Integrated Surface and Groundwater Modeling and Flow Availability Analysis for Restoration Prioritization Planning, Upper Mark West Creek Watershed, Sonoma County, CA

Prepared for:

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and

State of California, Wildlife Conservation Board
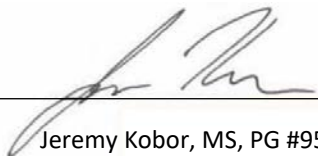1700 9th Street, 4th Floor, Sacramento, CA 95811
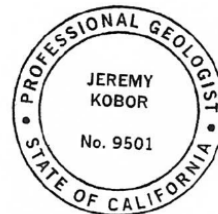
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Dedication

In recognition of those many residents of the Mark West Creek watershed that have suffered losses in the past few years to the Tubbs Fire and the Glass Fire, we dedicate this report in their honor. Many of the citizen contributors to this effort have been working for many years to advance the consciousness of the community with respect to wildfire hazards, fuel management and fire safe communities, and it is an unfortunate truth that there remains much to be done. We dedicate this report in the spirit of community service and the example that has been set by these citizens, families, friends, and communities.

Acknowledgements

Limitations

The descriptions of watershed and streamflow conditions described in this report are based on numerical model simulations which were developed using best available data and hydrologic practices. Available model input data varied widely in its resolution and accuracy, and while the model was calibrated successfully to available streamflow and groundwater monitoring data, the extent of available calibration data is relatively limited. All model scenarios represent hypothetical actions on the landscape and do not imply any interest or commitment on the part of landowners to implement them. Both the existing condition and scenario results represent approximations of real-world conditions that contain uncertainty and should be interpreted as a guide for understanding watershed hydrology and the effects of potential management actions rather than as precise quantitative predictions of actual or future conditions.

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Executive Summary

Introduction

The Mark West Creek watershed provides critical habitat for threatened and endangered anadromous fish and was recently identified in the California Water Action Plan as one of five streams statewide for targeted flow enhancement efforts. Effective implementation of a flow enhancement program requires a detailed understanding of the natural and man-made controls on spring and summer streamflows. The primary goal of this project is to provide a comprehensive hydrologic analysis of streamflow conditions and the relative effectiveness of various potential flow enhancement actions in upper Mark West Creek watershed relative to salmonid habitat requirements. The project provides a framework for prioritizing restoration efforts and developing effective strategies and projects to protect and enhance streamflows.

This study evaluates the upper 40 mi^2 of Mark West Creek watershed upstream of the Santa Rosa Plain (Figure E1) identified as critical salmonid summer rearing habitat in the State Water Resources Control Board Emergency Order WR 2015-0026-DWR (SWRCB, 2015). The study was conducted over a three year period and was completed by the Coast Range Watershed Institute (CRWI) in cooperation with the Sonoma Resource Conservation District (SRCD), Friends of Mark West Watershed, Sonoma County Regional Parks, and the Pepperwood Foundation. Assistance was also provided by local staff of California Department of Fish & Wildlife (CDFW). Funding for the project was provided by a Streamflow Enhancement Program grant from the California Wildlife Conservation Board (WCB).

O'Connor Environmental, Inc., completed the modeling analysis under contract with CRWI. The completed model is intended to serve as a tool to help evaluate the hydrologic consequences of future project proposals. The principal mission of CRWI as a tax-exempt scientific not-for-profit organization in this regard is to provide a virtual "home" for the model and to make it available for future use and updates as new management questions arise and new data become available. In this way, CRWI seeks to extend the benefits to the public of this grant-funded project beyond the immediate utility of its findings.

Approach and Methods

The principal element of the project was development and calibration of a distributed hydrologic model using the computer model code MIKE SHE. Inputs included a wide variety of climate, topographic, land cover, soils, water use, and hydrogeologic data. Outputs included estimates of the annual and seasonal water balance, streamflow hydrographs, and groundwater levels throughout the watershed. The model was constructed using 0.5-acre square grid cells to represent the landscape and stream channel cross sections spaced at 100-ft intervals to represent major stream channels. The model simulates continuous daily hydrologic conditions over a 10-yr period from water year 2009 to 2019. The model was calibrated to streamflow data at three locations and groundwater elevation data at nine locations supplemented by observations of flow conditions (wet vs. dry) on the main stem of Mark West Creek and mapped locations of seeps and springs.

A wide variety of existing and new data sources were used to construct the model. Topographic inputs were derived primarily from the Sonoma County LiDAR Digital Elevation Model (DEM). Climate inputs were derived from monitoring data collected by various entities as well as distributed climate estimates from the U.S. Geological Survey. Land cover data and vegetation properties were based on detailed mapping of vegetation communities provided by Sonoma County Agricultural Preservation and Open Space District in combination with LiDAR-derived Leaf Area Index data and literature-based rooting depth estimates. Soil properties were based on the U.S. Department of Agriculture's Soil Survey Geographic Database (SSURGO) and adjusted during model calibration.

Hydrogeologic inputs were based primarily on new analyses performed for this study which included interpretation of the distribution and thickness of geologic materials from more than
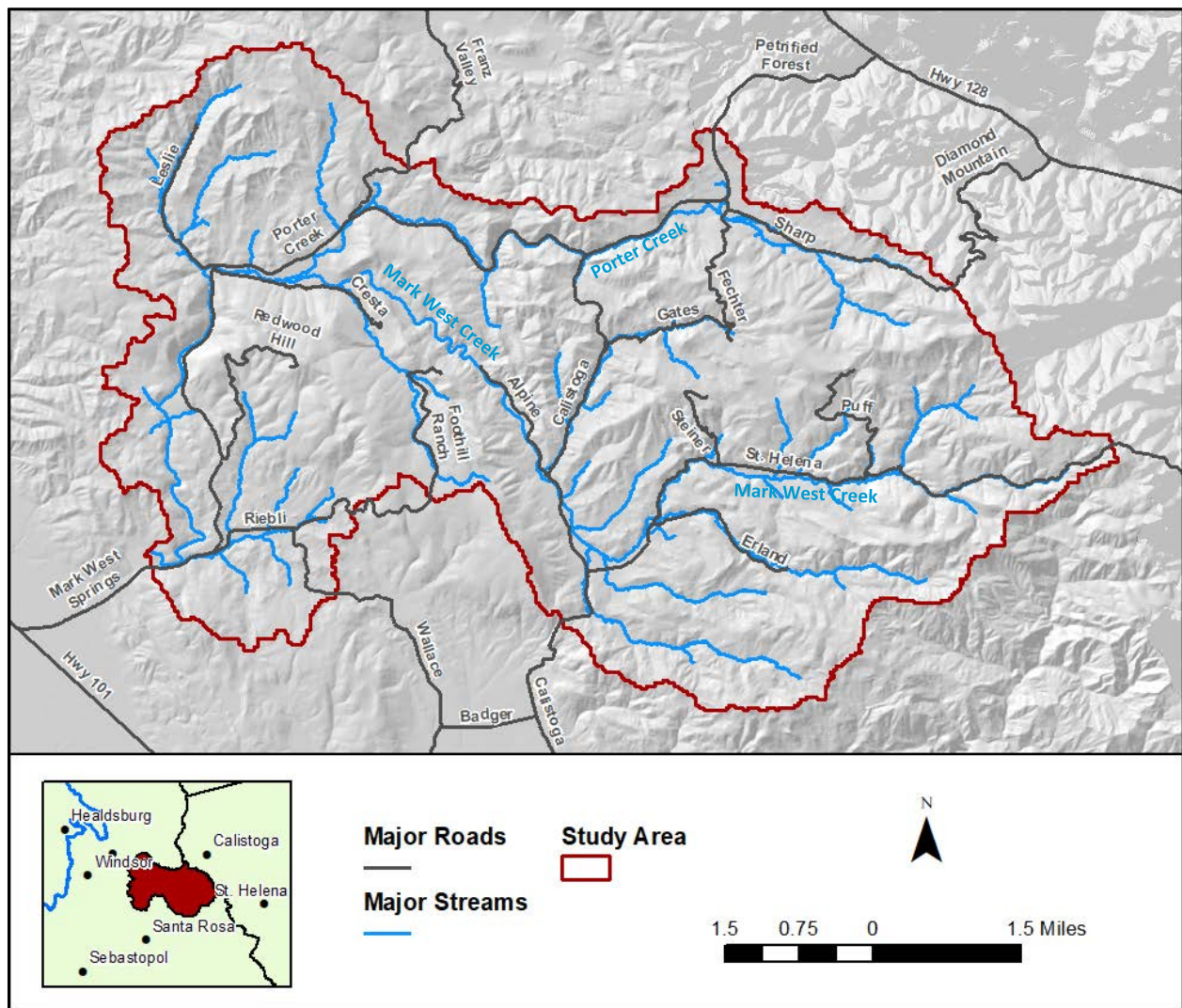
Figure E1: Map of the study area showing major roads and streams.

150 subsurface geologic logs obtained from Well Completion Reports and estimation of aquifer properties from analysis of pump tests completed for Sonoma County Well Yield Certifications at 23 wells. Estimates of the volumes, rates, and sources of water use were based on data from a variety of sources including the State Water Resources Control Board Emergency Order (Order WR 2015-0026-DWR) and Water Rights Database, available Well Completion Reports, spatial mapping of water uses (including vineyards, cannabis farms, wineries, and residences), literature values and other official estimates of water use for various purposes including data from the Town of Windsor and the City of Healdsburg.

Existing Hydrology and Streamflow

Annual precipitation varied widely over the 10-yr study period from 19.5 inches in 2014 to 61.2 inches in 2017, a pattern typical of streams in the California Coast Range (Table E1). Annual streamflow also varied widely from 8.3 to 32.8 inches, largely in response to precipitation patterns. Simulated Actual Evapotranspiration (AET), representing water use by vegetation plus evaporation, accounted for the largest outflow from the watershed over the long-term, ranging from 14.1 to 24.1 inches per year largely in proportion to annual precipitation (Table E1). Simulated annual infiltration recharge to groundwater varied substantially as a function of precipitation from 0.8 inches in the drought year 2014 to 10.1 inches in 2017, an unusually wet year (Table E1).

The simulated groundwater recharge rates indicate large spatial variability, with much of the watershed generating less than 2 in/yr and some portions of the upper watershed generating more than 20 in/yr (Figure E2). Numerous factors affect recharge rates; however, the spatial variations in recharge appear to be primarily controlled by soil properties, topographic position, and the west to east precipitation gradient. Recharge is concentrated in the upper Mark West Creek watershed upstream of and including the Van Buren Creek watershed, as well as in the upper Humbug Creek watershed (Figure E2).

The Climatic Water Deficit (CWD) provides a measure of the seasonal moisture stress and may be indicative of vegetation health and associated fire risk. This metric varied widely across the watershed from 15 to 40 in/yr except locally where lower rates occur due to availability of shallow groundwater (Figure E2). Topographic aspect appears to be a primary control on the spatial variability of CWD with north-facing slopes characterized by lower PET having significantly lower CWD values relative to south-facing slopes.

Groundwater discharge by seeps and springs represents the primary process responsible for generating summer streamflow in the watershed. This discharge is highly concentrated in the upper watershed with the watershed area upstream of Van Buren Creek generating 55% of the total springflow in the watershed despite representing only 17% of the total watershed area. Much of this discharge occurs along steep incised stream banks comprised of bedrock of the Sonoma Volcanics exposed in the upper watershed. Surface water-groundwater interaction through the streambed is relatively limited in most reaches owing to the limited depth and distribution of alluvium overlying bedrock in narrow valley bottoms. The exception to this occurs

Table E1: Annual watershed (top) and groundwater (bottom) water budgets simulated with the hydrologic model, units are inches of water per year.

| Water Year | Inflows | | Outflows | | | Change in Storage |
	Precipitation	Irrigation	AET	Streamflow	Groundwater Pumping	
2010	42.51	0.07	24.06	17.14	0.15	1.23
2011	43.97	0.07	23.13	17.92	0.15	2.84
2012	28.07	0.07	20.07	10.67	0.15	-2.76
2013	28.87	0.07	17.58	12.83	0.15	-1.62
2014	19.46	0.07	14.06	8.30	0.15	-2.97
2015	26.57	0.07	14.94	12.74	0.15	-1.19
2016	33.30	0.07	17.30	13.83	0.15	2.09
2017	61.18	0.07	21.47	32.75	0.15	6.88
2018	26.59	0.07	18.93	9.07	0.15	-1.49
2019	49.77	0.07	21.63	23.44	0.15	4.62
Average	**36.03**	**0.07**	**19.32**	**15.87**	**0.15**	**0.76**

| Water Year | Inflows | | Outflows | | | | | Change in Storage |
	Infiltration Recharge	Streambed Recharge	Interflow	Baseflow	Springflow	ET from Groundwater	Groundwater Pumping	
2010	6.05	0.71	4.29	0.76	0.58	0.82	0.15	0.16
2011	7.49	0.70	4.00	0.80	0.62	0.89	0.15	1.73
2012	2.22	0.57	1.72	0.63	0.84	1.08	0.15	-1.63
2013	2.39	0.58	2.19	0.60	0.68	0.98	0.15	-1.62
2014	0.84	0.52	1.09	0.50	0.76	1.06	0.15	-2.19
2015	2.10	0.66	1.53	0.59	0.67	1.02	0.15	-1.20
2016	4.44	0.60	2.55	0.67	0.48	0.75	0.15	0.44
2017	10.12	1.03	3.39	0.86	0.97	1.07	0.15	4.72
2018	2.87	0.53	1.91	0.62	0.72	1.06	0.15	-1.05
2019	8.17	1.03	3.48	0.83	0.99	0.99	0.15	2.76
Average	**4.67**	**0.69**	**2.61**	**0.69**	**0.73**	**0.97**	**0.15**	**0.21**

in a short reach of Mark West Creek immediately upstream of the Porter Creek confluence where relatively thick and broad alluvial deposits create losing conditions and local disconnection of surface flow in drier water years. Across the entire study area, the volume of water that recharges from streams to groundwater is approximately balanced by the volume that discharges to streams through the streambed (Table E1).

In wet years the average summer streamflow in Mark West Creek was about 0.7 cubic feet per second (cfs) below Van Buren Creek and 1.5 cfs below Porter Creek, whereas in dry years these flows declined to about 0.3 and 0.7 cfs, respectively (Figure E3 shows 10-yr average conditions). Except for the reach upstream of Porter Creek that experiences local surface flow disconnection during drier years, most reaches retain small but consistent streamflows even under drought conditions. Year to year variations in springtime streamflows were substantially larger than the variations in summer flows with average springtime flows below Van Buren Creek ranging from 2 to 8 cfs and below Porter Creek from 6 to 30 cfs.
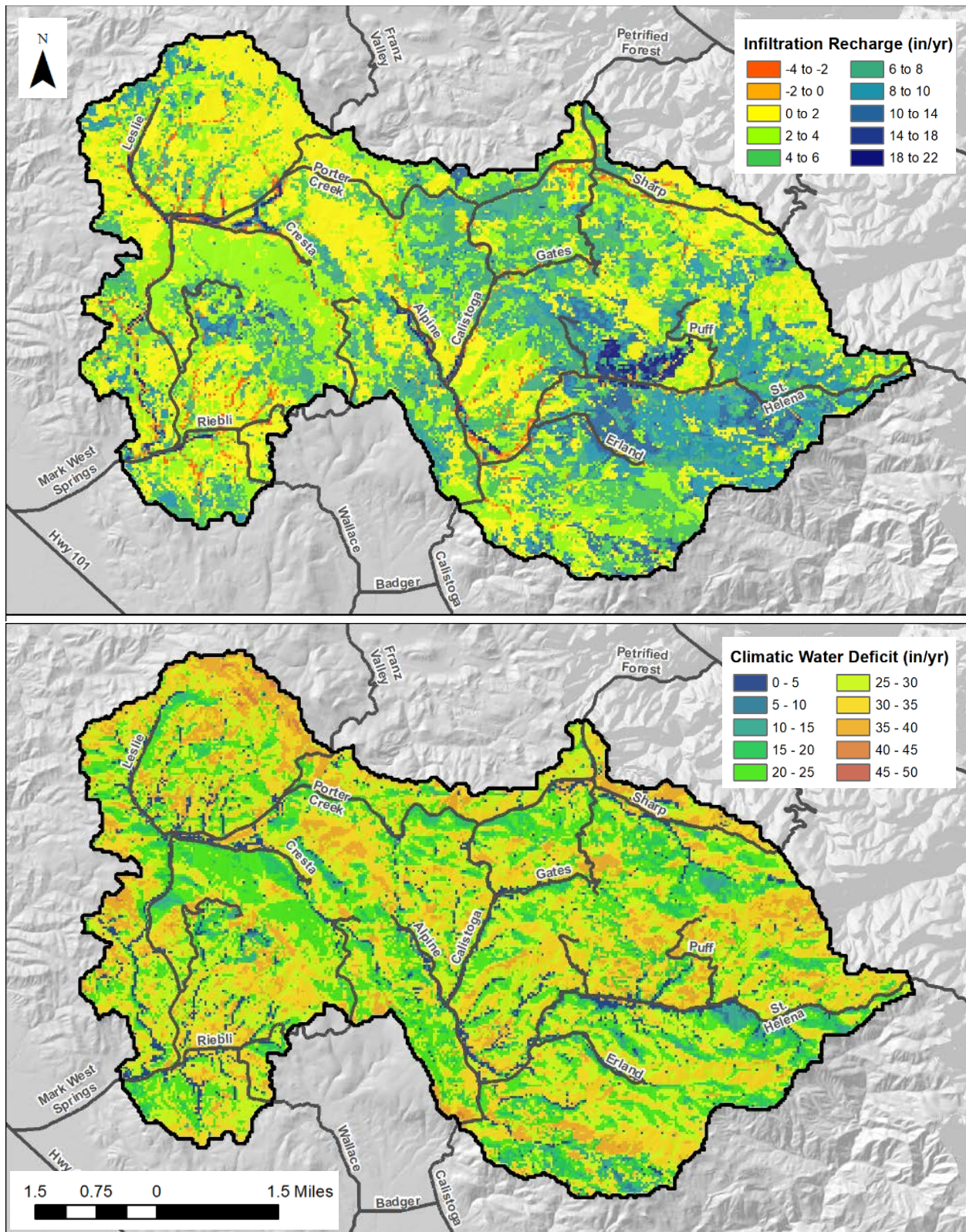
Figure E2: Mean annual infiltration recharge (top) and climatic water deficit (bottom) simulated with the hydrologic model of the upper Mark West Creek watershed.
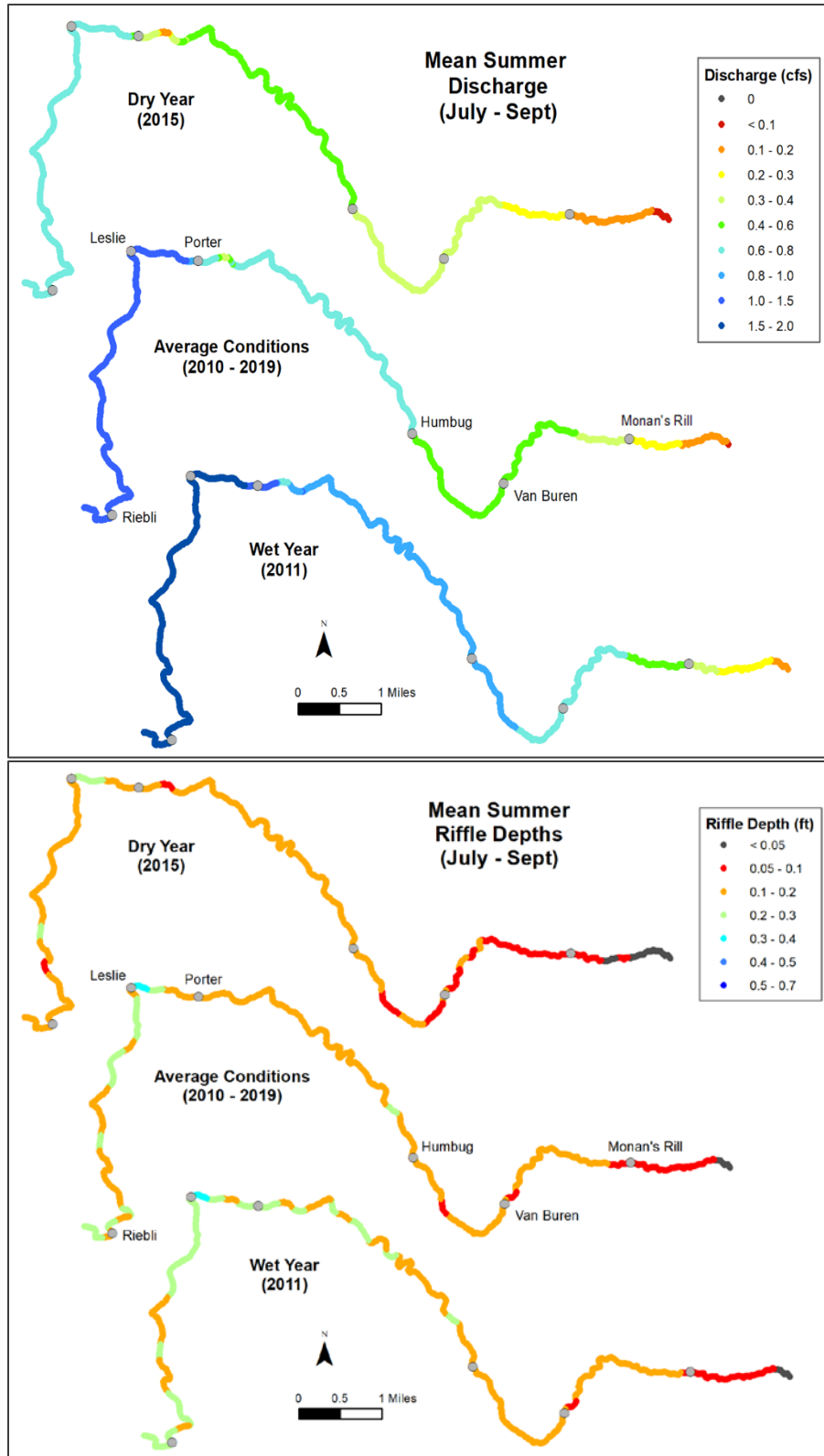
Figure E3: Mean summer streamflows (top) and riffle depths (bottom) in mainstem Mark West Creek simulated by the hydrologic model.

In most water years, average summer riffle depths remain above 0.1-ft in most locations downstream of Monan's Rill, and below Porter Creek depths reach 0.2 - 0.3 ft in many locations (Figure E3). Minimum flow depth in riffles are of interest as an indicator of fish habitat conditions. Average springtime riffle depths vary substantially between years. During the drought conditions of 2014, depths were less than 0.2-ft upstream of Van Buren Creek and between 0.2-0.4 ft below Porter Creek. In the wet water year 2017, riffle depths remained above 0.2-ft as far upstream as one river mile above Monan's Rill and were above 0.5-ft in portions of the lower watershed. The simulated spatial distributions of riffle depths reflect both reaches where riffle depths are limited by reduced streamflows (most notably the reach upstream of Porter Creek which loses flow to the alluvium) as well as where depths are limited by geomorphic controls such as the reaches about 1-mile upstream of Riebli Creek (Figure E3).

Existing Water Use

Total water use in the watershed was estimated to be approximately 430 ac-ft/yr, equivalent to about 0.5% of the mean annual precipitation. The largest uses are residential and vineyard irrigation which account for about 48% and 33% of the total water use respectively (Figure E4). Industrial uses account for the next largest fraction at about 9%. The remaining 10% consists of irrigation for pasture and other crops (6%), irrigation of cannabis (3%), winery use (<1%), and vineyard frost protection (<1%) (Figure E4). About 85% (367.1 ac-ft/yr) of the total use in the watershed is from groundwater with the remaining 15% (63.6 ac-ft/yr) coming from surface water sources. About 81% (51.5 ac-ft/yr) of the total surface water use is direct diversion to pond storage, 10% (6.7 ac-ft/yr) is direct stream diversions, and 9% (5.4 ac-ft/yr) is diversion at springs.
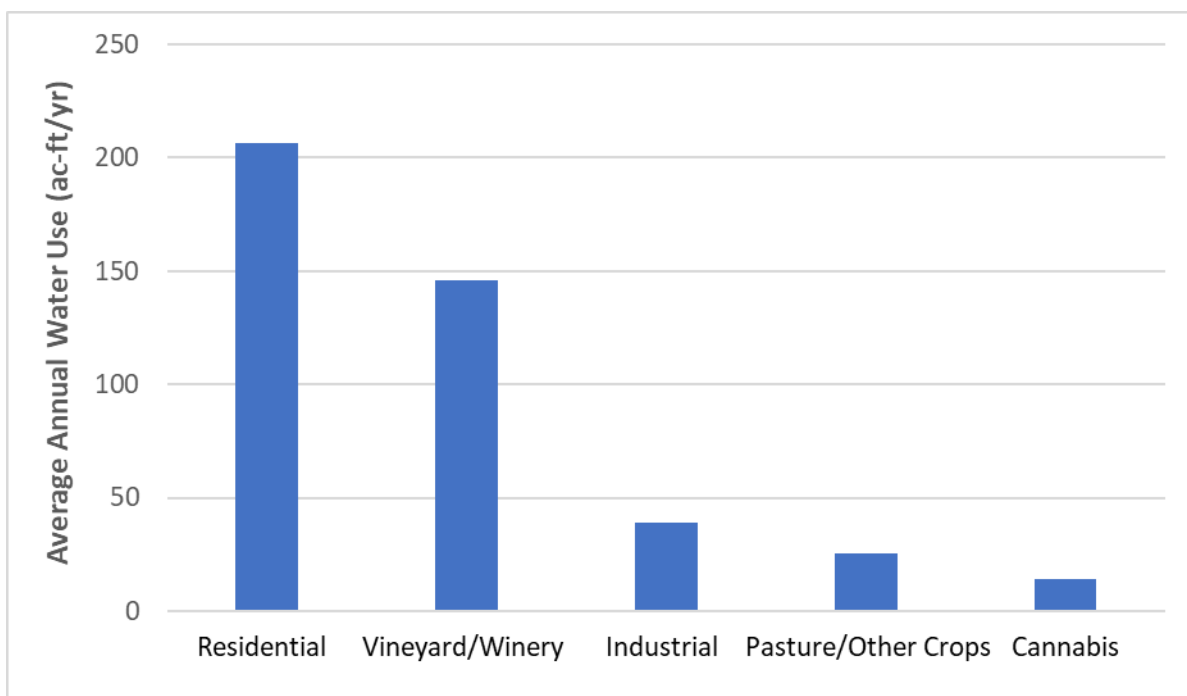
Figure E4: Water use in the Mark West Creek watershed study area by major water use category.

Fish Habitat Characterization

We developed two streamflow classifications based on the simulation results to represent habitat conditions, one for smolt outmigration and one for juvenile summer rearing. Both classifications focus on a 0.2-ft Riffle Crest Thalweg Depth (RCTD) threshold which is intended to represent the minimum flow conditions required to provide suitable habitat for salmonids (optimal habitat conditions require higher RCTDs than these minimum thresholds). We also compiled available continuous temperature data collected by CDFW, Trout Unlimited, CA Sea Grant, and Sonoma Water from 15 locations to develop a simple water temperature classification based on Maximum Weekly Maximum Temperature (MWMT) relative to thresholds of impairment for salmonids. Finally, we compiled available physical habitat data from CDFW habitat surveys and our own field observations to describe other important factors for salmonid habitat including pool characteristics along with spawning and winter refugia conditions.

A simple scoring system was used for each flow classification. Scores range from zero for reaches where RCTDs never reach the target of 0.2-ft during the summer rearing and spring outmigration timeframes in the 10-yr average condition to four for reaches that continuously maintain 0.2-ft RCTDs even during drought conditions. We developed a final habitat suitability classification based primarily on the flow and temperature classifications but also informed by the other available physical habitat data and recent fisheries monitoring information.
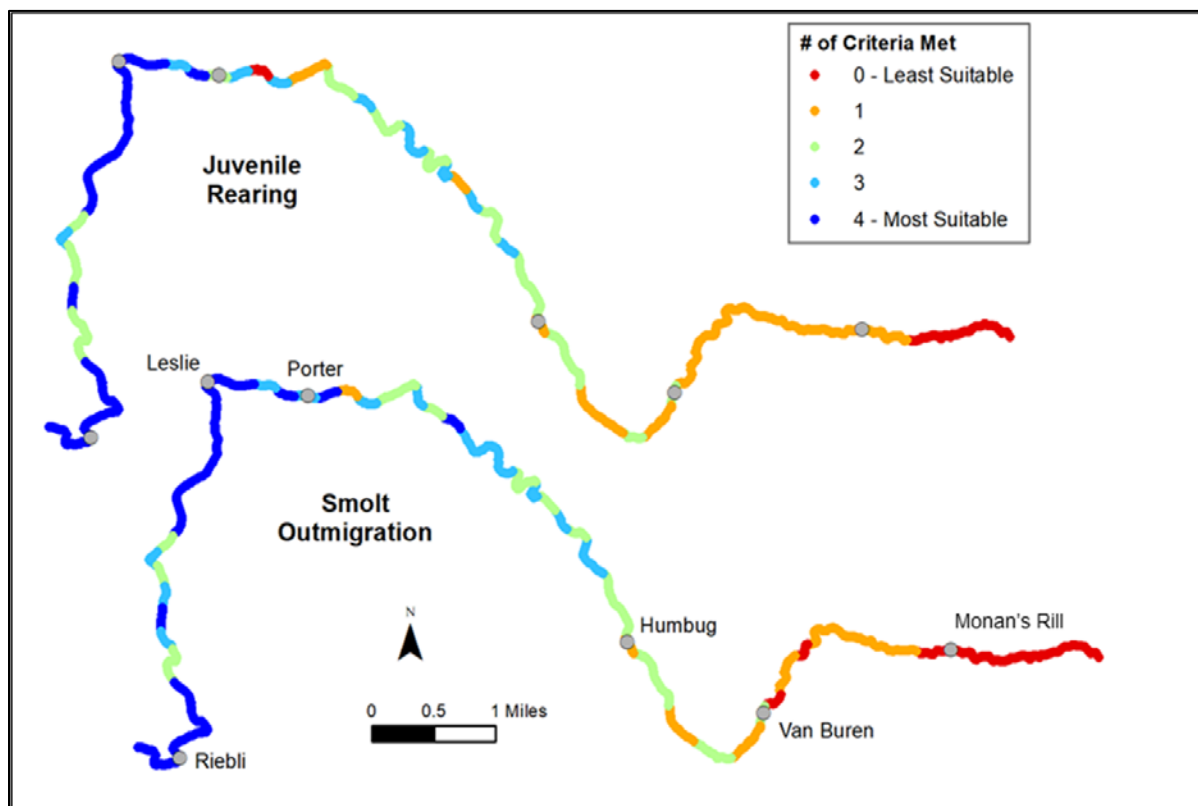
Figure E5: Flow-based habitat suitability classifications for juvenile rearing and smolt outmigration in mainstem Mark West Creek.

The flow-based habitat classification results indicate that most reaches are impaired for smolt outmigration and juvenile rearing (Figure E5). Upstream of Van Buren Creek either zero or one of four flow classification criteria are met, most reaches between Humbug Creek and Porter Creek meet two or three of the criteria, and most reaches below Porter Creek meet three or four criteria (Figure E5). Notable exceptions to this include short reaches upstream of Porter Creek and between Leslie and Riebli Creeks which are more flow-limited than adjacent upstream and downstream reaches. Most reaches are also impaired with respect to stream temperature, with two of three temperature criteria met upstream of Van Buren Creek and only one criterion met between Van Buren Creek and a point about 2-miles upstream of Porter Creek (Figure E5). Documented temperature impairment is most severe in the 2-mile reach upstream of Porter Creek with none of the criteria met (MWMT > 23.1 °C) at available monitoring stations; no data was available farther downstream (Figure E6).

We examined temporal variations in temperatures relative to streamflows observed at the stream gauges in the watershed and found no obvious correlations between streamflow and temperature at the most temperature-impaired locations. This suggests that streamflow is not the primary control on temperature and that even significant streamflow enhancement is unlikely to mitigate elevated temperatures. We also examined the relationship between pool depth and temperature in six pools monitored in 2017 by CDFW upstream and downstream of Humbug Creek. Pools with depths greater than 3.5-ft maintained temperatures below severely impaired levels whereas shallower pools less than 2.5-ft deep did not. Although based on a limited sample size and a single water year, these observations suggest that deep pools likely
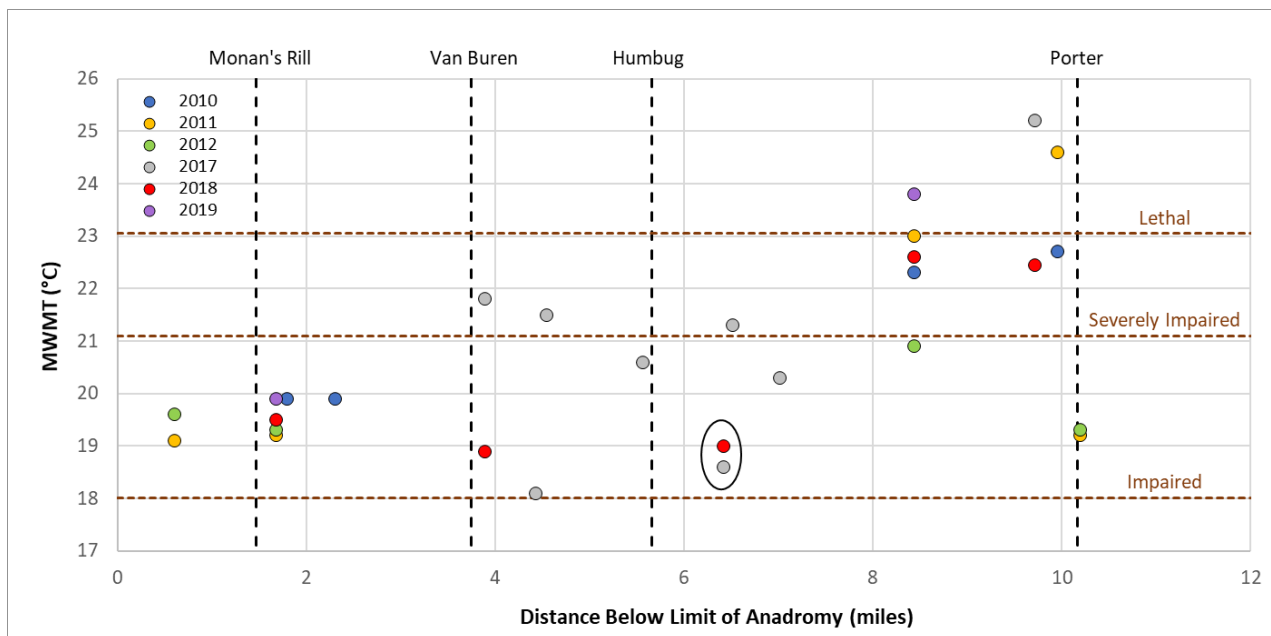
Figure E6: Longitudinal and temporal variations in Mean Weekly Maximum Water Temperature (MWMT) derived from continuous temperature data at 15 stations between 2010 and 2019, black oval indicates location of deep pool cold water refugia; temperature data from CDFW, Sonoma RCD, CA Sea Grant, and Trout Unlimited.

provide critical refugia for salmonids in Mark West Creek when extreme high temperatures occur in shallower pool habitats.

The overall salmonid habitat classification identifies an ~4 mile reach of Mark West Creek between about 0.5 river miles downstream of Van Buren Creek and about 2 river miles upstream of Porter Creek as providing the best overall habitat for salmonids in the watershed (Figure E7). This reach is considered most suitable because it represents the best combination of flow and water temperature conditions and is also consistent with available data and observations about other indicators of habitat quality such as pool and spawning conditions.
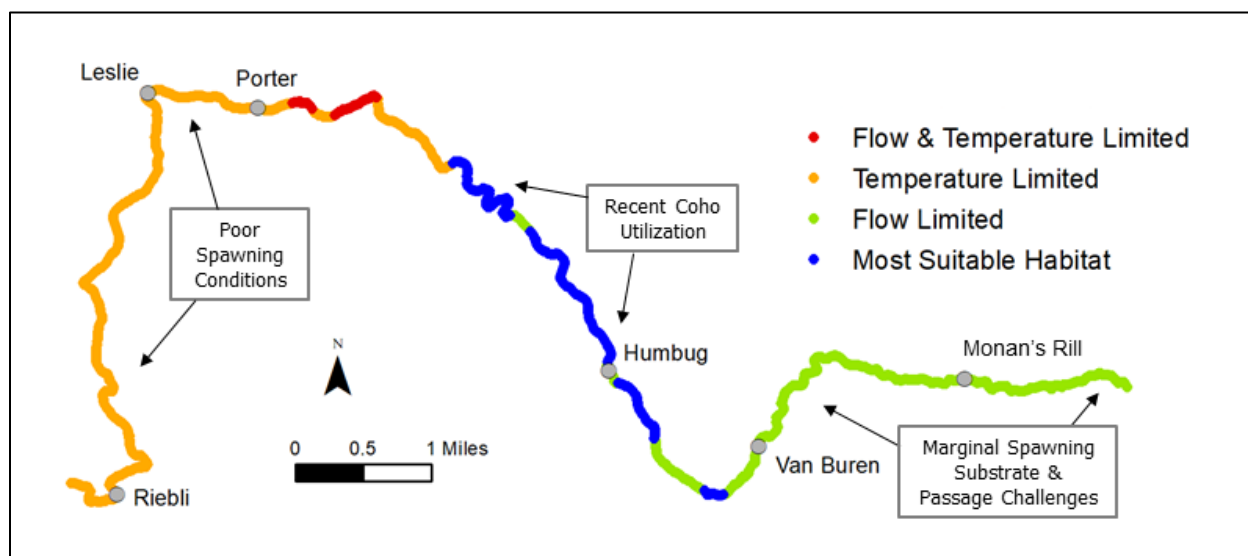
Figure E7: Final overall habitat suitability classification for Mark West Creek identifying the high priority reaches with the most suitable overall habitat conditions in blue.

Scenario Analysis

The model was used to evaluate alternative streamflow enhancement strategies along with predictions of climate change effects on streamflow. Individual enhancement strategies, combinations of these strategies, and alternative future climate conditions were evaluated in different model runs (scenarios) to identify advantages and disadvantages of different strategies under a variety of conditions. The scenario analysis is intended to provide guidance regarding streamflow management to stakeholders in the watershed, natural resource managers, and government regulatory authorities. Scenarios analyzed are summarized in Table E2.

Water Use
Analysis of changes in streamflow revealed that the sustained cumulative effects of surface water diversions and groundwater pumping are modest and that cessation of all water use would result in increases in mean summer streamflow of about 6% (0.04 cfs) in the ~4-mile high priority reach and ~8% (0.09 cfs) at the watershed outlet (Figure E13). The analysis suggests that the groundwater response timescales are long and the reported flow increases represent conditions

in the 10-yr period following 40-yrs without water use. Cumulatively, surface water diversion and groundwater pumping each have an approximately equal sustained effect on streamflows, however cumulative groundwater use is more than five times that of surface water use in the watershed. Surface water diversions were also found to result in more substantial short-term (daily) streamflow depletion up to about 14% with the largest impacts occurring in the reach downstream of Humbug Creek (Figure E8).

Streamflow depletion from groundwater pumping was found to occur over long (decadal) timescales. While we did find some sensitivity in the rate of depletion as a function of distance of wells from streams and springs and depths of screened intervals, all wells generated depletion given enough time. The rate of depletion from near-stream wells (within 500-ft) screened in the upper 200-ft was about 1.7 times the rate for wells at greater horizontal distance from streams screened at depths greater than 200-ft. No direct relationship between the seasonality of pumping and the timing of streamflow depletion was apparent, with maximum depletion occurring during winter despite maximum pumping occurring during the summer months. This results from pumping effects on groundwater recharge and discharge processes being most pronounced during the active recharge season and from buffering of summer streamflow depletion by reductions in transpiration of riparian vegetation.

Pond Releases

The summer pond release scenario generated the largest increases in average summer streamflow of the stand-alone scenarios, with increases of about 13-14% (0.08 cfs in the high priority reach and 0.16 cfs at the watershed outlet) (Figure E13). The predominance of gaining streamflow conditions (groundwater discharge to streams) in most reaches of the creek causes only limited flow losses to groundwater (losing streamflow condition) downstream of the releases, which makes this strategy particularly well-suited for this watershed which is characterized by a lack of thick alluvial deposits adjacent to streams. The springtime pond release scenario was designed to increase flows over a short (3-week) period coinciding with the timing of the end of typical peak smolt outmigration in May. Examination of discharge and riffle depth hydrographs during drought conditions of 2014 shows that the spring releases substantially increase flows in the identified high priority reach during this critical period, extending the duration of passable conditions by approximately two weeks.

Forest, Grassland, & Runoff Management

Large-scale implementation of forest, grassland, and runoff management projects resulted in modest but significant changes in the water balance. All three strategies increase groundwater recharge but through different mechanisms.   Forest management decreased actual evapotranspiration by about 5% on treated lands resulting in more water available for recharge, grassland management increased the water holding capacity of soils increasing soil water availability for recharge, and runoff management increased infiltration resulting in increased recharge as well as AET (Figure E9). Watershed-wide increases in infiltration recharge ranged from about 2-4% (230-420 ac-ft/yr).

Table E2: Overview of the scenarios evaluated with the hydrologic model.

Scenario Category	Scenario #	Scenario Name	Brief Description
Water Use	1	No Diversions	All surface water diversions turned off
	2	No Groundwater Pumping	All groundwater pumping turned off
	2B	No Pumping Near Streams	Wells within 500-ft of streams and screened in upper 200-ft turned off
	2C	No Pumping Near Springs	Wells within 500-ft of springs turned off
	2D	No Pumping From Tuff	Wells screened in surficial tuffaceous materials turned off
	2E	No Distal Pumping	Wells distal to streams/springs/tuff and not screened in upper 200-ft turned off
	3	No Water Use	All surface diversions and groundwater pumping turned off
Land/Water Management	4	Forest Management	Forest treatment on 7,054 acres of oak and Douglas Fir forests
	5	Grassland Management	Application of organic matter on 2,874 acres of grasslands
	6	Runoff Management	Manage runoff from 310 acres of developed lands to maximize infiltration
	7	Summer Pond Releases	Release water from three ponds with a total release of 0.19 cfs from June 15th to Sept 15th
	7B	Spring Pond Releases	Release water from three ponds with a total release of 0.82 cfs from May 7th to May 28th
	8	Combined Management	Combination of Scenarios 4 through 7
Climate Change	9	CNRM Climate Change	2070-2099 timeframe future climate as predicted by the CNRM model under the rcp8.5 emmisions pathway
	10	CCSM4 Climate Change	2070-2099 timeframe future climate as predicted by the CCSM4 model under the rcp8.5 emmisions pathway
	11	GFDL Climate Change	2070-2099 timeframe future climate as predicted by the GFDL model under the SRES B1 emmisions pathway
	12	MIROC esm Climate Change	2070-2099 timeframe future climate as predicted by the MIROC esm model under the rcp8.5 emmisions pathway
Mitigated	13	GFDL & Pond Releases	Combination of Scenarios 11 & 7 or 7B
	14	GFDL & Combined Management	Combination of Scenarios 11 & 7 or 7B

Figure E8: Changes to mean and minimum summer streamflow, and maximum hourly changes from cessation of all surface water diversions (Scenario 1).

Of the three management scenarios, forest management generated the largest increases in average summer streamflow (6%) in the high-priority reach followed by runoff management (3%), and grassland management (2%) (Figure E13). Runoff management generated a larger response at the watershed outlet (10%) reflecting the concentration of developed areas in the lower watershed. Increases in springtime discharges for the runoff and grassland management scenarios were minimal, however the forest management scenario generated increases of 0.5-0.7 in the high priority reach. These changes represent 4-6% of the total flow and primarily reflect small increases in runoff during spring storms.

Combined Management
Combining all the land/water management scenarios (pond releases with forest, grassland and runoff management), mean summer discharges in the high priority reach increased by about 21% (0.13 cfs) and by about 28% (0.31 cfs) at the watershed outlet (Figures E10 & E13). These changes

represent about 86% of the sum of the changes of the four individual scenarios indicating a small negative feedback in effectiveness when the effects on the water balance dynamics from the various actions are combined.
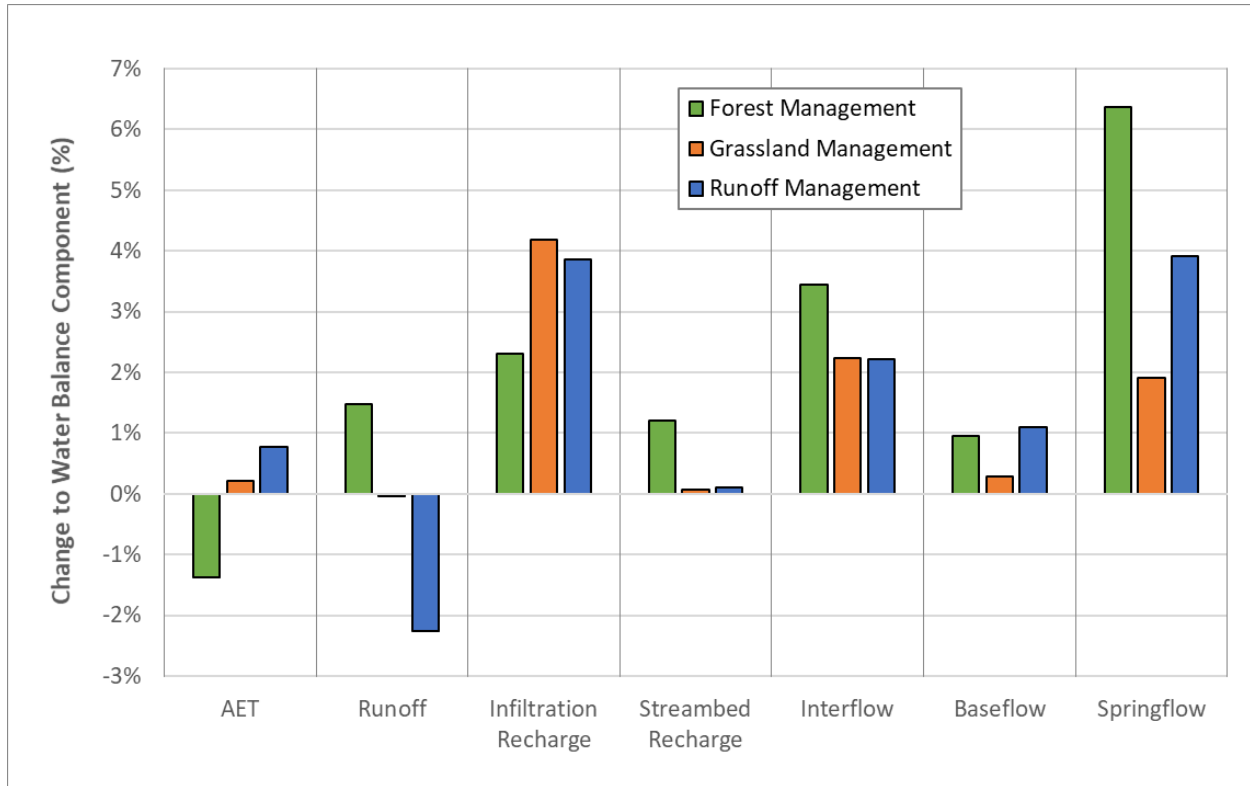
Figure E9: Watershed-wide percent change in select water balance components for the forest, grassland, and runoff management scenarios (Scenarios 4-6).
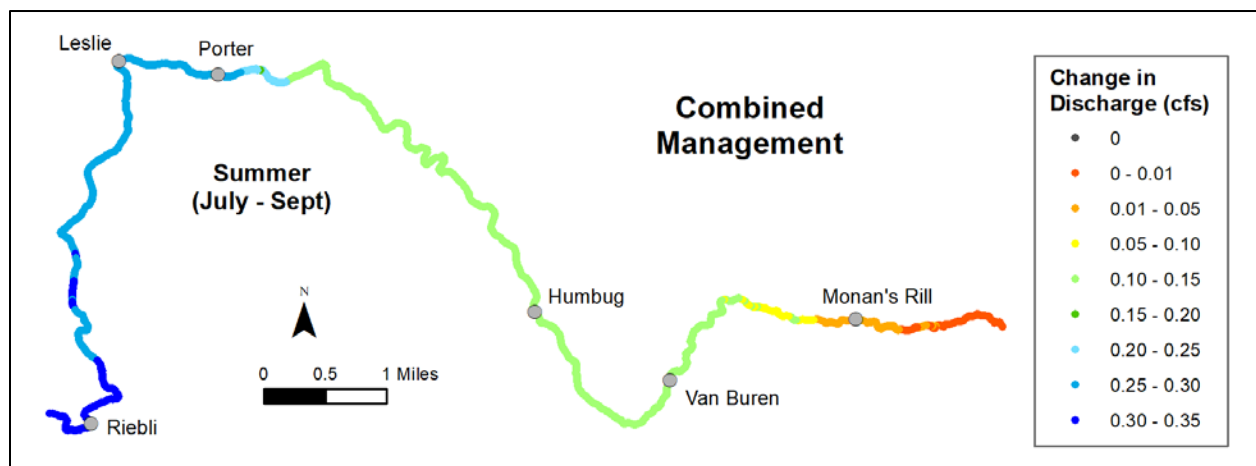
Figure E10: Simulated changes to the 10-yr average mean summer streamflow for the combined management scenario (Scenario 8, note the scale in the legend is different from previous figures for other scenarios).

Climate Change

Four climate change scenarios were selected to represent the range of plausible changes to precipitation and temperatures as predicted by available climate model data, and to include a scenario representative of the mean projections. These scenarios predict a range of maximum temperature increases of between 3.7 and 11.0°F and changes in mean annual precipitation ranging from a decrease of 21% to an increase of 37%.

The 10-yr mean annual water balance results indicate substantial variability in predictions of future hydrologic changes. The CNRM scenario predicts large increases in both infiltration recharge (44%) and streambed recharge (33%), the CCSM4 model predicts minimal changes in recharge, and the GFDL and MIROC esm scenarios predict significant decreases in infiltration recharge (29-40%) and streambed recharge (17-25%) (Figure E11). Increased recharge in the CNRM scenario results in increases in groundwater discharge expressed as interflow (32%), baseflow (11%), and springflow (36%). Similarly, groundwater discharge decreases for the scenarios that predict decreases in recharge. The largest decreases are predicted by the MIROC esm scenario where interflow, baseflow, and springflow are predicted to decrease by 30%, 21%, and 46% respectively (Figure E11). Comparison of the water balance for the driest of the 10 years in each simulation reveals that the trajectories of the changes in the water balance between the four scenarios are more similar during drought conditions than for long term average conditions, with all four scenarios predicting decreases in runoff, infiltration recharge, and streambed recharge under drought conditions (Figure E11).

