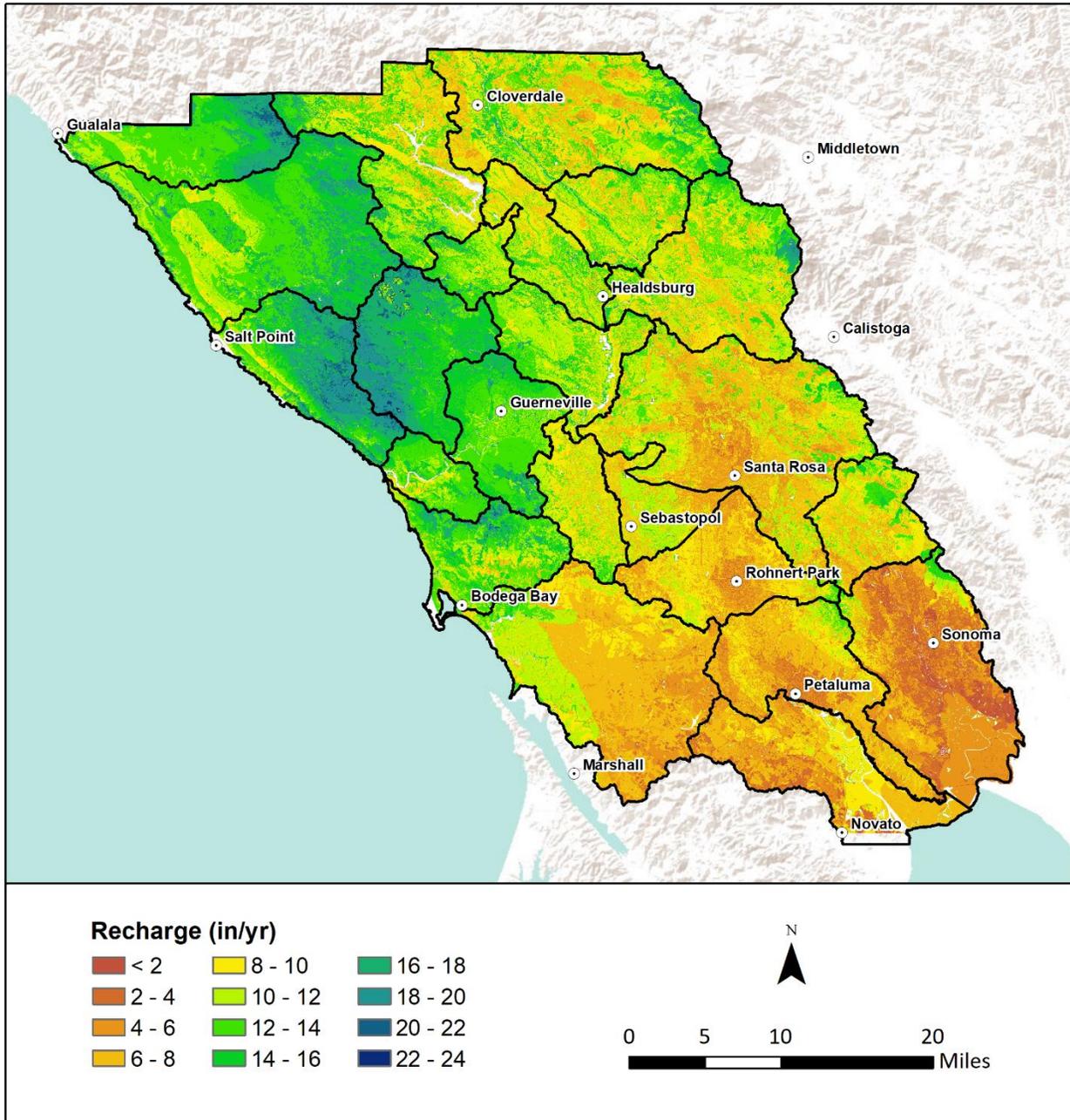


Figure 15: Water year 2010 Recharge simulated with the Sonoma County SWB model.