All four scenarios indicate increases in Climatic Water Deficit (CWD). The mean CWD for the watershed over the 10-yr simulation period is predicted to increase from 26.0 in/yr under existing conditions to between 30.3 and 33.9 in/yr under future climate conditions. Increases in CWD of this magnitude (17-30%) may be expected to lead to significant changes in vegetation communities and increases in fire risk. It is important to note that these simulations represent the hydrologic effects of changes in climate but do not include secondary effects that may be expected under a significantly altered future climate regime such as changes in vegetation cover and irrigation water demands.

The climate change scenarios generated a wide range of predictions of future streamflows with three of the four scenarios indicating decreases in average summer streamflow of between 6% and 47% and one scenario indicating increases of about 15-19% (Figure E13). In contrast to the variable predictions in mean summer discharges, all four models predict large decreases in mean spring discharges that would be expected to hinder outmigration of juvenile salmonids. The CNRM scenario produces the smallest decreases with mean spring discharge in the high-priority reach of Mark West Creek decreasing from 7.8 cfs to 5.1 cfs (Figure E13). The MIROC esm scenario predicts the largest decreases with flows in the high priority reach decreasing from 7.8 cfs to 3.0 cfs.

Figure E11: Percent change in various components of the water balance for the four climate change scenarios relative to existing conditions; 10-yr average conditions (top) and the driest water year in each 10-yr simulation period (bottom).

Mitigated Scenarios

The mitigated scenarios combine the pond release and combined management scenarios with the GFDL future climate scenario. These scenarios indicate that pond releases can likely offset a significant portion of the projected decreases in summer streamflow predicted by some of the climate models and if combined with forest, grassland, and runoff management, are likely large enough to completely offset these projected decreases (Figures E12 & E13). If future climate more closely resembles the predictions of the CNRM or CCSM4 models, pond releases and combined management would be expected to result in summer flow enhancement above existing conditions. None of the potential actions generate changes large enough to significantly offset the substantial decreases in springtime discharges predicted by the four climate scenarios. Shorter-duration flow releases over periods of days to weeks strategically timed during the critical smolt outmigration period in spring could increase flow depths above fish passage thresholds and likely provide a key climate change mitigation strategy to address predicted reductions in streamflow during the spring season (Figure E12).
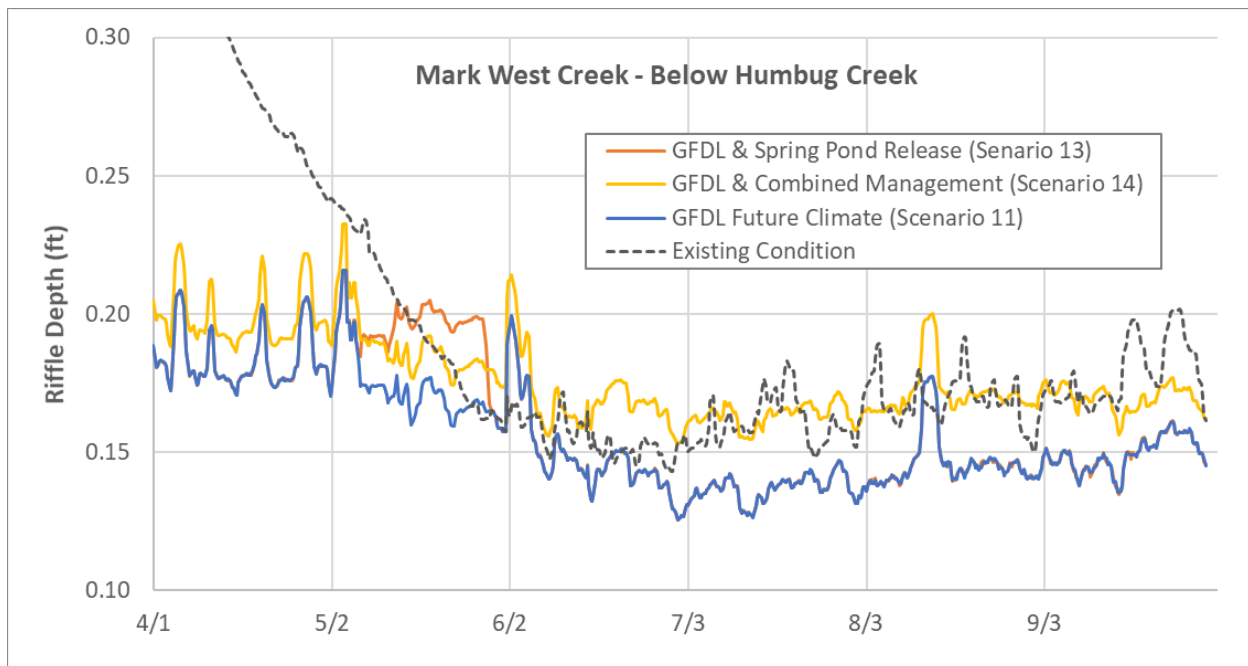
Figure E12: Spring and summer riffle depths for the driest year in the 10-yr simulation in Mark West Creek below Humbug Creek for existing conditions, the GFDL future climate scenario (Scenario 11), the GFDL & spring pond release scenario (Scenario 13), and the GFDL & combined management scenario (Scenario 14).
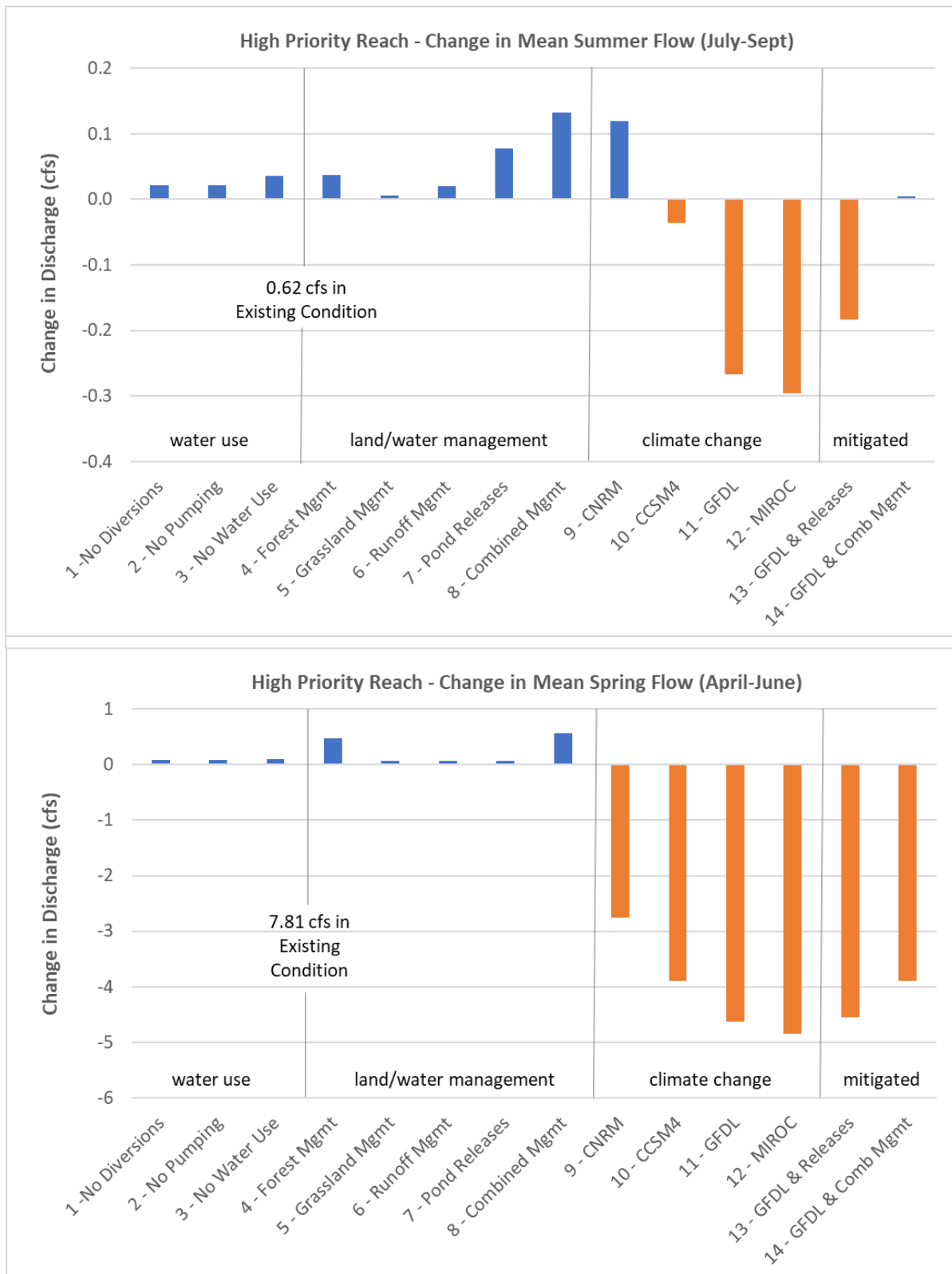
Figure E13: Summary of the simulated changes in mean summer (top) and mean spring (bottom) streamflow for Scenarios 1-14 averaged over the high-priority habitat reach.

Restoration & Management Recommendations

Habitat Enhancement
Based on simulated riffle depth and observed water temperature data informed by CDFW habitat inventory and CA Sea Grant fisheries monitoring data, the four mile reach extending from 0.2 miles upstream of Alpine Creek to 2.0 miles upstream of the Porter Creek confluence has the best overall conditions for supporting salmonids (Figure E14). We recommend that habitat enhancement projects be focused in this high priority reach where there exists the greatest likelihood of supporting overall reach conditions suitable for salmonids.

Based on a limited number of sample sites, water temperatures in the high priority reach appear to remain below severely impaired levels in pools with depths above about 3.5-ft whereas severely impaired temperatures occur in shallower pools (see Figure E6). More temperature monitoring and pool inventory analysis is recommended to identify pools providing critical temperature refugia. A temperature study is also warranted to better understand the controls on water temperatures and identify possible mitigation actions. Our preliminary findings suggest that streamflow is not the primary control on temperature and that encouraging formation of stable deep pools and maximizing shade on the stream surface are likely the most important immediate mitigation actions.

In-stream large wood (logs and trees) loads are low in Mark West Creek and projects to install large wood to encourage formation and enhancement of existing deep pools is recommended. Where needed, riparian planting projects to maximize shading of the summer water surface are recommended. Opportunities for development of off-channel habitat projects to enhance winter rearing habitat are also available in the identified reach, and these types of projects are also recommended to support improved conditions in the reach for other limiting life cycle stages.

Flow Protection/Enhancement
Summer baseflow throughout Mark West Creek is controlled primarily by spring discharge concentrated in the upper watershed. We recommend that the various flow protection and enhancement actions described below be focused in the watershed area contributing to the identified high priority reach where they are more likely to provide the most meaningful flow benefits. The portion of the watershed upstream of Van Buren Creek is of even greater importance for streamflow protection and enhancement given the disproportionate role this area plays in generating summer streamflow supplied to downstream reaches (Figure E14).

To assist in understanding the relative effectiveness of the various flow enhancement strategies we normalized simulated increases in streamflow based on a 'typical' parcel/project for six project types in consultation with Sonoma RCD. We also developed a rough cost estimate for each typical project and normalized the results again based on a $25,000 project cost. The six projects and estimated costs include:

- Groundwater Pumping Offset – installation of a 10,000 gallon rainwater catchment tank and associated reduction in groundwater pumping - $38,000

- Surface Diversion Replacement – replacement of a direct stream or spring diversion with a new groundwater well - $33,000
- Runoff Management – construction of an infiltration basin sized to capture the 10-yr 48-hr storm volume from a 3,000 ft^2 rooftop or other impervious area - $22,500
- Grassland Management – compost application on 4.6 acres of grassland (average per parcel acreage in the model scenario) - $7,000
- Forest Management – thinning and/or controlled burning on 5.6 acres of forested lands requiring treatment (average per parcel acreage in the model scenario) - $15,000
- Pond Release – summer flow release of 11.3 ac-ft from an existing on-stream pond (average release volume of the three ponds in the model scenario) - $20,000

Releasing water from existing ponds was found to be by far the most effective individual strategy for enhancing streamflows. On a cost basis, the streamflow benefits of one flow release project were found to be more than 50 times greater than an average surface water diversion replacement project and more than 500 times greater than an average grassland management project (the second and third most effective strategies, Figure E15). Examination of existing ponds revealed that there are only three ponds upstream of the high-priority reach with sufficient storage to provide meaningful releases, and we recommend that flow release projects be developed for these ponds if possible.

There are many existing ponds that could likely be enhanced, and new ponds could be created specifically for flow releases. Given the disproportionate effectiveness of pond releases for streamflow enhancement this approach should be seriously considered. Water temperature and other water quality and invasive species considerations should be an important aspect of planning flow release projects since water temperatures are already impaired and it is critical that flow releases do not further increase temperatures or introduce invasive species. There are various strategies that may be employed to mitigate elevated pond temperatures during planning and design (e.g. bottom releases, surface covering, cooling towers).

Replacing direct stream or spring diversions from surface water with groundwater pumping was the second most effective of the six project types, whereas offsetting groundwater pumping with storage was the least effective (Figure E15). While the modeling did suggest some relationship between the degree of streamflow depletion and the screen depth and distance of wells from streams/springs, these differences were modest and we did not find any direct relationship between the timing of pumping and the timing of streamflow depletion. These findings suggest that replacing direct stream and spring diversions with storage and/or groundwater pumping is a viable approach for enhancing streamflow conditions but that offsetting groundwater pumping with storage or shifting the timing of pumping from summer to winter is unlikely to lead to appreciable improvements in flow conditions. This is not to suggest that specific wells in specific locations are incapable of streamflow depletion; however, our review of well data and modeling results indicate that this would be uncommon in the study area.
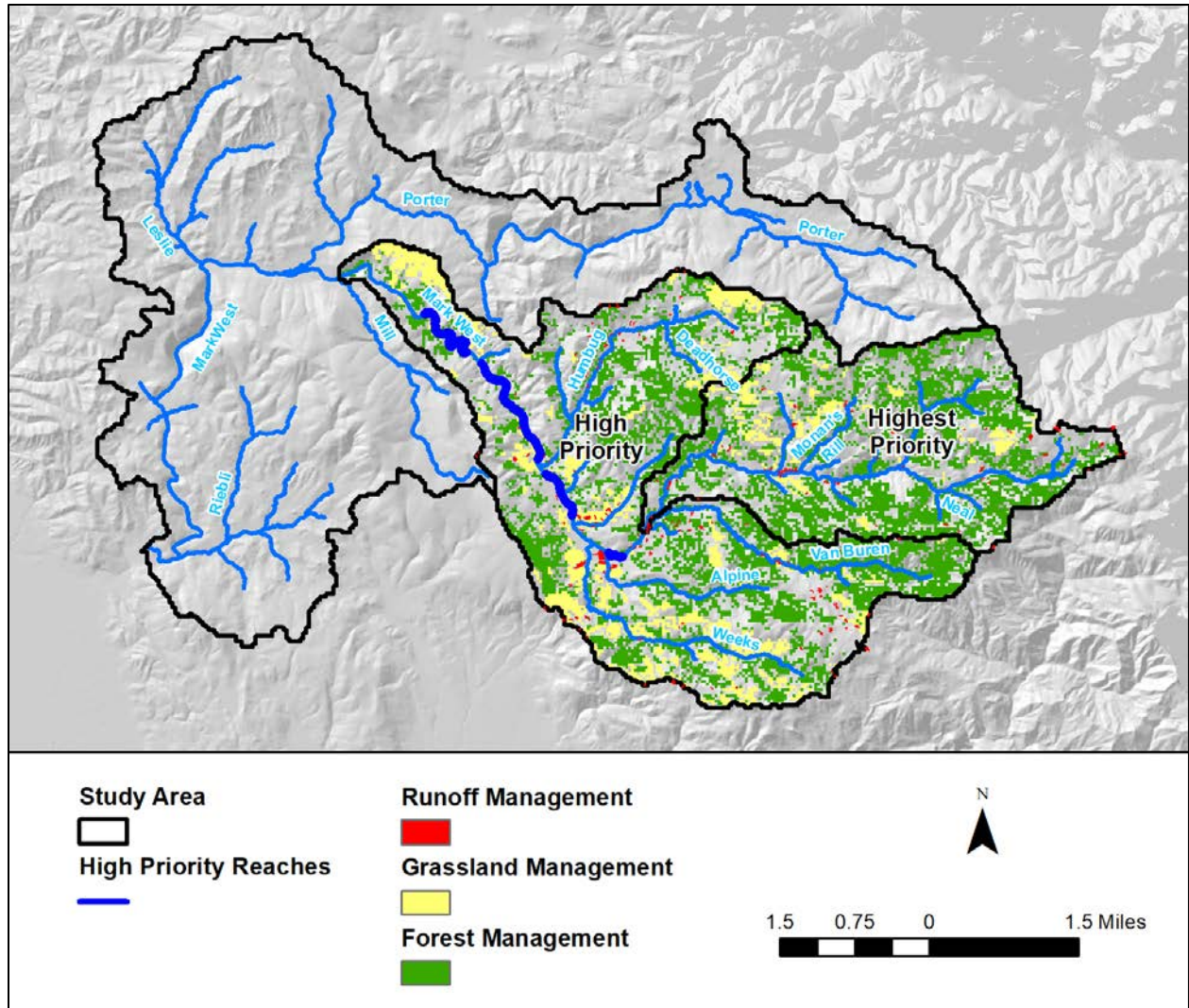
Figure E14: Locations of the identified high priority reaches for habitat enhancement projects and high priority watershed areas for flow enhancement projects.

Requiring new wells to be drilled at a specified minimum distance from a stream or spring or screened at a minimum depth may extend the length of time before streamflow depletion occurs; however, it will not prevent streamflow depletion from occurring. The long response timescale (decades) of streamflow to groundwater pumping revealed by our modeling suggests that a volumetric approach to managing groundwater is more likely to mitigate streamflow depletion compared to approaches focused on well location or time of use. It is important to note that the total pumping stress in the watershed is relatively small (~3% of mean annual infiltration recharge) and that the limited degree of streamflow depletion under existing conditions is not meant to suggest that groundwater pumping could not lead to significant streamflow depletion were the total volume of pumping to increase substantially in the future. That said, our analysis indicates that streamflow is not very sensitive to groundwater pumping at current rates.
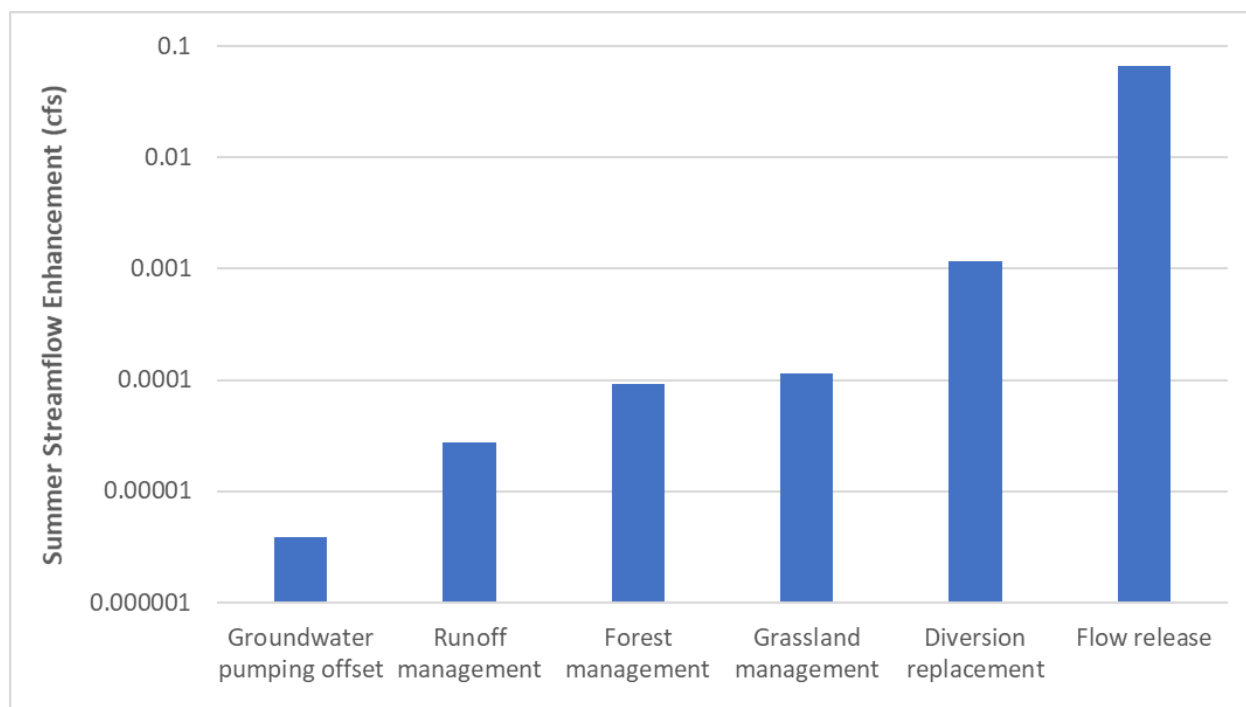
Figure E15: Summary of the simulated increase in mean summer streamflow for the six primary individual flow enhancement actions represented by the model scenarios and normalized to a $25,000 average project cost.

Grassland, forest, and runoff management were also found to result in summer streamflow improvement; however, the benefits per unit cost are one to two orders of magnitude lower than those of pond releases or diversion replacement (Figure E15). Grassland and forest management resulted in about equal benefits on a unit cost basis with about three to four times the effectiveness of runoff management. These three strategies also have important secondary hydrologic benefits in addition to enhancing streamflows in that they reduce seasonal vegetation moisture stress which may be expected to reduce fire risk. These benefits are in addition to the primary non-hydrologic benefits of these types of projects for reducing fuel loads (forest management) and sequestering carbon (grassland management). There are also potential negative consequences of extensive forest management in terms of potential habitat loss for avian and terrestrial species which must be carefully considered. In summary, while runoff, forest, and grassland management may not directly result in substantial streamflow improvement, these efforts have multiple benefits and are likely important strategies for managing fire risk and mitigating climate change impacts as discussed in more detail below.

Climate Change Adaptation
Climate change is expected to result in a dramatic decrease in springtime streamflow, particularly during drought conditions. These declines are expected to have significant effects on salmonid outmigration with some scenarios predicting impassable conditions developing as early as late winter and persisting through spring and summer. The only feasible strategy to mitigate these changes is to implement spring pond releases. While it may not be possible to significantly improve conditions throughout the smolt outmigration period, relatively high release rates could

be achieved for a period of several days to weeks to provide a window of passable flow conditions timed to coincide with expected peak smolt outmigration. Although the summer streamflow predictions vary widely, some scenarios show significant declines in summer streamflow. We recommend that flow release projects be developed and adaptively managed to provide a combination of larger pulses of streamflow during outmigration and lower-magnitude releases to sustain streamflow during summer baseflow depending on conditions in a given year.

The runoff, forest, and grassland management strategies influence the quantity of flow from springs which in general is relatively cold, therefore these approaches may be expected to assist in mitigating elevated water temperatures whereas the more effective strategies (pond releases and diversion replacement) would not be expected to provide significant temperature benefits. These strategies also help reduce vegetation moisture stress by increasing the quantity of water available to plants in the case of runoff and grassland management and decreasing water demand from the landscape for the case of forest management. Reduced moisture stress may be considered an important benefit in terms of reducing current wildfire risk and the increase in wildfire risk expected resulting from climate change. In summary, implementation of runoff, forest, and grassland management projects are expected to help build resiliency to climate change by providing multiple benefits beyond potential streamflow improvement and spring and summer pond releases provide a means of adaptively managing flow conditions for salmonids in the face of a changing climate.

Conceptual Designs

The final phase of the project involved development of conceptual designs for two site specific streamflow enhancement projects. The projects focus on the approach of runoff management and were selected to take advantage of local site conditions and project opportunities on properties managed by our project partners the Pepperwood Foundation and Sonoma County Regional Parks. The projects illustrate two possible approaches to managing runoff for enhanced groundwater recharge and we anticipate similar approaches as well as other alternative methods could be applied on parcels throughout the watershed.

Goodman Meadow
Site 1 is located within the Pepperwood Preserve at the Goodman Meadow near the headwaters of Leslie Creek in the northwest corner of the Mark West Creek watershed. The Goodman Meadow site consists of a relatively flat, approximately 12-acre natural basin perched on a topographic bench. The design converts portions of the meadow into an infiltration basin by constructing a berm and outlet structure along the downstream edge of the meadow (see Appendix A). The design creates approximately 5.3 ac-ft of storage within 1.4-acres comprising the lower portion of the meadow. Based on hydrologic modeling of the conceptual design, the basin would be capable of generating about 1.9 ac-ft/yr of additional infiltration recharge. This enhanced recharge would increase the mean springtime flow in upper Leslie Creek by about 0.01 cfs and extend the duration of connected surface flow by about 12 to 21 days.

<u>Mark West Regional Park</u>
Site 2 is located on a terrace on the east bank of Porter Creek about 1,800-ft upstream of its confluence with Mark West Creek. The site is slated to be developed as the main entrance and parking area for Mark West Regional Park managed by Sonoma County Regional Parks. Park facilities have not yet been designed in detail but are expected to be contained within approximately 3.1 acres currently occupied by a barn structure and an adjacent parking area and gravel road (see Appendix B). The stormwater management design described here is intended to become a part of the overall design for the park facilities and consists of collecting runoff from the developed portions of the park entrance in a network of diversion ditches and directing these flows into a series of two linear, gravel filled infiltration basins designed to maximize groundwater recharge. The total storage capacity of the basins is 0.65 ac-ft.

The scale of the site design features is too fine to be accurately represented in the regional hydrologic model; however, based on regional runoff management scenario results, we estimate that the project will generate between 0.3 and 1.2 ac-ft/yr of additional infiltration recharge. It is unlikely that the project by itself will generate significant increases in streamflow in Porter Creek, however the regional modeling suggests that large-scale adoption of stormwater best management practices has the potential to increase the mean springtime streamflow in lower Porter Creek by about 0.05 cfs and extend the duration of surface flow connection by up to 13 days.

Chapter 1 – Introduction

The project described in this report was completed by O'Connor Environmental, Inc. (OEI) under the direction of the Coast Range Watershed Institute (CRWI) in cooperation with the Sonoma Resource Conservation District (SRCD), Friends of Mark West Creek, Sonoma County Regional Parks, and the Pepperwood Foundation. The project was funded by a Proposition 1 Streamflow Enhancement Program grant (Grant Agreement No. WC-1996AP) from the California Wildlife Conservation Board (WCB).

The Mark West Creek watershed has been identified by California Department of Fish & Wildlife (CDFW) and National Oceanic & Atmospheric Administration National Marine Fisheries Service (NMFS) as providing some of the best remaining habitat for coho salmon (*Oncorhynchus kisutch*) in the Russian River watershed. Several factors have been identified as limiting for coho survival in the watershed including lack of quality pool habitat, lack of winter refugia, and insufficient summer baseflows (CDFG, 2004; NMFS, 2012). Numerous restoration projects have been implemented in the watershed in recent years aimed primarily at improving pool and off-channel habitat conditions. Additional efforts have begun to address the problem of insufficient stream flow primarily through water storage and flow release projects. Successful efforts to improve streamflow conditions will require greater understanding regarding the distribution of flow conditions and the various natural and man-made controls on these flows.

The combination of frequent drought conditions, ongoing and future climate change, and increasing human demand for water make development of strategies for sustaining or improving summer streamflow conditions of paramount importance for coho recovery in the Mark West Creek watershed. The goal of this project was to conduct a comprehensive analysis of the spatial and temporal distribution of streamflow conditions throughout the watershed relative to coho habitat requirements to assist in prioritizing restoration efforts and developing strategies for protecting/enhancing summer baseflows.

Specifically, this project involved the development, calibration, and application of a distributed hydrologic model (MIKE SHE) with inputs comprised of climate, topographic, land cover, soils, water use, and hydrogeologic data for the watershed. Model outputs include estimates of the annual and seasonal water balance, simulated stream flow hydrographs, and predicted groundwater elevations and flow gradients among many other hydrologic parameters. The modeling results provided the basis for performing an analysis of streamflow, characterizing the distribution and quality of available habitat for juvenile coho, and making recommendations about restoration priorities for various sub-reaches within the study area.

Additionally, the model has been applied to evaluate potential improvements to streamflow and aquatic habitat conditions resulting from various streamflow restoration strategies including forest management, stormwater management and recharge enhancement, adjustments to surface diversions and groundwater pumping regimes, and flow releases from existing ponds. Conceptual designs were developed for two specific projects which were identified and evaluated as part of the project. The model was also used to investigate the effects of ongoing climate

change on streamflow and habitat conditions. In addition to the findings and recommendations discussed in this report, the model also provides a working Decision Support System for ongoing restoration efforts and land and water management decision making and should be considered a "living" model that can be updated as new data and information become available and utilized to help answer new management questions as they arise.

Chapter 2 – Study Area Description

Overview

The Mark West Creek (MWC) watershed is part of the Coast Range Geomorphic Province draining approximately 57 mi^2 of the lower Russian River watershed discharging to the Laguna de Santa Rosa about five miles upstream of its confluence with the Russian River. MWC watershed is commonly divided into an upper watershed in the Mayacamas Mountains and a lower watershed located within the Santa Rosa Plain. Neighboring watersheds include Franz and Maacama Creeks to the north, Santa Rosa Creek to the south, and the Napa River to the east.

The study area is defined as the MWC watershed above Quietwater Road which encompasses all of the 40 mi^2 upper MWC watershed (Figure 1). The upper MWC watershed is characterized by relatively steep topography, confined channels, and bedrock aquifers. Elevations range from 180 feet at Quietwater Road to over 2,300 feet near the headwaters. The study area includes 18 river miles of MWC, several major tributaries such as Porter, Leslie, Humbug, Mill, Weeks, Alpine, and Van Buren Creeks as well as numerous smaller tributary streams. Quietwater Road was selected as the downstream boundary of the study area because it coincides with the extent of the reach identified as critical salmonid summer rearing habitat in the State Water Resources Control Board Emergency Order (WR 2015-0026-DWR). This boundary also approximately coincides with the boundary of the Santa Rosa Plain aquifer as defined by the State Groundwater Management Act (SGMA). Below Quietwater Road, MWC enters the alluvial system of the Santa Rosa Plain which has significantly different characteristics and water management issues.

Upper MWC was severely affected by the October 2017 Tubbs Fire which burned through approximately 48% of the study watershed (19.4 mi^2). Following the fire, forest management and fuel reduction have become a greater concern to many residents in the watershed. The watershed has a substantial number of existing and proposed cannabis cultivation operations which has also generated significant concern among residents, and county, state, and federal regulatory authorities regarding potential adverse impacts of cannabis cultivation on streamflow and salmonid habitat. In addition to being identified in state and federal recovery plans as a high priority watershed for restoration of endangered coho, MWC watershed was identified in the 2014 California Water Action Plan as one of five priority streams, and is the site of several ongoing studies including a CDFW Instream Flow Study and a hydrologic modeling effort by the U.S. Geological Survey (USGS) and Sonoma Water coupled to implementation of the SGMA in the Santa Rosa Plain Groundwater Basin.
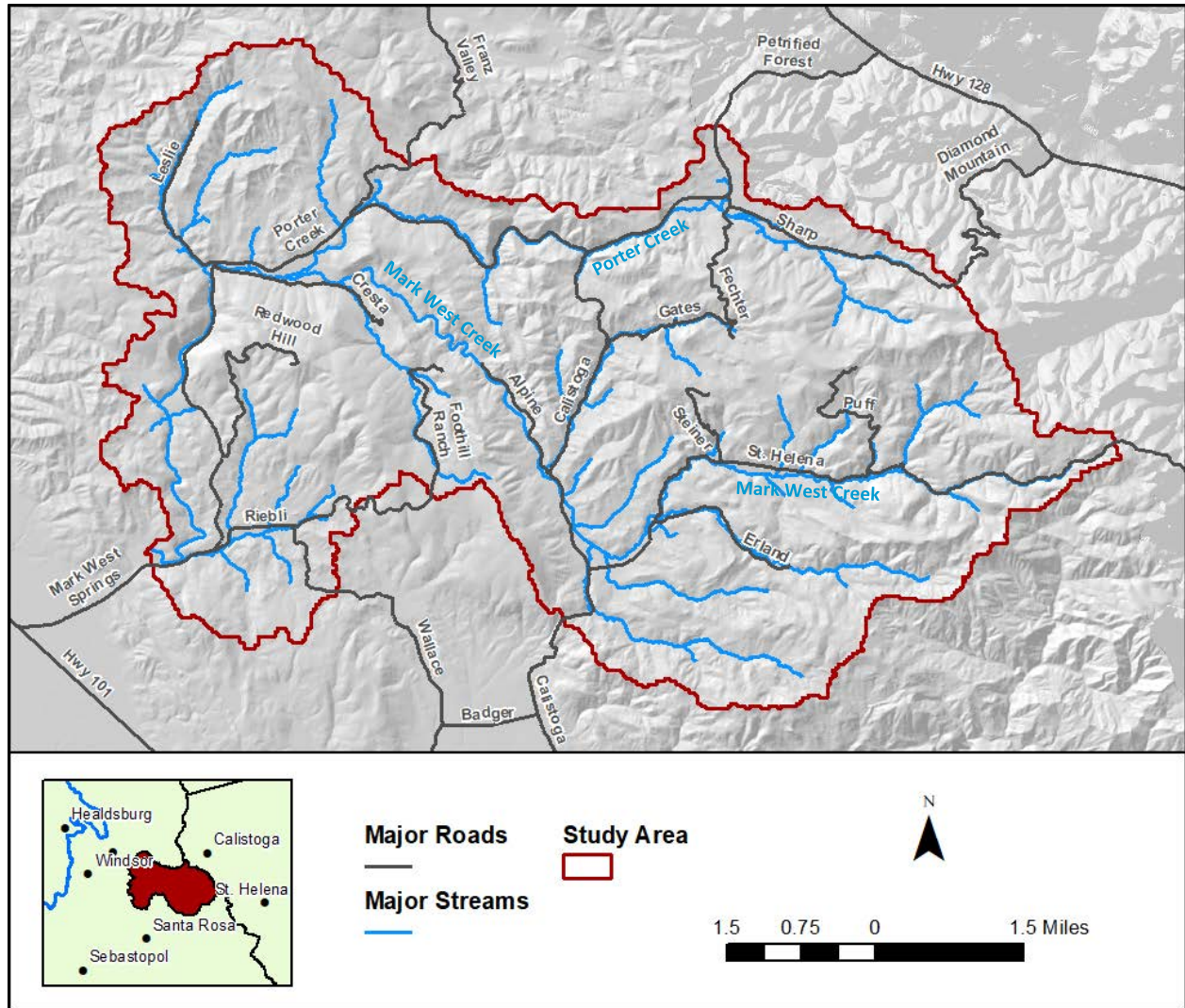
Figure 1: Map of the study area showing major roads and streams.

Climate

The upper MWC watershed has a Mediterranean climate characterized by cool wet winters and warm dry summers. Precipitation varies substantially across the study area from an average of approximately 38 inches per year near the Santa Rosa Plain to approximately 51 inches per year near the crest of the Mayacamas Mountains (Flint & Flint, 2014). For much of the year there is a strong east/west temperature gradient with warmer conditions in the higher elevations to the east relative to lower elevations to the west. This gradient is most pronounced during the daytime where mean maximum monthly temperatures are up to 6.9 °F (3.8 °C) higher at the St. Helena 4WSW climate station in the Mayacamas compared to the Santa Rosa climate station in the Santa Rosa Plain. During the winter (November – February) this gradient flattens or reverses with temperatures in the Mayacamas being the same or slightly (~1 °F) cooler than in the Santa Rosa Plain.

Land Use

Early settlement of the watershed began in earnest during the 1850s and 1860s due to reports of gold in the Russian River area and passage of the Homestead Act. During this time, land use activity in the upper portions of the watershed was focused on mining for silver and mercury, and livestock grazing. Agricultural activities were primarily focused in the lower portions of the watershed and included orchards, vineyards, and hop fields. Logging operations and associated road building also began around this time to clear fields for crops and support the demand for timber from the growing population in the Bay Area. Since World War II, agricultural development has increasingly been replaced by residential development (SRCD, 2015).

Existing land cover is primarily forest (72%), with the remainder divided between grassland (16%), shrubland (7%), developed and sparsely vegetated areas (3%), and agriculture (2%). Most of the forest areas are comprised of various species of oak (48%) and Douglas Fir (36%) with significant stands of Bay Laurel (5%), Coast Redwood (4%), and Madrone (2%) comprising most of the remainder. Ongoing forest succession has been occurring in the watershed in recent decades with expansion of Douglas Fir into Oak Woodlands. Vegetation recovery and potential changes to vegetation patterns following the October 2017 Tubbs Fire which burned about 48% of the study watershed area (20% with moderate or high burn severity) have not been well-quantified.

Land ownership in the watershed is primarily privately-owned rural residential properties with a few agricultural parcels. The Sonoma County Agricultural Preservation and Open Space District and Sonoma County Regional Parks own multiple properties including the Saddle Mountain Preserve, and the Cresta and McCullough Ranch which is slated to become the Mark West Regional Park. The Pepperwood Preserve in the northern portion of the watershed is the site of many ongoing scientific investigations and educational programs. The watershed also includes the Safari West wildlife preserve and portions of the Mayacamas Golf Club.

Geology

The geology of the Upper Mark West Creek watershed is complex and includes several distinct rock types which are offset by a series of faults and fracture zones. The northwest by southeast-trending Maacama Fault Zone bisects the study area and separates distinct geologies to the east and west. West of the Maacama Fault Zone, the study area is dominated by the early-Pleistocene and Pliocene-aged Glen Ellen Formation and bedrock units of the Pliocene and late-Miocene-aged Sonoma Volcanics (basalt and volcanic tuff). East of the fault zone, the study area is dominated by volcanic tuff and andesite of the Sonoma Volcanics and by the Cretaceous and Jurassic-aged Franciscan Complex. Other significant faults include the Larkfield, Rincon Creek, and Mark West Fault Zones to the west of the Maacama Fault Zone which form contacts between the Sonoma Volcanics and the Glen Ellen Formation. The Gates Canyon and Petrified Forest Thrust to the east of the Maacama Fault Zone place rocks of the Sonoma Volcanics in contact with older rocks of the Franciscan Formation.

Other geologic formations, including the Pliocene-aged Fluvial and Lacustrine Deposits of Humbug Creek and the Cretaceous and Jurassic-aged Great Valley Sequence occupy smaller portions of the study area. Quaternary-aged landslide and fluvial deposits are also present but

are typically shallow and occupy a relatively small portion of the study area. Interpretation of subsurface geologic conditions from Well Completion Reports reveals that the landslide and fluvial deposits are generally less than 25-ft thick and that most wells are completed in underlying bedrock units. The thickest and most widespread alluvium is found along Mark West Creek near its confluence with Porter Creek where it reaches thicknesses of up to 65-ft. Examination of Well Completion Reports also revealed that the Glen Ellen Formation is generally unsaturated and relatively thin (50-100 ft). Most wells drilled in the Glen Ellen Formation extend into the underlying Sonoma Volcanics where groundwater is more frequently found.

Aquatic Habitat

Coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*Oncorhynchus mykiss*) are present in upper MWC and its tributaries. CDFW habitat surveys were conducted in Porter Creek in 1974 and 1996, in Humbug Creek in 1996, and in Horse Hill, Mill, Weeks, and Van Buren creeks in 1997. These surveys documented steelhead presence in Porter, Mill, Humbug, and Van Buren creeks but not in Horse Hill or Weeks Creek. Coho were not documented in any of these tributary surveys.   Notable limiting factors in the tributaries included insufficient summer flows, inadequate pool habitat and riparian canopy, and a lack of quality spawning gravels.

Wild coho were observed in upper MWC in 2001 by CDFW during a snorkel survey as well as in more recent CA Sea Grant snorkel surveys. Available data from Sonoma Water and CA Sea Grant indicates that adult coho returned to spawn in MWC in water year 2011, 2012, and 2013 but not during the drought conditions of 2014. The Russian River Coho Salmon Captive Broodstock Program first released hatchery salmon into the MWC watershed in autumn of 2011; between 13,000 and 23,000 juvenile coho were released in Mark West Creek and Porter Creek each year between 2011 and 2014, and in 2016. In 2017, 6,000 fish were released only in Porter Creek. In addition to salmonids, California red-legged frog (*Rana draytonii*) and yellow-legged frog (*Rana boylii*), which are both listed as threatened, have been documented in the watershed.

Chapter 3 – Numerical Modeling Methodology

The hydrologic model of the upper Mark West Creek watershed was constructed using the MIKE SHE model (Graham and Butts, 2005; DHI 2017). Model code development activities have been ongoing since its inception in 1977 and the model has been applied successfully to hundreds of research and consultancy projects covering a wide range of climatic and hydrologic regimes around the world (Graham and Butts, 2005).

The MIKE SHE model is a fully-distributed, physically-based model capable of simulating all the land-based phases of the hydrologic cycle including overland flow, channel flow, evapotranspiration, unsaturated flow, saturated flow, and stream/aquifer interactions. The distributed nature of the model makes it well-suited for examining the hydrologic impacts of changes in climate and water management. Complex physics-based watershed models, while powerful tools, require extensive input data and should ideally be well-calibrated to observed stream flow and groundwater data spanning a number of years. It is important to bear in mind

that a model is a simplification of a complex and in some ways unknowable hydrologic system and although it can provide useful estimates of various flows and storages within the system, the estimates contain uncertainty and should not be viewed as a replacement for real data or as a static condition. Such models are best updated on a periodic basis as new data become available.

Overland Flow

The overland flow component of MIKE SHE solves the two-dimensional St. Venant equations for shallow free surface flows using the diffusive wave approximation. A finite-difference scheme is used to compute the fluxes of water between grid cells on a two-dimensional topographic surface. Net precipitation, evaporation, and infiltration are introduced as sources or sinks and the model assumes that a sheet flow approximation is valid for non-channelized surface flows and that roughness is uniform over various flow depths. The primary inputs of the overland flow module include topographic information in the form of a digital elevation model (DEM) and a corresponding spatial distribution of overland roughness coefficients (Manning's n) which is generally referenced to the model's land cover categories. Sub-grid-scale depressions in the topography and barriers to overland flow are represented conceptually through use of a detention storage parameter.

Channel Flow

The channel flow component of the model calculates unsteady water levels and discharges using an implicit finite-difference formulation to solve the one-dimensional St. Venant equations for open channel flow. The model is capable of simulating ephemeral stream conditions and backwater effects and includes formulations for a variety of hydraulic structure types including bridges, weirs, and culverts. Either a no-flow or a discharge boundary can be used as the upstream boundary condition, and the downstream boundary can be represented using a stage or stage discharge relation. Other than boundary conditions, the primary inputs for the channel flow model include channel geometry information and roughness coefficients for channelized flow (Manning's n).

Channel Flow Interactions

Interaction between the channel flow and overland flow components for the model is driven by the gradient between the overland water depths in a given grid cell and the head in a corresponding computational node in the channels and is computed using a broad crested weir equation. Depending on the direction of the gradient, the channel flow component of the model can either receive overland flow during runoff events or release water back into the floodplain as overland flow. The model is also capable of simulating backwater effects onto the overland flow plane due to restricted channel flow.

Evapotranspiration and Interception

Evapotranspiration (ET) is handled in the model using a two-layer water balance approach which divides the unsaturated zone into a root zone from which water can be transpired and a lower zone where it cannot. The model computes actual evapotranspiration (AET) as a function of potential evapotranspiration (PET) and the available water content in the vegetation canopy, overland flow plane, and the unsaturated zone. The model first extracts water from interception

storage which is based on vegetation properties including leaf area index (LAI) and an interception storage coefficient. Next, water is extracted from ponded water on the land surface and, finally, from within the unsaturated zone or, if the rooting depth exceeds the depth to water for a given timestep, the saturated zone. PET can be adjusted for each land cover category in the model through use of a crop coefficient (Kc). The simulated position of the water table along with the specified rooting depth determines the thickness of the zone of transpiration.

Unsaturated Flow

The unsaturated flow component of MIKE SHE functions with the two-layer water balance method described above. The method considers average conditions in the unsaturated zone and tracks available soil moisture to regulate ET and groundwater recharge using a one-dimensional (vertical) formulation. A soil map Is used to distribute the primary soil properties used to drive the model, including saturated hydraulic conductivity (K_{sat}) and moisture contents (Θ) at saturation, field capacity, and wilting point. The unsaturated flow component of the model interacts with the overland flow component by serving as a sink term (infiltration) and with the groundwater flow component by serving as a source term (recharge).

The unsaturated zone component of the model does not explicitly represent lateral movement through and discharge from the unsaturated zone commonly referred to as interflow. In the MWC watershed, interflow occurring at or near the contact between soils and underlying bedrock is expected to be an important process. Because interflow is often associated with a temporary increase in groundwater elevations during and following precipitation events, interflow processes can be approximated in MIKE SHE with a saturated zone drainage function.

Saturated Flow

The groundwater component of the model solves the three-dimensional Darcy equation for flow through saturated porous media using an implicit finite difference numerical scheme solved using the preconditioned conjugate gradient (PCG) technique which is nearly identical to that used in MODFLOW, a widely used U.S. Geological Survey groundwater model. The primary inputs to the model are horizontal and vertical hydraulic conductivity, specific yield, storage coefficients, and the upper and lower elevation of each layer(s) considered in the model. External boundary conditions can be no-flow, head, or gradient boundaries and pumping wells can be added as internal sinks. The lower boundary of the model is zero-flux or a specified flux-boundary, and the upper boundary condition is a flux term calculated by the unsaturated flow component of the model (recharge). If the water table reaches land surface, the unsaturated flow calculations are disabled and the groundwater component of the model interacts directly with the overland flow plane.

Chapter 4 – Model Construction

Model Overview

The Upper Mark West Creek hydrologic model is defined as the Mark West Creek watershed upstream of Quietwater Road. The model is discretized into over 50,000 45-meter by 45-meter (0.5-acre) grid cells covering a 40.2 mi^2 area. The grid resolution was selected to represent the watershed in as much detail as possible consistent with the overall resolution of input data while enabling reasonable computation times (about 100 hours).

The model simulates a continuous 10-yr period from 10/1/2009 through 9/30/2019 (Water Years 2010 - 2019). This period was selected because it corresponds to the period with the most data available for model calibration, is representative of long-term average precipitation conditions, and includes a wide variety of precipitation conditions ranging from the very dry Water Year (WY) 2014 when annual precipitation at the Santa Rosa and St. Helena 4SW climate stations was 14.9 and 28.9 inches respectively to the very wet WY 2017 when annual precipitation at the two stations was 50.2 and 74.0 inches respectively (Figures 2 & 3). Based on the long-term precipitation record for Santa Rosa from 1906 – 2019, WY 2014 was the 4th driest year on record and WY 2017 was the 5th wettest (Figure 2). The 2-yr rainfall total for WY 2013-2014 was the second driest on record (14.9 inches versus 12.8 inches for 1976-1977). Mean annual precipitation at the Santa Rosa climate station for the simulation period was 31.1 inches, which is similar to both the 1906-2019 and 1981-2010 averages of 30.2 and 32.1 inches respectively (Figure 2).

A longer streamflow record is available for the upper watershed, but streamflow data from the lower watershed (developed for this project to facilitate model calibration) is only available for WY 2018 and 2019. Although simulation of post-fire hydrologic impacts and subsequent recovery from the Tubbs Fire was not part of the scope of this project, given the timing and scale of the October 2017 fire event just prior to collection of streamflow data, it was necessary to incorporate a simplistic representation of the post-fire landscape into the model to facilitate calibration. Post-fire hydrologic effects are complex and adjust rapidly in the years following disturbance. An ongoing USGS is underway to better understand the effects of the fire on soil hydrologic conditions, and preliminary findings suggest highly localized effects and that recovery to pre-fire characteristics occurs rapidly (Perkins, personal communication).

We did not attempt to represent the long-term effects of fire or recovery; rather, we developed a version of the model representing the short-term effects (first and second year after disturbance) of the fire exclusively for calibration purposes, and maintained the pre-fire landscape for the primary simulation of existing conditions and future scenarios. This decision acknowledges that the available data describing vegetation in the watershed was collected prior to the fire and that the long-term recovered landscape is likely to more closely resemble the pre-fire landscape than the short-term post-fire landscape, and thus represents a more appropriate basis for evaluating management decisions.
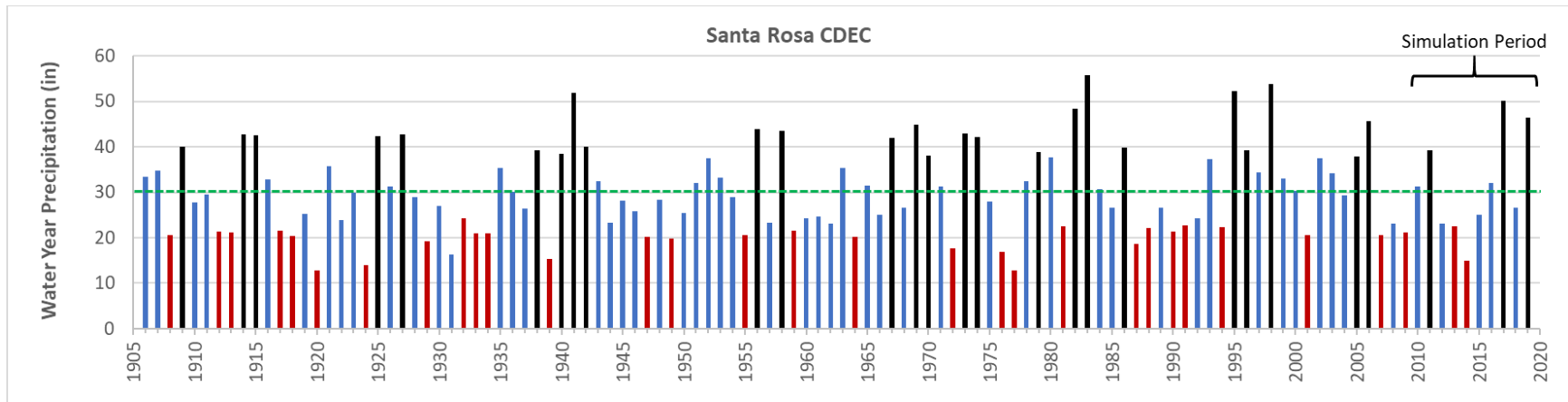
Figure 2: Long-term annual precipitation record for the Santa Rosa CDEC climate station (black and red values indicate wet and dry years defined as +/- 25% of the long-term average as shown with the dashed line).
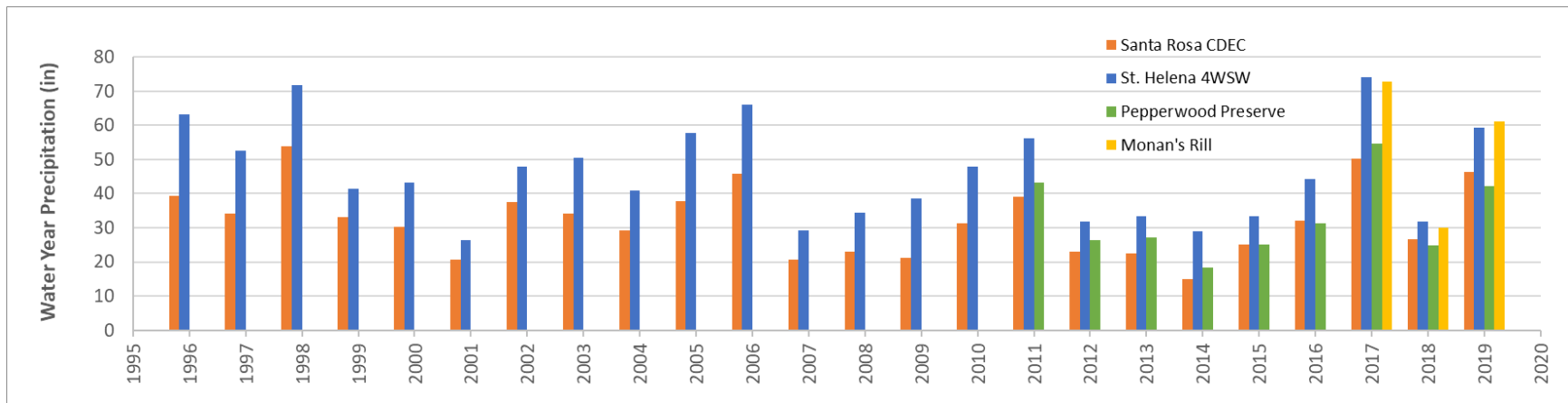
Figure 3: Annual precipitation records for various climate stations in and around the MWC watershed.
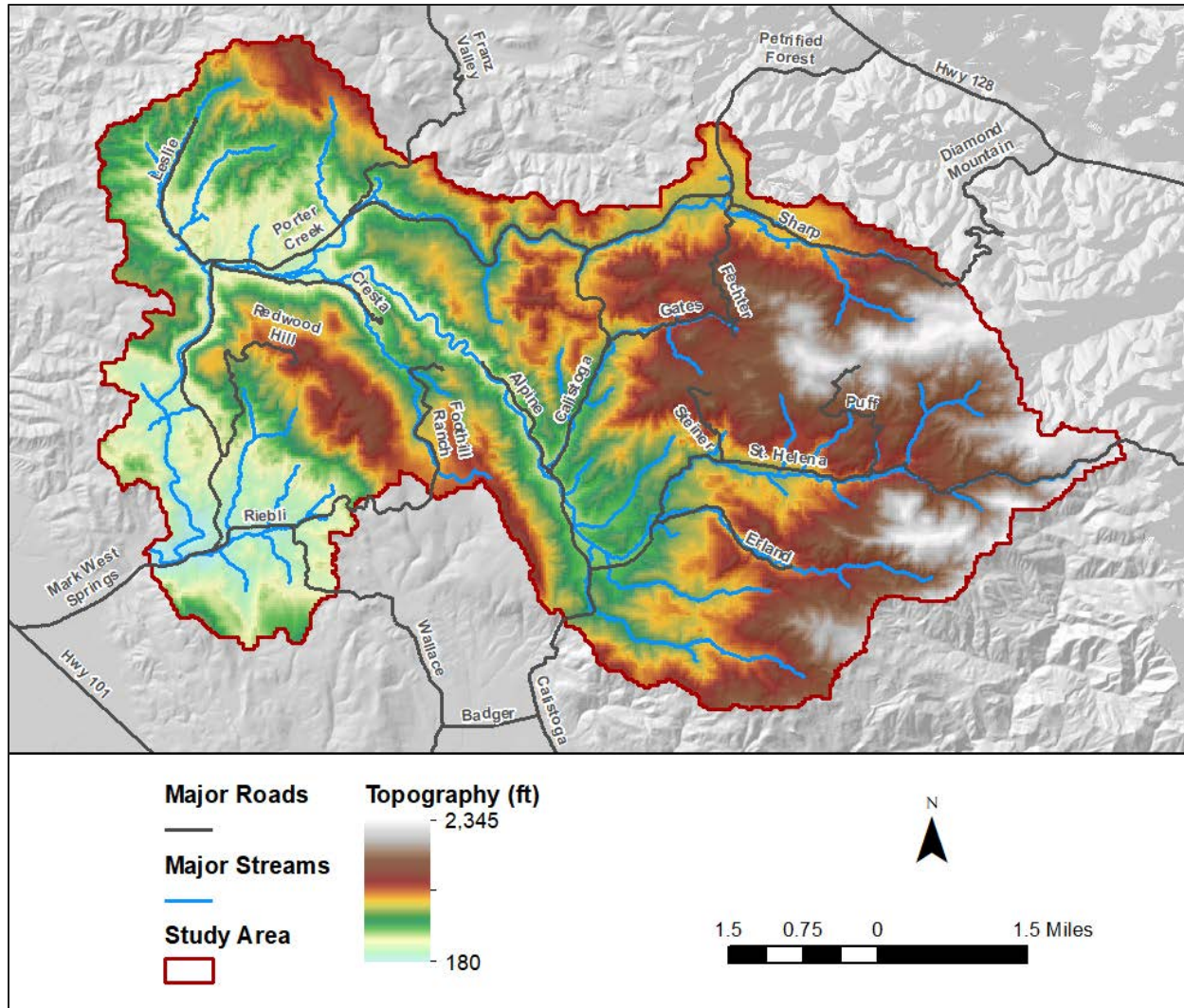
Figure 4: Topography used in the MWC hydrologic model.

Topography

Model topography is based on the 3-foot resolution Sonoma County LiDAR dataset (WSI, 2016) which was resampled to conform to the 45-meter grid cells used in the model. Elevations in the model domain range from 180 feet near Quietwater Road to 2,345 feet on Diamond Mountain near the border between Sonoma and Napa Counties (Figure 4).

Climate

Precipitation and Potential Evapotranspiration (PET) are the primary climatic inputs to the model; both are represented on a daily timestep. Based on the Basin Characterization Model (BCM) (Flint et al., 2013; Flint & Flint, 2014) which provides gridded estimates of average annual precipitation for the 1980-2010 period throughout California, a significant east-west gradient in precipitation exists across the watershed. Mean annual precipitation is estimated to increase

from 38 in/yr near the Santa Rosa Plain to 51 in/yr near the crest of the Mayacamas Mountains. Based on analysis performed for this study (as described below) PET varies primarily with aspect and is estimated to range from 30 to 52 in/yr. To account for the spatial variability in climate, the model domain was divided into 1-inch interval precipitation and PET zones (Figures 5 & 6).

Precipitation

There are several weather stations within the Upper Mark West watershed and surrounding areas (Figure 5). A long-term daily precipitation record dating back to Water Year (WY) 1906 is available from the Santa Rosa station operated by Sonoma County and located southwest of the watershed in the Santa Rosa Plain (Figure 2). A shorter but significant precipitation record dating to WY 1996 is available from the St. Helena 4WSW station operated by the California Department of Water Resources (DWR) and located southeast of the watershed along the ridge separating Sonoma and Napa County. Another significant record dating to WY 1991 is available from the Windsor station operated by the California Irrigation Management Information System (CIMIS) and located near the Town of Windsor. The Pepperwood Preserve has the longest operating precipitation station in the watershed dating to WY 2011. CRWI operated two stations at the Monan's Rill community in the upper watershed beginning in WY 2017. Three additional stations were installed by Sonoma Water in the watershed in February 2018 including Mark West Creek at Michelle Way, Mark West Creek at Porter Creek Road, and Mark West Regional Park (Figures 3 & 5).

The model domain is divided into 14 precipitation zones to account for the west to east gradient in precipitation (Figure 5). These zones are based on 1-inch annual isohyets derived from the BCM 1981-2010 mean annual precipitation data which is available at a 270-meter spatial resolution (Flint and Flint, 2014). Each zone was assigned to a rainfall station and precipitation was scaled up or down based on the ratio of the mean annual precipitation in the zone to the mean annual precipitation at the corresponding weather station. The station assignments vary throughout the simulation period as more stations became available during more recent time periods. For 10/1/2009 through 10/4/2010, all zones utilized the St. Helena 4WSW station. For the period 10/5/2010 to 11/15/2016, all zones utilized the Pepperwood station, and for the period 11/16/2016 to 2/1/2018, the 38 to 44-inch zones utilized the Pepperwood station and the 45 to 51-inch zones utilized the Monan's Rill station. For the most recent time period from 2/2/2018 to 9/30/2019, the 38 and 39-inch zones utilized the Michelle Way station, the 40 to 42-inch zones utilized the Pepperwood station, the 43 to 45-inch zones utilized the Mark West Regional Park station, and the 46 to 51-inch zones utilized the Monan's Rill station (Table 1 & Figure 7).

Comparisons between the BCM long-term average precipitation and the long-term average precipitation at the Santa Rosa and St. Helena 4WSW gages suggest that the BCM may over-predict rainfall by ~15-20%. Nevertheless, the magnitude of the gradient across the MWC watershed as predicted by the BCM agrees well with the station data, and the BCM provides the
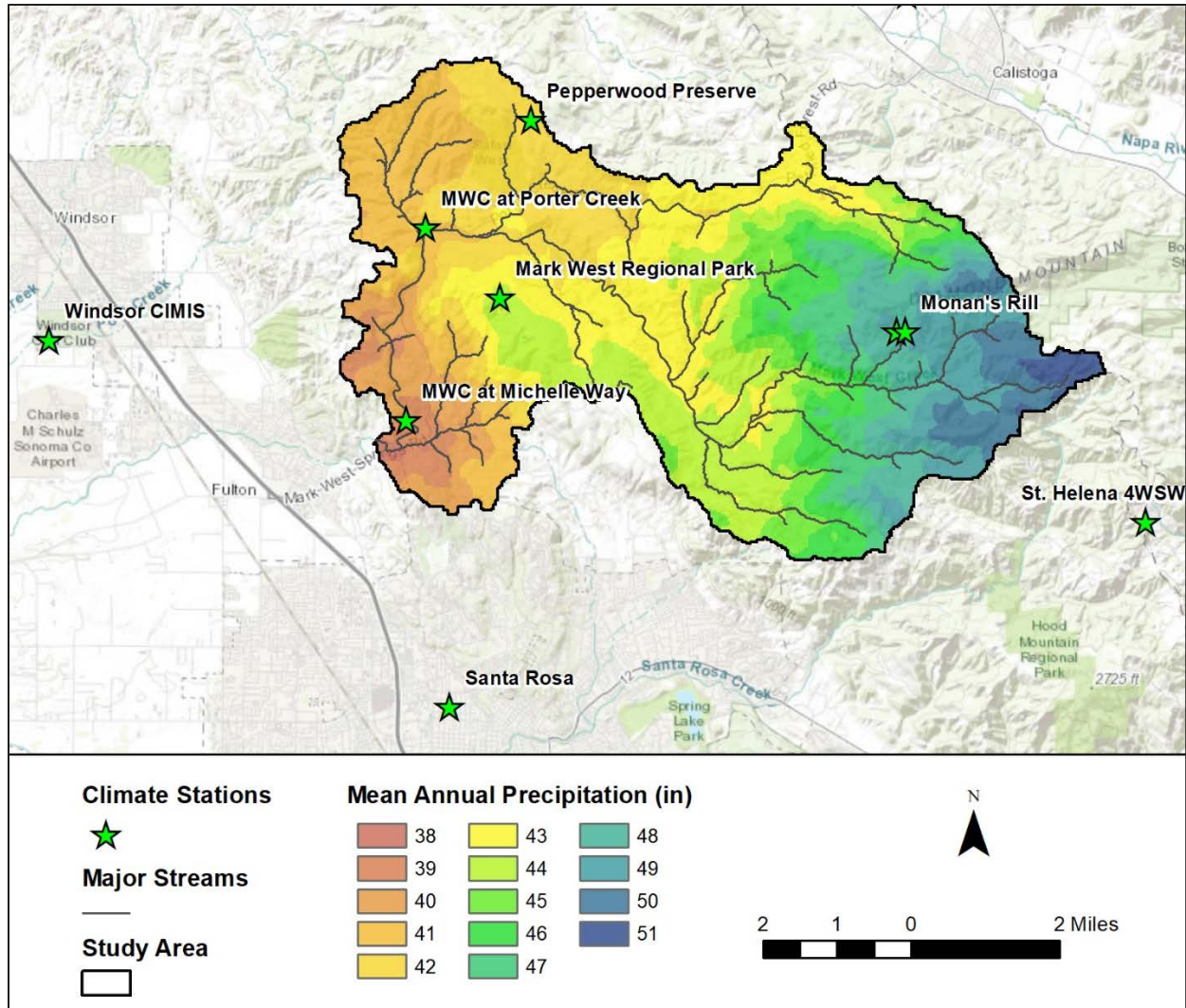
Figure 5: Precipitation zones and climate stations used in the MWC hydrologic model.
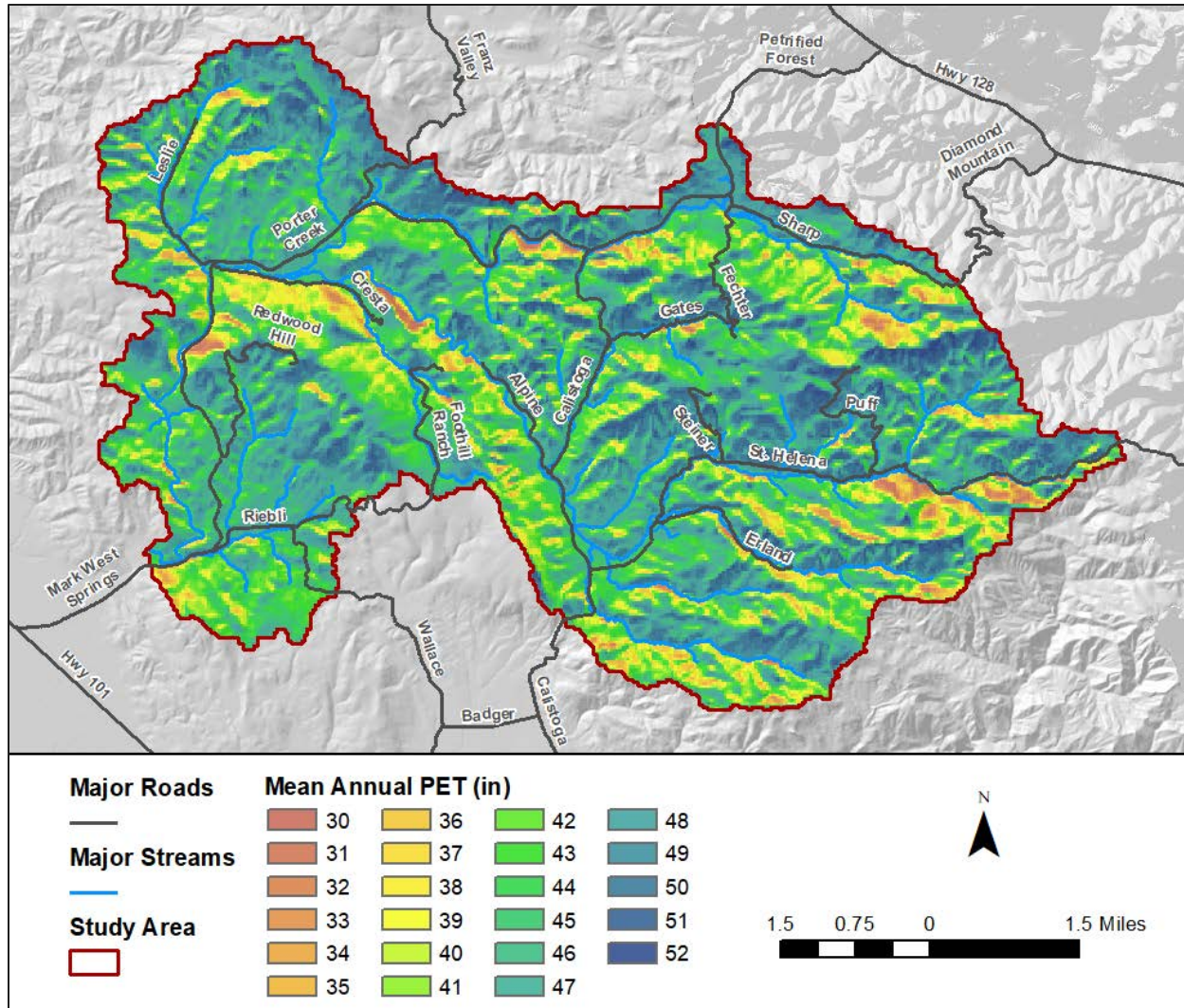
Figure 6: PET zones used in the MWC hydrologic model.

Table 1: Precipitation station assignments used for various time periods. Station codes and associated BCM mean annual precipitation values are as follows: MW – Michelle Way 38.5-in, PEP – Pepperwood 41.5-in, MWRP – Mark West Regional Park 43.8-in, MR – Monan's Rill 48.5-in, SH – St. Helena 4WSW 49.7-in.

	Precipitation Zone													
Time Period	38	39	40	41	42	43	44	45	46	47	48	49	50	51
10/1/2009 - 10/4/2010	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH
10/5/2010 - 11/15/2016	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP	PEP
11/16/2016 - 2/1/2018	PEP	PEP	PEP	PEP	PEP	PEP	PEP	MR	MR	MR	MR	MR	MR	MR
2/2/2018 - 9/30/2019	MW	MW	PEP	PEP	PEP	MWRP	MWRP	MWRP	MR	MR	MR	MR	MR	MR

best means to spatially distribute the available rainfall station data across the watershed. The actual 10-yr simulation period mean rainfall in the model varies from 30.8 inches/yr to 43.3 inches/yr consistent with the long-term mean from the available gauging data, whereas the BCM shows this variation as 38 to 51 inches.

Potential Evapotranspiration (PET)

Daily PET data from the Windsor CIMIS station was used to derive the PET timeseries used in the model (Figures 6 & 8). A gridded distribution of mean annual PET was created using the Hargreaves-Samani equation (Hargreaves and Samani, 1982). The calculations were performed using gridded solar radiation data from the National Solar Radiation Database (NSRDB, 2010) and average monthly minimum and maximum temperatures for the 1980 -2010 period from the BCM dataset (Flint & Flint, 2014). The empirically derived KT coefficient was calibrated based on reported PET from the Santa Rosa and Windsor CIMIS Stations. A KT value of 0.152 was selected, consistent with KT values of 0.15 to 0.16 previously proposed for the Bay Area.

From this annual distribution, the model domain was divided into zones, each corresponding to a one-inch range in average annual PET. Scaling factors were calculated for each zone as the ratio of PET at the Windsor CIMIS gage and the PET for a given zone. These scaling factors were then applied to the daily CIMIS data and applied to each zone in the model. From February 2013 to March 2017 PET was not reported at the Windsor CIMIS gage. This gap was filled using scaled data from the Santa Rosa CIMIS gage located west of Sebastopol. Smaller gaps and missing days of data were also filled using Santa Rosa data.
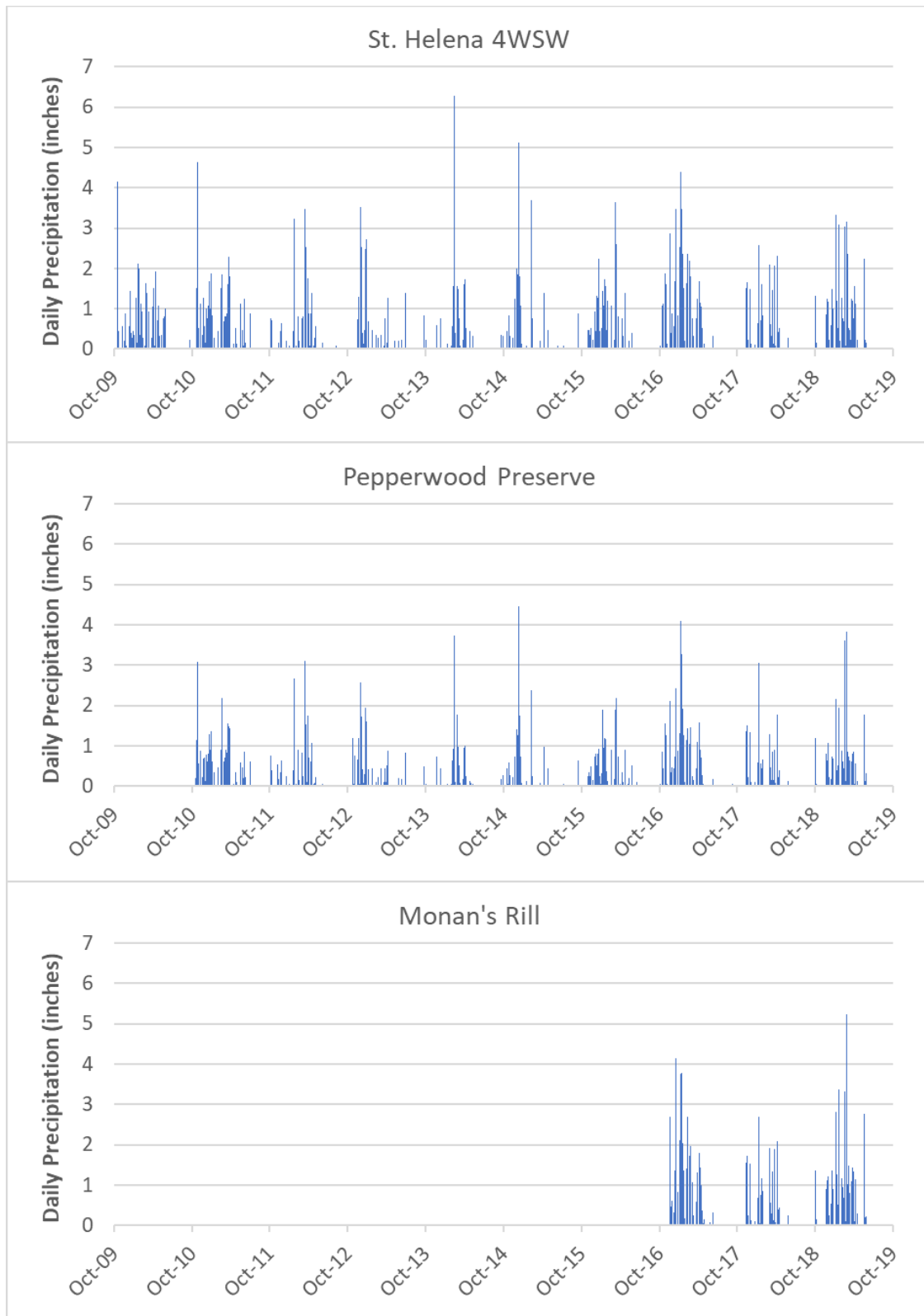
Figure 7: Daily precipitation at the five climate stations used in the MWC hydrologic model for the WY 2010 – 2019 simulation period.
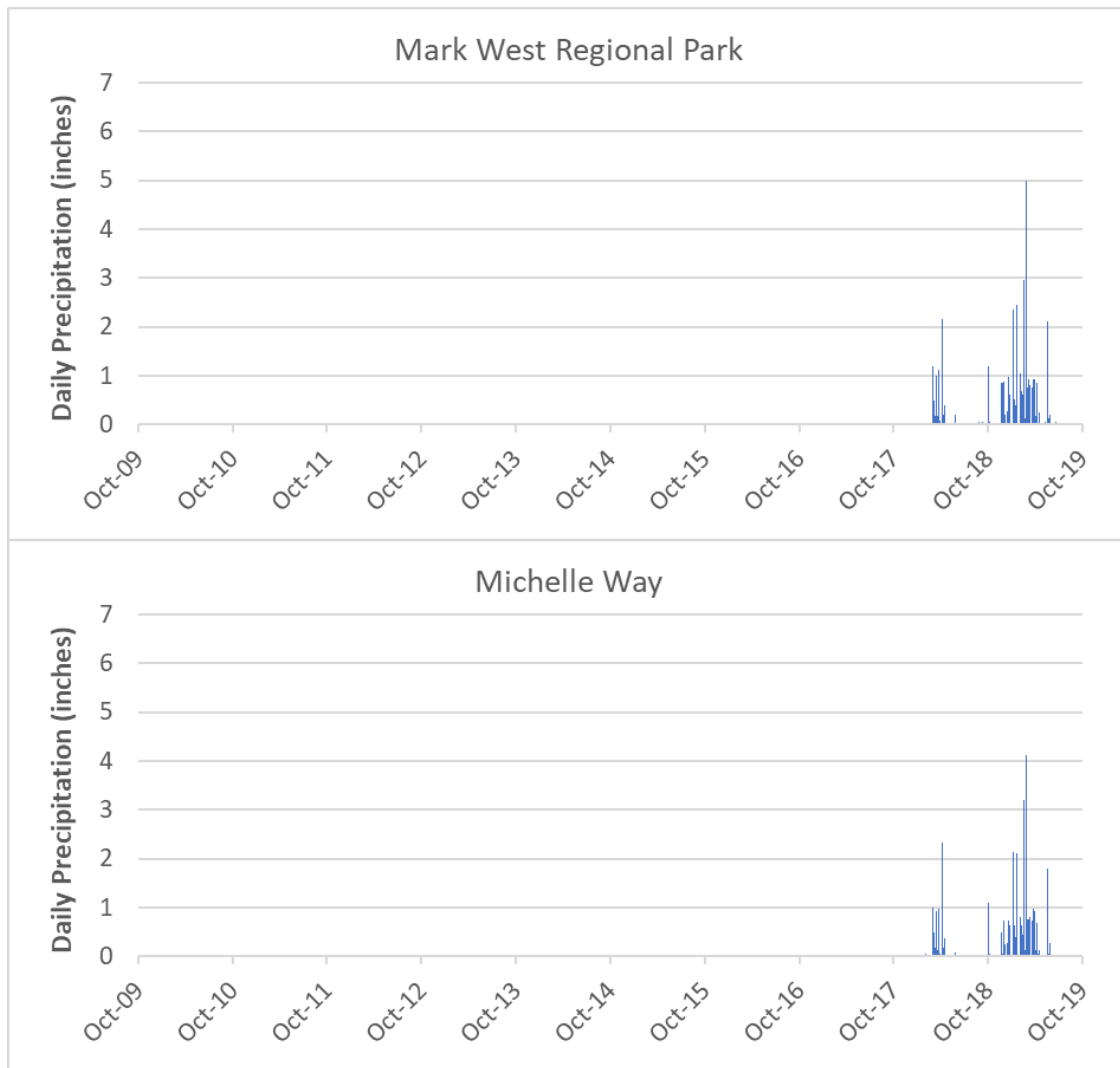
Figure 7 (continued)

Land Cover

Within the upper Mark West watershed, coniferous and deciduous forest are the dominant landcover types with grasslands making up much of the remaining area (Table 2). Land cover varies significantly with elevation in the watershed. Downstream of St. Helena Road, Mark West Creek and several other tributaries including Leslie, Porter, Riebli, and Weeks Creeks contain predominately oak woodland interspersed with other deciduous woodlands and grasslands. Upstream of St. Helena Road, Mark West Creek has several tributaries including Alpine, Humbug, and Van Buren Creeks; these tributary watersheds are dominated by coniferous forest including Coastal Redwoods and Douglas Fir. Several vineyards are located along the mainstem of Mark West Creek as well as along Porter and Riebli Creeks. Much of the Riebli Creek watershed, as
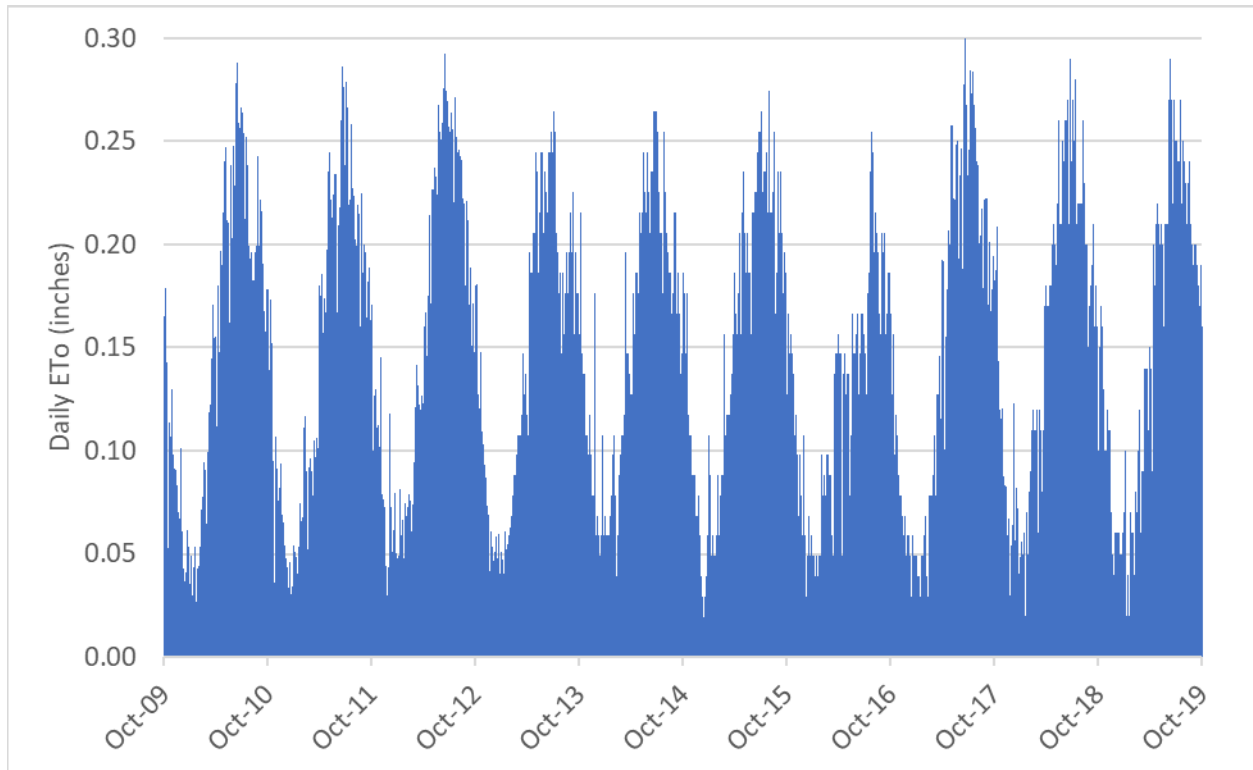
Figure 8: Daily PET at the Winsor CIMIS station used in the MWC hydrologic model for the WY 2010 – 2019 simulation period.

well as small portions of the uppermost Mark West Creek and Humbug Creek watersheds, contain relatively dense rural residential development.

The model domain was discretized into 28 land cover zones based on vegetation classes from the Sonoma County Vegetation Mapping & LiDAR Program's Fine Scale Vegetation and Habitat Map (Figure 9) (SCVMLP, 2015).   This map was generated for the Vegetation Mapping & LiDAR Program using automated processing of returns from the 2013 countywide LiDAR flight and interpretation of aerial imagery by the modelers (SCVMLP, 2015).   It includes a detailed accounting of dominant species including several species of oak and conifer and is intended for use at a scale of 1:5000 or smaller. Land cover zones that represent less than 0.3% of the model domain (approximately 0.1 mi^2) are grouped with similar or adjacent cover types. Because these land cover zones are based on 2013 data, they do not reflect changes caused by the 2017 Tubbs Fire which were accounted for separately as described below.

A unique combination of model parameters was assigned to each of the 28 land cover zones. These parameters include Leaf Area Index (LAI), Rooting Depth, Manning's Roughness Coefficient for overland flow, and Detention Storage. For land cover types with a deciduous vegetation component, the Leaf Area Index and Rooting Depth vary seasonally based on an assumed growing season of April 15th to October 15th with gradual parameter transitions occurring from March 15th to April 15th and from October 15th to November 15th. Dormant season values for deciduous land
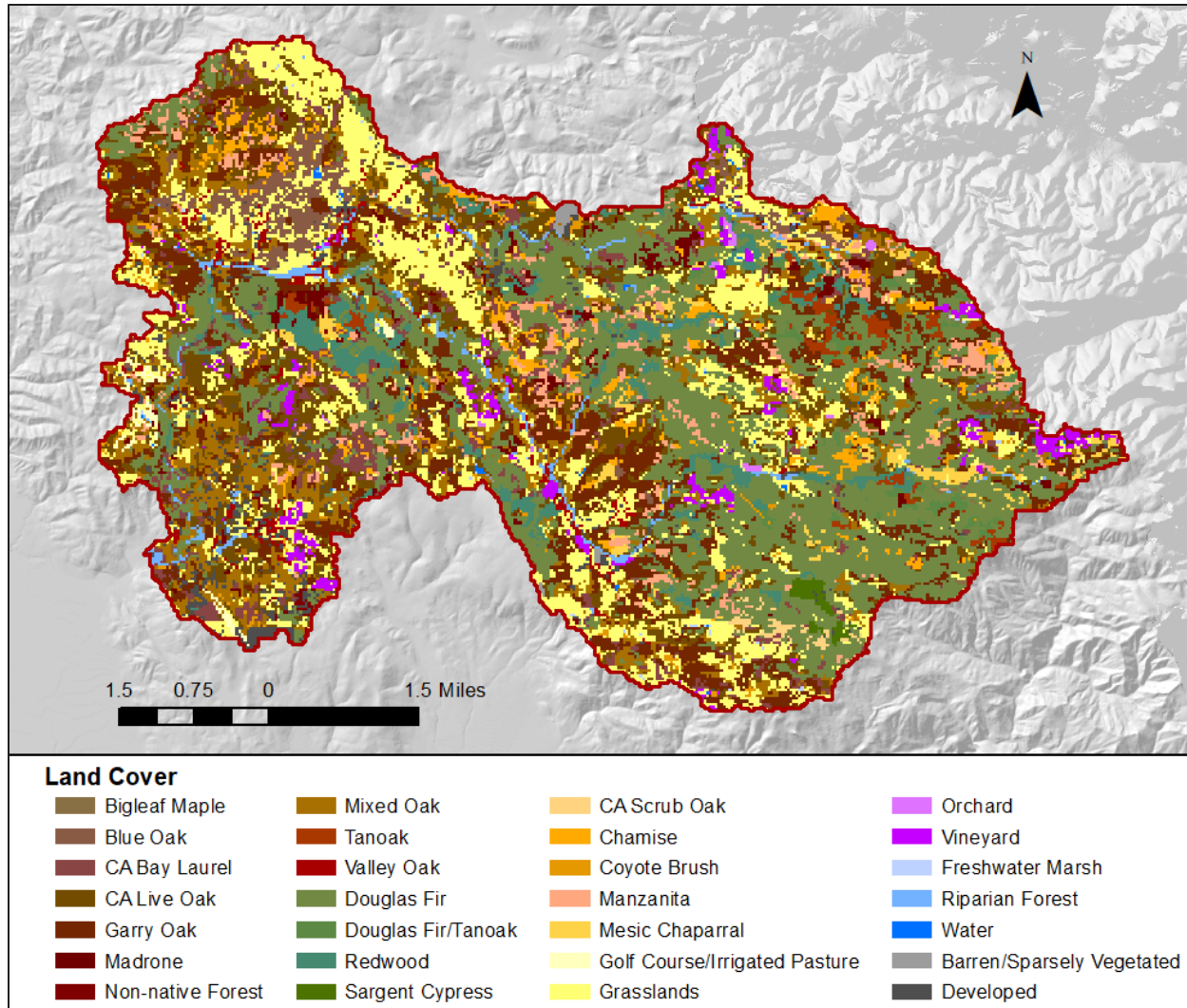
Figure 9: Land cover categories used in the MWC hydrologic model.

cover types were assumed to be equivalent to grassland values. For grasslands, the growing season was assumed to occur from December 15th to May 15th and the dormant season was assumed to occur from July 1st to October 15th with gradual parameter transitions in between. Many of these parameters are difficult to measure in the field and site-specific values are generally unavailable. With the exception of LAI, land cover parameters were initially estimated from literature values (e.g. Allen et al., 1988; TNC, 2018) and then adjusted within the range of reasonable limits as part of the calibration process (Table 2).

LAI was estimated for each vegetation zone using a spatially distributed LAI dataset created by the University of Maryland (Tang, personal communication, Tang, 2015) (Figure 10). This dataset was created using vegetation returns from the countywide LiDAR dataset and has a 3-foot spatial resolution. The remotely sensed LAI values in this dataset represent a combination of the canopy properties of individual plants and the density and spacing of those plants. This differs from LAI
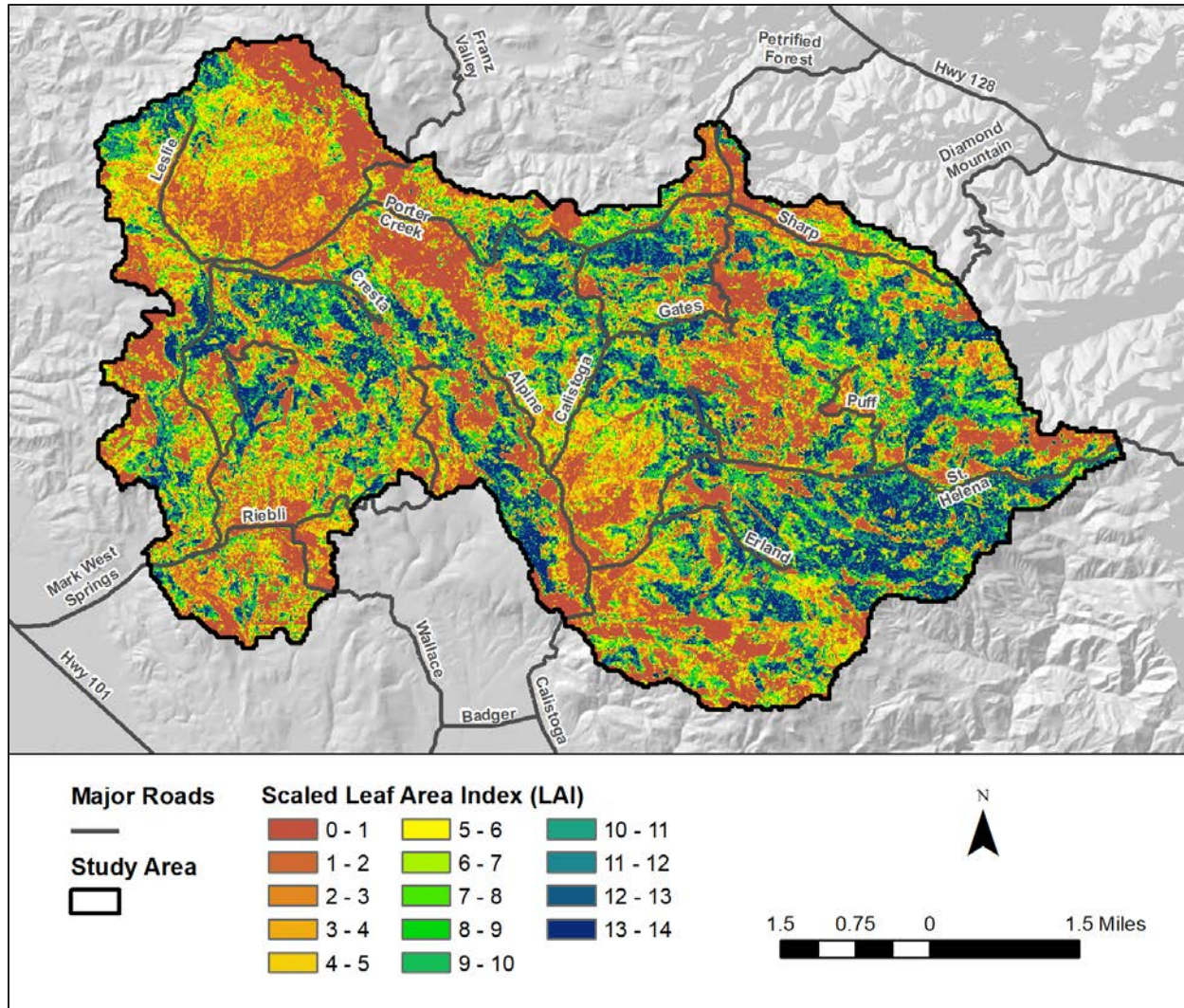
Figure 10: Distribution of LiDAR-derived Leaf Area Index (LAI).

Table 2: Land cover types and associated hydraulic and vegetation properties used in the MWC hydrologic model.

Land Cover Category	Proportion of Model Domain	Overland Flow Mannings n	LAI	Rooting Depth (ft)	Detention Storage (in)
Bigleaf Maple	0.2%	0.60	7.4	11.5	0.9
Chamise	2.2%	0.40	2.7	6.4	0.3
Madrone	1.3%	0.60	9.8	8.6	0.9
Manzanita	3.0%	0.40	4.3	6.6	0.3
Coyote Brush	0.8%	0.40	1.5	6.5	0.3
Barren/Sparsely Vegetated	0.2%	0.04	0.3	0.5	0.0
Grasslands	15.4%	0.24	0.4	2.1	0.3
Mesic Chaparral	1.5%	0.40	4.1	5.0	0.3
Sargent Cypress	0.3%	0.60	4.5	5.6	0.9
Irrigated Pasture	0.4%	0.24	0.4	3.1	0.3
Non-native Forest	0.2%	0.60	3.7	7.6	0.9
Tanoak	0.9%	0.60	1.5	15.0	0.9
Orchard	0.2%	0.24	11.3	6.7	0.9
Douglas Fir/Tanoak	0.9%	0.60	(8.0 - 14.7)	9.4	0.9
Douglas Fir	25.6%	0.60	(7.2 - 15.1)	3.7	0.9
Mixed Oak	8.4%	0.60	(4.0 - 10.1)	19.5	0.9
CA Live Oak	11.3%	0.60	(5.0 - 10.2)	24.0	0.9
Blue Oak	2.1%	0.60	(2.7 - 9.0)	15.0	0.9
CA Scrub Oak	0.3%	0.60	2.8	15.0	0.9
Garry Oak	11.3%	0.60	(4.0 - 10.8)	15.0	0.9
Valley Oak	0.9%	0.60	(3.9 - 9.8)	24.0	0.9
Redwood	3.2%	0.60	11.2	11.1	0.9
CA Bay Laurel	3.9%	0.60	8.1	3.0	0.9
Riparian Forest	1.1%	0.60	6.0	7.3	0.9
Vineyard	1.7%	0.24	1.0	4.9	0.3
Water	0.1%	0.04	1.0	0.5	0.0
Marsh	0.1%	0.04	0.5	1.3	0.0
Developed	2.3%	0.04	2.9	5.9	0.0
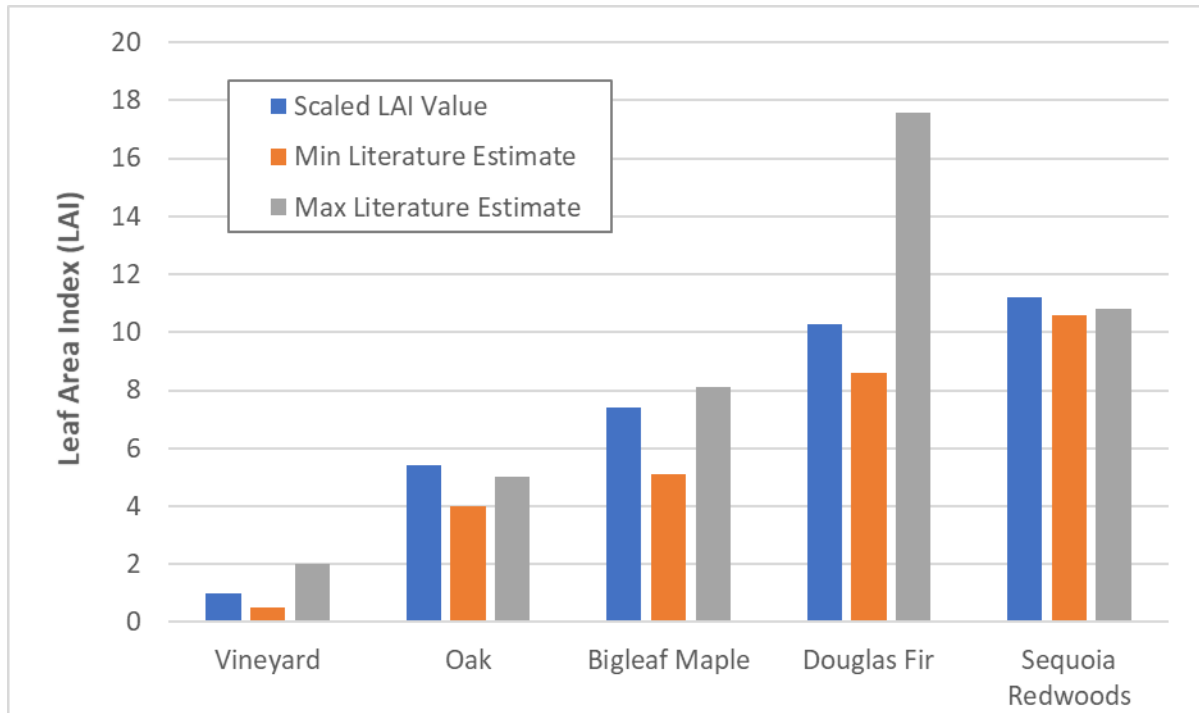
Figure 11: Comparison between scaled LAI values used in the MWC hydrologic model and estimates from the literature for various vegetation types.

values representing individual plant specimens which is the standard convention for empirical evapotranspiration equations used in our model. We compared the remotely sensed LAI values for various vegetation classes with individual specimen values from the literature (Iio & Ito, 2014; Johnson, 2003; Karlik & McKay, 2002; Scurlock et al., 2001) and translated the LiDAR-derived values to specimen values consistent with the literature by applying a uniform scaling factor to the LiDAR-derived LAI (Figure 11). LAI values were calculated for each of the vegetation zones in the model by calculating the mean LAI for each zone from the scaled LAI dataset (Table 2). For Douglas Fir, Douglas Fir/Tanoak, and the various types of Oaks, we further subdivided the LAI estimates into areas requiring no forest treatment, minor treatment, and major treatment based on LAI thresholds we defined from plot-scale forest mapping performed in the upper watershed as described in greater detail in the Chapter 8.
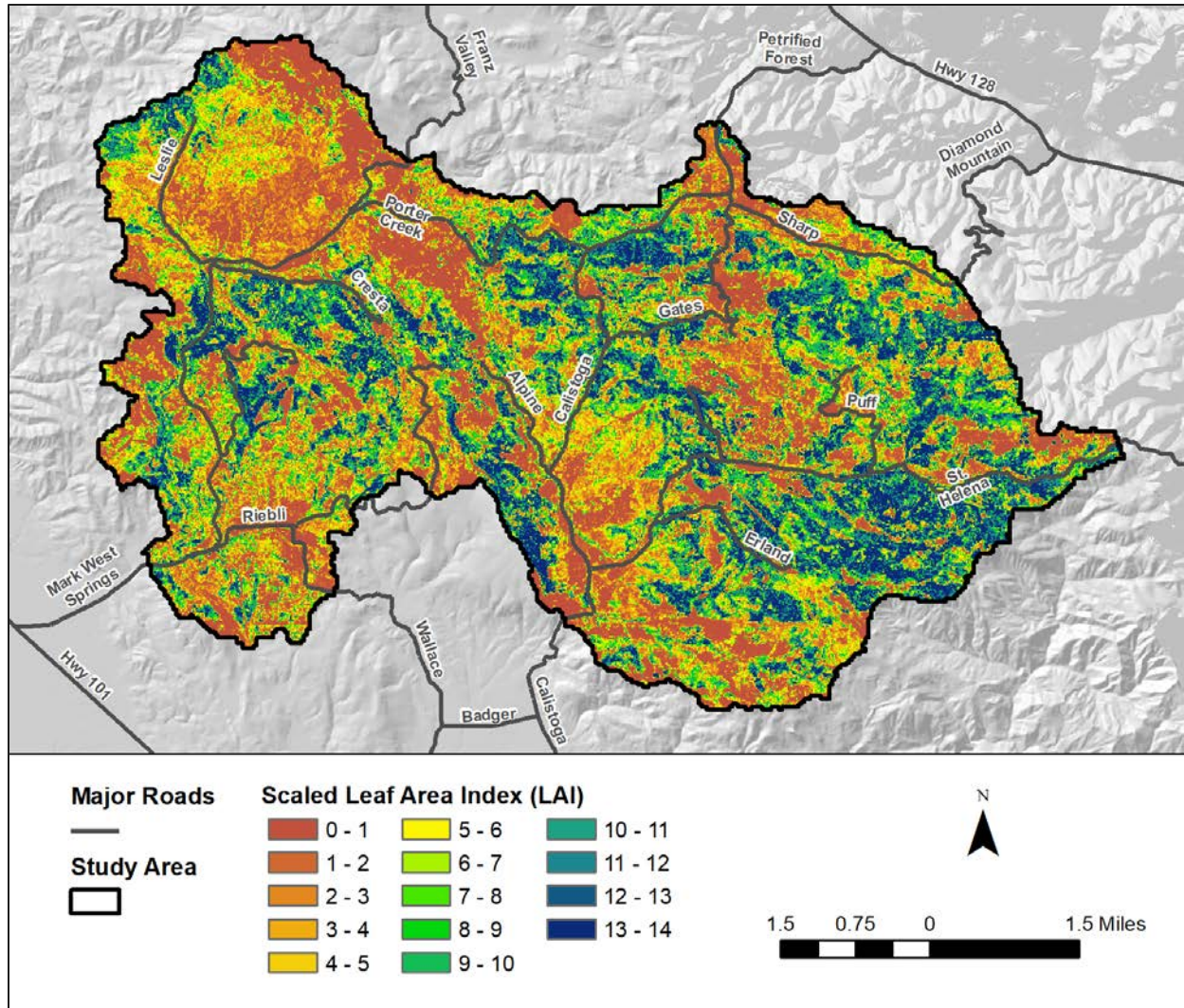
Figure 10: Distribution of scaled LiDAR-derived Leaf Area Index (LAI).
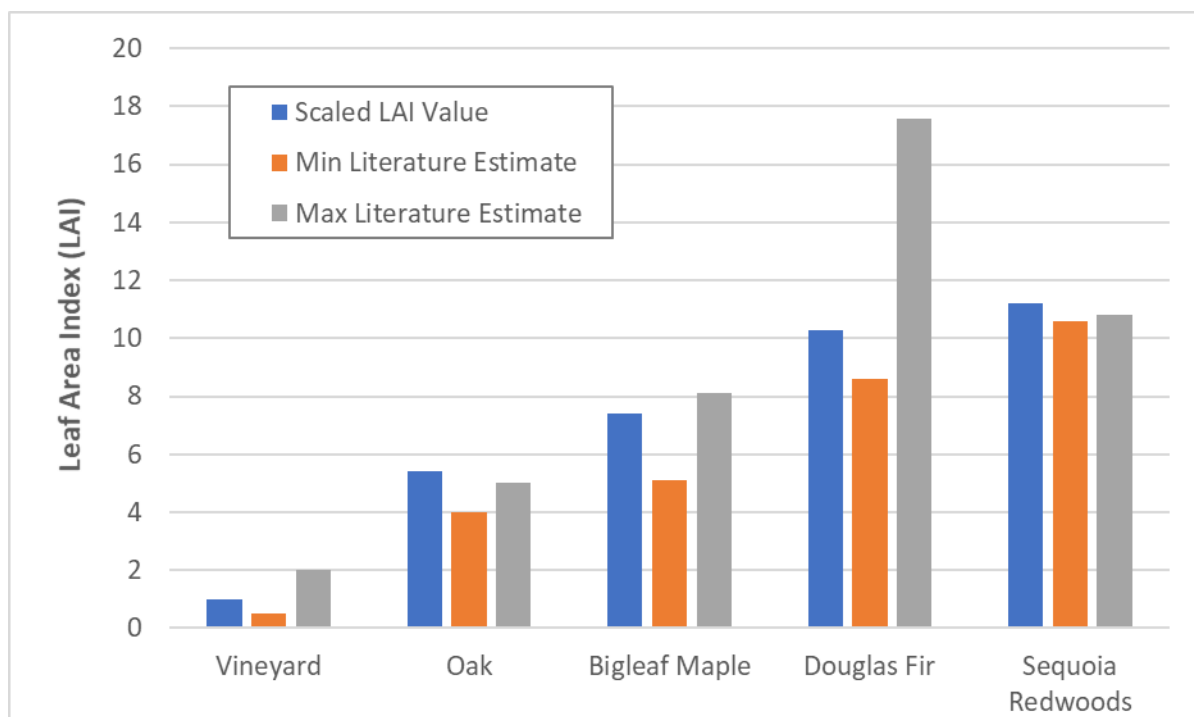
Figure 11: Comparison between scaled LAI values used in the MWC hydrologic model and estimates from the literature for various vegetation types.