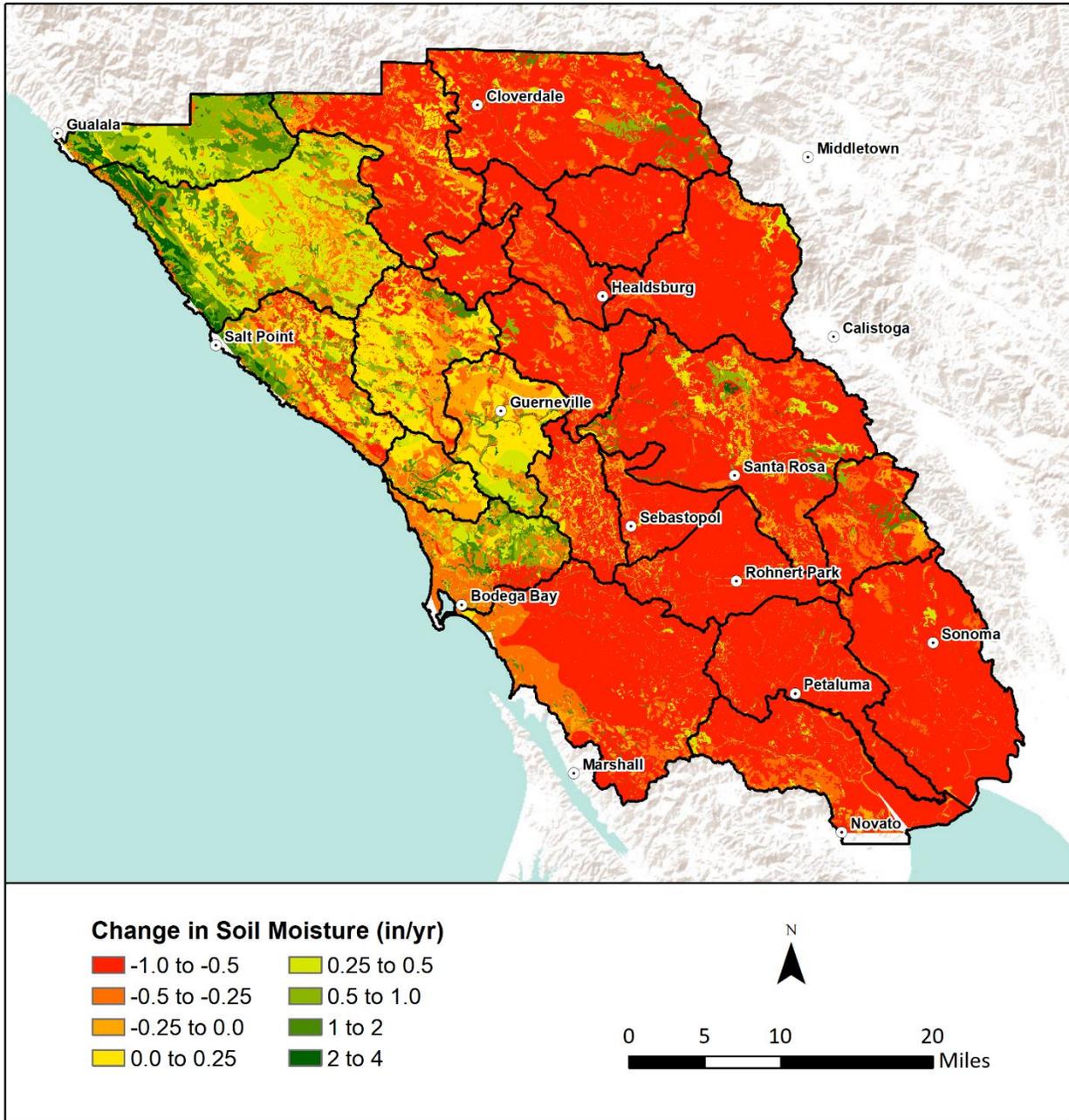


Figure 16: Water year 2010 Soil Moisture Change simulated with the Sonoma County SWB model.

## Discussion and Conclusion

Previous modeling studies have estimated water budget components in several larger watershed areas in the county including the Santa Rosa Plain, the Green Valley and Dutch Bill Creek watersheds, and the Sonoma Valley (Farrar et. al., 2006; Kobor and O'Connor, 2016; Woolfenden and Hevesi, 2014). Comparisons to these water budgets are useful for evaluating the SWB results. One would not expect precise agreement owing to significant variations in climate, land cover, soil types, underlying hydrogeologic conditions, and different spatial scales of modeling studies. These regional analyses estimated that AET was equivalent to between 44% and 49% of mean annual precipitation which is consistent with this analysis where the county-wide AET was equivalent to 48% of the annual precipitation. The regional analyses estimated that surface runoff ranged from 37 to 55% of the annual precipitation which is somewhat higher than this analysis where the equivalent county-wide value was 29%. In the regional analyses, recharge varied from 7% to 19% of the annual precipitation. The equivalent county-wide value from this study is somewhat higher at 22%.