Land Cover Adjustments for the Tubbs Fire

As discussed at the beginning of this chapter, we developed a second version of the model incorporating the short-term effects of the Tubbs Fire to facilitate calibrating the model to post-fire streamflow data collected within the burn area at Michelle Way. The canopy-damage raster dataset generated by SCAPOSD (Green & Tuckman, 2018) and Soil Burn Severity dataset generated by the U.S. Forest Service (USFS, 2018) were used to identify the portions of the watershed where we judged that the fire was severe enough to result in significant short-term changes in evapotranspiration. These areas included forested lands where canopy damage was >80% and non-forested lands where soil burn severity was classified as moderate or severe (Figure 12). The delineated area of hydrologically-significant vegetation damage is about 18% of the upper MWC watershed evaluated in this study and approximately 42% of the total identified burn area.

Post-fire vegetation data or Leaf Area Index (LAI) mapping is not available, therefore a simple means of adjusting vegetation parameters was employed for the subset of the burn area judged to have hydrologically significant fire damage. The vegetation in the burn area was assumed to have LAI and rooting depth properties mid-way between the original cover type (undisturbed) and grasslands (full conversion). This simple representation is intended to approximate the short-term effects (1-2 yrs) of the fire on evapotranspiration but is not intended to reflect long-term landscape recovery. A CalFire parcel-based shapefile identifying burned structures was used to identify wells and surface water diversions within the burn area to turn off in the model.
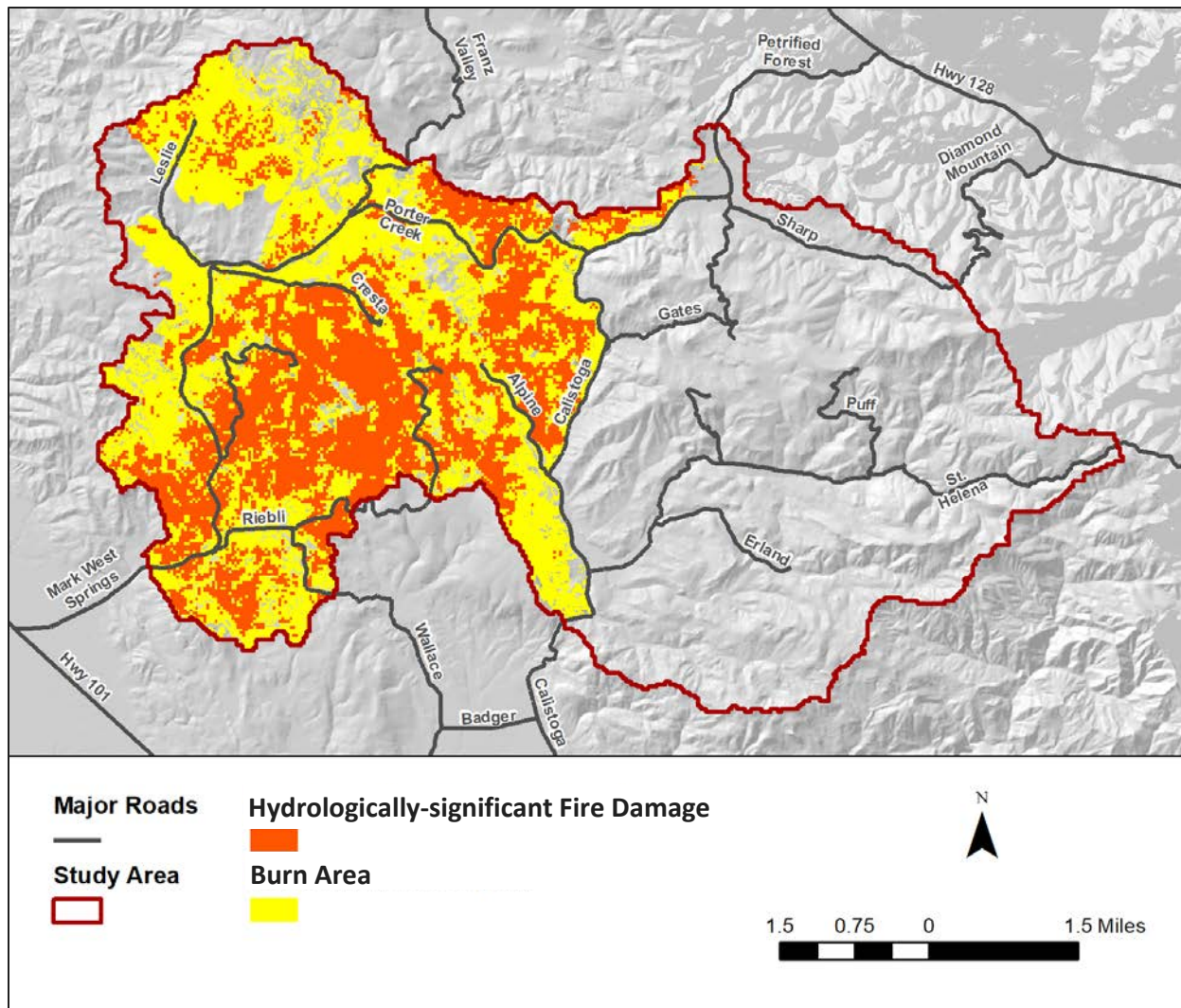
Figure 12: Footprint of the 2017 Tubbs Fire and the severely burned portion of the burn area where vegetation properties were adjusted in the MWC hydrologic model to reflect the fire for the purposes of model calibration.

Short-term fire effects on overland roughness and detention storage or soil hydraulic conductivities were not considered.

The version of the model with these adjustments to land cover values was used for model calibration only. The pre-fire representation of cover was retained for model simulations of existing conditions and scenario evaluations since the long-term effects of the fire on vegetation patterns are unknown and future vegetation is expected to resemble pre-fire conditions more so than immediate post-fire conditions.

Surface Water
Channelized flows are represented using a detailed stream network derived from the 3-foot resolution Sonoma County LiDAR dataset (WSI, 2016). This network includes all major perennial streams and many smaller tributaries as well as all major on-stream ponds. Off-channel ponds,

some intermittent streams, and ephemeral tributaries are not explicitly represented in the stream network. In total, 79 river miles of stream and 18 on-stream ponds are included and represented by approximately 3,300 cross-sections in the surface water hydraulics component of the model.

Streams

The stream network includes all channels with a drainage area of more than 0.2 mi^2 and a stream length of at least 500 feet. These limits were designed to maximize the extent of the channel network within the limits of the ability of the LiDAR data to accurately represent channel geometry and to avoid excess computational burden. These thresholds allow for inclusion of all perennial streams and all reaches with slope characteristics (<7%) indicative of potential salmonid habitat suitability. In a limited number of cases, channels were extended to include on-stream ponds. Additionally, three channels with drainage areas of less than 0.2 mi^2 were included based on the presence of perennial summer baseflow as observed during stream surveys performed August 27th through August 29th, 2018 by OEI and CDFW staff.

The stream network was derived from the 3-foot Sonoma County LiDAR dataset by computing flow directions and flow accumulations using standard ArcGIS techniques.   Channel-cross sections were extracted from the LiDAR DEM at 100-ft intervals for major channels and those known to contain salmonids, including Mark West, Alpine, Humbug, Leslie, Mill, Porter, Riebli, Van Buren, and Weeks Creeks. For the remaining channels, cross-sections were extracted at 200-ft intervals.

Prior to defining the stream network and extracting cross sections, a series of cross sections were surveyed in the field and compared to LiDAR-derived cross sections at various drainage areas and locations throughout the watershed.   These comparisons revealed that the LiDAR dataset represents the channel geometry with acceptable accuracy at drainage areas above about 0.2 mi^2. In some cases, accuracy was reasonably high in smaller drainage areas; however, when smaller streams were incised relatively deeply the LiDAR did not capture the details of the channel geometry in sufficient detail for hydraulic modeling. Examples comparing survey- and LiDAR-derived cross sections with accuracy judged to be acceptable for purposes of hydraulic simulation in the model are shown in Figure 14.

A uniform Manning's Roughness coefficient (n) of 0.055, representative of rocky channels with brush along the banks (Chow, 1959), was applied to all cross-sections. A downstream boundary condition was defined as a rating curve established using normal depth calculations for the downstream-most cross section in the model. Because all inflows are generated by other spatially distributed components of the MIKE SHE model, upstream boundary conditions are zero-discharge inflows.
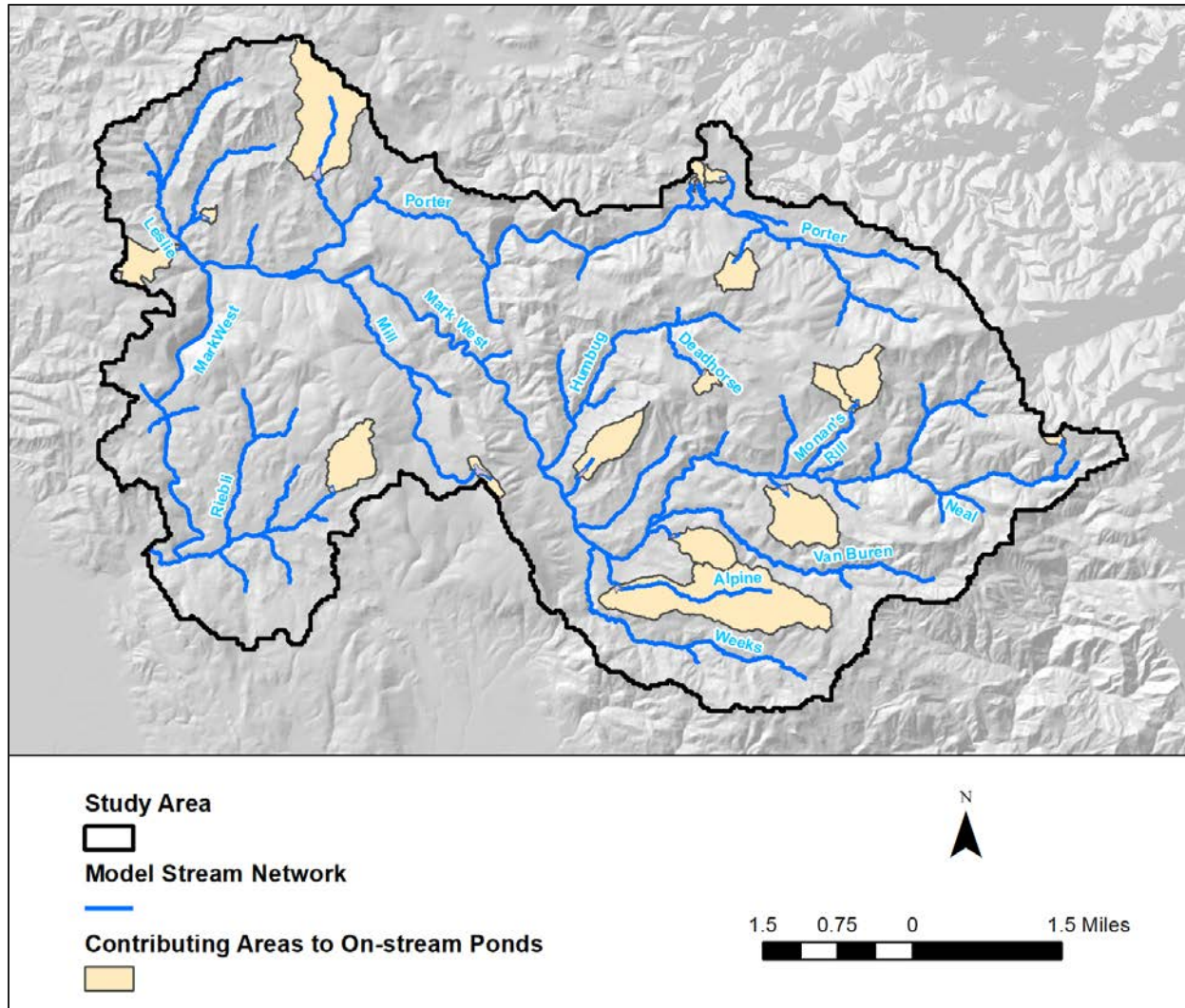
Figure 13: Stream network and on-stream ponds included in the MWC hydrologic model.

Ponds

Within the model domain, approximately 80 ponds have been identified using the 3-foot Sonoma County LiDAR DEM and aerial photography. The majority of these are small off-stream ponds which were not explicitly included in the surface water component of the model. Thirteen on-stream ponds with significant (>0.2 mi^2) contributing areas were included in the model along with five ponds with smaller contributing areas but significant reported water uses.

A stage-storage relationship for each of the 18 ponds included in the model was derived from the 3-foot Sonoma County LiDAR DEM. These data were collected in autumn 2013 and observed water surface elevations are assumed to reflect typical end-of-season storage levels in each pond. The stage-storage relationship for a given pond was associated with cross sections at the upstream and downstream edges of the pond, and cross sections were added at the pond's spillway. Water in the ponds is not explicitly represented in the model grid therefore evaporation
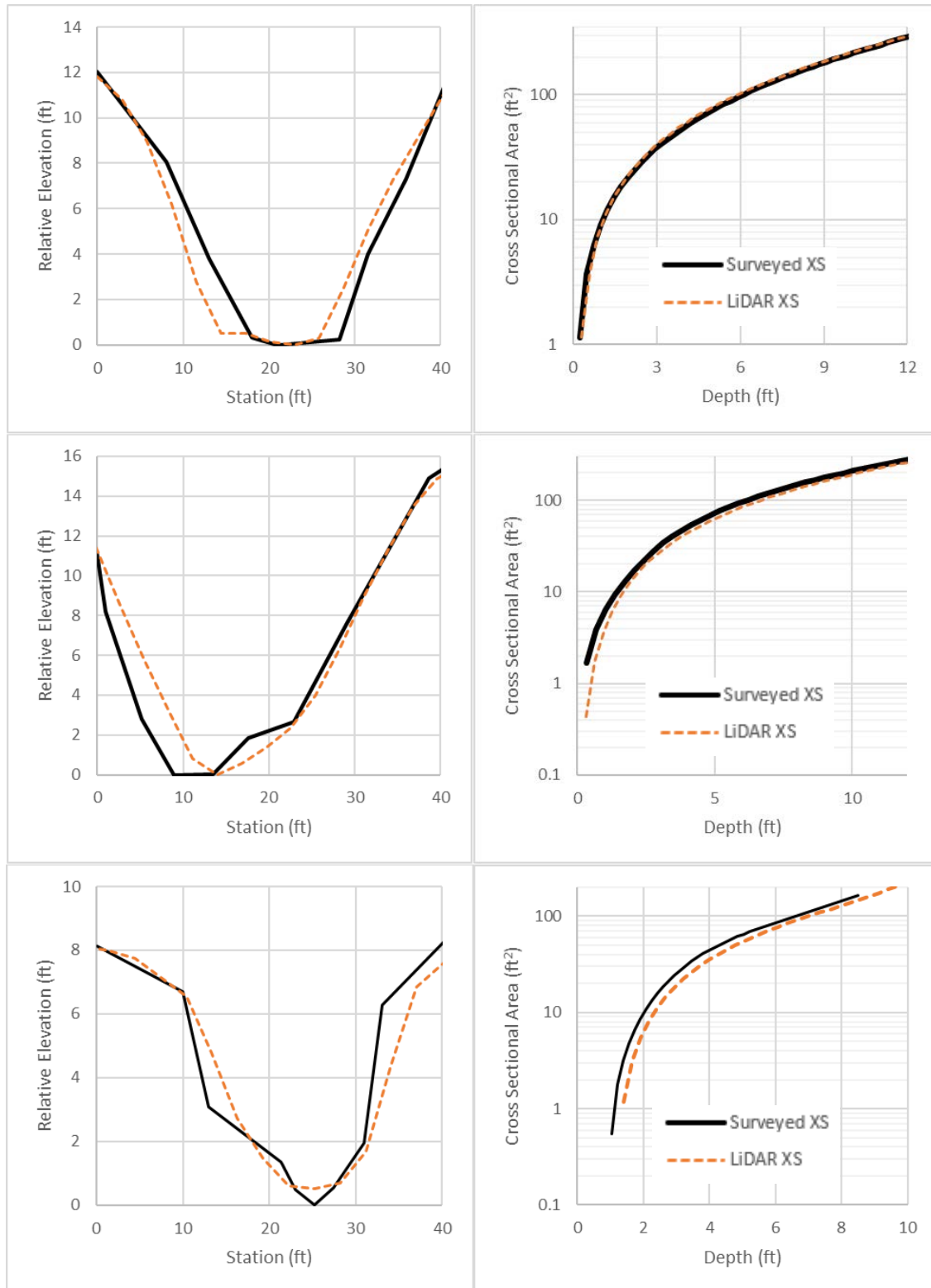
Figure 14: Comparisons between survey- and LiDAR-derived channel cross sections and corresponding depth/area relationships for an unnamed tributary to Mark West Creek with a 0.3 mi² drainage area (top), upper Mark West Creek with a 0.5 mi² drainage area (middle), and upper Porter Creek with a 2.0 mi² drainage area (bottom).

from each pond was included as a surface water boundary condition based on the surface area of the pond and the daily PET data described above.

Soils

The model domain is discretized into 23 different soil zones based on the National Resource Conservation Service's (NRCS) Soil survey Geographic Database (SSURGO) accessed through the Web Soil Survey (WSS). Where reported soil types are similar or where they represent a small portion of the model domain, they are grouped with other similar soil types.

Most soils in the model domain are loams and clay loams. The distribution of soil textures appears to be correlated with underlying geology. Loam soils generally occur in areas underlain by the Sonoma Volcanics and clay loam soils occur in areas underlain by the Franciscan Complex. A major divide in soil types is formed by the Maacama Fault Zone which runs through the central
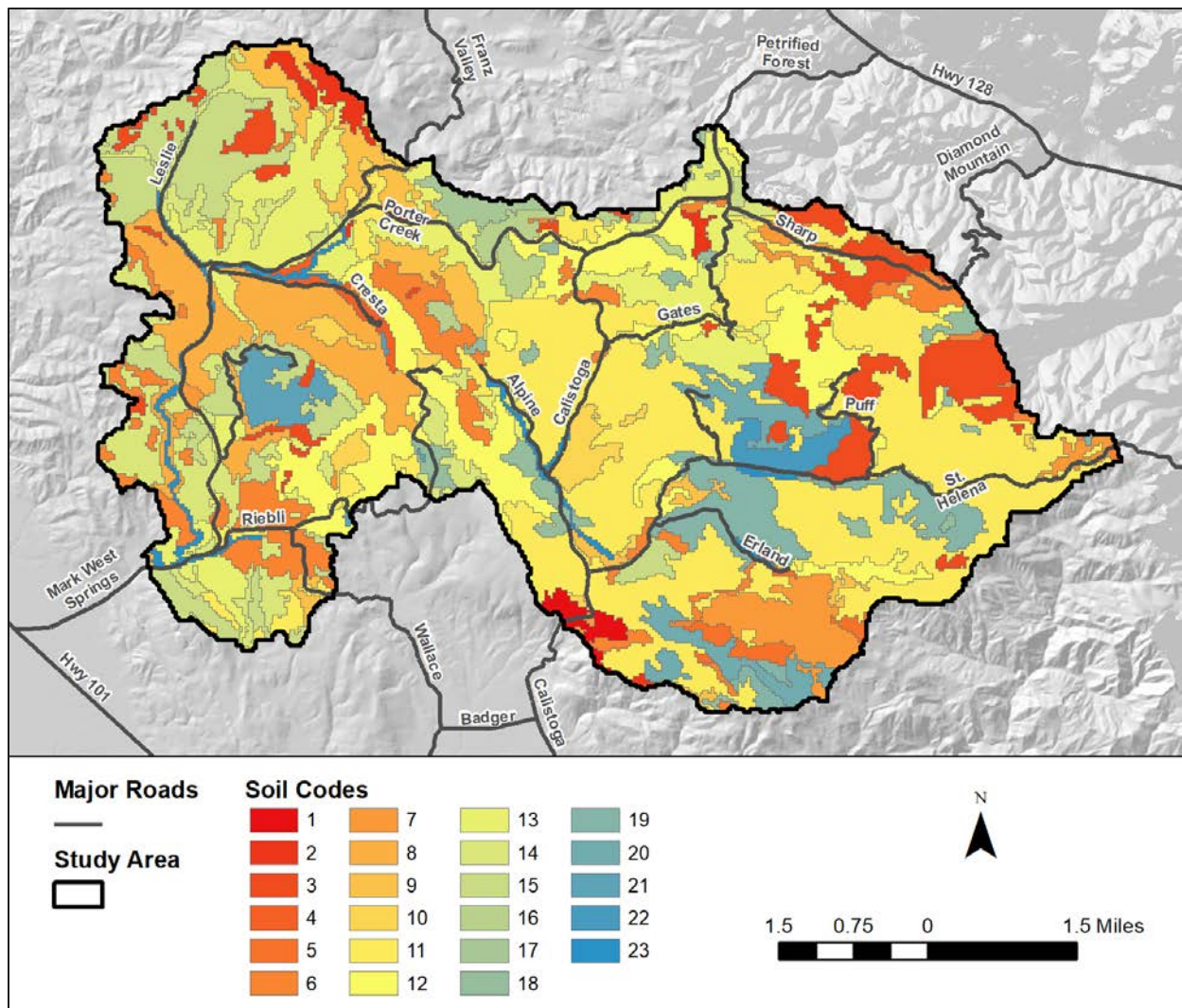
Figure 15: Soil codes used in the MWC hydrologic model (see Table 3 for associated property values).

portion of the study area intersecting Mark West Creek near the confluence with Porter Creek. Downstream of the confluence, the model domain is dominated by NRCS Hydrologic Soil Group B and C soils including the Felta Very Gravelly Loam, Laniger Loam, and Red Hill Clay Loam. Upstream of the confluence, the model domain is dominated by Group D and some Group C soils including the Boomer Loam, Goulding Clay Loam, Henneke Gravelly Loam, and Laniger Loam. Group B soils are relatively well-drained and can absorb and transmit water at relatively high rates whereas Group D soils absorb and transmit water very slowly and thus generate high runoff rates. Group C soils have hydrologic properties intermediate between B and D soils. Group A soils do not occur in the study area.

Initial estimates of the saturated hydraulic conductivity and the moisture contents at saturation, field capacity, and the wilting point for each of these soil types were derived from the physical properties report in the SSURGO database and final values have been determined through model calibration. For each zone, saturated hydraulic conductivity was initially estimated using the rate

Table 3: Final calibrated values of soil moisture contents at saturation, field capacity, and wilting point, and saturated hydraulic conductivities used in the MWC hydrologic model.

Soil Code	θsat	θfc	θwp	Ksat (ft/day)
1	0.485	0.366	0.191	0.001
2	0.483	0.220	0.175	0.001
3	0.472	0.216	0.114	0.002
4	0.464	0.271	0.150	0.002
5	0.453	0.161	0.058	0.002
6	0.458	0.301	0.157	0.003
7	0.468	0.195	0.105	0.004
8	0.457	0.304	0.135	0.006
9	0.502	0.342	0.173	0.006
10	0.453	0.270	0.125	0.007
11	0.461	0.195	0.097	0.011
12	0.460	0.224	0.109	0.011
13	0.463	0.235	0.073	0.011
14	0.468	0.103	0.056	0.011
15	0.468	0.139	0.076	0.011
16	0.483	0.232	0.071	0.013
17	0.463	0.186	0.075	0.013
18	0.423	0.246	0.145	0.014
19	0.479	0.254	0.120	0.026
20	0.457	0.280	0.132	0.026
21	0.498	0.350	0.177	0.050
22	0.463	0.168	0.049	0.079
23	0.377	0.019	0.002	0.116

reported for the most limiting layer of each soil. Initial values for water content at field capacity and wilting point were estimated using the weighted average for all horizons within each zone. Saturated water content is not reported by SSURGO and initial values were estimated using the reported average bulk density for each zone and an assumed soil particle density of 2.65 g/cm³.

The initial values for soil moisture contents were not adjusted significantly. Excluding the alluvial soils which have significantly different properties, soil moisture content at saturation, field capacity, and the wilting point ranged from 0.42 to 0.50, 0.10 to 0.37, and 0.05 to 0.19 respectively. Successful calibration required significantly lower Ksat values relative to the SSURGO estimates. This can be attributed to the model's simplified 2-layer water balance approach which does not account for variations in Ksat as a function of soil moisture, and thus typically requires lower Ksat values to represent overall infiltration dynamics. Additionally, the unsaturated zone in much of the watershed is relatively thick and comprised of soil strata plus underlying weathered and unweathered bedrock, therefore this parameter reflects an average Ksat value for the full unsaturated zone derived from calibration rather than a true soil property. The calibrated saturated hydraulic conductivity values ranged from 0.01 ft/day for clay soils to 0.12 ft/day for alluvial soils (Table 3).

Interflow

As described in Chapter 3, interflow is represented in the model with a saturated zone drainage function. Drain levels and time constants were derived through calibration and primarily influence the springtime flow recession. A time-varying drain level tied to precipitation patterns was required to adequately reproduce the springtime flow recession. A spatially uniform drain level of 20-ft below land surface was used to activate the drainage process during and following
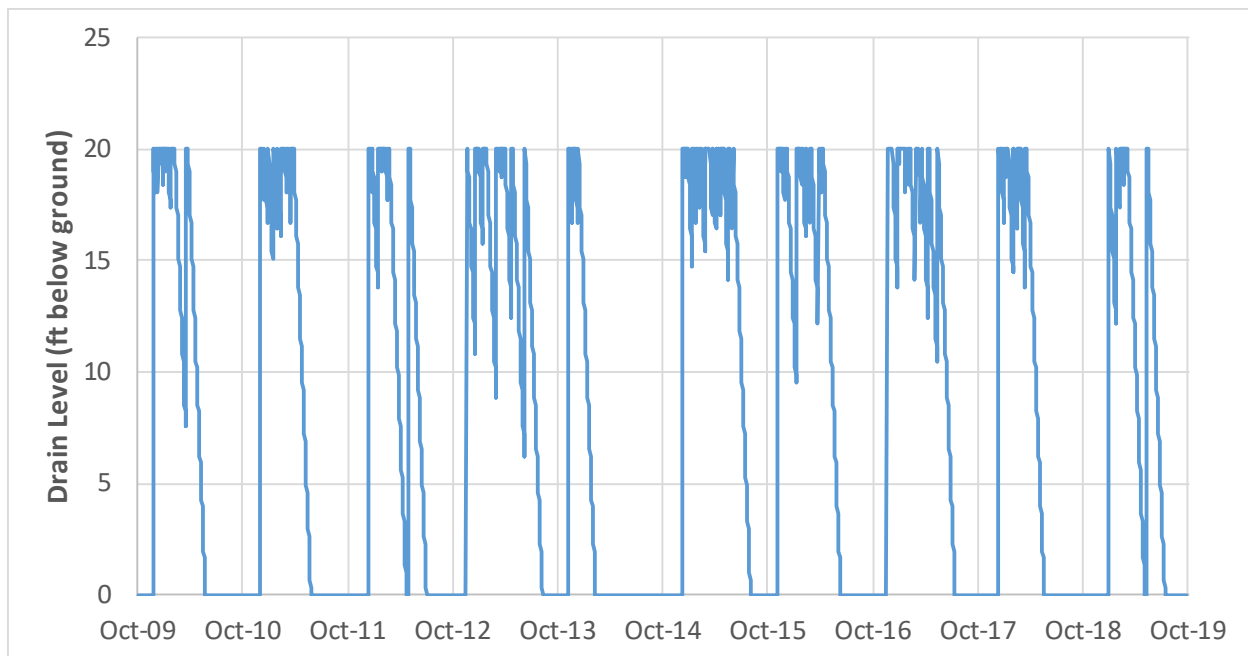
Figure 16: Timeseries of drain levels used to represent interflow in the MWC hydrologic model.

significant precipitation events (defined here as >0.2 in/day). On the third consecutive day with no significant precipitation, drain levels were decreased towards zero at a uniform rate of 0.33 ft/day until a subsequent precipitation event triggered levels to be reset to 20-ft. To account for the delay in the onset of interflow due to low antecedent soil moisture at the beginning of each wet season, drainage was only activated when 2.5 inches of precipitation had fallen over the preceding 21 days (Figure 16).

Hydrogeology

Model Discretization and Boundary Conditions

The geology in the MWC watershed is complex and much of the watershed is characterized by alternating layers of more permeable tuffaceous materials and less permeable basalt and andesite of the Sonoma Volcanics. These layers have varying extents and thicknesses and in some areas are mantled by younger rocks of the Glen Ellen Formation and/or Quaternary Alluvium. As described in detail below, substantial subsurface information could be gleaned from available geologic logs included in Well Completion Reports (WCRs) and aquifer test data obtained from pump test data collected as part of Sonoma County's regulatory requirements for development in water-scarce areas that culminate in Well Yield Certification (WYC).

Despite the available data, it was not possible to accurately delineate individual layers or lenses of geologic materials to use in developing the vertical discretization of the model layers. Given this complexity, we discretized the model into six layers, with layer elevations defined relative to the surface topography. Layers 1-5 generally having a uniform 100-ft thickness and Layer 6 has a uniform 300-ft thickness for a total thickness of 800-ft. The only variation in layer thickness is associated with the alluvium where Layer 1 ranges in thickness from 25- to 50-ft and gradually increases to 100-ft outside of the alluvial body. Where Layer 1 thickness is less than 100-ft, Layer 2 thickness is correspondingly greater than 100-ft such that the base of Layer 2 is 200-ft below land surface (Figure 17 & Table 4).

The base of Layer 6 is defined as a no flow boundary as are the lateral boundaries around the model domain. Available groundwater elevation data is very limited and insufficient for characterizing any groundwater inflows/outflows that may occur across the watershed boundaries. In most areas the no flow boundary assumption (equivalent to assuming a groundwater divide occurs coincident with surface topography) is likely reasonably accurate, however some groundwater outflow likely occurs along portions of the south and southwest watershed divides where more permeable units of the Sonoma Volcanics may contribute flow to alluvial materials in the Santa Rosa Plain down-gradient from our study area. We did not attempt to quantify this component of the groundwater budget as part of our analysis owing to a lack of available data and our focus on processes within the upper watershed.

With the exception of pumping wells which are described in the Water Use section below, all other saturated zone boundary conditions such as infiltration recharge, ET from groundwater, and stream/aquifer interactions are calculated internally by the model through the coupling to other components of the model rather than specified as model inputs.

Figure 17: Simplified geologic map and locations of wells where pump test data was available and locations of wells where stratigraphic data was available.

Table 4: Layer thicknesses used in the groundwater component of the MWC hydrologic model.

Layer	Thickness (ft)
1	25 - 100
2	100 - 175
3	100
4	100
5	100
6	300
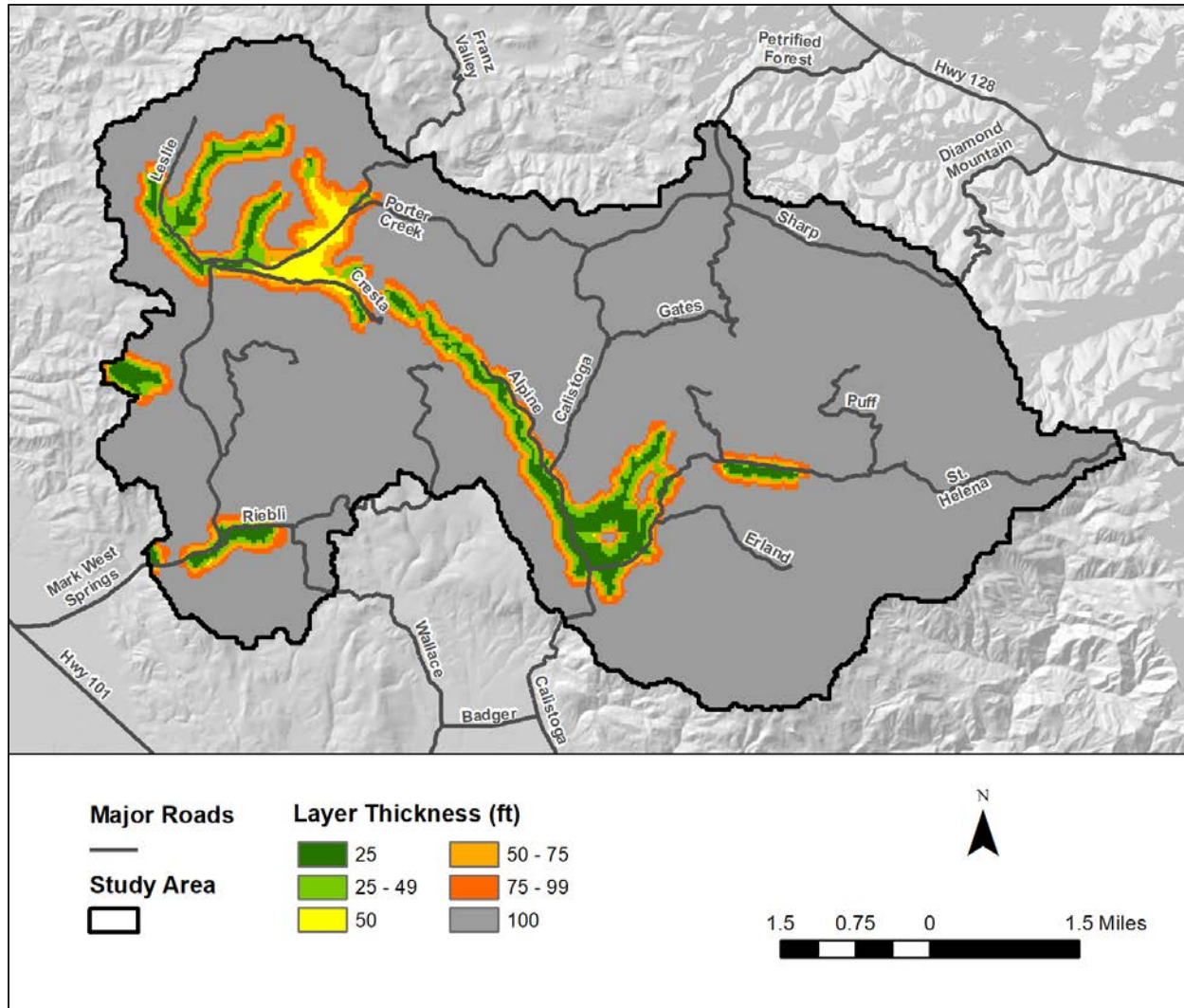
Figure 18: Thickness of groundwater model Layer 1.

Despite the available data, it was not possible to accurately delineate individual layers or lenses of geologic materials to use in developing the vertical discretization of the model layers. Given this complexity, we discretized the model into six layers, with layer elevations defined relative to the surface topography. Layers 1-5 generally having a uniform 100-ft thickness and Layer 6 has a uniform 300-ft thickness for a total thickness of 800-ft. The only variation in layer thickness is associated with the alluvium where Layer 1 ranges in thickness from 25- to 50-ft and gradually increases to 100-ft outside of the alluvial body. Where Layer 1 thickness is less than 100-ft, Layer 2 thickness is correspondingly greater than 100-ft such that the base of Layer 2 is 200-ft below land surface (Figure 18; Table 4).

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With the exception of pumping wells which are described in the Water Use section below, all other saturated zone boundary conditions such as infiltration recharge, ET from groundwater, and stream/aquifer interactions are calculated internally by the model through the coupling to other components of the model rather than specified as model inputs.

Distribution and Description of Geologic Materials

WCRs were obtained for more than 350 wells in the watershed and a subset of these had both detailed descriptions of geologic materials as a function of depth (geologic logs contained in WCRs) to provide useful stratigraphic information and reliable location information to associate the well with a parcel or a specific location. Geologic contacts (vertical boundaries between significantly different rock types) were identified in the logs depending on the geologic materials intersected.

Sonoma Volcanics

Most geologic logs from wells in the Sonoma Volcanics (SV) identify alternating layers of tuffaceous material and other volcanic rocks with andesite being the dominant material in the eastern portion of the watershed and basalt in the western portion. Contacts between tuffaceous materials and other volcanic rocks were delineated where a relatively clear interpretation could be made from the geologic log. Approximately 148 wells provided stratigraphic information within the SV (Figure 17). Within each 100-ft to 300-ft thick model layer interval penetrated by a given well, the geologic materials were classified as predominately (>80% of a given interval) tuffaceous material, predominately basalt or andesite, a combination of materials (<80% of either material), or underlying Franciscan Formation. In most portions of the watershed rocks of the SV extend through the full 800-ft sequence represented in the model. The interpretation becomes less certain with increasing depth from Layer 1 through Layer 6 as the number of wells penetrating a given interval decreases from 148 in Layer 1 to 74 in Layer 3 to just 9 wells in Layer 6 (Figure 17).

Glen Ellen Formation

In and near the Leslie and Riebli Creek subwatersheds, the contact between the Glen Ellen Formation and the underlying Sonoma Volcanics was delineated at 15 wells (Figure 17). These wells revealed that the Glen Ellen Formation ranges in thickness from approximately 130-ft in the upper Leslie Creek watershed to less than 50-ft in the lower watershed and in the Riebli Creek watershed exposure. Static water levels reported in these WCRs revealed that the formation is generally unsaturated and that all the wells are screened predominately in the underlying

Sonoma Volcanics where groundwater is available. The Leslie Creek watershed exposure is much coarser than the materials in Riebli Creek with the former typically described as sand and gravel or sandstone, and the latter typically described as clay or sandy clay. The spatial extent of the available data is insufficient for interpolating an isopach map, therefore a highly simplified representation of the Glen Ellen thickness was developed based on the available information. The Glen Ellen is only present in Layer 1 where we assumed 50-ft thickness in the Riebli Creek and lower portions of the Leslie Creek exposures and 100-ft thickness in the portions of the Leslie Creek exposure above 700-ft in elevation.

Franciscan Complex and Great Valley Sequence
A contact between the Sonoma Volcanics and the underlying rocks of the Franciscan Complex was delineated in a few wells located in the vicinity of the surficial contact between the units. The orientation of these contacts is unknown and the model generally assumes a vertical contact between these materials that extends across the full 800-ft thickness of the model consistent with the deepest available geologic logs which show both of these materials extending to considerable depth. Although hydrogeologic properties may vary substantially within the Franciscan, these variations are expected to depend upon the degree and interconnectivity of fracturing which cannot be characterized from the available data. Owing to the lack of data and the typically low permeability of the Franciscan relative to other geologic materials in the watershed, this unit was assigned uniform hydrogeologic properties. No available wells were located within the exposures of Great Valley Sequence materials in the watershed, consistent with the general experience in the region indicating that that this geologic unit provides poor aquifer material. These materials account for only a small portion of the study area and were treated as equivalent to the Franciscan Complex.

Quaternary Alluvium
A total of 35 WCRs were located within alluvial materials in the watershed (Figure 17). Water level data from the WCRs indicate that the alluvium is unsaturated at about half of these well locations and generally thin (< 25-ft at 22 of the 35 wells), only exceeding 50-ft in the vicinity of the Porter Creek/Mark West Creek confluence where the maximum reported thickness was 60-ft. The alluvium does not appear to be a significant source of water to wells and all of the wells are screened predominately within the underlying geologic materials where groundwater is available. The available geologic logs indicate the alluvium consists of primarily sand, gravel, and boulders with lesser quantities of clay and sandy clay.

The spatial extent of the data is insufficient for interpolating an isopach map, therefore a simplified representation of alluvium thickness was developed based on the available information. Using available surficial geologic mapping, topographic expressions interpreted from LiDAR data, and the subsurface thicknesses as described in WCRs, we reduced the extent of alluvium so as to exclude areas where thicknesses are too small to represent in the model. The alluvium falls entirely within Layer 1, and for most of the revised alluvium extent we assumed a 25-ft thickness, except for the area upstream of the confluence of Mark West and Porter Creeks where we assumed a 50-ft thickness (see Figure 17 for extent & Figure 18 for thickness).

Humbug Creek Lacustrine Deposits

Only a few of the available wells penetrated the Humbug Creek Lacustrine Deposits. They indicate that this material is generally around 25-ft thick and very fine-grained. It is typically described as clay and is generally unsaturated with wells screened in underlying geologic materials. We represented this material in model Layer 1 and assumed a uniform 25-ft thickness based on the extent of the mapped surface exposure.

Aquifer Properties

Hydraulic Conductivity Values

We compiled available pump test data from Well Yield Certifications obtained from the County of Sonoma. A subset of four tests was selected for aquifer analysis based on those tests where 1) the well completion details were known, 2) the test was performed for at least eight hours with a relatively constant pumping rate, 3) drawdowns and pumping rates were reported frequently enough to generate a detailed time-drawdown curve, and 4) the drawdown had stabilized by the end of the test (Figure 17). For the four tests meeting all criteria, the time drawdown data was analyzed using AQTESOLV software and a type-curve matching approach was used to derive estimates of the aquifer Transmissivity (T). The Storage Coefficient (S) cannot be estimated from single-well test data, therefore we solved for T using a range of reasonable estimates of S from the literature and from our previous experience evaluating aquifer test data in similar geologic materials in the region. Depending on the aquifer conditions and drawdown responses, a variety of solutions were used including radial solutions such as the Theis and Cooper-Jacob solutions (Theis, 1935; Cooper & Jacob, 1946), as well dual-porosity solutions such as the Moench slab blocks solution (Moench, 1984). Where more than one solution provided an equally valid description of the data, final T values used in the model were derived by averaging the estimates from the individual solutions.

An additional 19 tests also met the afore-mentioned criteria with the exception of the time-drawdown data which was not detailed enough for type-curve matching to drawdown data (Figure 17). For these tests, the Specific Capacity (Sc) was calculated and used to estimate T using an empirical relationship (Driscoll, 1986). We found good agreement between the T values estimated in AQTESOLV and the T values derived empirically using Sc suggesting that the simplified Sc-based approach is capable of providing reasonable estimates of T (Table 5). The dual-porosity solutions yield an estimate of the Hydraulic Conductivity (K) directly, and T values from the radial solutions were converted to K estimates using the aquifer thickness as derived from the test data and well completion details (Table 6).

We grouped the test data into five categories based on the dominant lithology as interpreted from available WCRs. Test data were classified as representative of Franciscan Complex or one of four categories within in the Sonoma Volcanics: predominately tuff, predominately basalt, predominately andesite, or a mixture of tuffaceous and other volcanics. There are obvious contrasts in well completion details and responses to pumping between the various lithologies with shallower wells (mean of 158-ft) and limited drawdowns (mean of 1.7-ft) within the tuff and deeper wells (mean of 387-ft) and larger drawdowns (mean of 9.9-ft for basalt and 48-ft for

andesite) in the hard rock volcanics. Wells in the Franciscan Complex were also generally deeper (mean of 331-ft) and experienced much larger drawdowns (mean of 214-ft) (Table 6).

We calculated the geometric mean of the K estimates for the Sonoma Volcanics for each lithologic category and found that K values varied by nearly two orders of magnitude between the various volcanic materials. The highest value, 23 ft/day, was found for the tuff, followed by the mixed volcanics (3.7 ft/day), and the basalt (0.94 ft/day) and andesite (0.37 ft/day). In the Franciscan Complex, K values were an order of magnitude lower than the andesite (geometric mean of 0.029 ft/day) (Table 6).

No pump test data was available for wells screened entirely within the Glen Ellen Formation, the Humbug Creek Lacustrine Deposits, or the Quaternary Alluvium. This is not surprising given that our analysis showed that few if any wells are completed in these materials which are generally thin and often unsaturated. We relied on descriptions of the geologic materials as described in geologic logs on available WCRs to estimate K values for these materials from literature values (Domenico & Schwartz, 1990). Our initial estimates of K for the coarse-grained northern exposure of the Glen Ellen Formation was 30 ft/day and 0.038 ft/day for the fine-grained southern exposure and for the Humbug Creek deposits. Initial estimates for the alluvium were 30 ft/day in most of the study area and 120 ft/day for the thicker alluvial body delineated upstream of the confluence of Mark West and Porter Creek.

As described in Chapter 5, the initial K estimates were adjusted within reasonable limits to obtain a good fit between measured and simulated potentiometric surface elevations measured at monitored wells and baseflows as described from stream gauge data. Within the Sonoma Volcanics, values were adjusted using a uniform scaling factor in order to maintain the degree of contrast between materials as described from the pump test analyses. The final calibrated values are ~3.8% of the original estimates within the Sonoma Volcanics, the Glen Ellen Formation, and the Humbug Creek deposits. Final values for the Franciscan are ~3.2% of the original estimates, and final values for the alluvium were left unchanged (Table 7). The differences between the original and final values are generally within an order of magnitude of the range of estimates from individual pump tests. These differences are significant but also relatively modest considering that K varies by at least six orders of magnitude in the various materials in Sonoma County and that K estimates for individual pump tests evaluated in this project vary by more than four orders of magnitude. It is plausible that values derived from pump tests over-estimate bulk K values for the large sequences of geologic materials represented by the model layers since most drillers of production wells seek to preferentially screen wells within tuffaceous or highly fractured bedrock intervals to maximize well production and efficiency. Anisotropy in the form of the ratio between horizontal and vertical K was derived through calibration, and the final value was 94 in all units except the alluvium which was parameterized as isotropic.

Specific Yield and Storage Coefficient Values
Previous estimates of the Specific Yield (Sy) for the Sonoma Volcanics range from less than 0.01 to 0.05 and estimates for the Glen Ellen Formation range from 0.03 to 0.20 (Cardwell, 1958; Herbst et al. 1982). Our final calibrated value for Sy in the Sonoma Volcanics was 0.05, and we

Table 5: Comparison of estimates of Transmissivity (T) derived from pump test data analyzed in AQTESOLV and calculated based on the Specific Capacity (Sc).

Material	AQTESOLV T (ft^2/day)	Sc Derived T (ft^2/day)
Sonoma Volcanics	350	710
Sonoma Volcanics	930	1200
Franciscan Complex	1.2	4.9
Franciscan Complex	16	11

Table 6: Pump test and well completion details and estimates of aquifer Hydraulic Conductivity (ft/day).

	Well Depth (ft)	Drawdown (ft)	Test Length (min)	Average Pumping Rate (gpm)	Aquifer Thickness (ft)	Sc (gpm/ft)	K (ft/day)	Source
Sonoma Volcanics Tuff	100	1.7	480	11.4	118	6.7	15	Sc
	150	2.0	480	17.0	138	8.5	16	Sc
	260	2.0	510	25.3	177	13	19	Sc
	70	1.8	480	10.7	61	5.9	26	Sc
	210	1.1	480	14.2	70	13	49	Sc
	158	**1.7**	**486**	**15.7**	**113**	**9.3**	**23**	
Sonoma Volcanics Basalt	807	6.0	510	4.0	177	0.67	1.0	Sc
	420	13.0	480	11.6	215	0.89	1.1	Sc
	200	10.8	500	13.7	140	1.3	2.4	Sc
	476	**9.9**	**497**	**9.8**	**177**	**0.94**	**1.4**	
Sonoma Volcanics Andesite	320	86.0	510	5.0	144	0.06	0.11	Sc
	460	49.0	600	5.0	209	0.10	0.13	Sc
	420	47.0	480	45.3	386	1.0	0.67	Sc
	80	10.0	1440	3.5	91	0.35	1.0	Sc
	320	**48.0**	**758**	**14.7**	**208**	**0.37**	**0.31**	
Sonoma Volcanics Undifferentiated	260	20.0	1530	7.5	91	0.38	1.1	Sc
	220	8.0	1230	21.2	229	2.6	1.5	AQTESOLV
	320	25.0	720	30.0	143	1.2	2.2	Sc
	200	4.8	540	8.9	181	1.9	2.7	Sc
	305	2.0	540	4.4	79	2.2	7.4	Sc
	380	2.0	520	6.5	95	3.3	9.2	Sc
	76	3.3	730	14.7	65	4.4	14	AQTESOLV
	252	**9.3**	**830**	**13.3**	**126**	**2.3**	**3.7**	
Franciscan Complex	540	428.0	720	7.8	614	0.018	0.0019	AQTESOLV
	280	175.0	480	6.0	270	0.034	0.034	Sc
	245	209.9	875	8.3	296	0.040	0.054	AQTESOLV
	260	40.9	510	4.4	152	0.11	0.189	Sc
	331	**213.5**	**646**	**6.6**	**333**	**0.050**	**0.029**	

Table 7: Final hydrogeologic properties used in the calibrated MWC hydrologic model.

Material	Present in Layers	Kh (ft/day)	Kh/Kv	Sy	S (ft^{-1})
Sonoma Volcanics	1 to 6	0.0082 - 0.60	94	0.05	2.0E-04
Franciscan	1 to 6	0.00090	94	0.10	1.1E-05
Glen Ellen	1 to 2	0.0010 - 0.79	94	0.04 - 0.20	1.0E-04 - 5.4E-04
Humbug Creek	1	0.001	94	0.04	5.4E-04
Alluvium	1	30 - 120	1	0.30	1.5E-04

Table 8: Range and average Hydraulic Conductivity (K) values for the Sonoma Volcanics in model Layers 1 through 6.

Layer	Sonoma Volcanics Kh (ft/day)	
	Range	Mean
1	0.0082 - 0.60	0.40
2	0.0082 - 0.60	0.29
3	0.0082 - 0.60	0.28
4	0.0082 - 0.60	0.24
5	0.0082 - 0.60	0.21
6	0.0082 - 0.32	0.10

used a value of 0.04 in the fine-grained Reibli Creek exposure of the Glen Ellen and 0.20 in the coarser Leslie Creek exposure (Table 7). No estimates of Sy were available for the Franciscan Complex, the Humbug Creek Deposits, or the Alluvium in the study area, thus estimates were based on literature values from similar materials (Freeze & Cherry, 1979; Domenico & Schwartz, 1990). We used values of 0.04, 0.10, and 0.30 for the Humbug Creek, Franciscan, and alluvium respectively (Table 7). Johnson (1977) estimated a value for the Storage Coefficient (S) for the Sonoma Volcanics of 1.6E-04 (ft^{-1}). No estimates of S are available for the other geologic materials in the watershed; therefore, estimates were based on literature values from similar materials (Domenico & Mifflin, 1965). Values ranged from 1.1E-05 (ft^{-1}) for the Franciscan Complex to 5.4E-04 (ft^{-1}) for the Humbug Creek Deposits (Table 7).

Hydrogeologic Property Distributions

As described above under the heading Distribution and Description of Geologic Materials, we classified geologic materials within the Sonoma Volcanics in each vertical interval corresponding to one of the six model layers using the same four categories examined with the pump test analyses. We assigned each of the well locations with available stratigraphic information the

corresponding geometric mean K value from the pump test analyses and interpolated K distributions for each layer in a GIS using kriging (Figure 19). K values for the other materials were assumed to be homogeneous and these materials were assigned corresponding K values from literature estimates as described above. The model layering was constructed such that the base of Layer 1 corresponded to the base of the Quaternary Alluvium; therefore, K estimates were used directly in the model for areas of Layer 1 with alluvium. For the Humbug Creek deposits and lower portions of the Glen Ellen Formation which do not penetrate the full thickness of Layer 1, we calculated a depth-averaged K value based on the relative thicknesses of these materials and underlying formations (Figure 19).

The interpolated K maps for the Sonoma Volcanics reveal that tuffaceous material is widespread in the watershed and that the proportion of tuffaceous versus other volcanic rocks (principally andesite and basalt) generally decreases with depth as is apparent from the mean K value for the volcanics which decreases from 0.40 in Layer 1 to 0.10 in Layer 6 (Figure 19). A significant block of primarily tuffaceous material is present in the upper Mark West and Humbug Creek watersheds, and the interpreted WCRs indicate that the volcanics become dominated by andesite below about 300-ft (Figure 19). Another significant block of primarily tuffaceous material underlies the Glen Ellen Formation in the Leslie Creek watershed where it extends from the base of the Glen Ellen to about 400-ft below land surface and becomes more basaltic-dominated material at greater depths. A third relatively thin block of tuff occurs at greater depth (400 to 500-ft below land surface) in portions of the lower watershed, and less widespread and generally thin blocks of tuff are also present in other portions of the upper Mark West and Porter Creek watersheds (Figure 19).
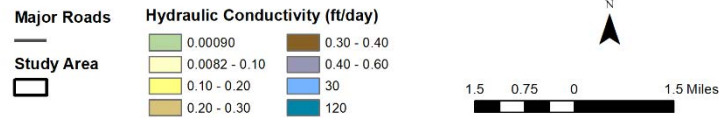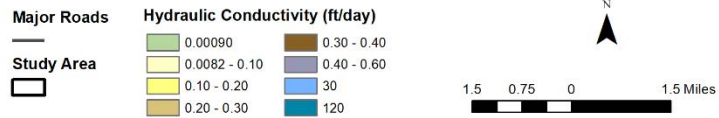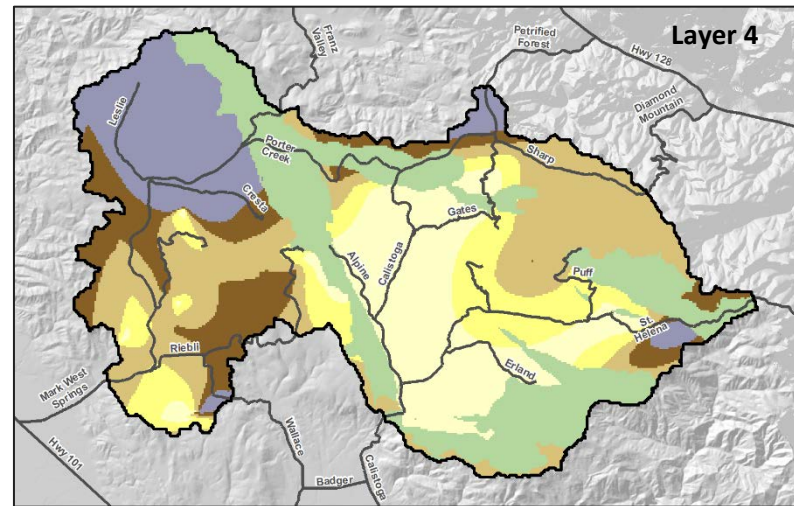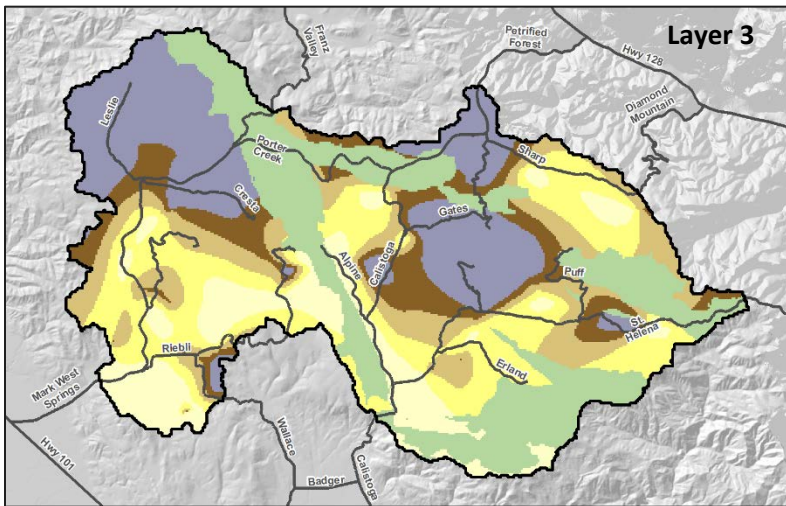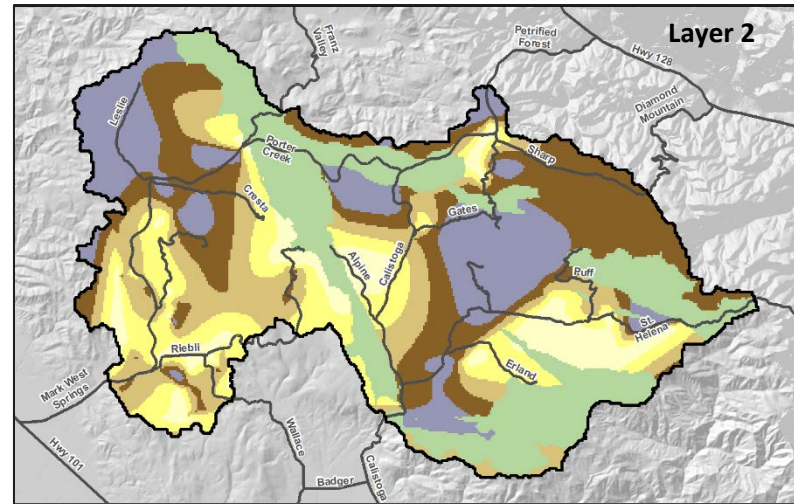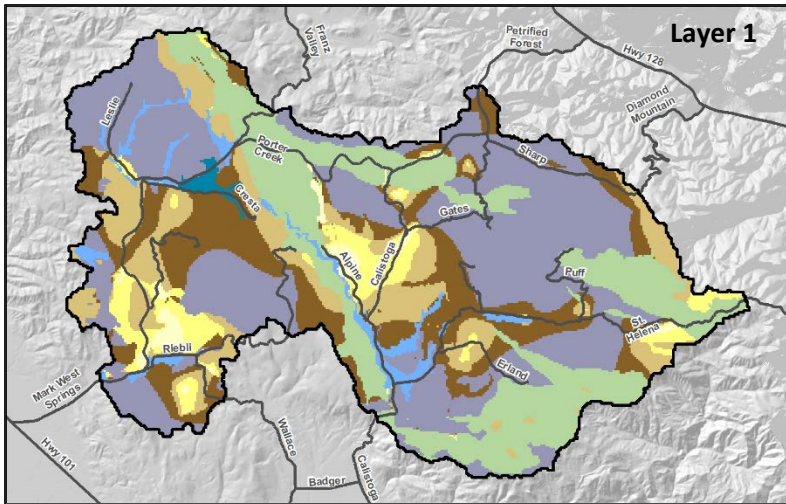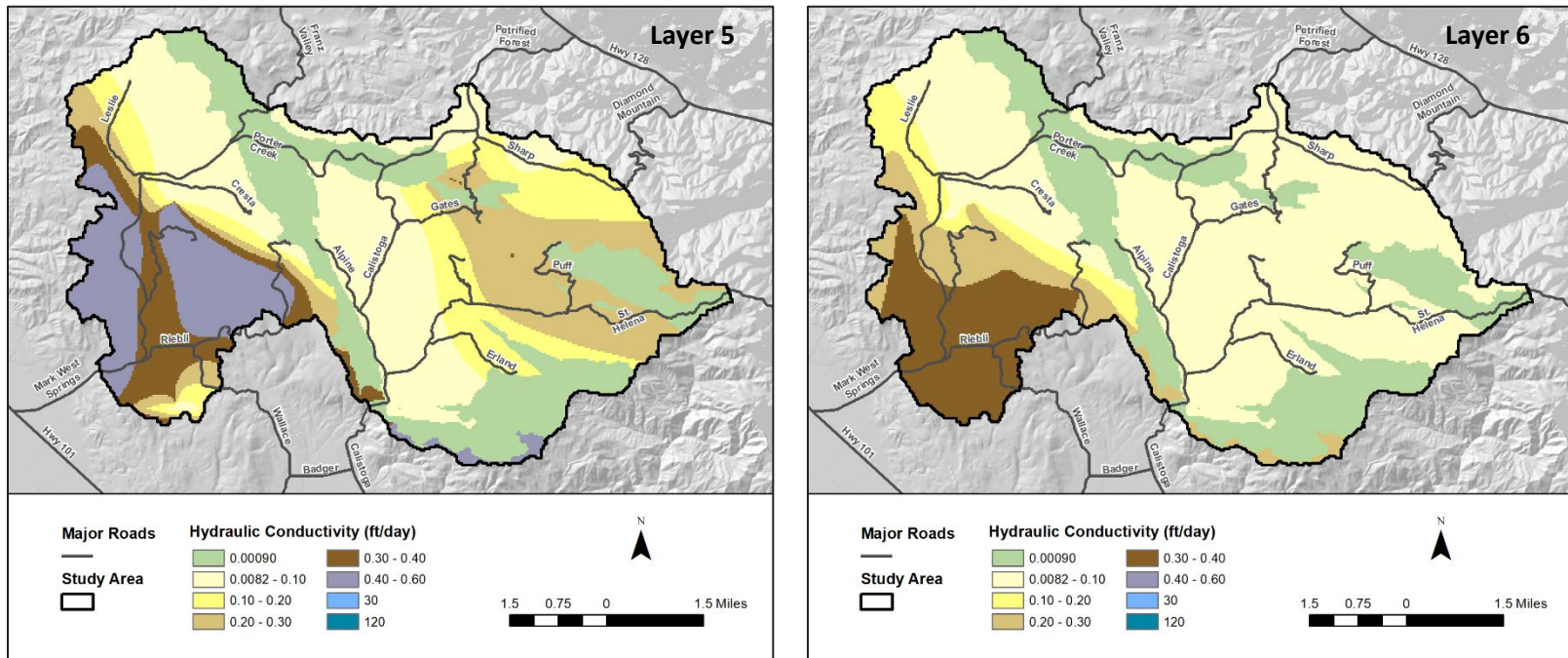
Figure 19: Horizontal Hydraulic Conductivity distributions for model Layers 1 through 6.

Water Use

Water Use Categories and Spatial Distribution
Water uses were calculated on a parcel by parcel basis. We identified the following use categories: Residential, Vineyard Irrigation, Pasture Irrigation, Cannabis Irrigation, Irrigation of Other Miscellaneous Crops, Vineyard Frost Protection, Winery Production and Visitation Use, and Miscellaneous Industrial Uses. The water uses on each parcel were identified using a variety of remotely sensed data and other datasets provided by various governmental entities. Acreages of vineyard, pasture, and other croplands were obtained from the Sonoma County Vegetation Mapping & LiDAR Program's Fine Scale Vegetation and Habitat Map (SCVMLP, 2015).   Satellite imagery was reviewed to verify the accuracy of the identified agricultural lands and to identify vineyards planted after 2013 when the underlying LiDAR dataset on which this map is based was collected. In total we found 442.4 acres of vineyard and 12.8 acres of irrigated pasture and other crops (primarily olives).

All vineyards with frost protection systems that use water are required to register with the Sonoma County Agricultural Commissioner's office. Most vineyards in the model domain are located on ridgetops and hillsides where vineyards in Sonoma County are generally less likely to require frost protection than vineyards located on valley bottoms. Additionally, some vineyards may also have permanent or portable fans or heaters for frost protection. A review of the Sonoma County Frost Protection Registration database revealed that three parcels within the model domain are registered as using water for frost protection. One additional parcel with vineyard in the model domain indicated in the SWRCB's 2015 Russian River Information Order (SWRCB Information Order) that they also use water for frost protection. One of these vineyards obtains water from ponds located outside the watershed and three use groundwater from within the watershed. The three vineyards using water from within the watershed for frost protection total 16.9 acres.

Existing cannabis cultivation operations were identified from registration and permit records from the NCRWQCB and the County of Sonoma. It is common knowledge that many existing operations are not identified in the permit system. To account for water use by unregistered cannabis cultivators, we reviewed publicly-available satellite imagery and identified the size and location of all visible cultivation sites in the watershed. In total we identified 47 parcels with outdoor and mixed-light cannabis operations totaling approximately 9.8 acres of cultivation area. Indoor operations could not be identified by aerial imagery and thus this component of cannabis irrigation use may be under-estimated.

The number of residences on each parcel was obtained from the County of Sonoma's parcel GIS coverage. Seven small mutual water companies and the City of Santa Rosa each serve a small area in the southwest portion of the watershed. Information about the well locations and number of residences supplied by each well was obtained from the SWRCB's State Drinking Water Information System (SDWIS) and used to adjust the residential use estimate to account for residences supplied by water from outside the watershed and residences not in the watershed but supplied by water from within the watershed. Census block data from the 2010

U.S. Census provided an estimate of the total population served by water from the watershed. When combined with the corresponding number of residences, this yields an estimate of the average number of people per residence (2.09) which could then be used along with per capita use rates to calculate the total residential use for each parcel. In total there are approximately 2,518 people served by water obtained from within the watershed.

Winery production volumes and annual guest visitation totals were obtained from a GIS dataset provided by the County of Sonoma. Total winery production for the eight wineries in the watershed is approximately 44,300 cases per year. There are only two primary industrial users in the watershed which were handled on a case-by-case basis. Quarterly water use volumes for Mark West Quarry were obtained from reports submitted to the County of Sonoma, and monthly groundwater pumping volumes for Safari West were obtained from the SWRCB Information Order. No use for the Mayacama Golf Club was included since productions wells for the golf club and associated residences are located outside the study area.

Standard Use Rates
Standard use rates were established for the various use categories in the study area using data from the SWRCB Information Order, local municipalities, and literature sources. We examined rates and use categories from the SWRCB Information Order and identified those entries in and around the study area where rates were reported to be based on physical measurements such as totalizer readings or pump fuel usage. In most cases, the method of use estimation was unknown or not based on physical measurements. Given the uncertainty in the accuracy of these estimates, we only relied on those estimates based on physical measurements. In many cases, the reported uses contained a mix of use types (e.g. vineyard irrigation and residential) which prohibited calculation of per acre irrigation or per capita residential use. After careful examination of the data, we were only able to identify four parcels where residential use could be reliably estimated and three parcels where vineyard irrigation use could be estimated.

Total annual per capita use calculated for the four residential parcels in the Mark West Creek watershed for 2014/2015 averaged approximately 23,100 gallons (0.071 acre-ft/yr). We compared the annual use estimates to data from the nearby Town of Windsor. Based on the available data from the SWRCB's Water Conservation and Production Reports from 2014 to 2018, the average annual per capita use was approximately 26,700 gallons (0.082 acre-ft/yr) which is in reasonably good agreement with the Mark West data. Due to the small sample size of the local data, the calculated monthly averages are heavily influenced by individual users, whereas the Windsor data is based on thousands of connections and is therefore expected to provide a better estimate of typical use in the area. We relied on the average per capita monthly data from the Town of Windsor to generate use estimates for the model (Table 9 & Figure 20); it is acknowledged that this method may over- or under-estimate actual residential use in the study area.

Total annual vineyard irrigation use for the three parcels in the Mark West Creek watershed for 2014/2015 (totaling 80 acres of vineyard) ranged from 0.21 to 0.53 ac-ft/ac/yr. As part of a parallel project in the Mill Creek Watershed, we obtained recycled water delivery data for

2017/2018 from the City of Healdsburg for four parcels in the Dry Creek Valley totaling 142 acres which provided a very accurate means of estimating vineyard irrigation rates for the region and validating the estimates derived from the SWRCB Information Order data. The Dry Creek data showed very similar annual rates ranging from 0.17 to 0.55 ac-ft/ac/yr, and the average annual total calculated from the Mark West parcels (0.32 ac-ft/ac/yr) was nearly identical to the average annual total calculated in Dry Creek (0.31 ac-ft/ac/yr). To provide a more robust estimate of the temporal distribution of vineyard irrigation we calculated monthly mean rates from the three parcels in Mark West plus the four parcels in Dry Creek for use in the model, which yields mean annual use of 0.32 ac-ft/ac/yr (Table 9 & Figure 20). In the model, vineyards are irrigated from May through October with irrigation peaking at 0.09 acre-ft/acre/month in June (Figure 20).

Based on guidance provided by the University of California Davis and Sonoma RCD, the timing of water use for frost protection is based on the wet-bulb temperature (Snyder, 2000; Minton et al., 2017). Wet bulb temperature was calculated on an hourly timestep using air temperature and relative humidity data from the Windsor CIMIS station (Stull, 2011). Frost protection is assumed to occur any time the hourly wet bulb temperature is 0.5°C or lower during the typical March 15th – May 15th frost protection season. The rate at which each parcel uses water for frost protection was calculated as the product of vineyard acreage and reported sprinkler and micro-sprinkler application rates as described in the Sonoma County Frost Protection Registration database (Table 9). Based on these assumptions, the annual number of hours of frost protection ranged from one in 2013 to 25 in 2011, the average annual application rate was 0.069 ac-ft/ac/yr, and the maximum rate was 0.18 ac-ft/yr.

Table 9: Standard water use rates and summary of total water use for the various use categories represented in the MWC hydrologic model.

Use Category	Unit Definition	Use per Unit (ac-ft/yr)	# of Units	Total Use (ac-ft/yr)
Residential	Person	0.082	2,518	206.5
Vineyard Irrigation	Acre	0.32	442.4	141.6
Vineyard Frost Protection	Acre	0.069	16.9	1.2
Pasture/Other Irrigation	Acre	2.00	12.8	25.6
Outdoor Cannabis	Acre	1.34	5.9	7.9
Hoop-house Cannabis	Acre	1.53	3.9	6.0
Winery	1,000 Cases of Wine	0.073	44	3.2
Misc. Industrial	Lump Sum	-	-	38.8
Sum				**430.7**
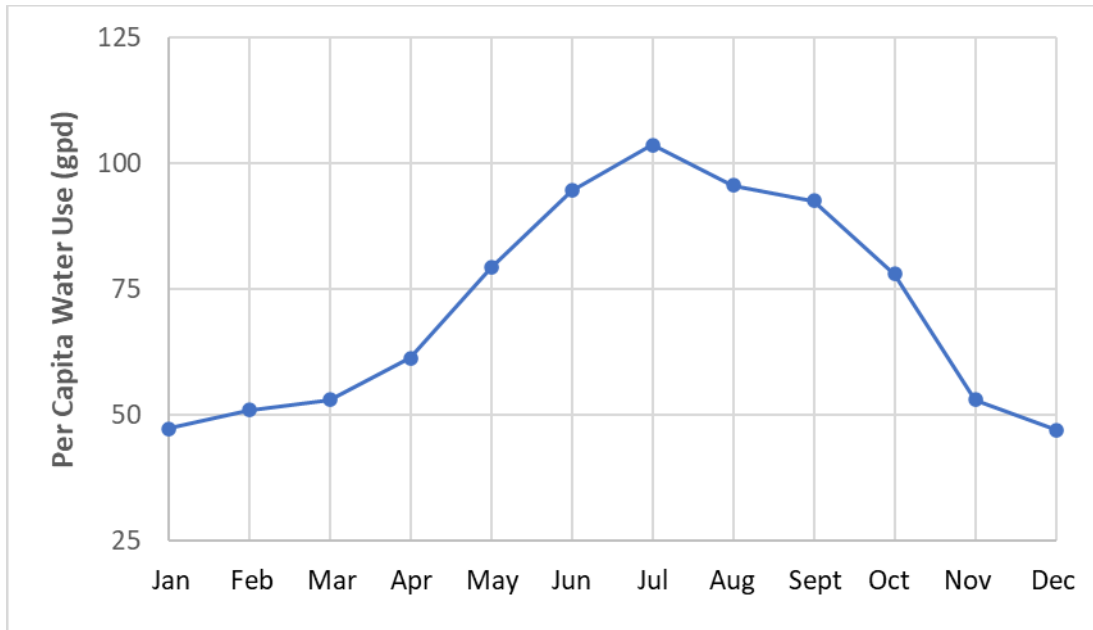
Figure 20: Mean (2014-2018) monthly per capita residential use from the Town of Windsor used to calculate residential use in the MWC hydrologic model.
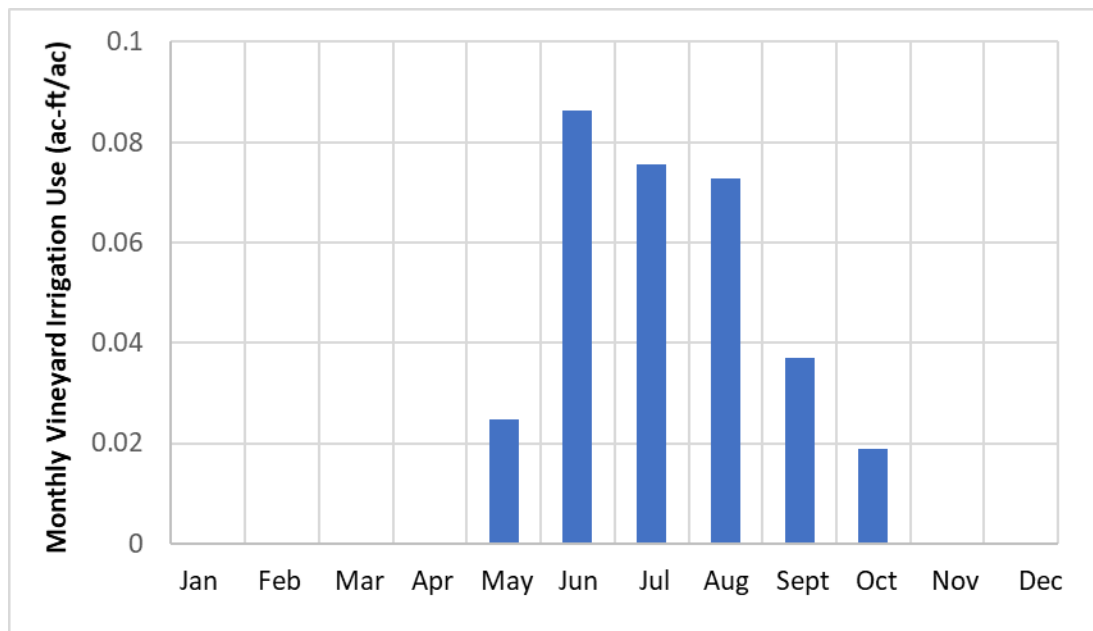
Figure 21: Mean (2014-2015 and 2017-2018) monthly per acre vineyard irrigation use compiled from Information Order data in the Mark West Creek watershed and recycled water delivery data in the Dry Creek Valley and used to calculate vineyard irrigation use in the MWC hydrologic model.

No reliable pasture irrigation rates could be determined from the available data, therefore we relied on a regionally-appropriate value of 2.0 ac-ft/ac/yr (County of Napa, 2015). Based on field reconnaissance and review of available aerial imagery and GoogleEarth Street View products, most orchards within the study area are mature walnut and apple orchards which are typically dry-farmed in Sonoma County. Less than 2 acres each of olive orchard and vegetable crops were identified and were assumed to be irrigated at rates similar to pasture. The total acreage of irrigated pasture, olive orchard, and vegetable crops in the study area is only 12.8 acres.

Cannabis use rates are based on cannabis irrigation data collected by the NCRWQCB for Humboldt, Mendocino, and Sonoma Counties. Typical irrigation rates of 1.34 ac-ft/acre/yr for outdoor cultivation and 1.53 ac-ft/acre/yr for hoop-house cultivation were selected based on a presentation summarizing this data which also provided a monthly distribution of use (Dillis, 2018) (Table 9).

Winery production, employee, and guest water use rates were based on the County of Napa's Water Availability Analysis Guidance Document (County of Napa, 2015) (Table 9). The monthly distribution of winery production was taken from the Winery Wastewater Handbook (Chapman et al., 2001). Winery guest use, which is relatively minor within the study area, was assumed to be constant throughout the year (Table 9). As discussed above Industrial use was based on parcel-specific reported rates from Sonoma County and the SWRCB Information Order rather than on standard rates.

Water Sources

Parcels with surface water diversions were identified from the SWRCB Electronic Water Rights Information Management System (eWRIMS) and the SWRCB Information Order. For unpermitted cannabis cultivation operations where the water source was unknown we assumed surface water use if there was a perennial stream, spring, or pond located on the parcel, which was the case for 9 of the 47 cannabis operations in the study area. For all other parcels we assumed groundwater use. Where multiple wells are located on a given parcel, we divided the total use for the parcel between the various individual wells. When eWRIMS or the SWRCB Information Order indicated that a parcel has both surface water and groundwater supplies, surface water diversions were subtracted from groundwater pumping.

After consolidating duplicate records from the various sources, we excluded diversions reported as inactive or with zero use, as well as those where the SWRCB Information Order states use; however, the reported uses are for evaporation losses and recreation or aesthetics rather than for consumptive uses. We only identified two off-channel ponds with small reported consumptive uses estimated to total approximately 1.3 ac-ft/yr which were accounted for as groundwater use given that the model does not explicitly represent off-stream ponds. For spring diversions, we attribute the location of the diversions to the nearest stream in our model, thus treating it as equivalent to a direct diversion. There are a total of 52 surface water diversions in the model, 24 of these are direct stream diversions, 19 are spring diversions, and 9 are diversions from on-stream ponds represented in the model (Diversion timeseries are based on average monthly diversion volumes. Where possible, reported diversion volumes from eWRIMS and the

SWRCB Information Order were used. If reported diversion volumes from the SWRCB Information Order were not based on physical measurements or if no diversion volumes were reported, volumes were calculated using the standard use rates for the uses on a given parcel.).

Where possible, wells were located at specific locations on a given parcel from location information available on WCRs, the SWRCB Information Order, and in some select cases site visits. The SWRCB Information Order was especially helpful in this regard by providing a means of tying many more wells to specific locations than would have otherwise been possible. Nevertheless, many of the locations reported in SWRCB Information Order data proved to be parcel centroids and it is not possible to locate all wells at a level of detail beyond the parcel scale. More specific location data was used for 458 of the 792 wells in the model. We initially placed all the remaining wells at parcel centroids, but review of the parcels along upper Mark West Creek and Humbug Creek revealed that residences in these areas are generally located much closer to the creek than the centroid of the parcel. There are certainly many exceptions, but wells are often placed in relatively close proximity to the areas they serve, so to avoid over-estimating the distances between wells and streams, we placed theses stream-side parcel wells along upper Mark West Creek and Humbug Creek at the centroids of the residences as indicated by the impervious areas delineated in the Sonoma County fine-scale vegetation mapping data (SCVMLP, 2017).

Well completion details could be determined from WCRs for 189 wells and we associated the wells without WCRs with the nearest well with a WCR within the same geologic terrain to estimate well depth and screened interval information for all wells in the model. About 47% of the wells are screened at least partially within the upper 100-ft of aquifer material but most of these are screened to greater depths with only 5% of the wells screened entirely in the upper 100-ft. About 34% of the wells are screened entirely within the upper 200-ft of aquifer material and about 78% are screened entirely within the upper 400-ft with the remainder screened within the upper 700-ft (Figure 22).

Water Use Timeseries

Surface Water Diversions

Diversion timeseries are based on average monthly diversion volumes. Where possible, reported diversion volumes from eWRIMS and the SWRCB Information Order were used. If reported diversion volumes from the SWRCB Information Order were not based on physical measurements or if no diversion volumes were reported, volumes were calculated using the standard use rates for the uses on a given parcel. The monthly volumes calculated for each diversion are used to calculate a diversion timeseries. These timeseries were calculated on a 6-hour timestep and account for pumps shutting on and off and the estimated capacities of these pumps. A 6-hour timestep was selected to provide a reasonable representation of sub-daily variability while maintaining reasonable computational efficiency. Separate pumping regime assumptions are made for direct diversions and for spring and pond diversions.

Direct diversions were assumed to fill storage tanks completely and then resume once these tanks had been partially emptied. Based on storage tank sizes reported in the SWRCB
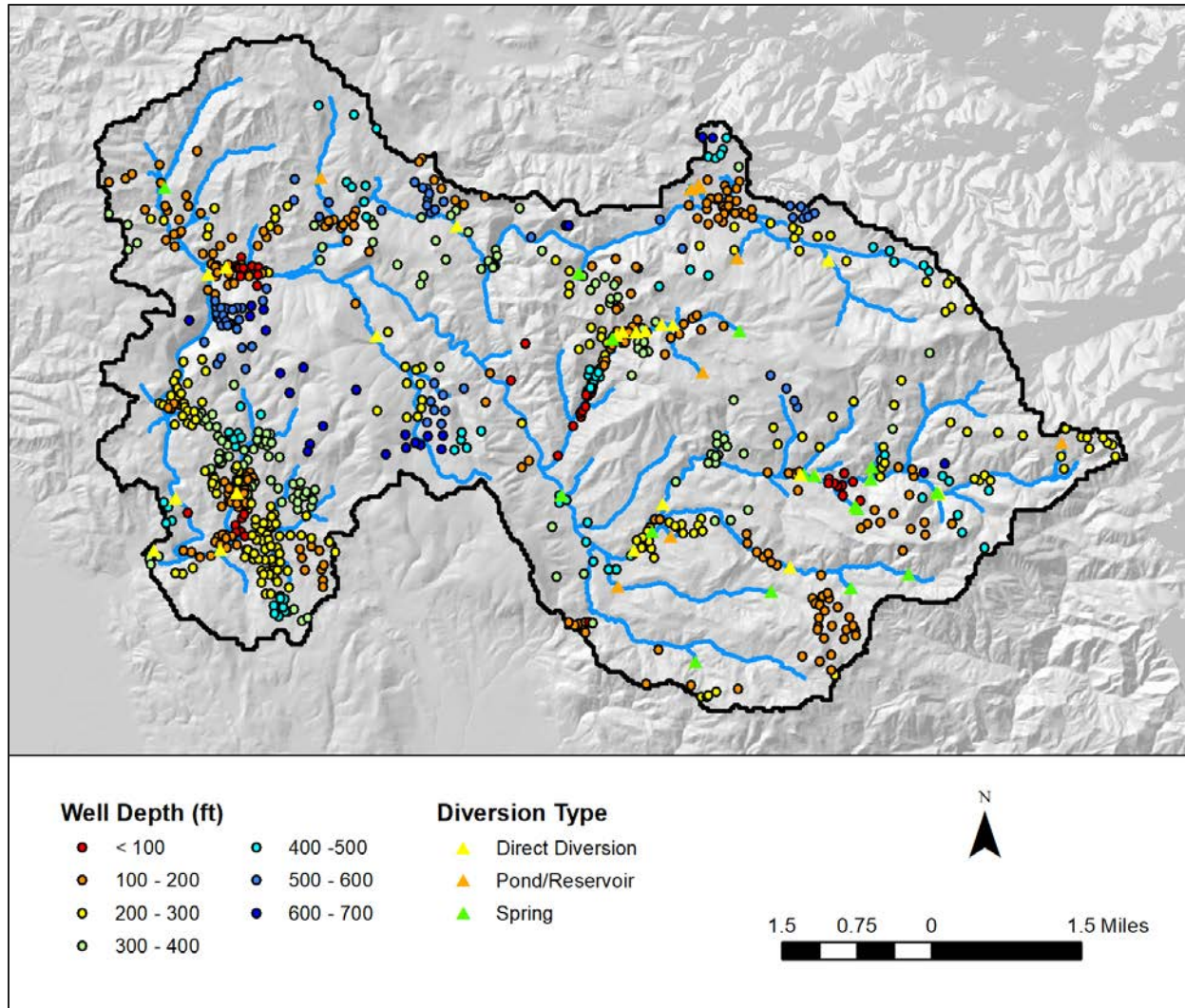
Figure 22: Locations of surface water diversions and groundwater wells in the MWC hydrologic model.

Information Order, the typical tank size for a residence with a direct diversion is approximately 3,000 gallons. Such a tank would need to be filled completely twice a month to supply a typical residence, or approximately four times per month if the tank were only partially emptied. Less data is available for agricultural tank sizes but the limited data supports use of a similar pumping frequency. Consequently, direct diversions were assumed to divert a fraction of the monthly volume on the 1st, 8th, 15th, and 22nd of each month. Some diversion volumes were met using the assumed pumping rates with less than four pumping events per month, in which case they are only active 1-3 times per month depending how quickly the demand is met for each month. For larger demands, the four per month diversion periods were assumed to continue for as long as necessary based on the diversion rate. Typical spring and pond diversions deliver water in near real-time and thus do not require large storage tanks. This results in more frequent, shorter-duration pumping intervals relative to direct diversions. Therefore, daily use was calculated from

the monthly volumes and all daily use was considered to be supplied during a single 6-hour timestep.

In addition to developing estimates of the frequency and duration of diversions, it is necessary for modeling to assume a start time. There is likely little to no coordination between diverters regarding the timing of pump activation, and probably some general tendency for coincident pumping due to coincident timing of irrigation demands and work schedules. We made the conservative assumption that all diversions start simultaneously at the beginning of the day, and the diversions on weekly schedules all occur on the same days. These various assumptions result in a maximum instantaneous diversion rate on the 1st of each month, and spikes in rates at regular intervals which is considered to represent a 'worst case' diversion timing scenario (Figure 25).

Where possible the diversion rates used to calculate the diversion timeseries were obtained from eWRIMS or the SWRCB Information Order. However, most diversions rates were either not reported or the reported rates were not realistic given the reported units. Where specific rates were not available, standard rates were used as derived from reported rates in the SWRCB Information Order that were based on actual physical measurements. Standard rates were derived for two diversion types: domestic/small agricultural operations and larger agricultural operations. We combined our analysis of the SWRCB Information Order data for Mark West Creek with analysis of the data for Mill Creek where we are completing a parallel modeling study, and we also restricted the selected entries to include only those based on physical measurements. Based on twelve diversions from the Mark West and Mill Creek Watersheds, the typical residential and small agricultural diversion rate is estimated to be 2.69 gpm (0.006 cfs). Diversion rates for larger agricultural operations varied greatly but typically ranged between 0.01 and 0.03 cfs and a typical diversion rate of 9.0 gpm (0.02 cfs) was used. A monthly timeseries of the total direct and spring diversion volumes and the total pond diversion volumes in the model is shown in Figure 23 and Figure 25, and an example of the 6-hr interval total direct and spring diversion timeseries for July 2010 is shown in Figure 25.
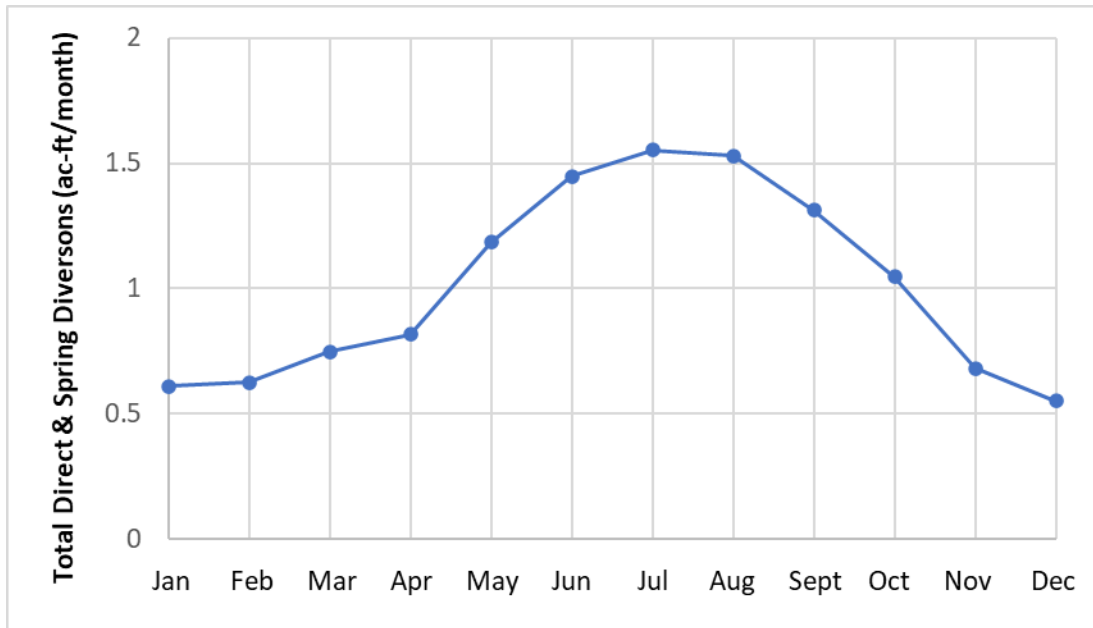
Figure 23: Total monthly direct and spring diversion volumes used in the MWC hydrologic model.
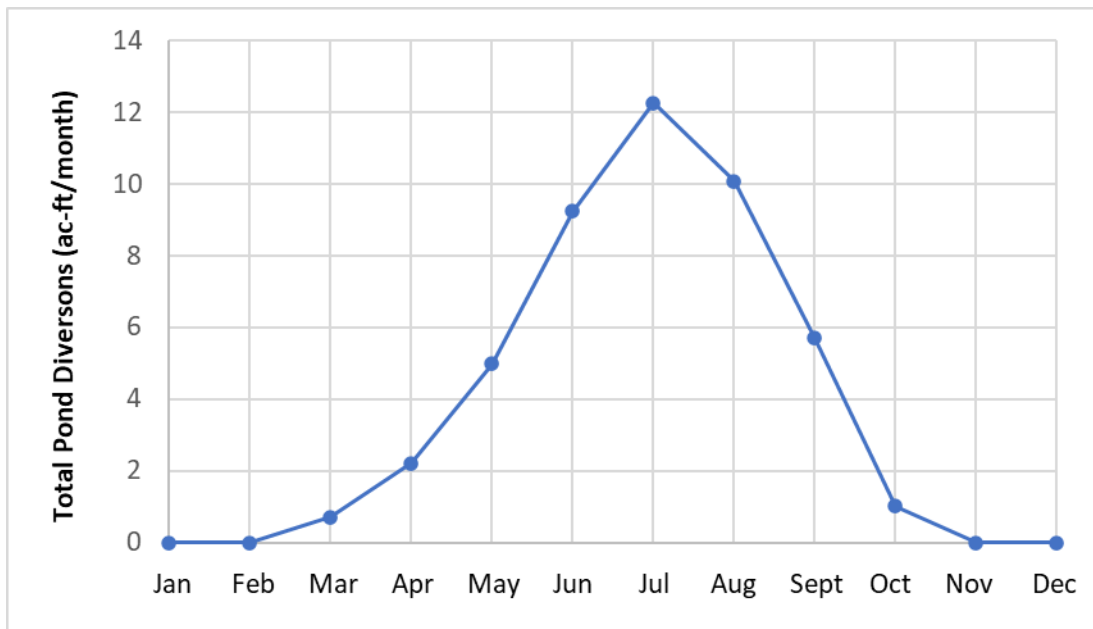
Figure 24: Total monthly pond diversion volumes used in the MWC hydrologic model.
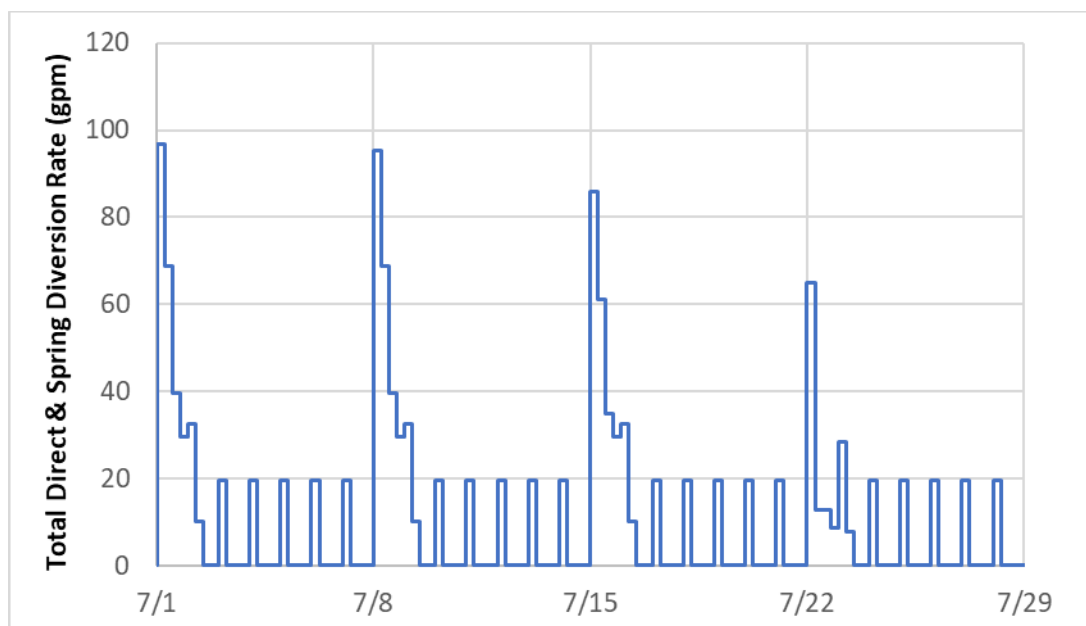
Figure 25: Example of the 6-hr interval timeseries of total direct and spring diversions used in the MWC hydrologic model for July of 2010.

Groundwater Wells

Wells are assumed to be pumped on a daily basis, either supplying water in real-time or topping off a tank.   The groundwater pumping timeseries was calculated by converting estimated monthly volumes to a daily demand and pumping each well at its estimated yield until this daily demand was met.   This timeseries was calculated on an hourly timestep consistent with the hourly timestep used to drive the groundwater component of the model.   Estimated yields are based on pump test data associated with Well Yield Certifications obtained from the County of Sonoma as analyzed and discussed in the Aquifer Properties section above.   Typical yields of 13.7 gpm and 6.6 gpm were calculated for the Sonoma Volcanics and the Franciscan Complex respectively (Table 6).   Other geologic materials in the watershed including the Quaternary Alluvium, the Glen Ellen Formation, and the Humbug Creek Deposits are not a significant source of water to wells as discussed above under the heading Distribution of Geologic Materials.

Wells supplying large vineyards, used for frost protection, or supplying multiple connections as mutual water company wells are likely have higher than average yields.   To account for this, the maximum daily pumping duration is capped at 6 hours per day.   If a well cannot supply the required daily volume within this 6-hour window, the pumping rate was increased until it could. The pumping rates used for these wells, up to 78 gpm in the Sonoma Volcanics and up to 37 gpm in the Franciscan, are still within the range of reasonable values for these formations.

The only component of pumping that varies in the model from year to year is the frost protection pumping which accounts for a relatively small component of the total pumping.   A monthly timeseries of the total groundwater pumping volumes applied in the model is shown in Figure 26

and an example of the hourly total pumping timeseries for 1 3-day period in early July is shown in Figure 27.
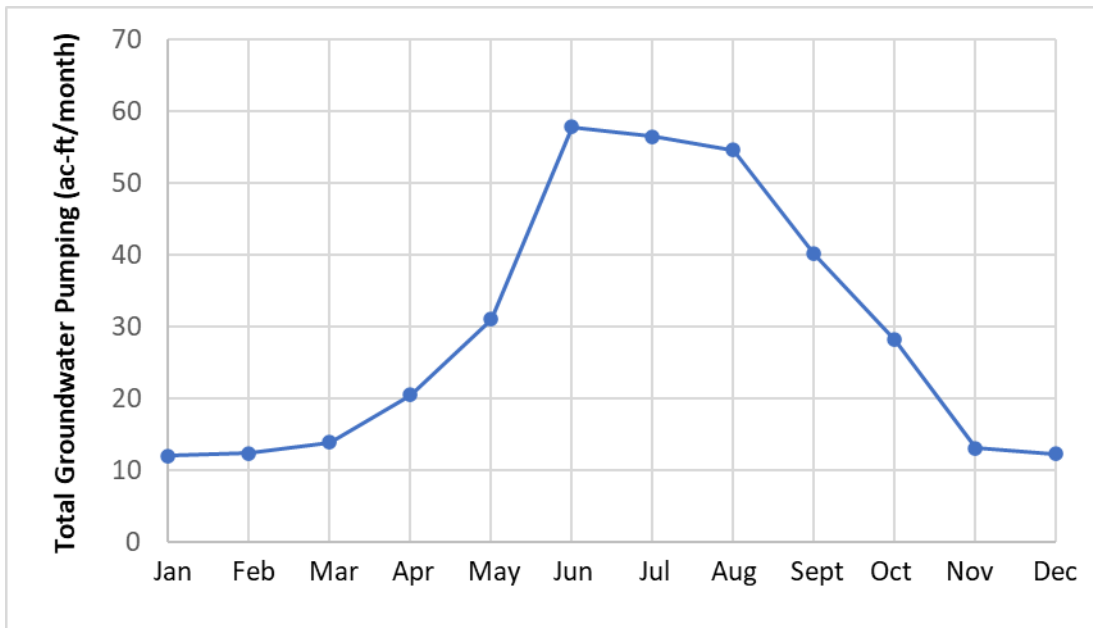
Figure 26: Total monthly groundwater pumping volumes used in the MWC hydrologic model.
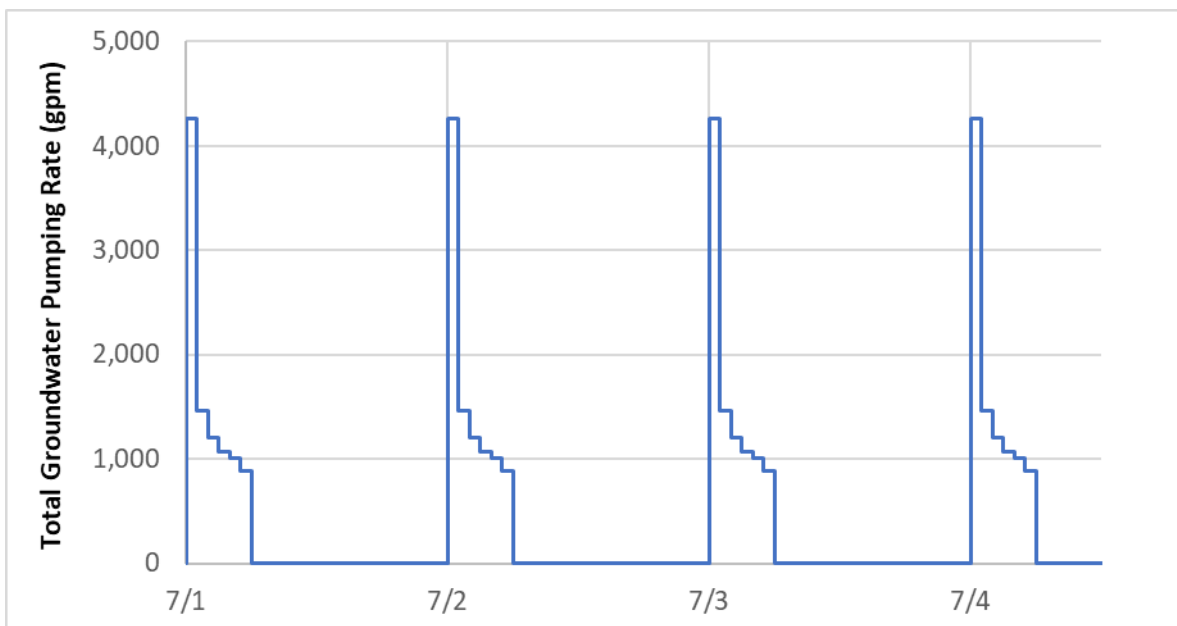
Figure 27: Example of the 1-hr interval timeseries of total groundwater pumping in the MWC hydrologic model for a 4-day period in early July.

Water Use Summary

Total water use from all sources in the watershed is estimated to be approximately 430.7 ac-ft/yr. The largest uses are residential and vineyard irrigation which account for about 48% and 33% of the total water use (Table 9; Figure 28). Industrial uses account for the next largest fraction at about 9%. The remaining 10% consists of irrigation for pasture and other crops (6%), irrigation of cannabis (3%), winery use (<1%), and vineyard frost protection (<1%) (Table 9; Figure 28). About 85% (367.1 ac-ft/yr) of the total use in the watershed is from groundwater with the remaining 15% (63.6 ac-ft/yr) coming from surface water sources. About 81% (51.5 ac-ft/yr) of the total surface water use comes from pond storage, 10% (6.7 ac-ft/yr) comes from direct stream diversions, and 9% (5.4 ac-ft/yr) comes from springs.

Direct stream and spring diversions are concentrated in Humbug Creek, and upper Mark West Creek in and upstream of Van Buren Creek (Figure 22). The highest concentration of wells occurs in the Reibli Creek subwatershed which is generally more urbanized given its proximity to the City of Santa Rosa. Higher concentrations of wells also occur in upper Mark West Creek, upper Porter Creek, and the lower Leslie Creek area (Figure 22). The pattern of development in the watershed has tended to occur along the stream corridors as can be seen in the well distribution with 50% of the wells located within 500-ft of a stream and 73% located within 1,000-ft (based on the modeled stream extent).