At the local scale, the simulation results indicate sensitivity of the water budget components to variations in topographic position, land cover, and soil texture, however at the watershed scale much of the variation in the principal water budget components (AET, surface runoff, and recharge) are correlated with variations in precipitation across the county (Figure 17). AET increases as a function of precipitation in watersheds with annual precipitation up to about 45 in/yr. Above 45 in/yr AET remains relatively constant (average of about 27 in/yr). This suggests that in portions of the county experiencing low precipitation, AET is limited by available soil moisture in contrast to areas of the county with higher precipitation where AET is limited by the potential ET. Although surface runoff varies more or less linearly as function of precipitation (Figure 17), the slope of the relationship with precipitation increases above precipitation of about 45 in/yr. This suggests that surface runoff increases with precipitation more sharply where precipitation is great enough to fully satisfy potential ET. Recharge also varies linearly as a function of precipitation (Figure 17).

The recharge estimates presented here arguably represent the best available county-wide estimates produced at a fine spatial resolution using a consistent and objective data-driven approach. The current analysis focused on a single water year, 2010, and was calibrated to streamflow gauge-derived monthly surface runoff rates at five locations. Future work to expand the analysis to additional water years and calibrate to additional gauge locations would help to further evaluate, refine, and quantify the uncertainty associated with the model's recharge estimates.

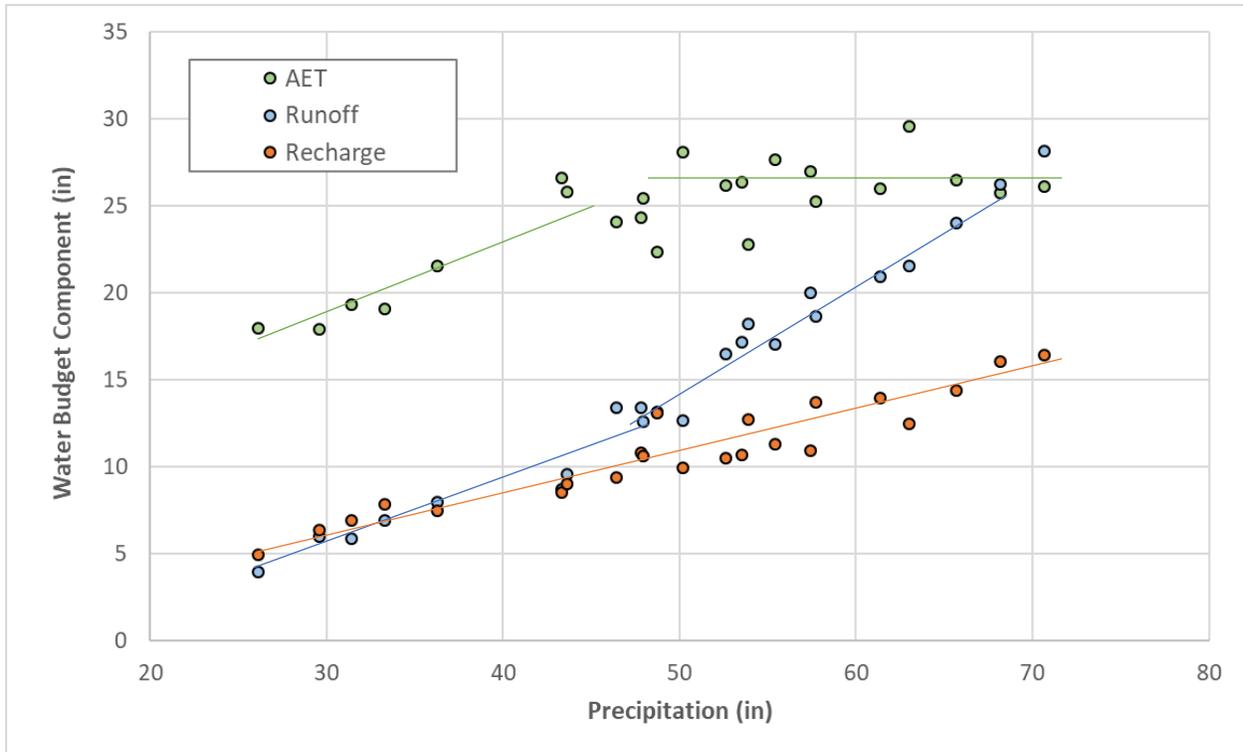


Figure 17: Principal water budget components simulated with the SWB model for major watersheds in Sonoma County as a function of annual precipitation. Trend lines fit by eye.

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