Irrigation

The water extracted from wells and surface water diversions for irrigation of vineyards, pasture, and other crops is applied to the land surface as irrigation in the model (see Figure 9 for locations of irrigated crops in the model). The monthly application volumes match the standard use rates as discussed above. Based on previous work with vineyard operators in Sonoma County, vineyards are typically irrigated at intervals of about one week to one month. We assumed a twice-monthly irrigation schedule and developed our irrigation timeseries by distributing the monthly volumes between the two irrigation events each month.   We assumed a similar irrigation frequency for pasture and other irrigated crops in the model. Although many vineyard operators use a block rotation schedule for irrigation, the twice-monthly schedule accounts for the temporal effects of irrigation on soil moisture and is decoupled in time from the extraction of that water which is based on assumed pumping rates and tank storage volumes as discussed above. We did not apply water used for cannabis as irrigation in the model since cultivation areas are generally smaller than the 0.5-acre grid scale and many cultivators use pots or fabric bags which limit the potential for interaction with surrounding soils. Water for frost protection of vineyards was also applied back to the land surface as irrigation in the model in real-time based on the calculated demand as discussed above.
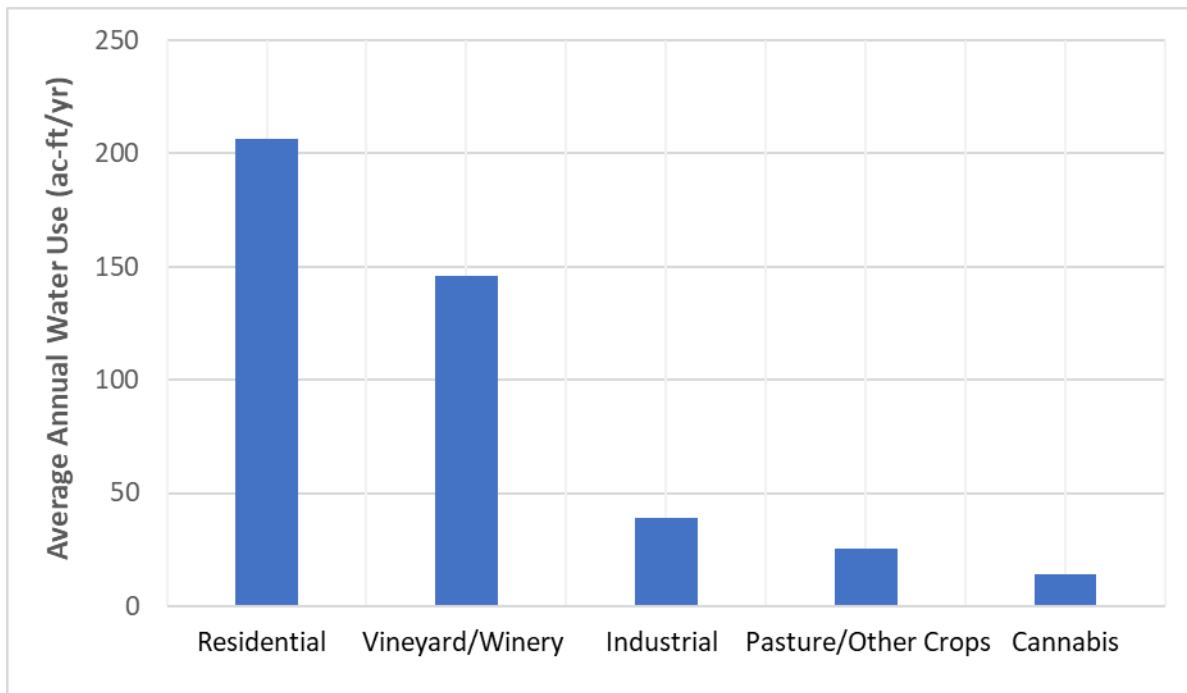
Figure 28: Breakdown of total water use in the MWC hydrologic model by use category.

Chapter 5 – Model Calibration

Calibration of a distributed hydrologic model like MIKE SHE is complicated by the large number of inter-related process and parameters involved. Previous modeling experience has indicated that results are most-sensitive to a relatively small subset of the model parameters including the overland flow Detention Storage and Roughness, unsaturated zone Saturated Hydraulic Conductivity and moisture contents, interflow Drain Levels, groundwater Hydraulic Conductivity, and the streambed Leakage Coefficient. The calibration focused on adjusting these seven parameters within a range of plausible values (to maximize the fit between observed streamflow and groundwater data and mapping information.

Available Data

Several stream gauges have been operated in the watershed at various times over the past ten years including a series of gauges installed in 2010 by the Center for Ecosystem Management and Research (no longer in existence); some of which were re-established by Trout Unlimited (TU) in 2018. In 2018, Sonoma Water established several new gauges to serve as a warning system for potentially hazardous post-fire runoff events and the CRWI installed a gauge on lower Monan's Rill in the upper watershed. Additionally, OEI installed two gauges on upper Monan's Rill tributaries in 2017 and gauging in and near Humbug Creek has also been undertaken by CDFW in recent years.

Despite the relatively large number of stage sensor records available, most of the available data is only from the past few years and only relatively limited development of rating curves and discharge records has occurred. CEMAR and TU collected streamflow measurements and developed low flow (summer baseflow) rating curves at their sites, however rating curves have not been developed for the Sonoma Water sites. Even at the CEMAR/TU sites, no discharge measurements of storm runoff were previously collected, thus prior to this study no continuous rating curves or streamflow records had been developed in the watershed.

We selected three sites for additional streamflow gauging and rating curve development, the CRWI site on Monan's Rill, one of the TU stations in the upper watershed at Rancho Mark West, and one of the Sonoma Water stations in the lower watershed at Michelle Way (Figure 29). We measured discharges at the three sites at approximately monthly intervals between March 2018 and August 2019. For lower flows we used standard wading techniques and a topset rod and flow meter, and for higher flows we used a bridge crane and a flow meter. For all gauging efforts we followed standard USGS stream gauging protocols (USGS,2010).

We obtained the discharge measurements collected by CEMAR for the previous installation at the Rancho Mark West site which operated from March 2010 to December 2014. The original pressure transducer was still installed in the channel near the new instrument that TU installed in February 2018, allowing the older and newer stage records to be combined by applying an elevation offset between the instruments as measured in the field. This made it possible to combine the older CEMAR record from 2010-2014 with data collected from 2018-2019 to develop continuous rating curves and flow records for this site from 3/11/2010 – 12/10/2014 and 2/23/2018 – 7/25/2019.

At Michelle Way, we developed rating curves from our discharge measurements which allowed for the development of continuous flow records from 2/27/2018 – 9/30/2019. We also developed rating curves at Monan's Rill; unfortunately, an instrument malfunction resulted in a large data gap and we were only able to develop continuous flow records for 5/1/2018 – 12/13/2018 and 3/25/2019 – 9/30/2019 which excludes most of the larger runoff events that occurred in 2018/2019. Given the paucity of runoff events captured at this gauge, we focused on the May through September time period for calibration at this location.

In addition to streamflow data, other supplemental sources of calibration data include locations of known springs and perennially-flowing tributaries and wet/dry mapping data collected by CA Sea Grant, CDFW, and Sonoma Water. We compiled the locations of springs and seeps mapped in the field along main-stem Mark West Creek by OEI and CDFW staff in August 2018, spring locations from the National Hydrography Dataset (NHD), springs indicated in the SWRCB's Information Order, springs identified during field reconnaissance and from landowner information, and springs mapped by Pepperwood staff on the Pepperwood Preserve. We also compiled the locations of all flowing tributaries from the August 2018 survey. These data represent all known locations of springs (a groundwater discharge output in the model), but is not a complete inventory of springs and is biased towards showing more springs in locations where detailed spring mapping has been completed such as along main-stem Mark West Creek
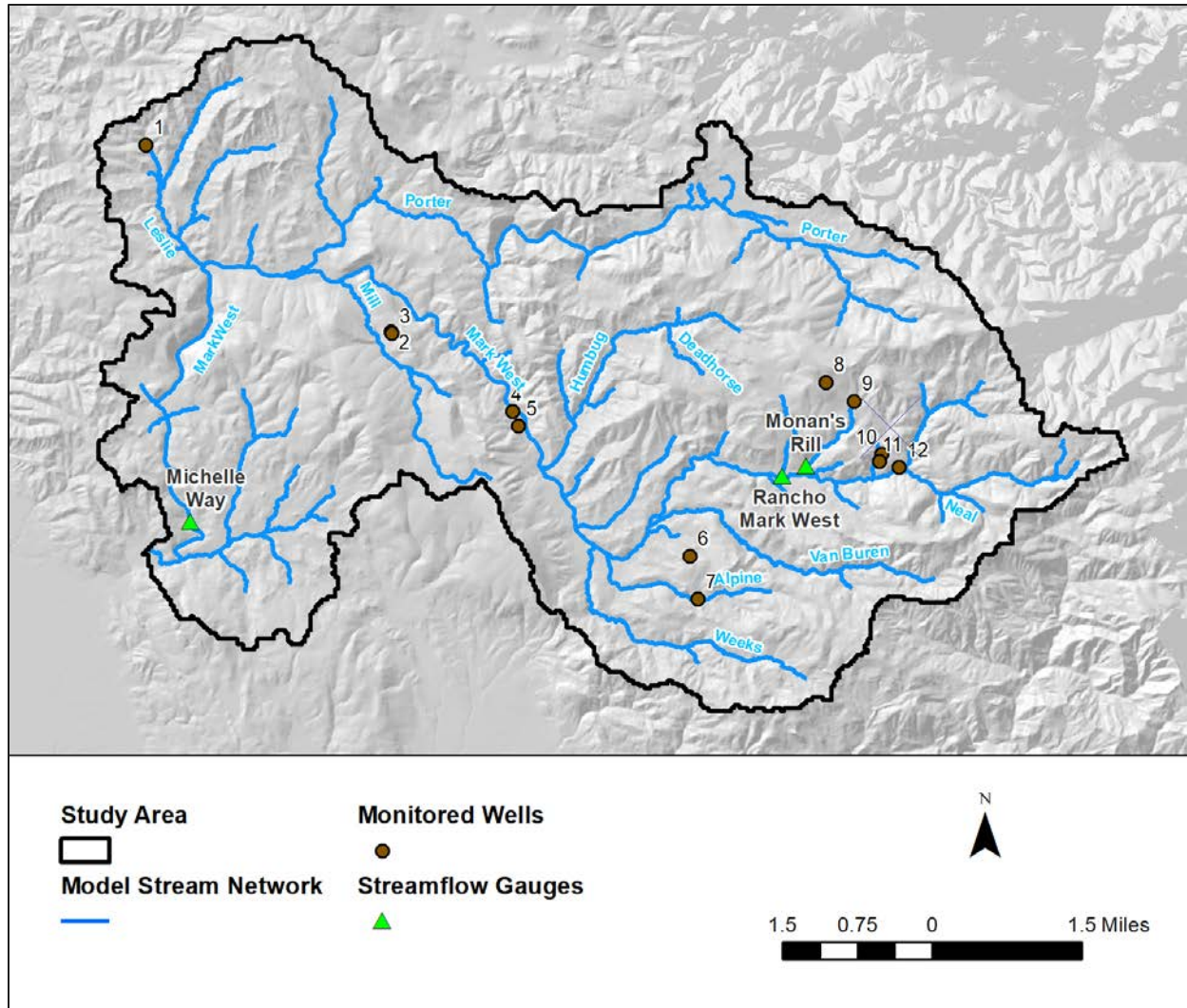
Figure 29: Locations of streamflow gauges and groundwater wells used for calibration of the MWC hydrologic model.

and at the Pepperwood Preserve. Wet/dry mapping data is available for 2012 – 2018 and we focused on the years with the most complete spatial coverage, 2015 – 2018. For purposes of this comparison we considered flows less than 0.01 cfs as equivalent to a field condition of dry and flows less than 0.10 cfs as equivalent to a field condition of intermittent.

Except for a few wells at the Pepperwood Preserve and Monan's Rill, almost no existing groundwater monitoring data was available for the watershed. To develop some field-based understanding of groundwater conditions in the watershed, we established a network of landowners willing to participate in a groundwater monitoring program and collected groundwater elevation data at 16 wells at approximately 5-week intervals between May 2018 and June 2019. Wells are completed in both of the major geologic formations in the watershed, the Franciscan Complex and the Sonoma Volcanics, and they are concentrated in the upper

watershed where landowner interest in participation was high. Well casing heights were measured and data was collected relative to top of casing using an electronic sounding tape.

Many of these wells are domestic water supply wells and thus measurements could potentially be influenced by drawdown associated with recent pumping. To minimize such effects, we established a regular monitoring and notification schedule and residents voluntarily abstained from pumping for 24-hrs prior to measurements. The data for four of the wells was not useful for calibration owing to a variety of factors including obvious pumping influences, one seasonally dry hole, and one well located just outside the watershed. Of the remaining 12 wells (Figure 29), we were unable to locate a Well Completion Report for three; given the lack of screened interval information for these wells, we prepared comparisons between simulated and observed water levels but excluded them from the calibration statistics owing to the uncertainty about which model layer is represented by the observations. Seven of the nine monitoring wells used for model calibration are completed in the Sonoma Volcanics and the other two (Wells 4 & 5) are completed in the Franciscan Complex. Three of the wells are screened entirely within Layers 1 & 2 (upper 200-ft), seven are screened entirely within Layers 1-3, and two are completed entirely in Layers 1-4.

Streamflow Calibration

Four goodness-of-fit statistics were used to evaluate the agreement between model simulated stream discharges and measured stream discharges. These statistics included the Mean Error (ME), Root Mean Square Error (RMSE), the total Percent Volume Error (PVE), and the Nash-Sutcliffe model efficiency coefficient (NSME) (Nash and Sutcliffe, 1970). ME, RMSE, and PVE provide an overall measure of the model bias and have been calculated separately at all three gauges for the full period of record and for the low flow season from May through September. The NSME provides an overall measure of the predictive capability of the model. A NSME value of zero indicates that model predictions are as accurate as the mean of the measured data and a value of one indicates a perfect calibration. The PVE and NSME have only been calculated for the full period of record since it they are not well-suited for describing data with limited temporal variability such as spring/summer baseflow recessions. To avoid the May through September statistics being dominated by a handful of days with storm runoff, we defined an upper threshold below which to calculate statistics more representative of the model's ability to predict flow recession and baseflow. The thresholds were 0.4 cfs, 2 cfs, and 5 cfs at the Monan's Rill, Rancho Mark West, and Michelle Way gauges, respectively.

Due to the limited period of record it was deemed appropriate to calibrate the model to all of the available data rather than divide the simulation into calibration and validation periods as is more typically done when long-term gauging data is available. Figures 30 through 32 show the comparison between model-simulated and measured discharges at the three gauging sites for the full periods of record, and Figures 33 through 35 show the comparison between model simulated and measured discharges at the three sites for just the May through September low flow season that is most critical from the perspective of salmonid habitat.

The agreement between simulated and measured stream flows was generally good at all three of the gauging locations. The model reproduces the quick flow responses in stream flow during runoff events that is characteristic of the watershed and the overall shape of rising and receding flows. Peak flows are captured reasonably well; however, large differences in peak flows do occur for certain events particularly in the older portion of the record at the Rancho Mark West station. RMSE values for the full periods of record were 13.6 and 68 cfs and NSME were 0.79 and 0.90 at the Rancho Mark West and Michelle Way gauges respectively (Table 10). The total percent volume error was -5.2% at Rancho Mark West and 8.4% at Michelle Way (Table 10). We established targets for successful calibration as a NSME value of 0.60 or greater and a PVE of +/- 10% which are met at both stations.

During low flow periods most critical for understanding coho habitat, the model performance is also generally very good. The shape of the spring flow recessions is well captured but the timing of the flow recession in the upper watershed is delayed in the model by one to two weeks relative to the observed data resulting in over-predicted flows during the May/June timeframe. The flow recession timing matches the observed timing more closely in the lower watershed. Magnitudes of summer baseflow are in reasonably good agreement, but there is a tendency to over-predict late summer flow, particularly in the lower watershed. RMSE values for the May through September low flow period ranged from 0.10 cfs at the Monan's Rill gauge to 0.83 cfs at the Michelle Way gauge (Table 10).

The map of observed springs and flowing tributaries was compared to a map of spring locations and flowing tributary streams as simulated in the model for August 2018 (Figure 36). The model correctly predicts the August 2018 flow condition in all 14 tributaries in the study area greater than 0.3 mi^2 as well as in 7 of the 11 smaller tributaries (Figure 36). The spring location comparison also indicates generally good agreement with a high concentration of springs in the upper watershed in both the observed and simulated maps. The model does not show as many springs in the central reach of Mark West Creek between Porter and Humbug creeks or on the Pepperwood Preserve property as is indicated by the field data. Concentrations of springs in upper Porter, upper Humbug, and lower Mark West Creeks not shown in the observed data likely reflect lack of mapping in those areas rather than lack of springs (Figure 36). Overall, the model appears to reproduce the general locations of groundwater discharge and perennial streamflow in Mark West Creek with reasonable accuracy.

Comparison between wet/dry mapping data collected by CA Sea Grant and Sonoma Water in August and September of 2015 through 2018 and a model simulated wet/dry classification for equivalent dates indicates that both the model and the field data show flow persisting in the majority of main-stem Mark West Creek even during dry years such as 2015 (Figure 37 - Figure 40). Both the model and the field data show dry/intermittent conditions beginning at about the same location in the upper watershed as well as dry/intermittent conditions occurring upstream of the Porter Creek confluence in some water years, however the field data indicates the reach with dry/intermittent flow conditions extends upstream of Porter considerably farther than was captured in the model (Figure 37 - Figure 40).

Table 10: Streamflow calibration statistics for the MWC hydrologic model.

Period	Gauge	Drainage Area (mi^2)	# of Daily Observations	ME (cfs)	RMSE (cfs)	PVE (%)	NSME
Full Record	Rancho Mark West	4.6	2,202	-0.4	13.6	8.4%	0.79
	Michelle Way	35.8	581	-2.6	68.0	-5.2%	0.90
	Monan's Rill	0.5	298	0.02	0.10	-	-
May - Sept	Rancho Mark West	4.6	1,017	0.15	0.28	-	-
	Michelle Way	35.8	290	0.32	0.83	-	-
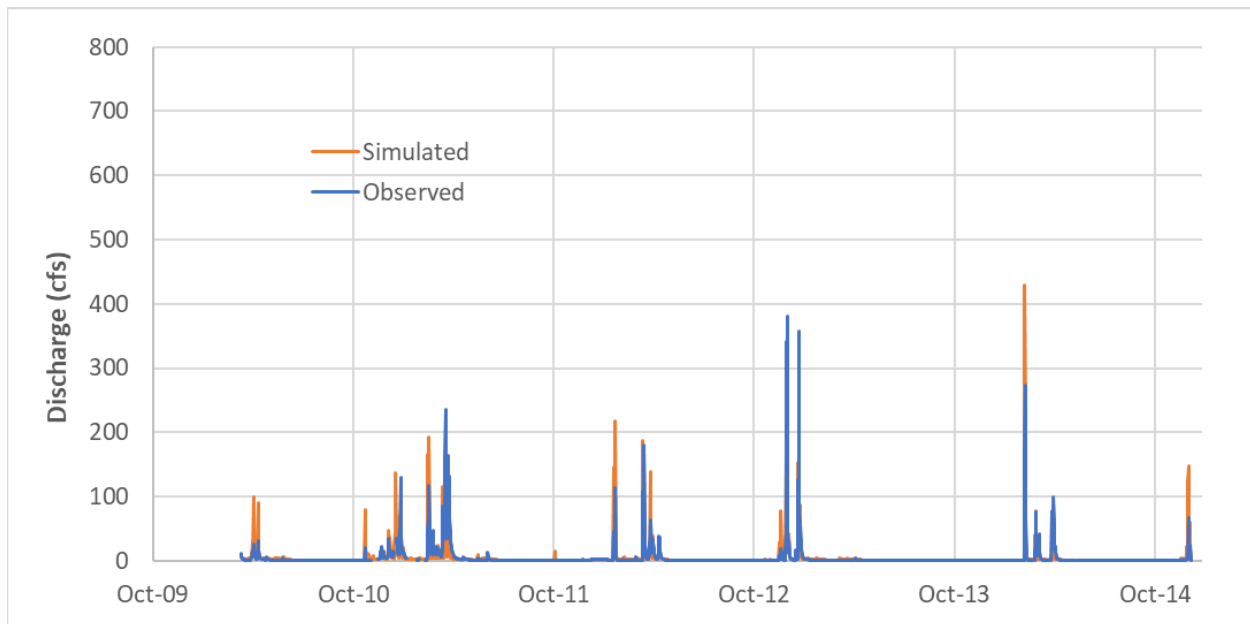
Figure 30: Comparison between model simulated and observed streamflow for the 2010 – 2014 period of record at the Mark West Creek at Rancho Mark West gauge.
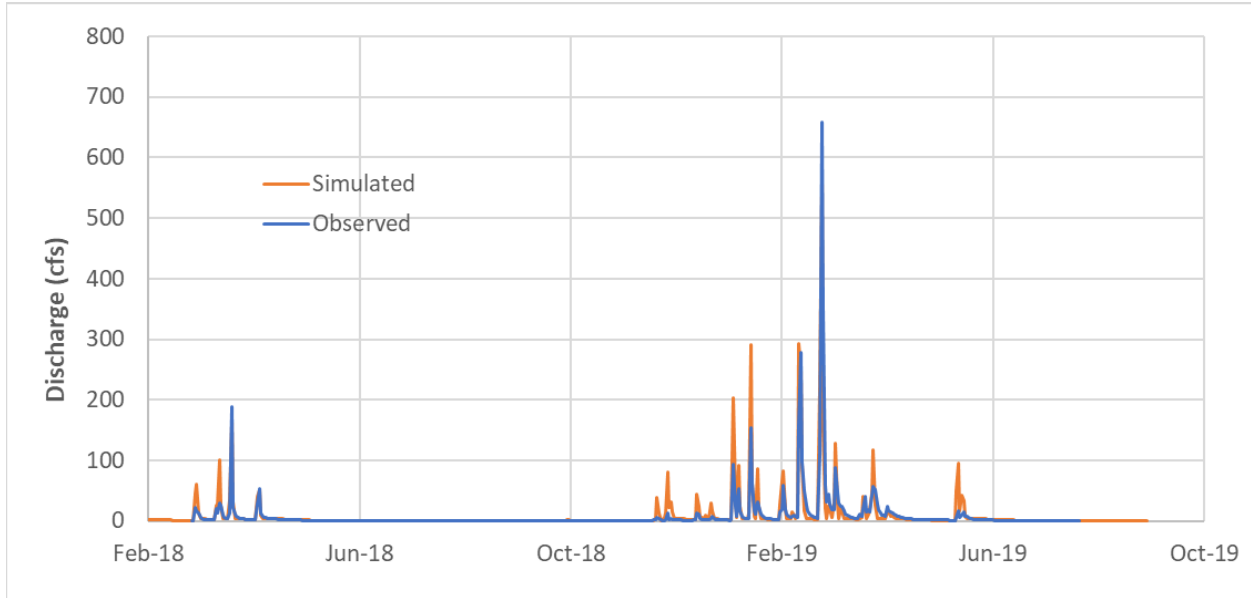
Figure 31: Comparison between model simulated and observed streamflow for the 2018 – 2019 period of record at the Mark West Creek at Rancho Mark West gauge.
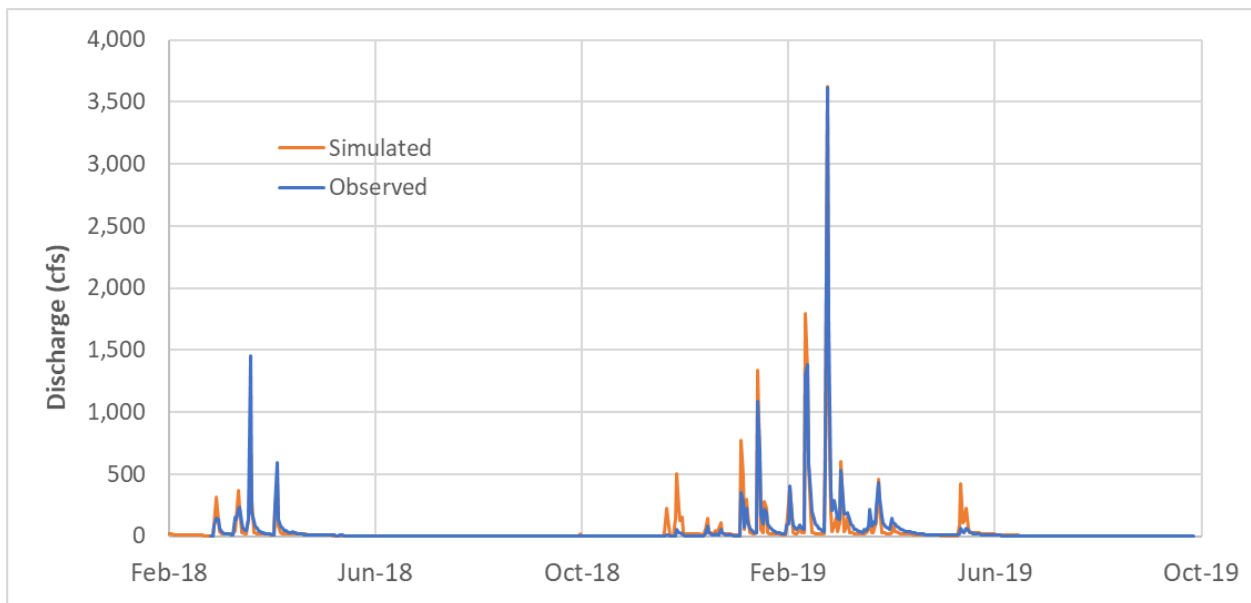
Figure 32: Comparison between model simulated and observed streamflow for the 2018 – 2019 period of record at the Mark West Creek at Michelle Way gauge.
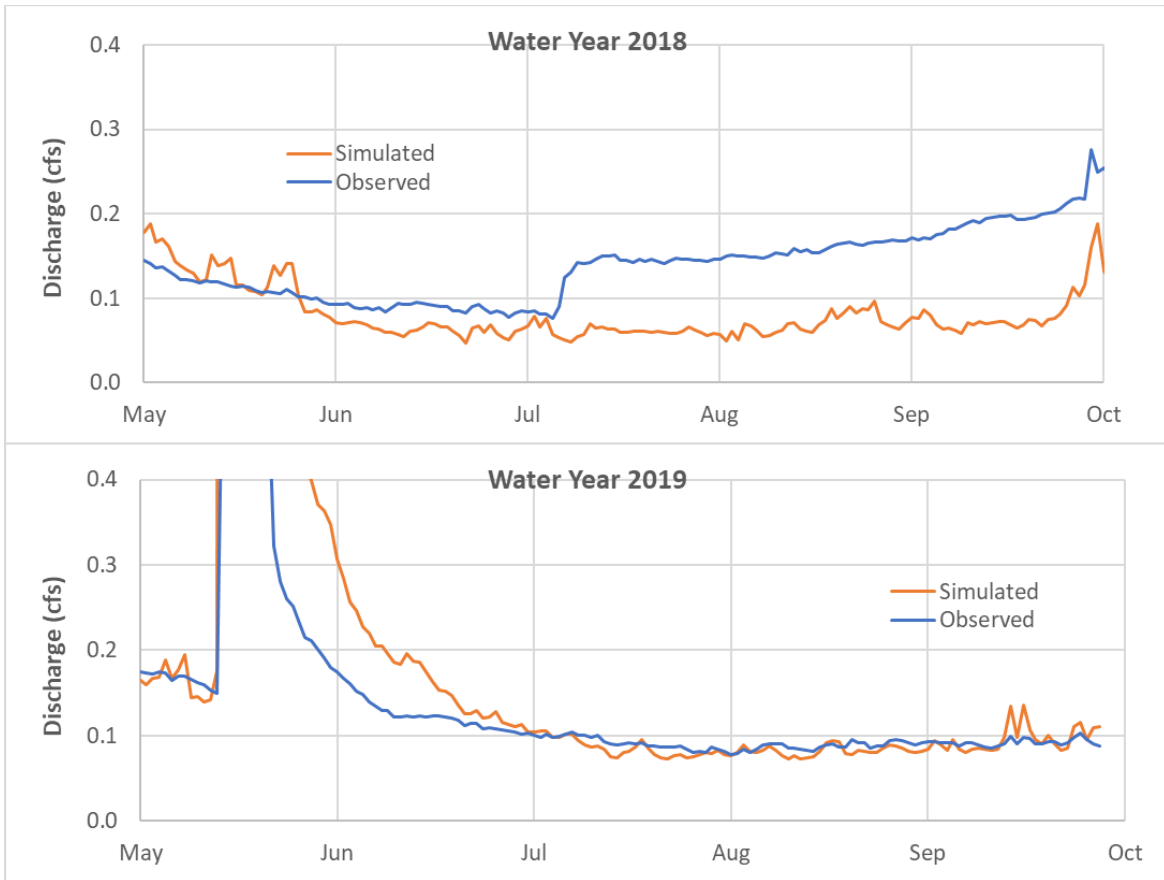
Figure 33: Comparison between model simulated and observed streamflow for the 2018 – 2019 May through September low flow period at the Monan's Rill gauge.
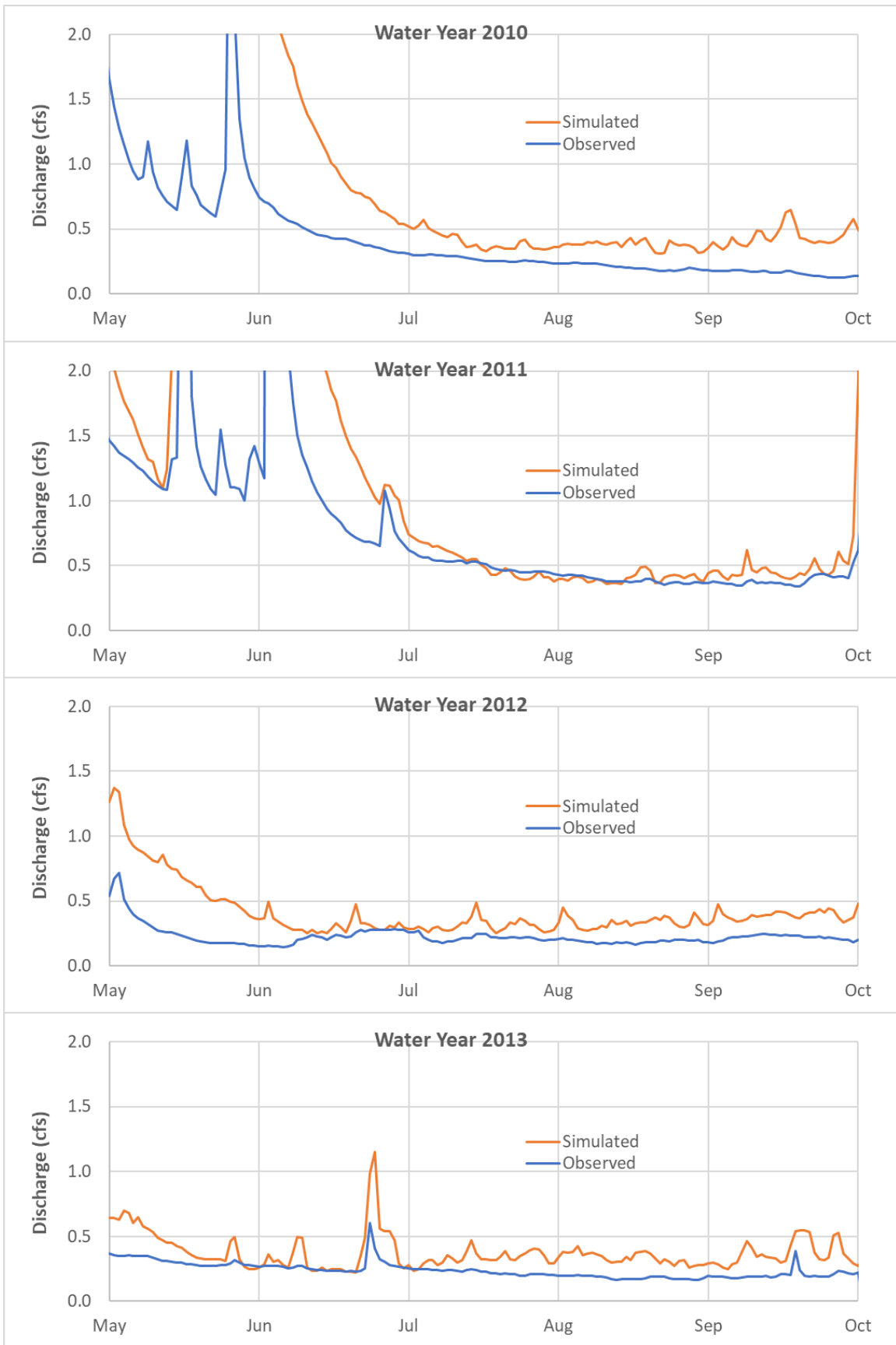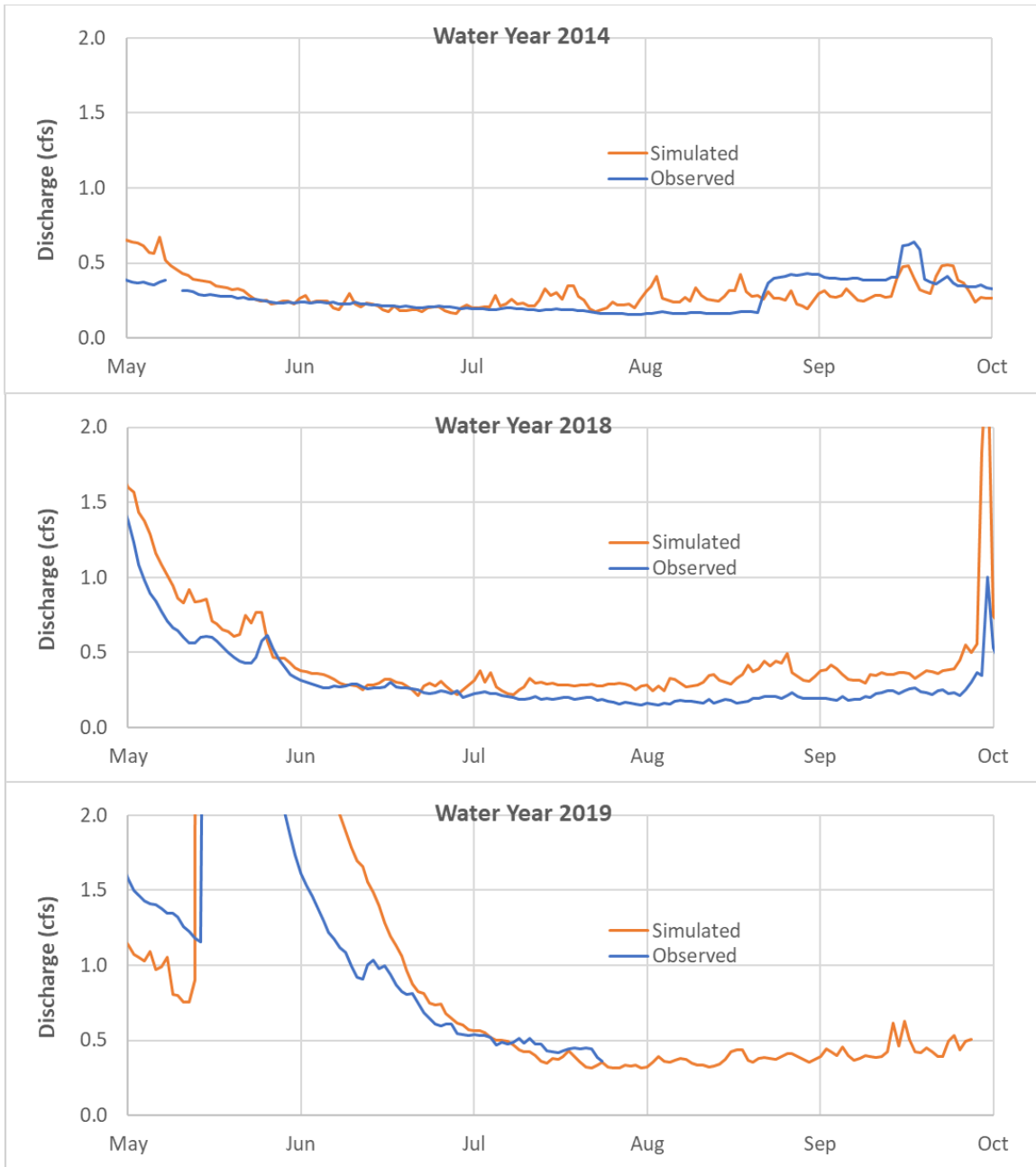
Figure 34: Comparison between model simulated and observed streamflow for the 2010 – 2014 and 2018 – 2019 May through September low flow period at the Mark West Creek at Rancho Mark West gauge.
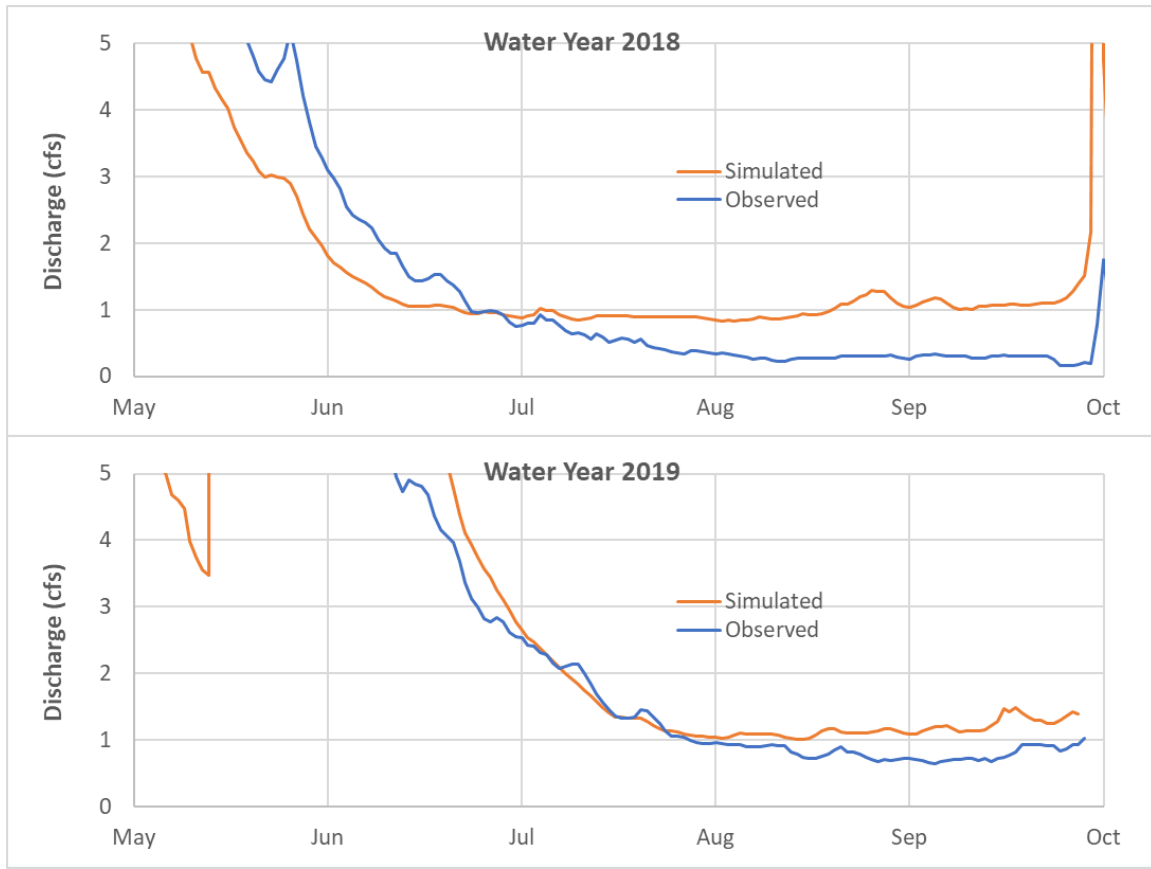
Figure 35: Comparison between model simulated and observed streamflow for the 2018 – 2019 May through September low flow period at the Mark West Creek at Michelle Way gauge.
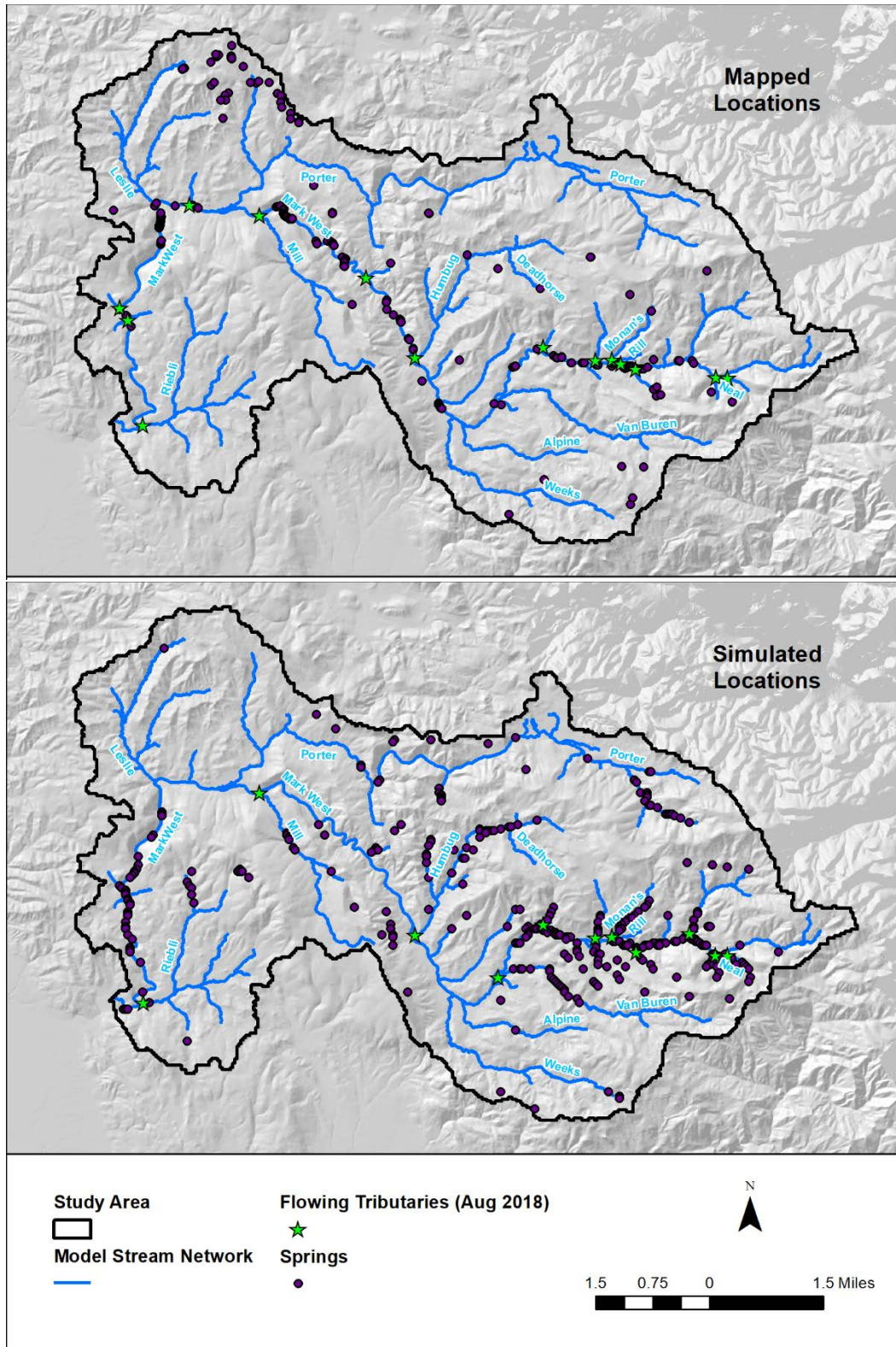
Figure 36: Comparison between known spring locations and locations of perennial springs as simulated in the MWC hydrologic model.
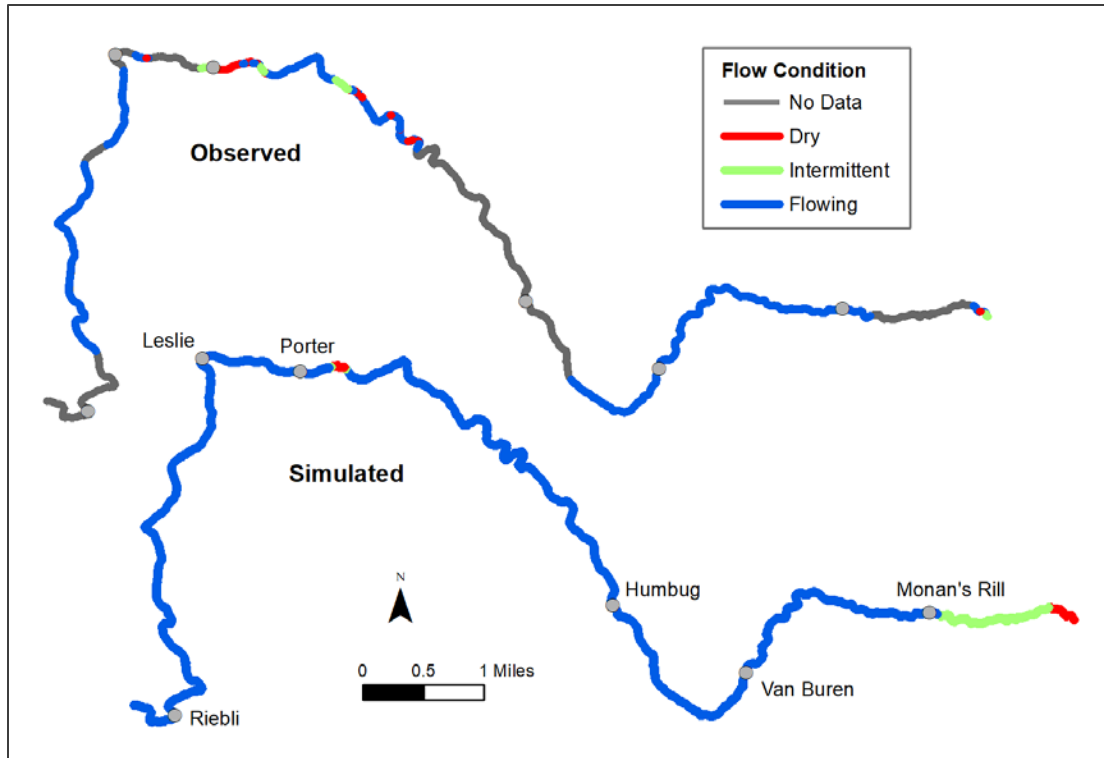
Figure 37: Comparison between observed and simulated late summer flow condition for 2015.
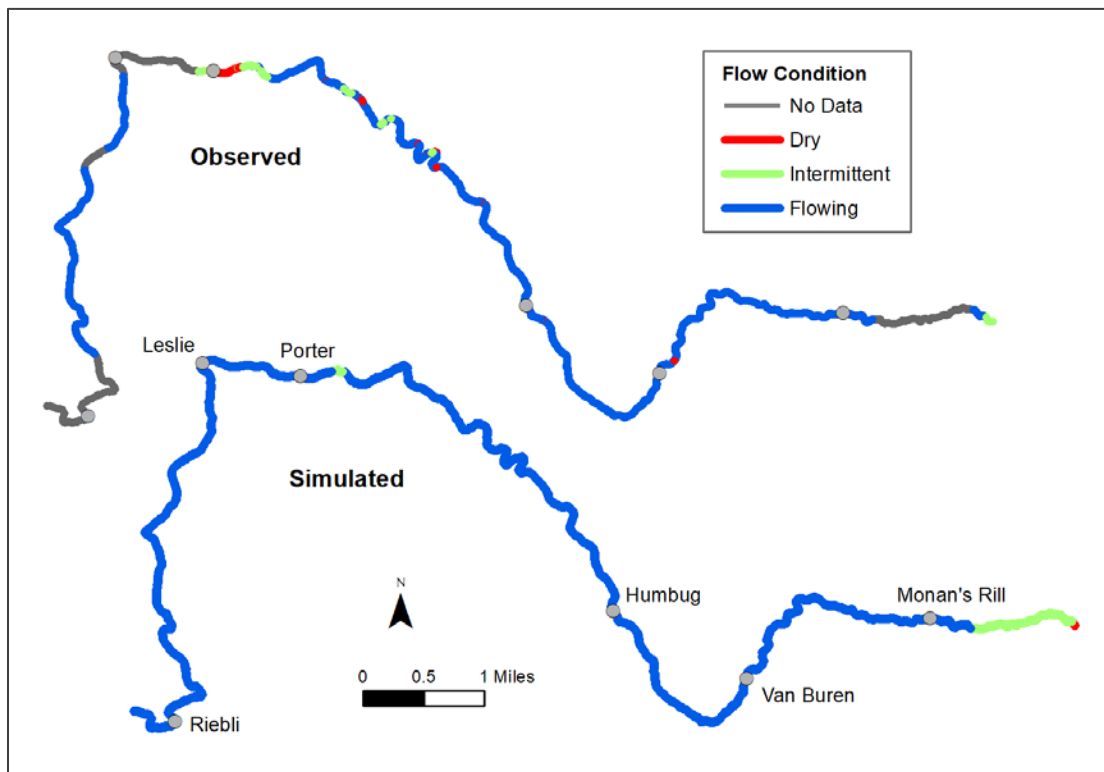
Figure 38: Comparison between observed and simulated late summer flow condition for 2016.
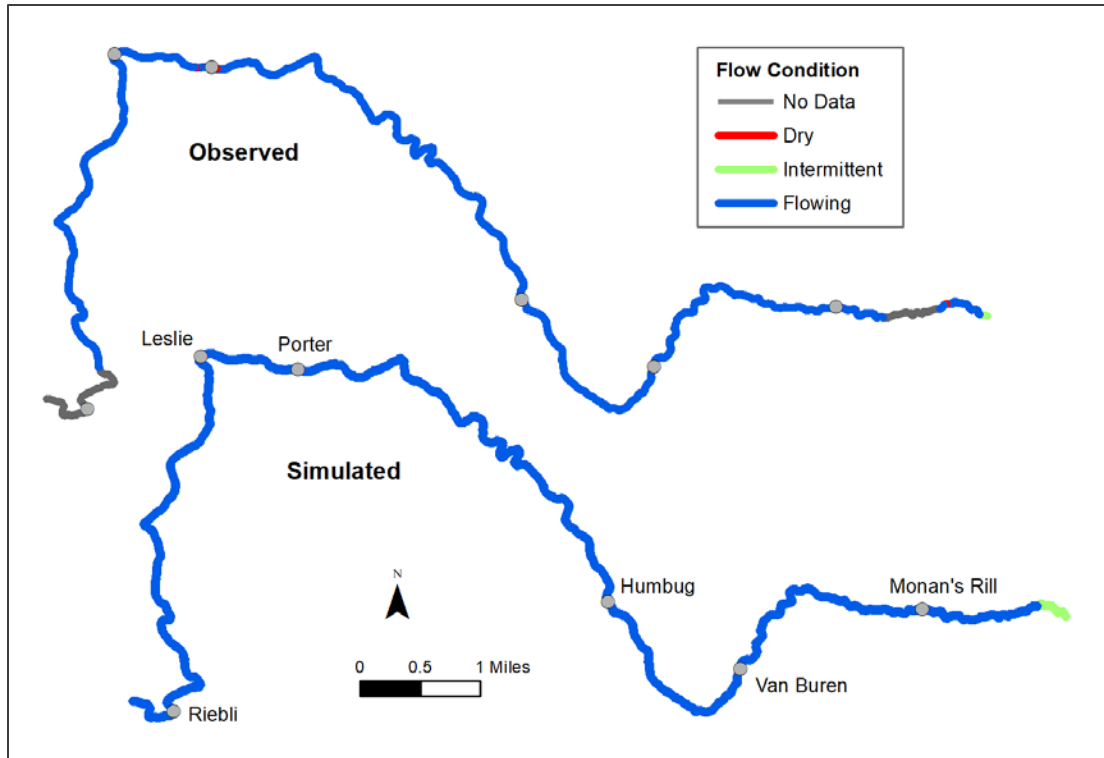
Figure 39: Comparison between observed and simulated late summer flow condition for 2017.
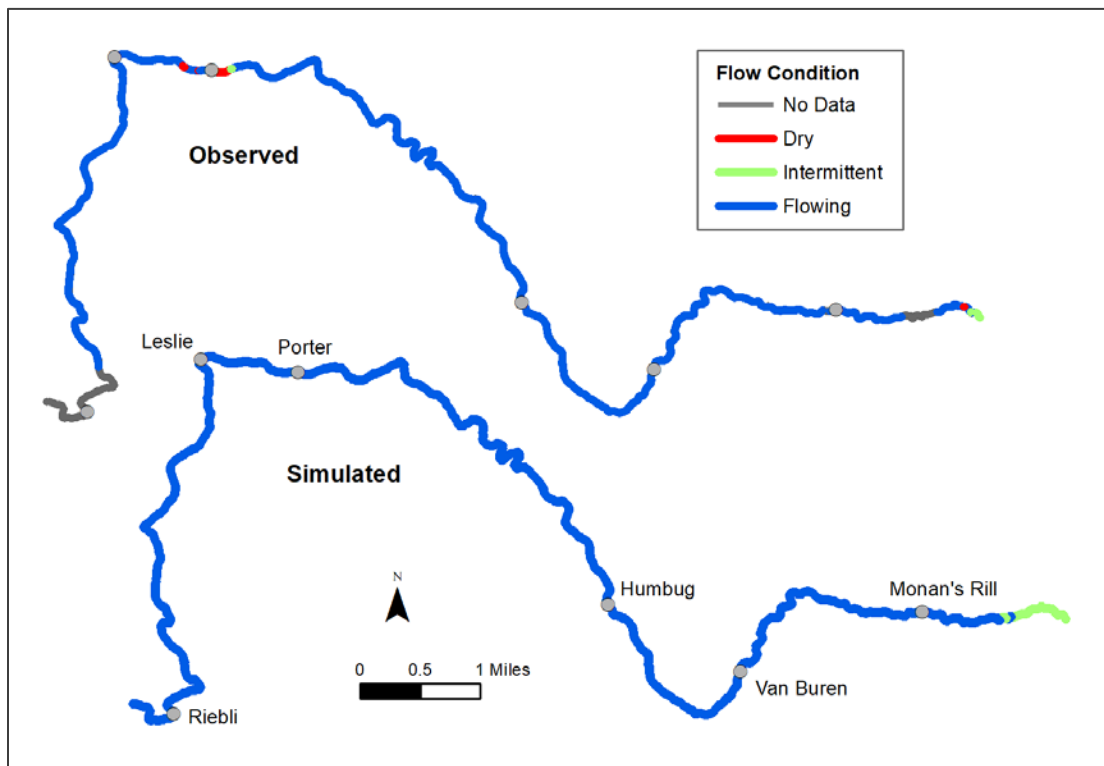
Figure 40: Comparison between observed and simulated late summer flow condition for 2018.

Groundwater Calibration

In order to evaluate the agreement between model simulated groundwater elevations and measured groundwater elevations, Mean Error (ME) and Root Mean Square Error (RMSE) were calculated for the residuals (difference between simulated and observed groundwater elevations) at each of the nine monitoring wells. Due to the limited periods of record at the available monitoring locations it was deemed appropriate to calibrate the model to all of the available data rather than divide the simulation into calibration and validation periods as is more typically done when long-term monitoring data is available. The composite comparison of simulated and measured groundwater elevations is shown in Figure 41. Figure 42 shows the comparison between model-simulated and measured groundwater elevations for each of the seven monitoring wells with available data and calibration statistics are presented in Table 11.

Overall, the observed groundwater elevations are reasonably well-predicted by the model. MEs range from –11.3 to 15.4-ft with an average error of 5.2-ft (Table 11). RMSEs range from 1.1 to 18.6-ft with an average of 9.9-ft. Small seasonal fluctuations occur in all of the wells with maximum elevations generally occurring in March or April and minimum elevations occurring in October or November presumably in response to seasonal recharge patterns. Four of the nine wells (all in the Sonoma Volcanics) show very steady elevations throughout the monitoring period (<3.5-ft annual fluctuation), four show modest fluctuations between 7 and 13-ft, and one shows significant fluctuation on the order of 35-ft (Figure 42). In most cases, the seasonal fluctuations predicted by the model are less than what was observed, with seasonal fluctuations in the model ranging from 0.2-ft to 13.2-ft. Excluding one well with anomalously high fluctuation, the mean seasonal fluctuation simulated in the model was 3.5-ft compared to 6.3-ft based on monitoring observations.

Although the model was able to reproduce observed groundwater elevations with reasonable accuracy, the available monitoring data is very limited both in spatial and temporal extent. Calibration of the groundwater component of the model was also complicated by the difficulties associated with interpreting the observed data which often represents composite head elevations from multiple screened intervals spanning as much as 250-ft. Additional groundwater monitoring from dedicated monitoring wells screened to target specific geologic layers is recommended to support further calibration/validation of the model results with respect to groundwater.

Table 11: Groundwater calibration results for the MWC hydrologic model (see Figure 29 for locations).

Well ID	# Observations	Layer #	ME	RMSE
3	8	2	0.7	3.0
4	11	1	15.0	15.5
5	12	1	-11.3	11.5
7	5	1	-5.7	5.9
8	11	1	15.4	18.6
9	10	1	11.6	12.1
10	11	1	13.9	14.0
11	10	1	7.7	7.8
12	11	1	-0.7	1.1
Mean			**5.2**	**9.9**
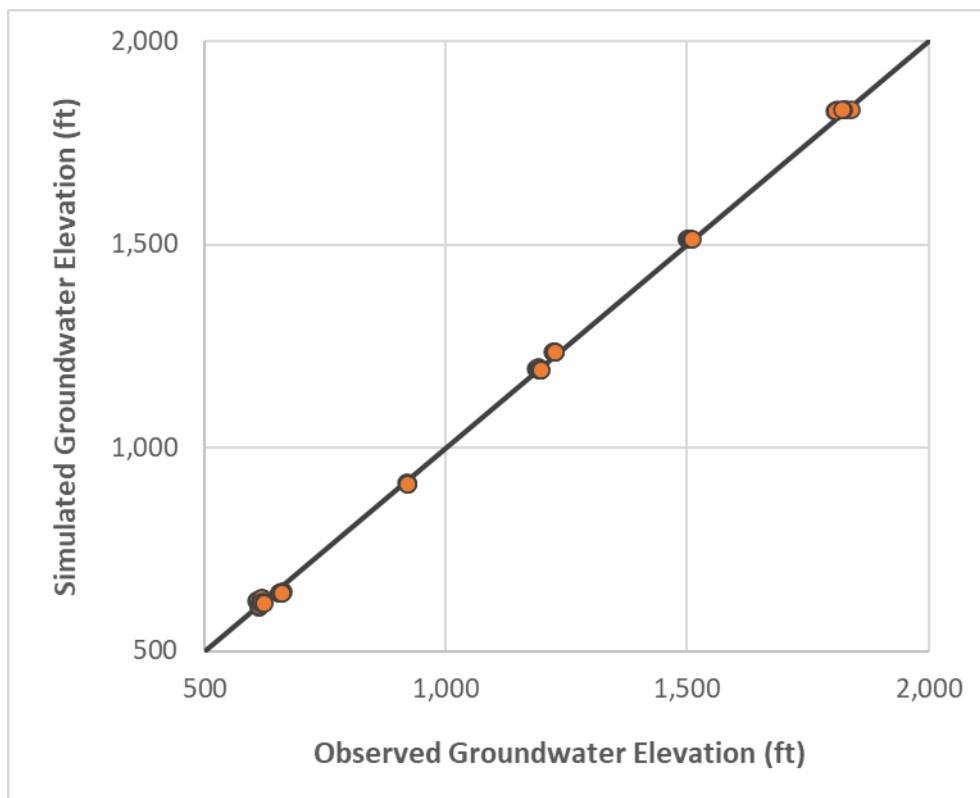
Figure 41: Composite comparison between simulated and observed groundwater elevations (black line shows a 1:1 fit).
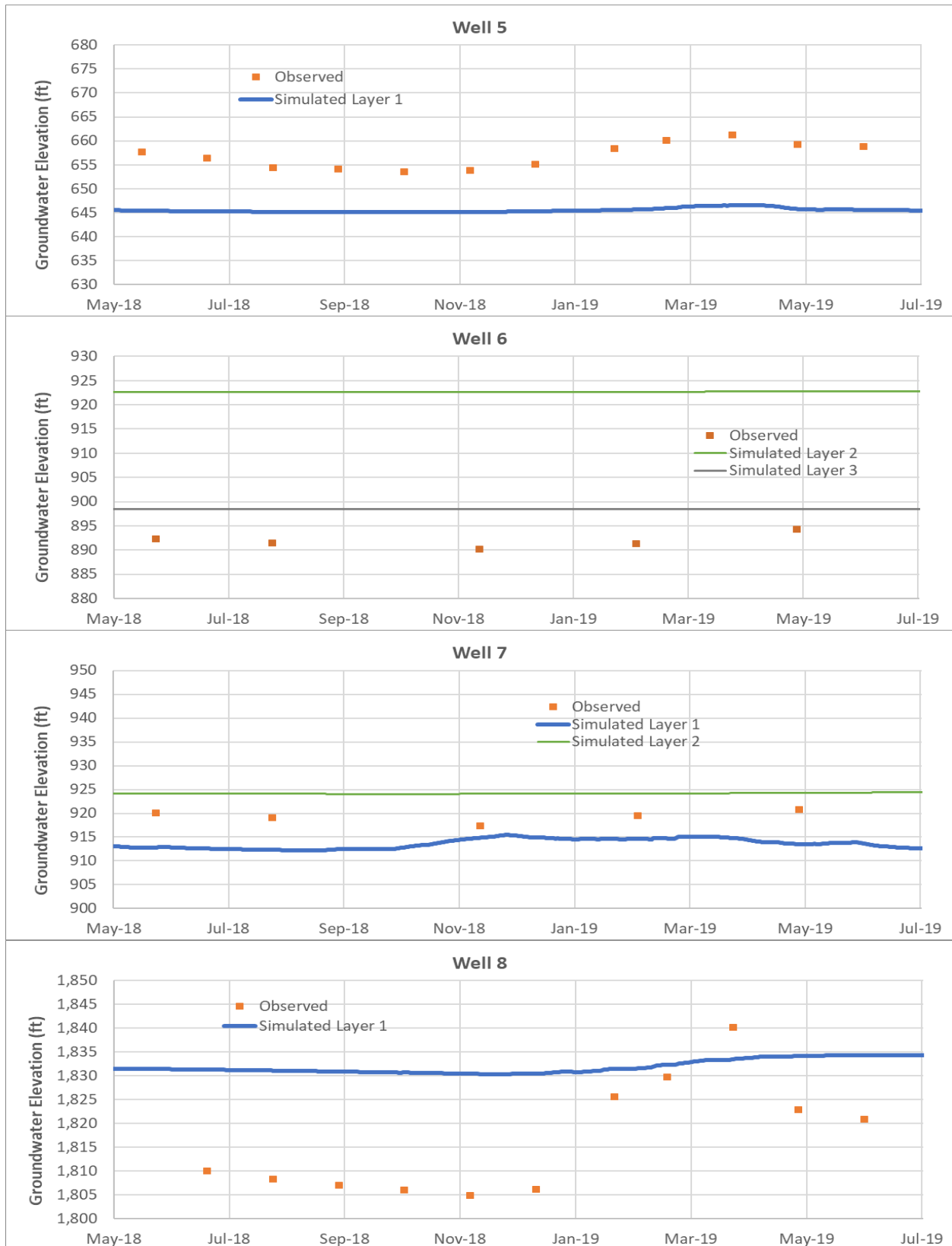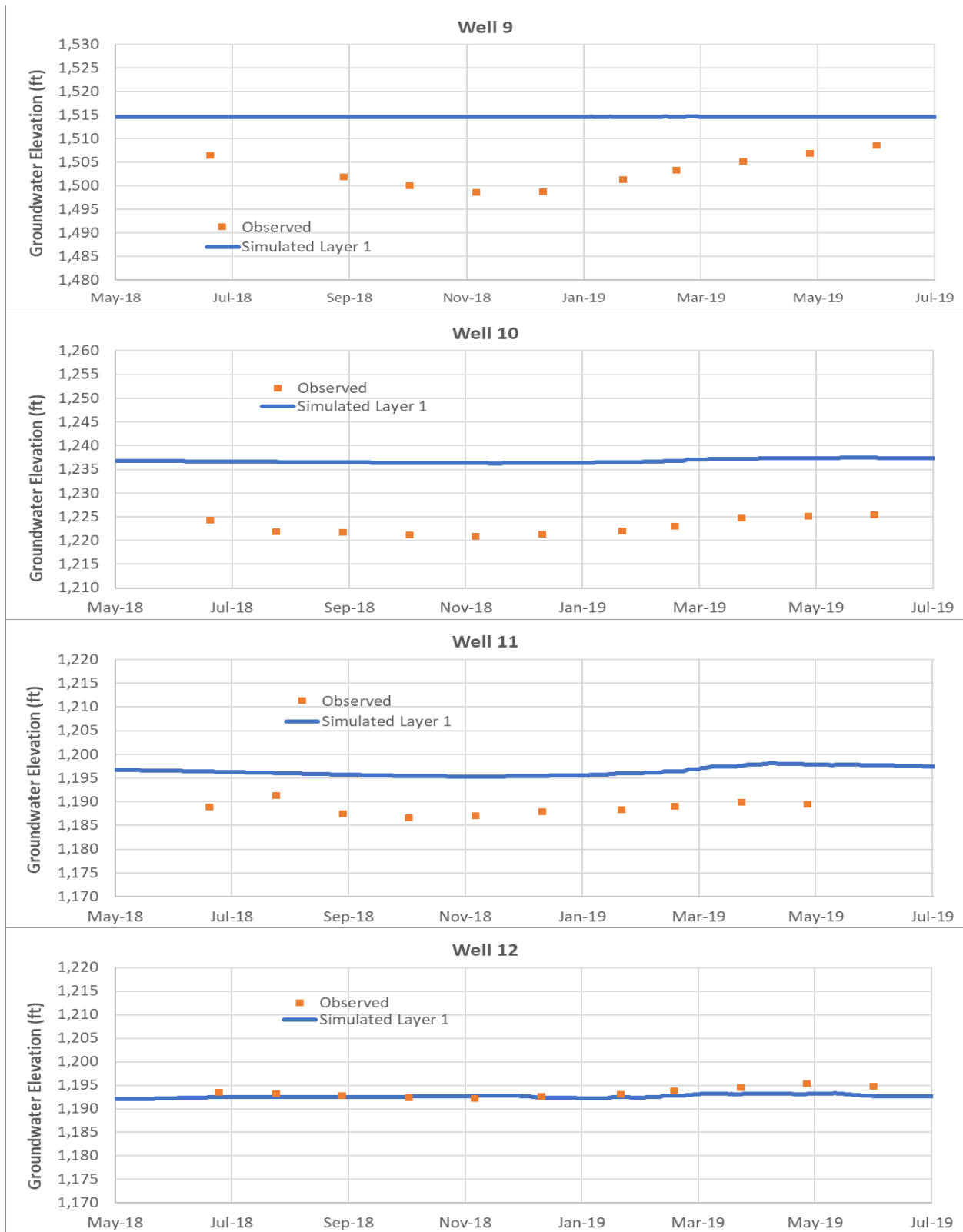
Figure 42: Comparisons between model simulated and observed groundwater elevations (thicker lines indicate simulated data used for calibration).

Chapter 6 – Model Results

Water Balance

A description of the water balance is one of the most fundamental outputs from the model. Water balance information can be extracted for the full study area or for any subarea. A water balance may be highly detailed (e.g. decompose ET into interception, evaporation, transpiration from the unsaturated zone, and transpiration from groundwater) or more general, and can be developed for the watershed as a whole or for a specific component of the hydrologic system such as the saturated zone. A general annual water balance for the whole watershed and a more detailed groundwater water balance have been developed for each of the simulated Water Years of 2010 - 2019. A monthly water budget is also presented for selected water budget terms as are maps depicting the spatial variations of key water budget components.

Watershed Water Balance

The primary inflow to the upper MWC watershed is precipitation, which ranged from 19.5 inches in the dry water year of 2014 to 61.2 inches in the wet water year of 2017 (Table 12). Irrigation is a minor additional source of inflow (0.07 in/yr) and it was uniform between water years owing to the way irrigation demands were estimated. Except for the two wettest years of the simulation (2017 & 2019) when streamflow exceeded Actual Evapotranspiration (AET), AET was the largest outflow from the watershed. Variations in AET were significantly less than variations in precipitation and ranged from 14.1 inches in 2014 to 24.1 inches in 2010 (Table 12). Stream flow was the next largest outflow from the watershed, and it varied substantially and in a similar fashion to precipitation ranging from 8.3 inches in 2014 to 32.8 inches in 2017. Groundwater pumping was approximately two orders of magnitude less than AET or stream flow (0.15 in/yr) and was relatively uniform owing to the way water demands were estimated. The watershed boundaries were represented as no-flow boundaries in all components of the model, therefore there are no external inflow or outflow terms in the water budget. Increases in storage of up to 6.9 inches occurred during the wet water year of 2017 and decreases in storage of up to 3.0 inches occurred during the dry water year of 2014 (Table 12).

Groundwater Water Balance

Infiltration recharge represented the largest source of inflow to the groundwater system in the MWC watershed and varied widely as a function of precipitation from 0.8 inches in 2014 to 10.1 inches in 2017 (Table 13). In contrast, streambed recharge was relatively constant ranging from 0.5 to 1.0 inches. In most water years, infiltration recharge is several times larger than streambed recharge. Under drought conditions such as occurred in 2014, streambed recharge becomes a more significant fraction of the total recharge accounting for about 38% of total recharge. Approximately half of the total recharge leaves the groundwater system quickly as interflow, which is the largest source of groundwater outflow varying from approximately 1.1 to 4.3 inches (Table 13). ET from groundwater was the next largest outflow term and was relatively uniform ranging from 0.8 to 1.1 inches.

Springflow and baseflow are also significant outflow terms. Both represent groundwater discharge in the model with the former representing discharge to the land surface or along

unsaturated stream banks and the later representing discharge through the bed and wetted banks of the stream. Both of these discharge components were relatively uniform with springflow ranging from 0.5 to 1.0 inches and baseflow ranging from 0.5 to 0.9 inches (Table 13). Baseflow and streambed recharge are approximately equal in magnitude, thus the net gain in groundwater discharge through the bed and wetted banks of streams is near zero when averaged across the watershed; this highlights the importance of springflow as the key mechanism for sustaining summer streamflows in the watershed. Groundwater pumping was a relatively small component (~3%) of the total outflow at 0.15 inches, and there are no subsurface inflows or outflows owing to the no-flow boundary assumption used in the model. Storage decreases of up to 2.2 inches occurred in dry years such as 2014 and storage increases of up to 4.7 inches occurred in wet years such as 2017 (Table 13).

Table 12: Annual watershed water budget simulated with the MWC hydrologic model; all units are inches.

	Inflows		Outflows			
Water Year	Precipitation	Irrigation	AET	Streamflow	Groundwater Pumping	Change in Storage
2010	42.51	0.07	24.06	17.14	0.15	1.23
2011	43.97	0.07	23.13	17.92	0.15	2.84
2012	28.07	0.07	20.07	10.67	0.15	-2.76
2013	28.87	0.07	17.58	12.83	0.15	-1.62
2014	19.46	0.07	14.06	8.30	0.15	-2.97
2015	26.57	0.07	14.94	12.74	0.15	-1.19
2016	33.30	0.07	17.30	13.83	0.15	2.09
2017	61.18	0.07	21.47	32.75	0.15	6.88
2018	26.59	0.07	18.93	9.07	0.15	-1.49
2019	49.77	0.07	21.63	23.44	0.15	4.62
Average	**36.03**	**0.07**	**19.32**	**15.87**	**0.15**	**0.76**

Table 13: Annual groundwater water budget simulated with the MWC hydrologic model; all units are inches.

	Inflows		Outflows					
Water Year	Infiltration Recharge	Streambed Recharge	Interflow	Baseflow	Springflow	ET from Groundwater	Groundwater Pumping	Change in Storage
2010	6.05	0.71	4.29	0.76	0.58	0.82	0.15	0.16
2011	7.49	0.70	4.00	0.80	0.62	0.89	0.15	1.73
2012	2.22	0.57	1.72	0.63	0.84	1.08	0.15	-1.63
2013	2.39	0.58	2.19	0.60	0.68	0.98	0.15	-1.62
2014	0.84	0.52	1.09	0.50	0.76	1.06	0.15	-2.19
2015	2.10	0.66	1.53	0.59	0.67	1.02	0.15	-1.20
2016	4.44	0.60	2.55	0.67	0.48	0.75	0.15	0.44
2017	10.12	1.03	3.39	0.86	0.97	1.07	0.15	4.72
2018	2.87	0.53	1.91	0.62	0.72	1.06	0.15	-1.05
2019	8.17	1.03	3.48	0.83	0.99	0.99	0.15	2.76
Average	**4.67**	**0.69**	**2.61**	**0.69**	**0.73**	**0.97**	**0.15**	**0.21**

Spatial and Temporal Variations of Water Budget Components

The monthly water balance results illustrate the strong seasonality of precipitation and streamflow typical of Mediterranean climates (Figure 43). As a result of the seasonal fluctuations in Potential Evapotranspiration and soil moisture availability, AET was generally lowest during the late fall and early winter and highest during the spring, progressively decreasing throughout the summer months as available soil moisture diminished (Figure 43). During average and wet water years, infiltration recharge occurred in most months between November and April, whereas in the drought conditions of 2014, recharge only occurred during the month of February (Figure 43). The number of days with significant (>0.1-in) recharge varied widely between 4 days in 2014 and 34 days in 2017.

Significant variations in infiltration recharge occur across the watershed with much of the watershed generating less than 2 in/yr and portions of the upper watershed generating more than 20 in/yr (Figure 44). Numerous factors affect the recharge rates, however the spatial variations in recharge appear to be primarily controlled by soil properties, topographic position, and the west to east precipitation gradient. Recharge is concentrated in the upper Mark West Creek watershed upstream of and including the Van Buren Creek watershed, as well as in the upper Humbug Creek watershed (Figure 44). Higher recharge rates also occur locally in portions of the central Porter Creek watershed, and the upper Leslie Creek and upper Reibli Creek watersheds, although recharge rates in these watersheds are generally low. Small negative recharge rates (indicative of net groundwater discharge) occur along valley-bottom areas particularly in the lower watershed (Figure 44). As discussed earlier, recharge only occurred during four days during a single month in the drought of 2014, and much of the watershed experienced negative or near-zero recharge (Figure 45).

As discussed earlier, groundwater discharge occurs in the model both as springflow (subaerial discharge) and as baseflow (subaqueous discharge). Across the entire watershed, springflow is responsible for generating most of the summer streamflow given that net groundwater discharge in the spring and summer months is near zero (e.g. streambed recharge ≈ baseflow discharge). Locations of perennial springflow were discussed previously as part of the calibration discussion in Chapter 5 (see Figure 36). The spatial patterns of surface water/groundwater interaction indicate that gaining conditions predominate throughout the spring and summer months in much the upper watershed upstream of Van Buren Creek, as well as in upper Humbug Creek, portions of upper and central Porter Creek, and lower Mark West Creek below Leslie Creek (Figure 46 & Figure 47). During spring, losing conditions occur in Mark West Creek upstream of Porter Creek, and in the lowest portions of many of the tributary watersheds, notably Porter Creek and Weeks Creek (Figure 46). By late summer, most of the losing reaches in the tributary streams become inactive as streamflows drop to zero (Figure 47). The area overlying the deepest alluvial body in the watershed near and upstream of the confluence of Mark West and Porter Creeks is the most active area in terms of surface water/groundwater interaction. Losing conditions persist throughout the summer months in this area, however the effect on streamflow is localized given that most of the flow loss returns to the stream as baseflow where the alluvium pinches out downstream (Figure 47).

AET varies substantially throughout the watershed, and in most locations rates range from about 10 to 30 in/yr. AET as high as 50 in/yr occurs locally along certain stream channels where transpiration of riparian vegetation is not limited by soil moisture availability due to accessibility of shallow groundwater (Figure 48). Spatial variability of AET is primarily a function of variability in available soil moisture and vegetation water requirements, with the two factors being inextricably linked. Climatic water deficit (CWD) is defined as the difference between PET and AET and is a useful metric for describing the seasonal moisture stress. In the 10-yr average condition the annual CWD ranged from 15 to 40 in/yr across most of the watershed, except locally where rates were near zero due to accessibility of shallow groundwater and associated insensitivity to soil moisture availability (Figure 49). Topographic aspect appears to be a primary control on the spatial variability of CWD with north-facing slopes characterized by lower PET having significantly lower CWD values relative to south-facing slopes. During the drought of 2014, CWD values increased substantially to between 30 and 50 in/yr across most of the watershed (Figure 50). The 10-yr mean CWD across the watershed was 26.0 in/yr compared to 32.7 in/yr in 2014.
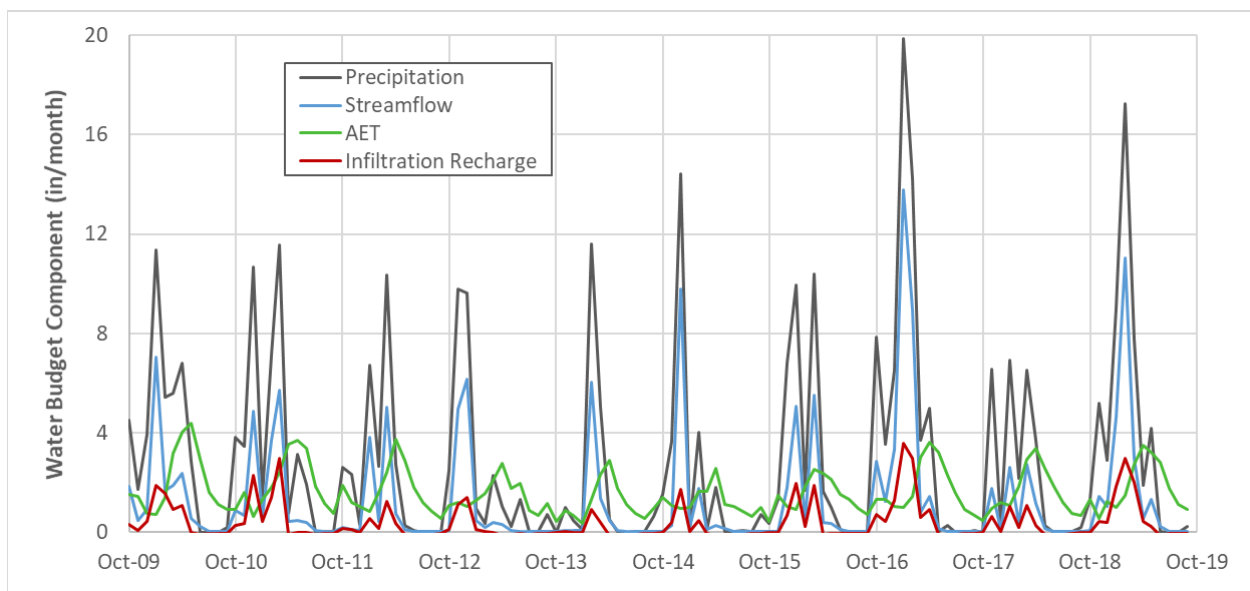
Figure 43: Monthly variation in select water budget components simulated with the MWC hydrologic model.
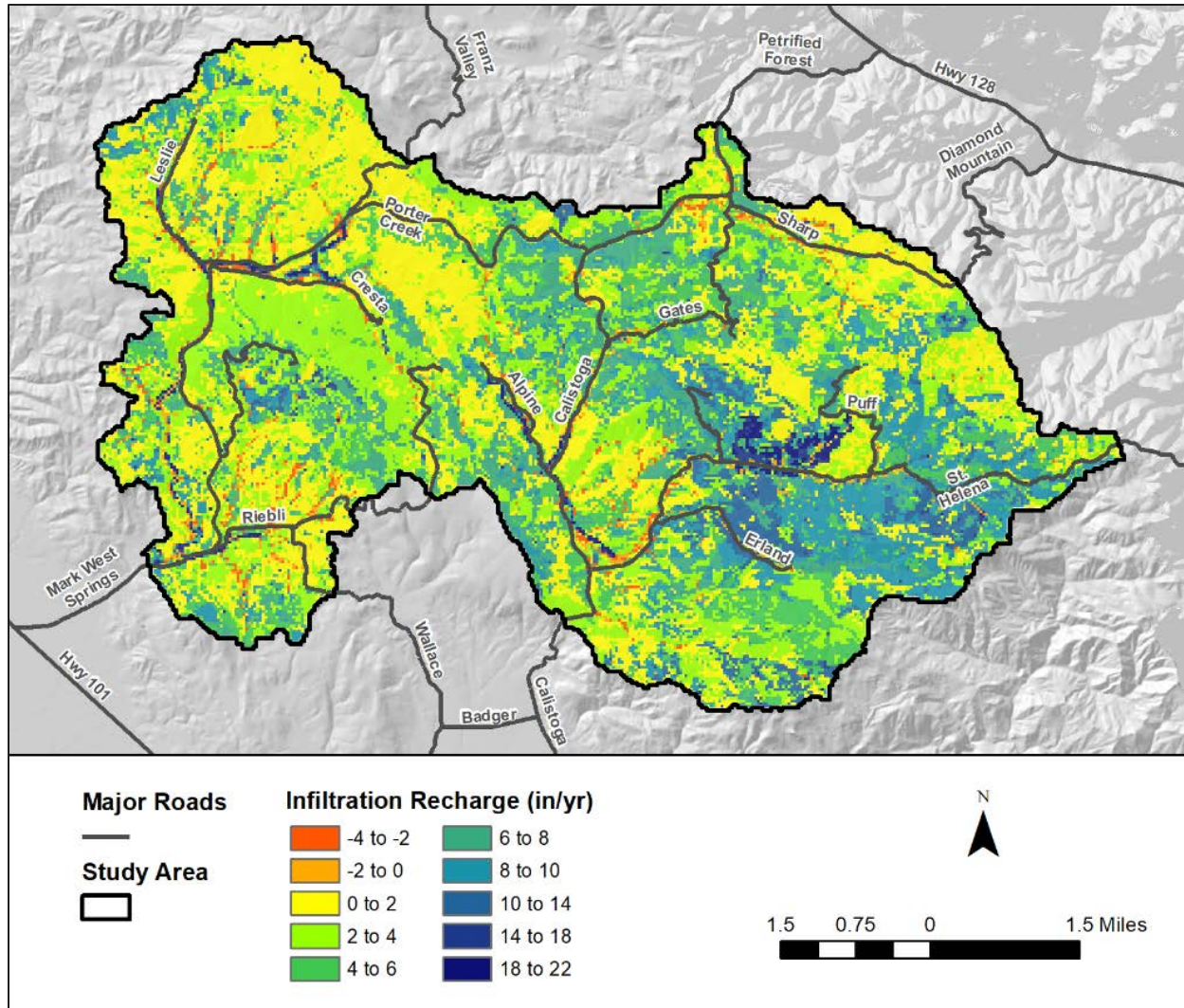
Figure 44: Mean annual infiltration recharge for water years 2010-2019 simulated with the MWC hydrologic model.
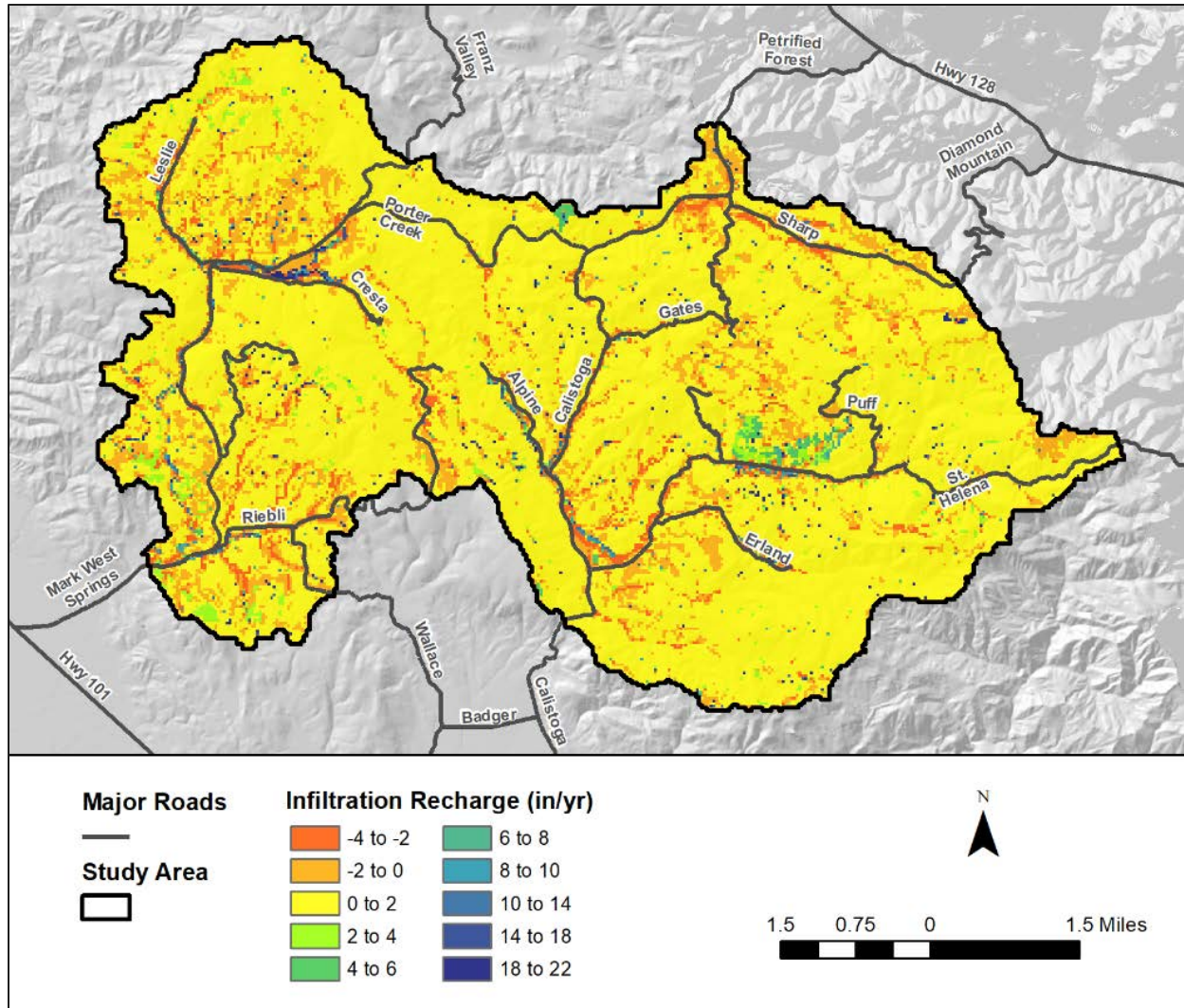
Figure 45: Infiltration recharge for water year 2014 simulated with the MWC hydrologic model.
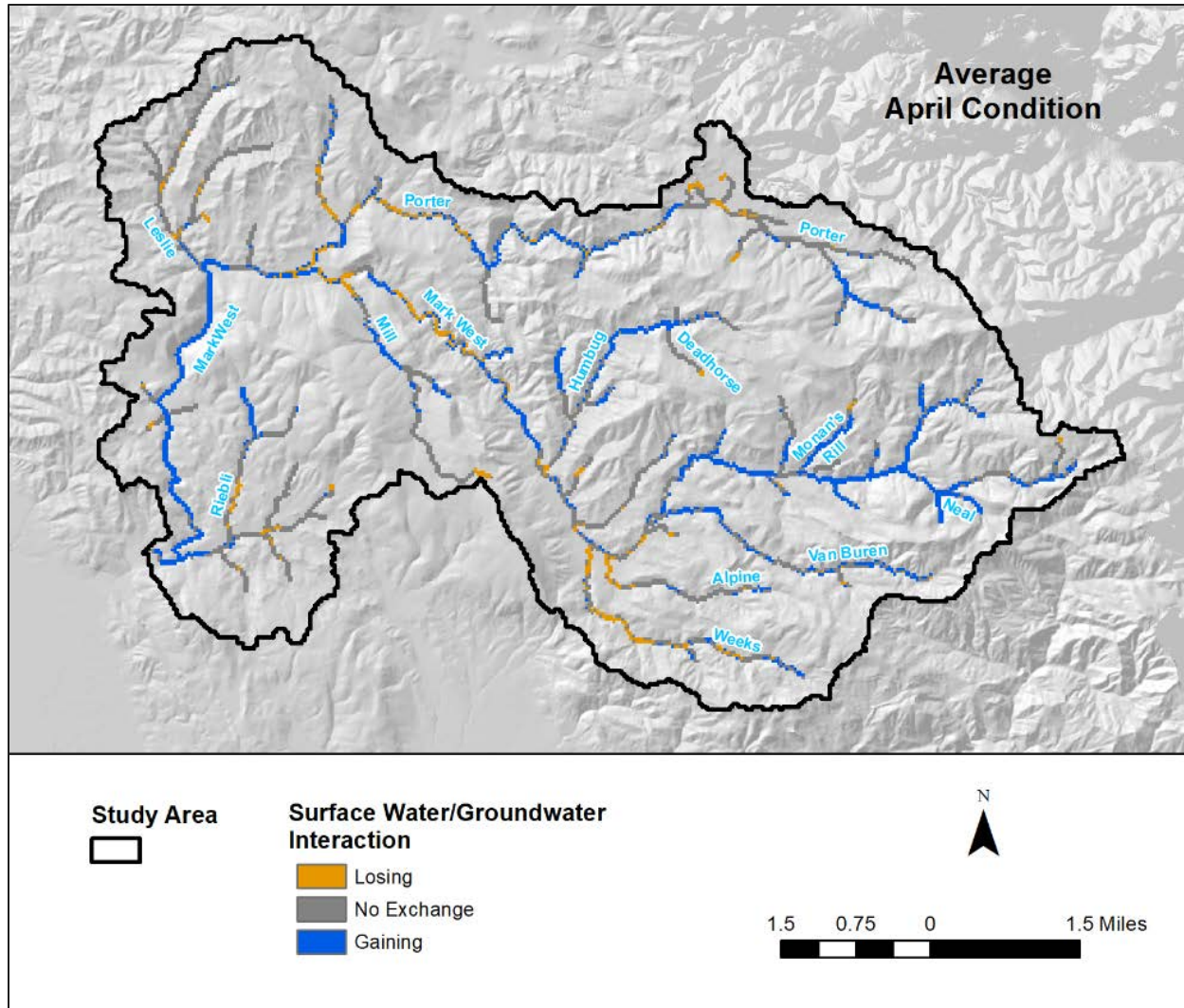
Figure 46: Extent of gaining and losing reaches for the month of April (2010-2019 mean value) as simulated with the MWC hydrologic model.
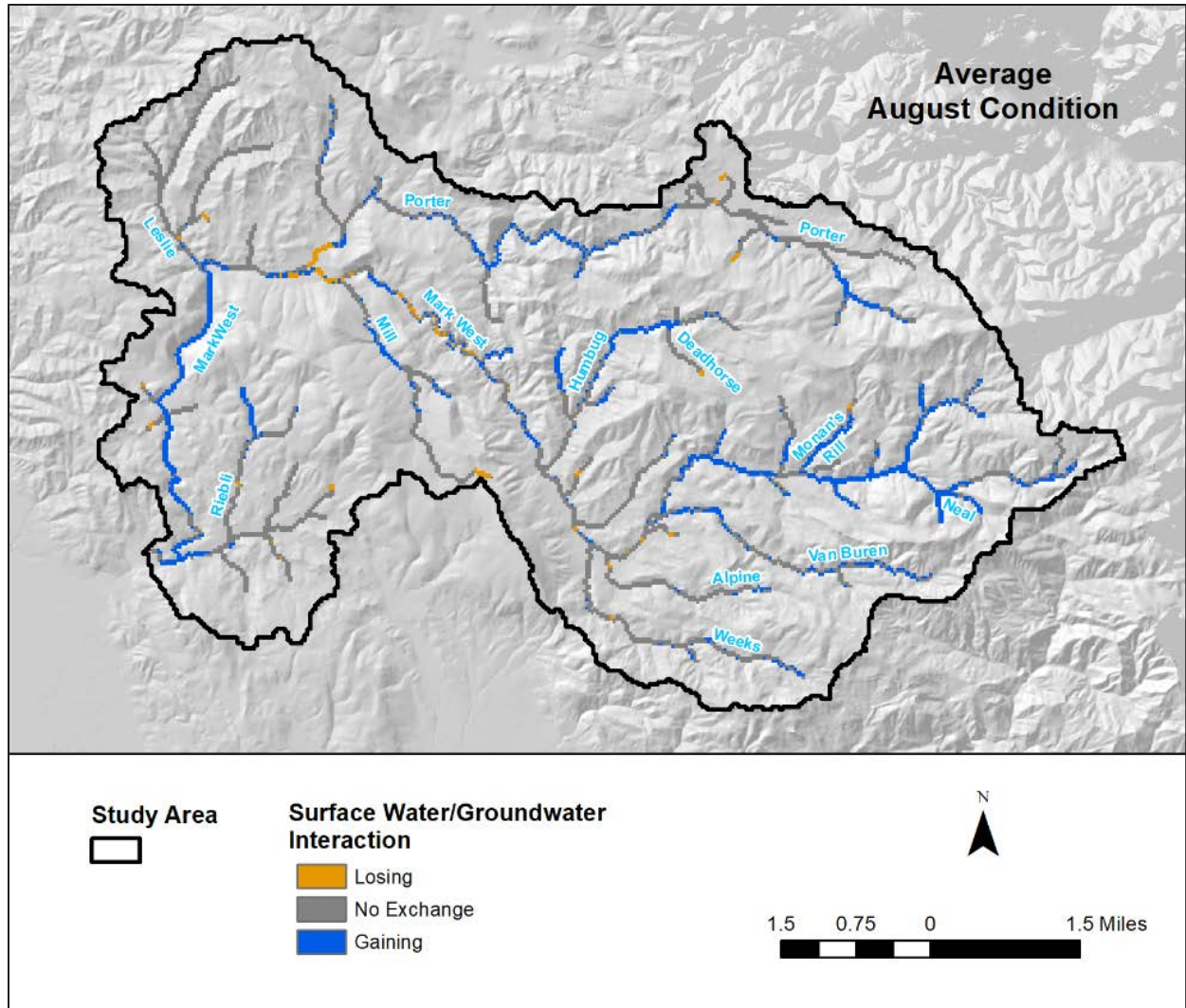
Figure 47: Extent of gaining and losing reaches for the month of August (2010-2019 mean value) as simulated with the MWC hydrologic model.
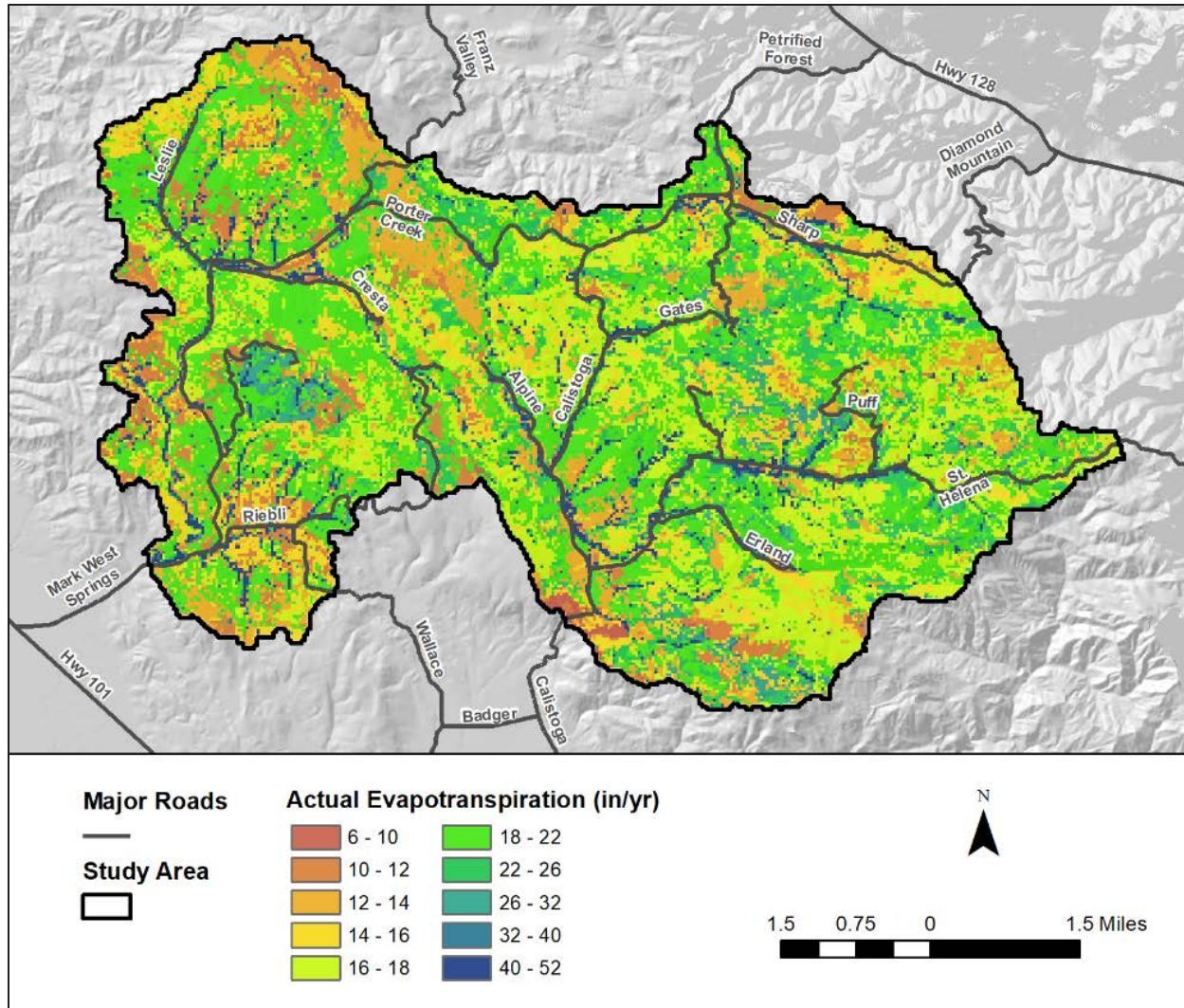
Figure 48: Mean annual Actual Evapotranspiration (AET) for water years 2010-2019 simulated with the MWC hydrologic model.
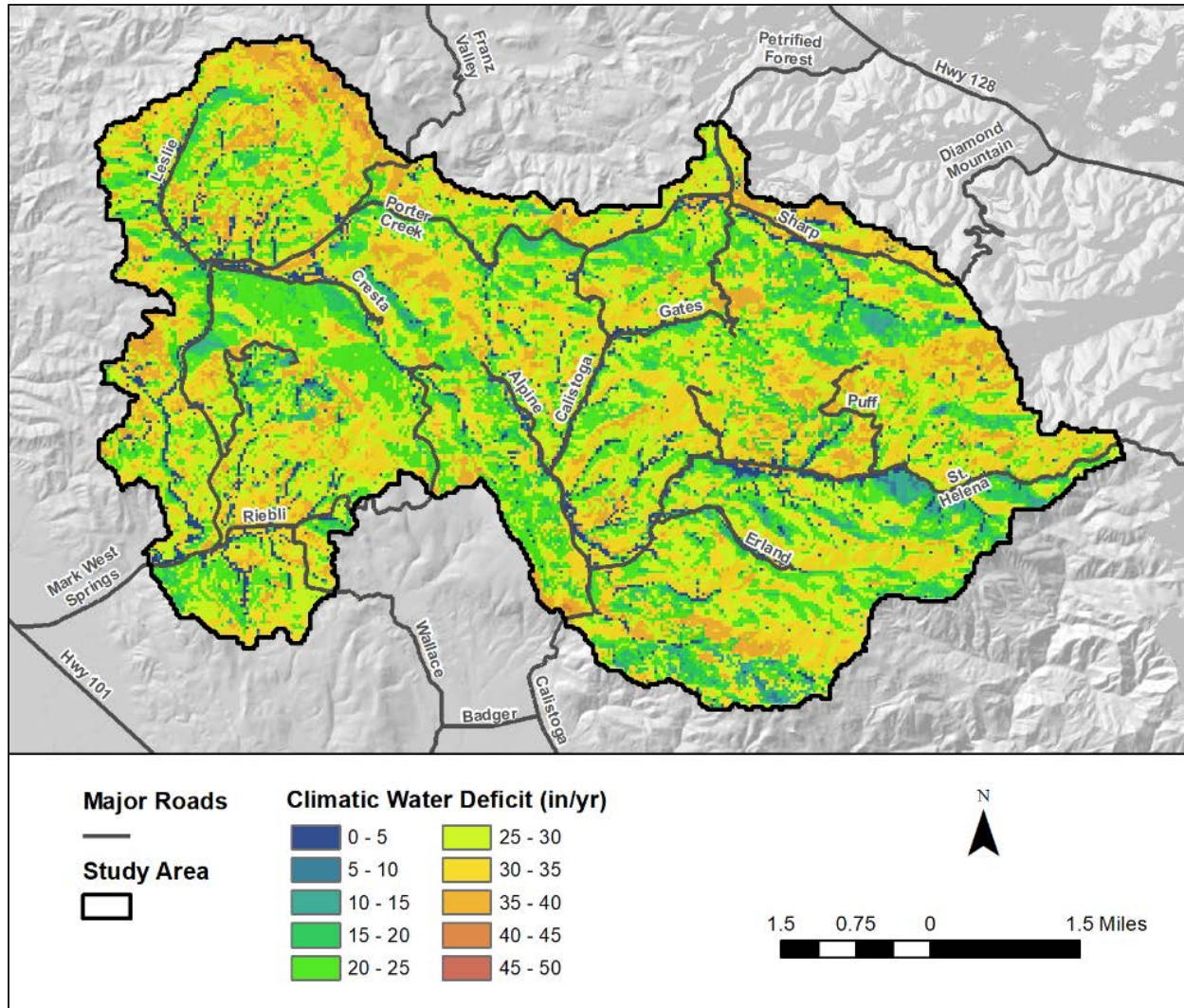
Figure 49: Mean annual Climatic Water Deficit (CWD) for water years 2010-2019 simulated with the MWC hydrologic model.
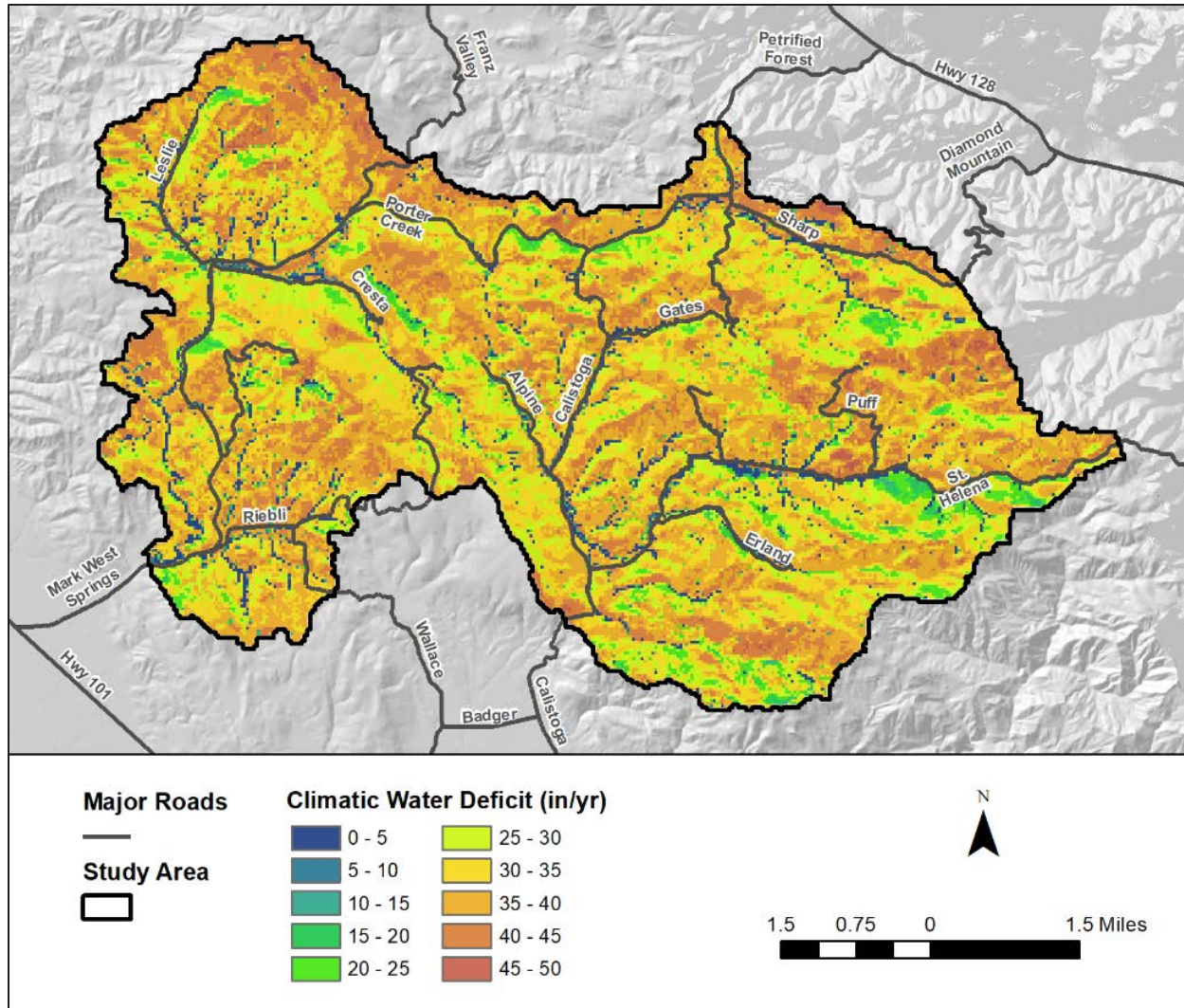
Figure 50: CWD for water year 2014 simulated with the MWC hydrologic model.

Groundwater Flow

Two hydrogeologic cross sections were prepared, one in the upper watershed downstream of Monan's Rill and one in the central watershed downstream of Humbug Creek (Figure 51). These sections show the vertical and horizontal variations in Hydraulic Conductivity, as well as the simulated equipotential lines, and approximate flow directions (perpendicular to equipotential lines) and locations of groundwater discharge predicted by the model. It is important to note that in both cross sections there is a significant downstream (out of the page) component to the flow directions not visible in this one-dimensional cross section view. Equipotentials are based on simulation results for 10/1/2010 but are representative of the regional patterns of groundwater flow throughout the simulation period which do not show significant variation at the regional scale of the cross sections.

The northern portion of the upper cross section (A-A') passes through the area with the thickest sequence of primarily tuffaceous volcanic materials that was identified from available Well Completion Reports. A transition to more andesitic-dominated materials occurs throughout the cross section with increasing depth, which is typical of our characterization of the volcanics in the upper watershed (Figure 52). Franciscan Complex, which was represented by simple vertical contacts owing to lack of data with which to describe contact orientation, occurs in the southern portion of the cross section.   A thin deposit of Quaternary Alluvium is present within a relatively narrow band along the stream channel. Flow is primarily vertical downward within the higher elevation portions of the cross section (Figure 52). Mid-way along the hillslopes above Mark West Creek, the flow directions transition toward horizontal and a vertical groundwater divide occurs beneath the creek with vertical upward flow in the upper ~300-ft (model Layers 1-3) and vertical downward flow in the lower ~500-ft (model Layers 4-6). Springs occur where upward vertical groundwater flow intersects the land surface. This primarily occurs along the lower hillslopes and stream banks in the upper watershed and appears to be associated with horizontal transitions from more tuffaceous to less tuffaceous materials as well as with steep dissected topography (Figure 52).

The cross section below Humbug Creek (B-B') passes through the relatively thin Humbug Creek Deposits on the northeast side of Mark West Creek which are underlain by primarily andesitic rocks of the Sonoma Volcanics. (Figure 53). A contact between the volcanics and the Franciscan Complex associated with the Maacama Fault Zone occurs near the creek in this reach, and a second contact occurs ~2,000-ft southwest of the creek with a mixture of tuffaceous and andesitic materials occurring in the southwest portion of the cross section. A thin deposit of Quaternary Alluvium is present within a narrow band along the stream channel. Flow is primarily vertical downward within the higher elevation portions of the cross section (Figure 53). A shallow flow path with more horizontal flow occurs mid-way along the hillslope northeast of Mark West Creek, and a somewhat deeper horizontal flow path also occurs at a similar topographic position on the other side of the creek within the Franciscan Complex.

A vertical groundwater divide occurs beneath the creek and adjacent hillslopes with vertical upward flow in the upper ~300-ft and vertical downward flow in the lower ~500-ft. A cone of depression associated with pumping from the well located in the Franciscan Complex is readily apparent and influences the flow directions along the adjacent hillslope (Figure 53).   Large persistent cones of depression like this one are relatively uncommon in the model and appear to coincide with wells exhibiting both high production rates and low aquifer Hydraulic Conductivity. Although there is some intersection of equipotentials with the land surface, rates of groundwater movement through these materials are very low and the model does not predict significant springflow in the vicinity of this cross section.

Streamflow & Riffle Depths

The model simulates streamflows and the depth of surface flow across riffles on the stream bed (i.e. riffle depths) throughout the various tributaries in the watershed; however, this discussion focuses on the main-stem of Mark West Creek where nearly all of the available suitable salmonid habitat is contained. The reach shown on subsequent maps extends upstream to the limits of

anadromy associated with a natural waterfall as identified in the CDFW Fish Passage Barrier Database.

April through June (hereafter referred to as Spring) mean streamflows varied substantially between water years with the driest conditions occurring in water year 2014 when flows ranged from less than 2 cfs above Van Buren Creek to 6-10 cfs below Porter Creek. The wettest conditions occurred in water year 2010 with flows above Van Buren Creek on the order of 4-8 cfs and flows below Porter Creek in excess of 30 cfs (Figure 54). July through September (hereafter referred to as Summer) mean streamflows were significantly lower than during Spring and also varied much less between water years. The driest conditions occurred in 2015 when flows ranged from less than 0.3 cfs above Van Buren Creek to 0.6-0.8 cfs below Porter Creek. The wettest summer conditions occurred in 2011 when flows ranged from less than 0.7 cfs above Van Buren Creek to more than 1.5 cfs below Porter Creek (Figure 55).

To assist in relating flow conditions to salmonid habitat requirements, we also compiled simulated water depths (hereafter referred to as riffle depths) which were found to be loosely equivalent to riffle crest thalweg depth conditions as discussed in greater detail in Chapter 7. The results were post-processed from model output data by extracting the minimum simulated depth per 1,000-ft of channel length (10 cross sections) to better represent riffle crest conditions observed in the field. Average Spring riffle depths during the drought of 2014 ranged from less than 0.2-ft upstream of Van Buren Creek to 0.2-0.4 ft below Porter Creek. In the wet water year 2017, riffle depths in the upper reaches were above 0.2-ft all the way to upstream about one river mile beyond Monan's Rill (Figure 56). Summer mean riffle depths are significantly lower than Spring depths and are relatively consistent between water years. In typical conditions, depths remain above 0.1-ft in most locations downstream of Monan's Rill, and below Porter Creek depths reach 0.2-0.3 ft in many locations (Figure 57). The simulated spatial distributions of riffle depth reflect both reaches where riffle depths are limited by reduced streamflows, most notably the reach upstream of Porter Creek which loses flow to the alluvium, as well as where depths are limited by geomorphic controls such as the reaches about 1-mile upstream of Riebli Creek (Figures 56 & 57).
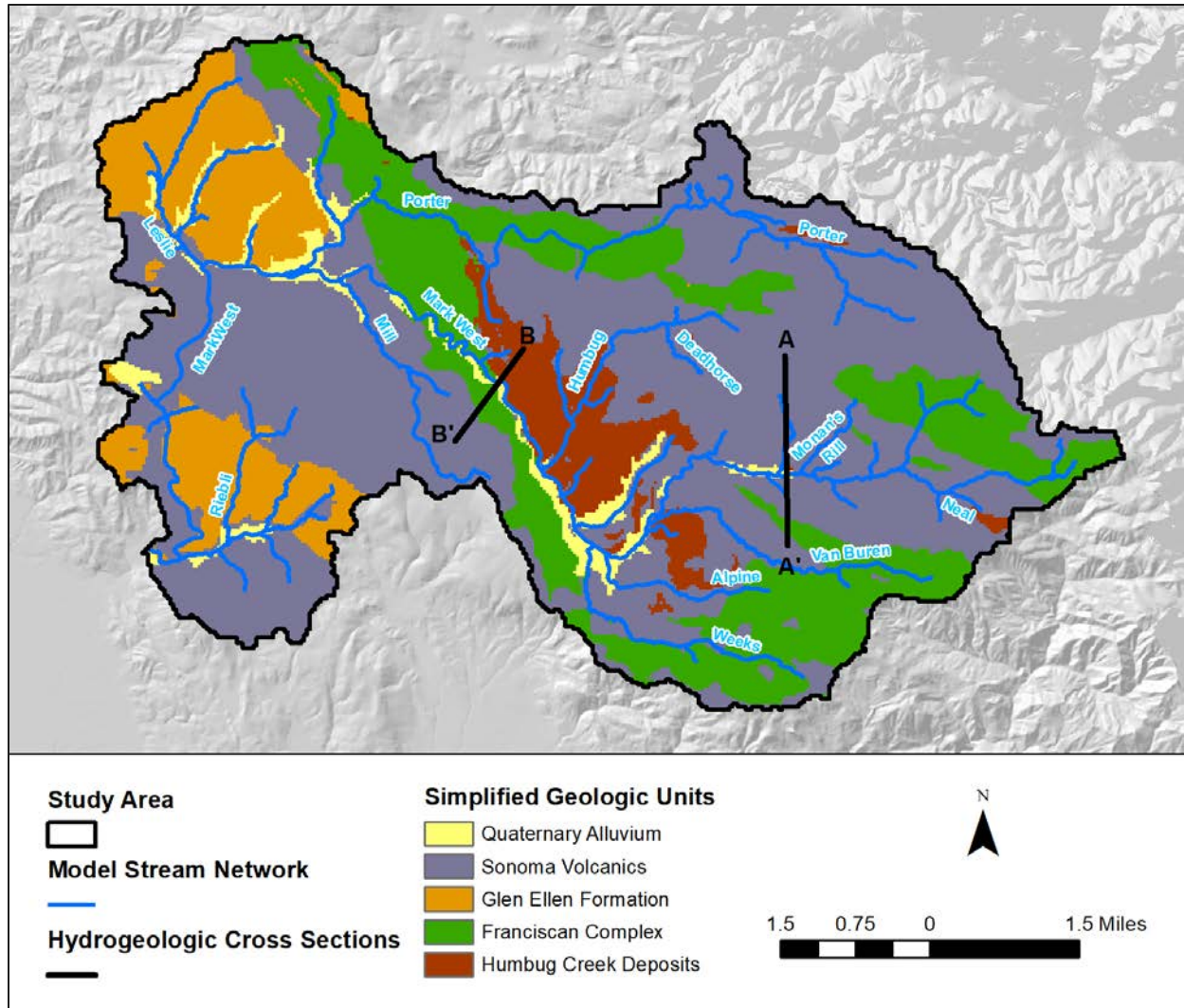
Figure 51: Simplified geologic map and locations of hydrogeologic cross sections A-A' and B-B'.

Figure 52: Hydrogeologic cross section A-A' showing hydraulic conductivities, equipotentials, and approximate flow directions as simulated with the MWC hydrologic model (see Figure 51 for location).
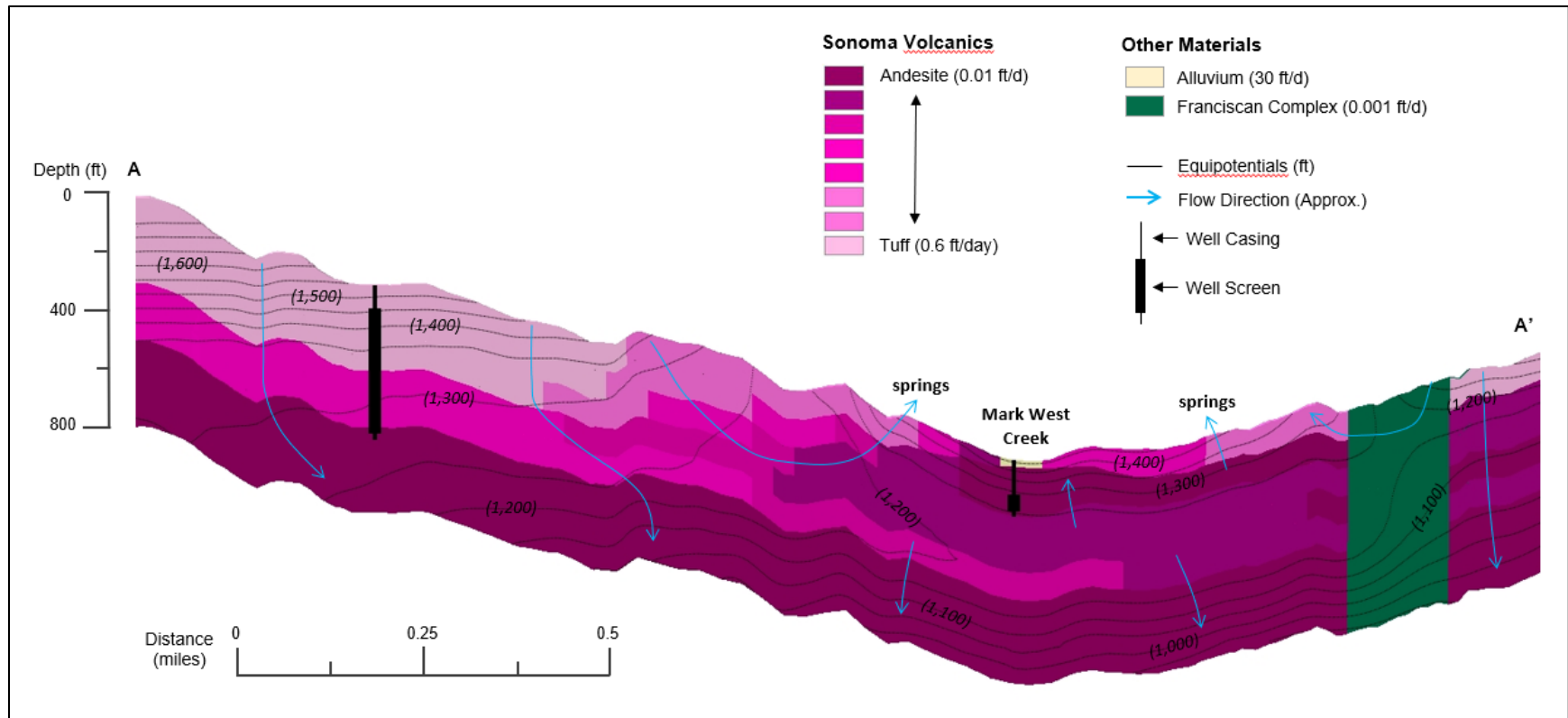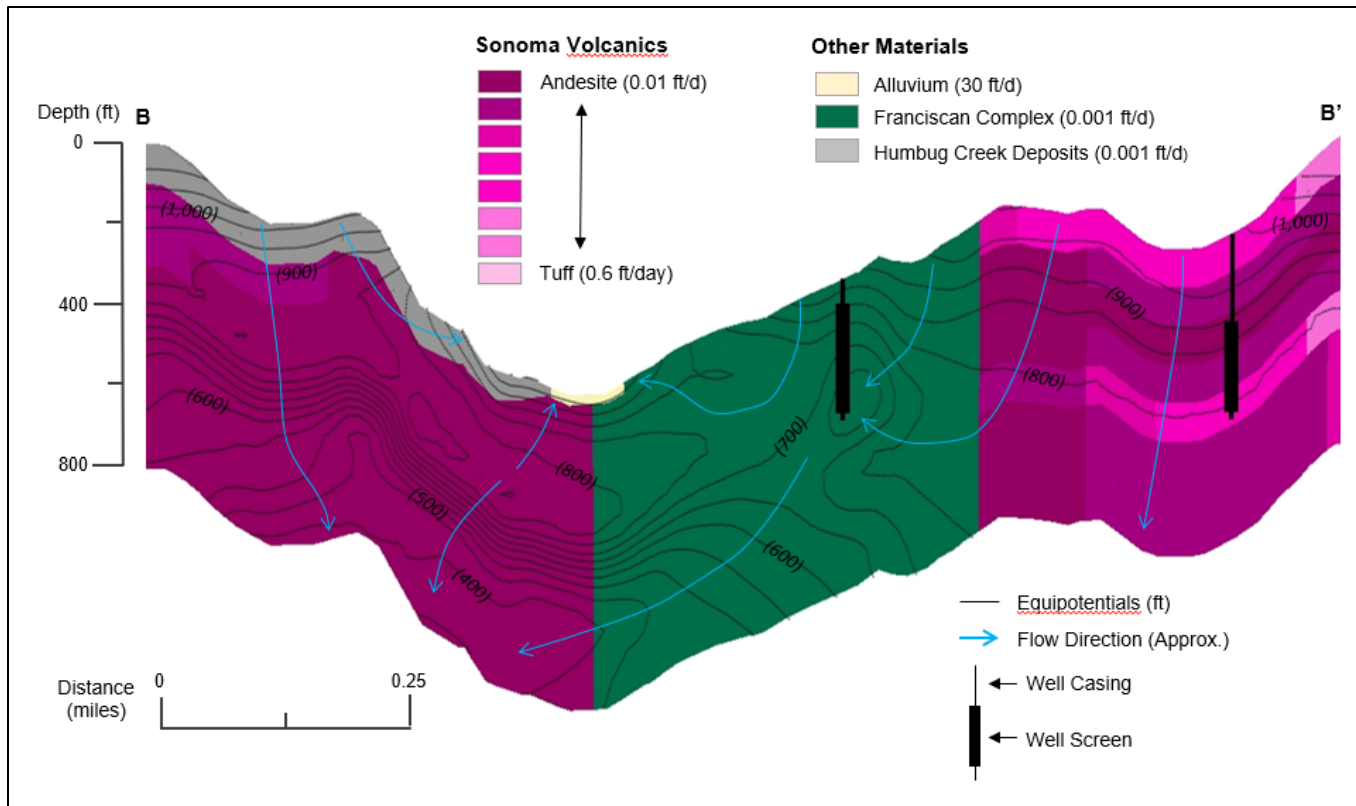
Figure 53: Hydrogeologic cross section B-B' showing hydraulic conductivities, equipotentials, and approximate flow directions as simulated with the MWC hydrologic model (see Figure 51 for location).
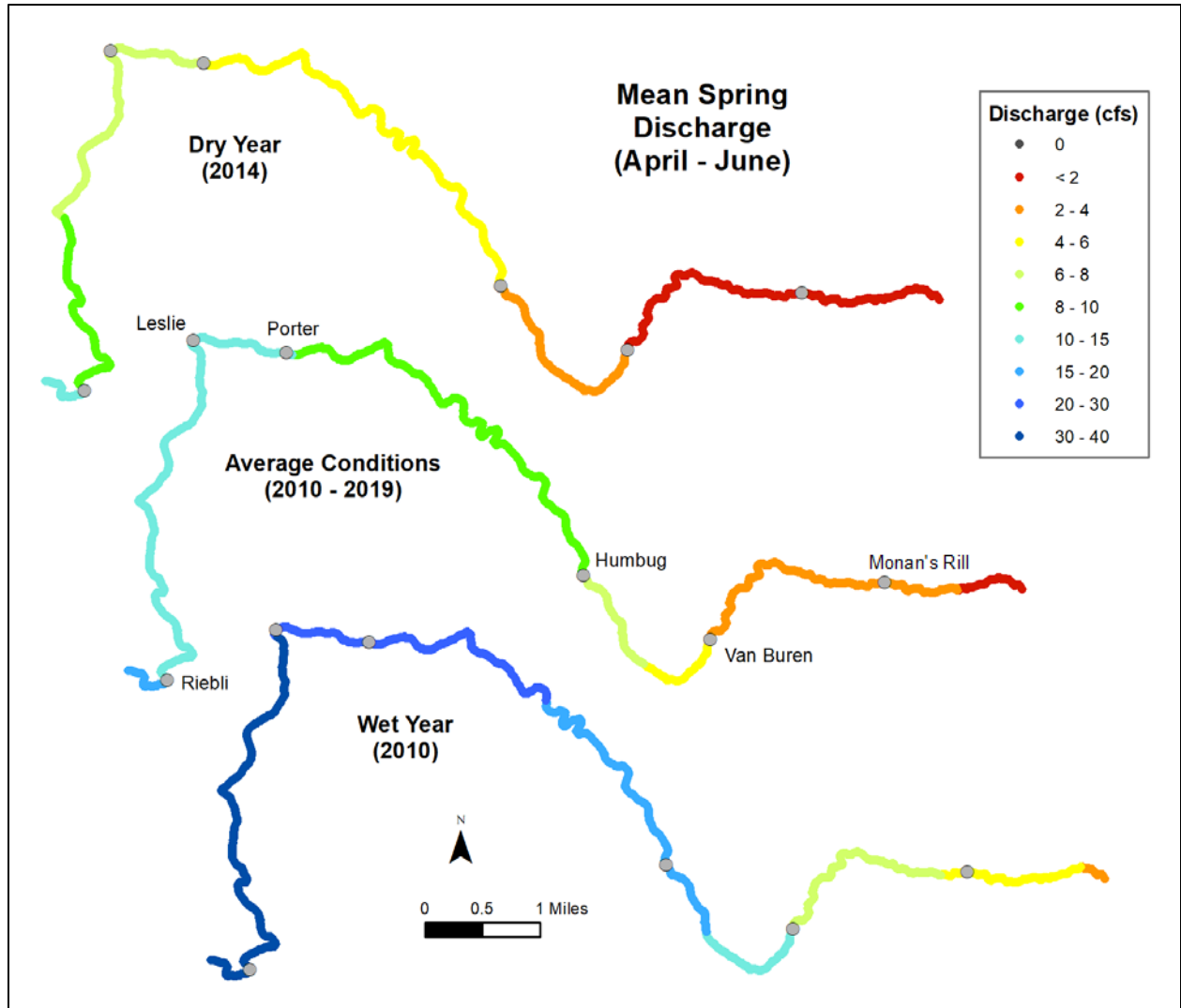
Figure 54: Mean simulated Spring (April – June) streamflows for dry, average, and wet water year conditions.
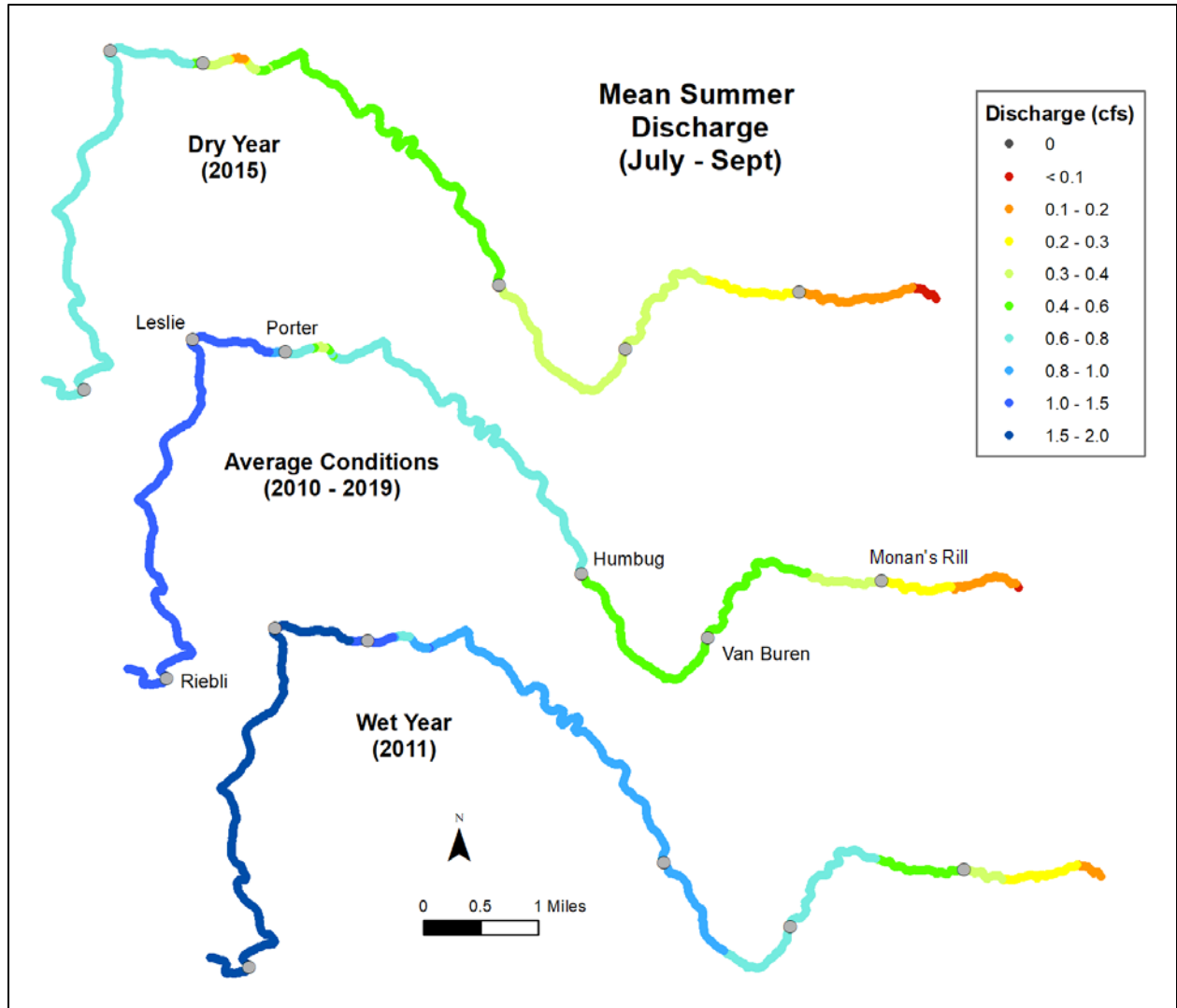
Figure 55: Mean simulated Summer (July - Sept) streamflows for dry, average, and wet water year conditions.
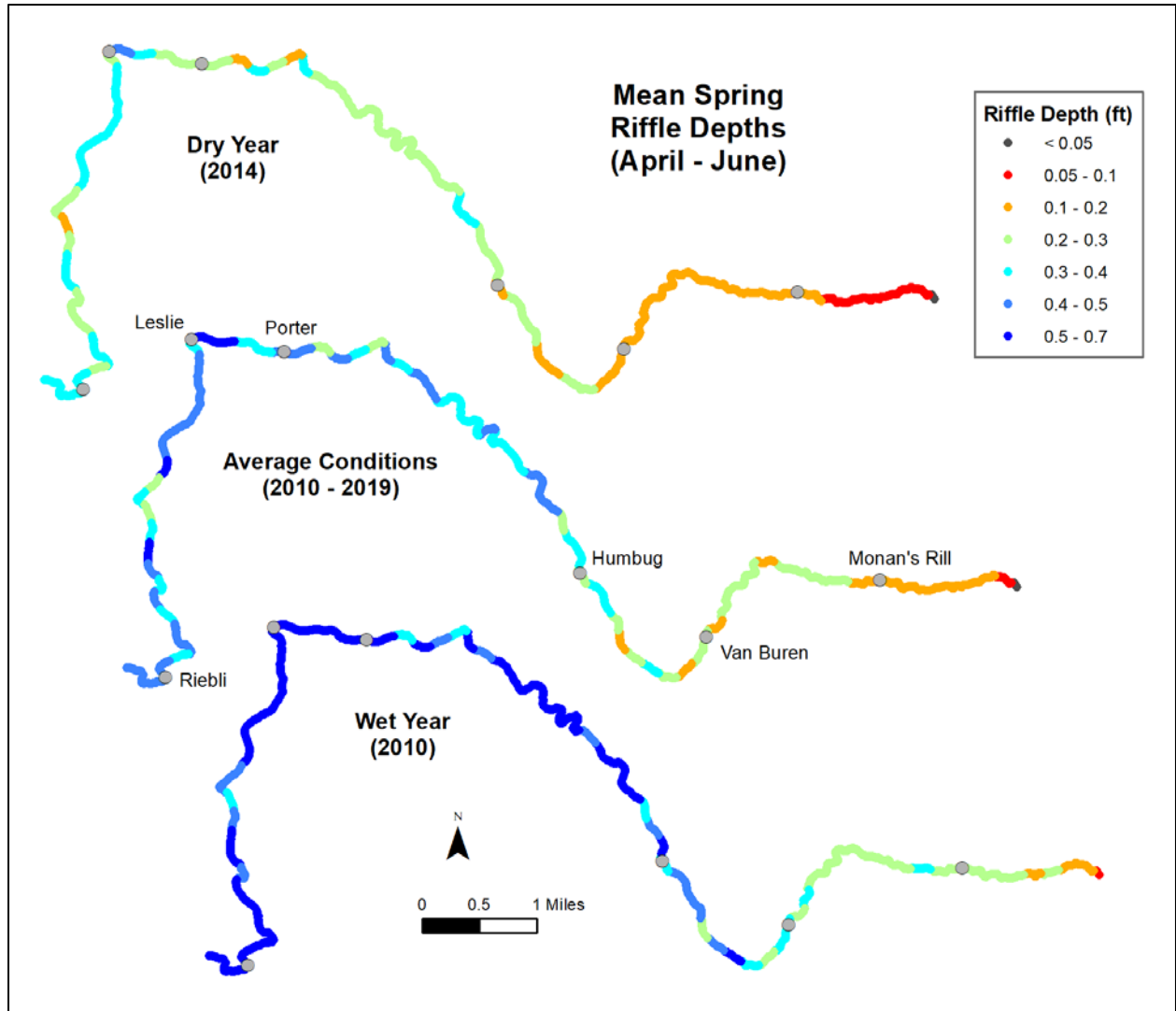
Figure 56: Mean simulated Spring (April – June) riffle depths for dry, average, and wet water year conditions.
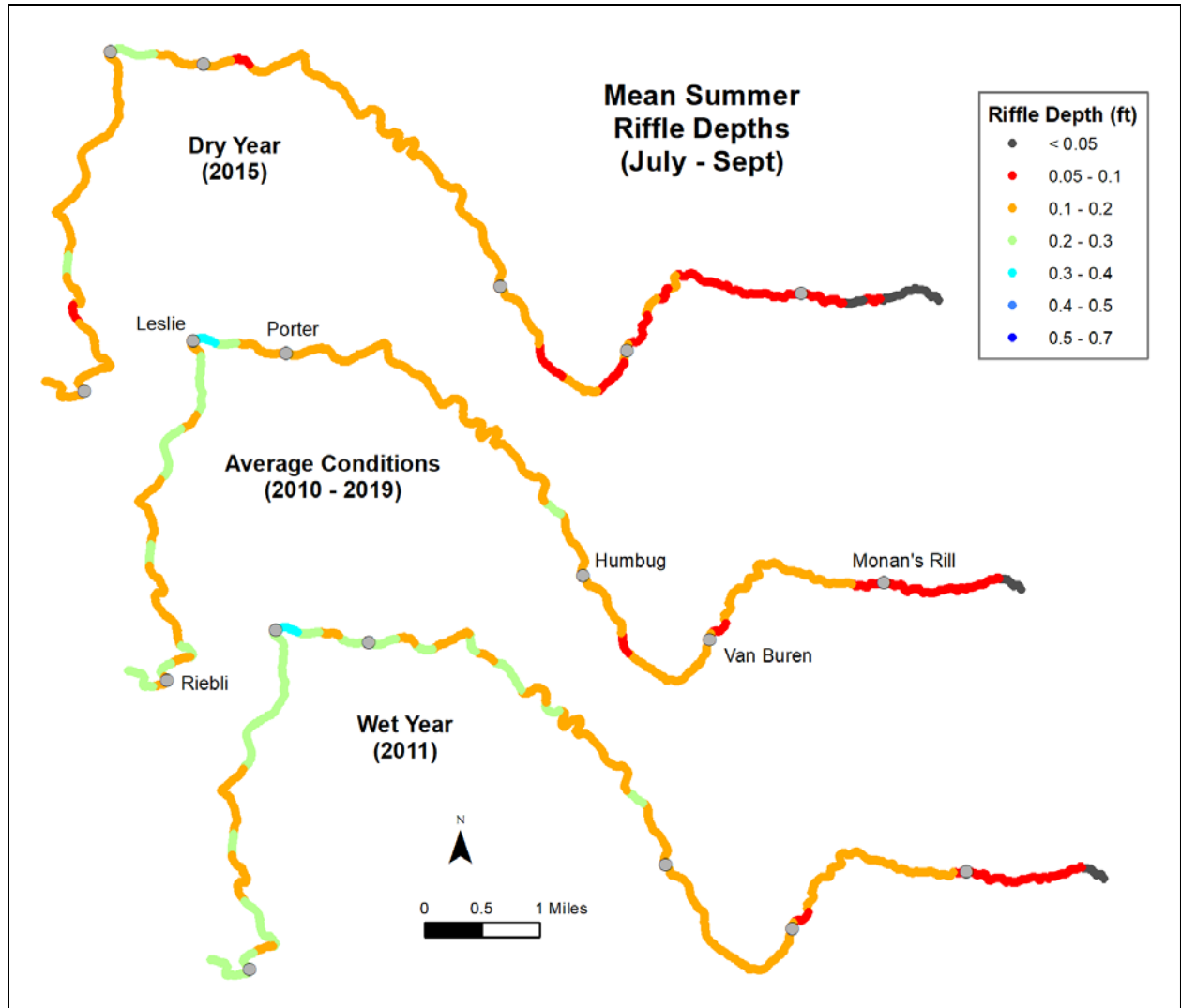
Figure 57: Mean simulated Summer (July - Sept) riffle depths for dry, average, and wet water year conditions.

Chapter 7 – Habitat Characterization and Prioritization

Background

Inadequate stream flow to support juvenile rearing habitat during the summer months has been identified as a primary limiting factor for coho survival in Russian River tributaries (CDFG, 2004; NFMS, 2012). Flows during the spring outmigration period may also be limiting in some cases. Numerous methods have been developed to relate stream flow conditions to habitat quality and define minimum flow requirements for a specific species and life stage of interest. These methods include applying regional regression equations that have been developed from multiple habitat suitability curve studies (e.g. Hatfield & Bruce, 2000), wetted perimeter and critical riffle depth methods (e.g. Swift, 1979, R2 Resource Consultants, 2008), and direct habitat mapping approaches (e.g. McBain & Trush, 2010).

Regional regression equations produce discharge estimates for Mark West Creek and other Russian River tributaries that are an order of magnitude higher than typical conditions during the summer months. Given that coho persist in these tributaries despite these very low flow conditions, application of these regional equations may be of limited value for delineating the extent and quality of existing habitat with respect to streamflow. Direct habitat mapping approaches require extensive fieldwork and site-scale characterization which is beyond the scope of this reginal planning study; a concurrent CDFW Instream Flow Study utilizing such methods is being conducted in upper Mark West Creek.

A simple approach to utilizing hydrologic model results to delineate habitat availability (and the selected approach for this study) is to relate water depths simulated in the model to riffle crest thalweg depths (RCTDs) which have been investigated as important indicators of salmonid habitat suitability. This approach assumes that the simulated water depths are representative of conditions at riffle crests. This assumption is consistent with the limitations of the LiDAR topographic data which does not penetrate water and therefore would be expected to capture riffles and pool water surfaces but not pool geometries. To validate this assumption, we measured riffle crest thalweg depths (RCTDs) at nine riffle crests identified in three reaches of Mark West Creek across a range of typical low to moderate flow conditions and compared the resulting discharge/RCTD relationships to relationships extracted from the model for equivalent locations (Figure 58).

There was generally good agreement between the measured and simulated discharge/RCTD relationships, and the agreement was improved by sampling the cross section within a given 1,000-ft reach with the lowest simulated depths (i.e. finding the cross section most representative of conditions at nearby riffle crests). At most riffle crests observed in the field, maximum depths occur across a relatively narrow width commonly associated with gaps between small clusters of individual cobbles. This level of topographic detail is not captured in the model topography, therefore a small residual depth (0.05-ft) was added to the simulated values to account for the effects of this microtopography. The simulated discharges associated with a RCTD of 0.2-ft ranged from 0.21 to 0.46 cfs based on interpolation between field measurements, and from 0.18 to 0.53 cfs as simulated in the model (Figure 58).

Previous research has demonstrated relationships between RCTDs and various indicators of salmonid habitat suitability including fish passage, water quality, and abundance of benthic macroinvertebrates. Maintaining suitable riffle depths to allow for fish passage is critically important during smolt outmigration (typically mid-February to mid-June) and is also important for facilitating pool selection prior to summer rearing. A minimum passage depth of 0.3 feet has been estimated for juvenile coho (R2 Resource Consultants, 2008; CDFW, 2017). This depth criterion and methodology is somewhat conservative by design and fish passage is thought to occur in Russian River tributaries at shallower depths, therefore it is useful to define a lower criterion below which passage is presumably not possible. For the purposes of this study, that depth was defined as 0.2 feet expressed as a RCTD. It is important to note that we are applying this depth threshold to RCTDs rather than based on CDFW critical riffle methodology. We calculated the flows required to achieve a 0.2-ft depth from our field data following CDFW protocols for performing Critical Riffle Analysis (CDFW, 2017). This resulted in estimates of required flows ranging from 2.0 to 3.2 cfs, which are about 5 to 10 times higher than the typical summer flows experienced in the watershed.

Another key factor in summer survival is the suitability of water quality conditions in the pools that provide rearing habitat for salmonids. Maintaining sufficient flow between riffles is key to maintaining oxygenation in pool habitats, and monitoring in Green Valley Creek has shown that coho survival begins to decline when pools become disconnected with mortality increasing as a function of length of disconnection (Obedzinski et al., 2018). Through extensive field monitoring in Green Valley, Dutch Bill, and Mill Creeks, CA Sea Grant found a statistically significant relationship between RCTDs and Dissolved Oxygen (DO) concentrations in intervening pools, with ~80% of the pools with RCTDs greater than 0.2-ft maintaining suitable DO concentrations above 6 mg/L (CA Sea Grant, 2019). As discussed below in greater detail, water temperature conditions are higher in Mark West Creek relative to the monitored streams nearer the Pacific Ocean in Sonoma County, therefore while we still consider RCTDs to be an important indicator of water quality in Mark West Creek, temperature considerations must be accounted for in more detail.

In addition to suitable water quality, another factor critical summer rearing habitat for salmonids is the availability of a reliable food supply in the form of benthic macroinvertebrates (BMI) which are concentrated in riffle habitats with sufficient flow velocity. Velocities at riffles between about 1.0 and 2.5 ft/s have been shown to be optimal for BMI (Giger 1973, Gore et al., 2001). As part of our riffle crest analysis in Mark West Creek we measured velocities and interpolated relationships between RCTDs and thalweg velocities (Figure 59). At lower flows, depths were too low to measure velocity at more than a few locations across the riffle, however in most cases velocities approaching those at the thalweg only occurred across a relatively small portion of the riffle profile. To ensure that the threshold velocity represents a condition that provides suitable habitat for BMI across larger swaths of the riffle we applied a minimum velocity threshold of 1.5 ft/s and do not consider the upper velocity limit important over the range of summer flows experienced in Mark West Creek. This exercise revealed that 0.2-ft was also a useful threshold for describing the approximate minimum RCTD that corresponded to adequate velocity at riffle crests for BMI (Figure 59).
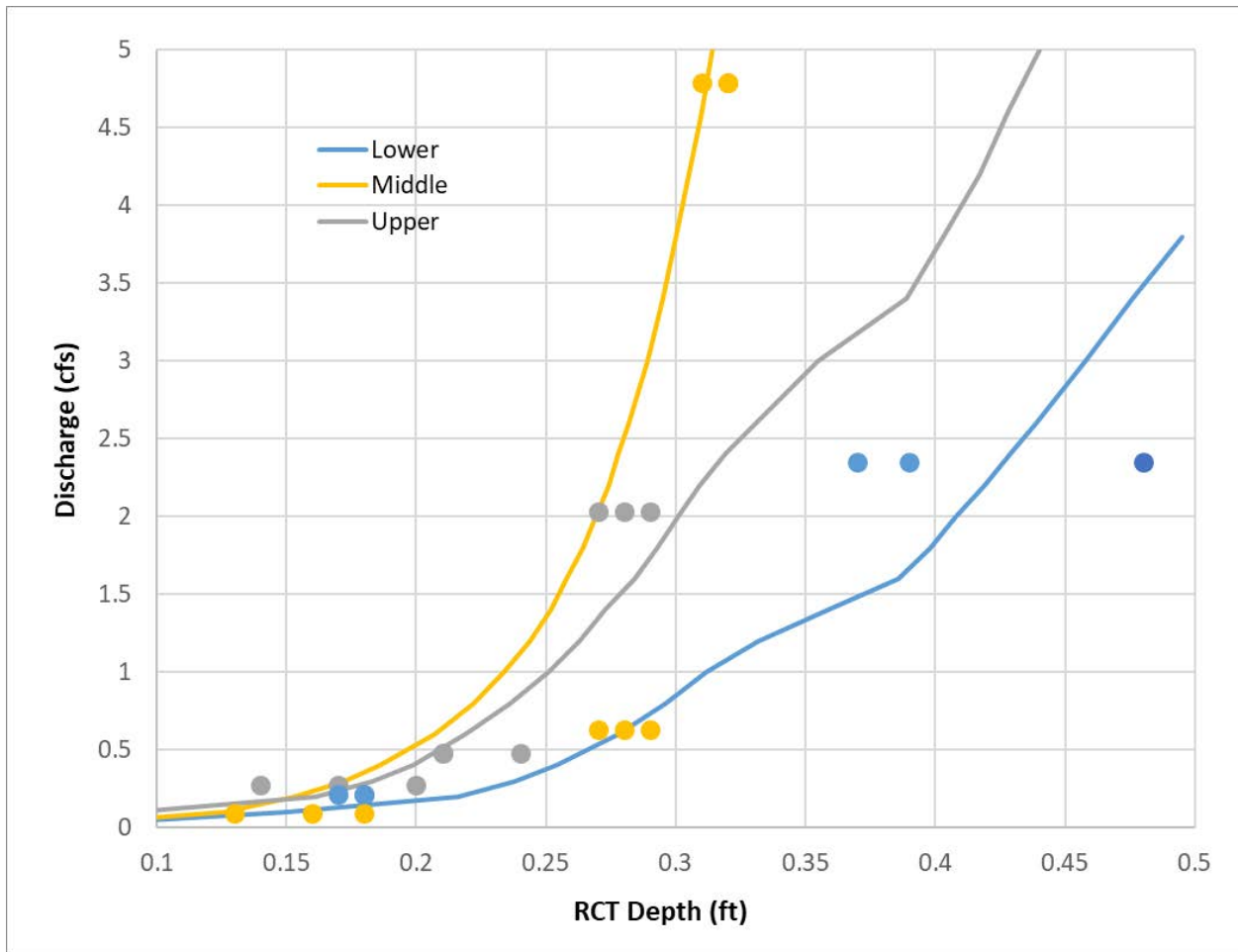
Figure 58: Comparisons between RCTD/discharge relationships measured in the field (points) and simulated with the MWC hydrologic model (lines).
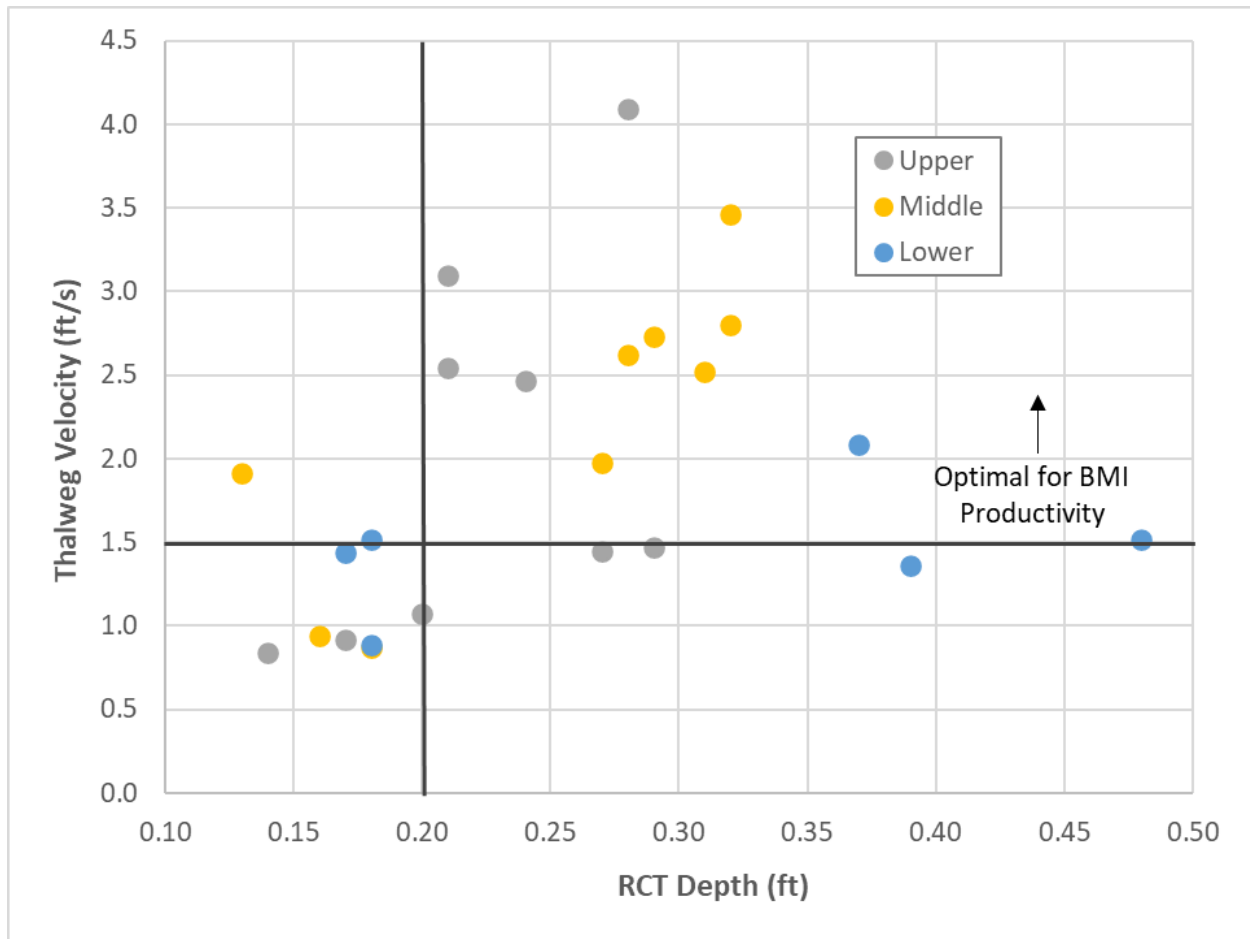
Figure 59: Relationship between RCTD and velocity based on measurements at nine riffles crests in Mark West Creek.

Approach

We developed two streamflow classifications with respect to salmonid habitat condition, one for smolt outmigration and one for juvenile rearing. Both classifications focus on the 0.2-ft RCTD threshold which is intended to represent the minimum flow conditions required to provide suitable (not optimal) habitat for salmonids. It is important to note that the primary goals in defining a minimum flow threshold for this study were to 1) assist in distinguishing between reaches with varying levels of habitat suitability under existing and plausible future flow conditions in the watershed to aid in prioritizing reaches for restoration projects, and 2) to distinguish between conditions that are likely suitable versus not suitable rather than attempting to distinguish between optimal and suboptimal conditions. Optimal summer rearing habitat conditions for salmonids, particularly coho salmon, are rarely found or non-existent in most lower Russian River tributaries.

We obtained smolt outmigrant trap data collected by Sonoma Water in Mark West Creek for 2012-2018. These traps were only deployed during April and May to capture the primary pulse of outmigration. CA Sea Grant has collected data from outmigrant traps in other Russian River

tributaries over the full outmigration season from late February to late June. We compared the CA Sea Grant data in Mill Creek for 2014-2019 with the Mark West data and found very similar outmigration timing with peak outmigration occurring between the first week of April and the third week of May in both creeks. CA Sea Grant's analysis of the Mill Creek data (which we believe is representative of Mark West Creek) indicated 80% of the outmigrants had moved by the week of May 21st in a late outmigration year and 99% had moved by the week of June 18th (Nossaman Pierce, personal communication). We developed habitat suitability criteria based on these dates and a RCTD threshold of 0.2-ft as follows:

- Maintain RCTD threshold through week of May 21st in the 10-yr average condition
- Maintain RCTD threshold through week of June 18th in the 10-yr average condition
- Maintain RCTD threshold through week of May 21st in drought years
- Maintain RCTD threshold through week of June 18th in drought years

We followed a similar approach for the juvenile rearing habitat classification focused on July-September conditions. In our previous flow-based habitat classification work in Green Valley/Atascadero & Dutch Bill Creeks, we focused on differentiating between reaches where pools remain connected, become disconnected for short periods of time, and become disconnected for longer periods of time (OEI, 2016). Disconnected pools are relatively rare in Mark West Creek (with the exception of a short reach above Porter Creek), therefore this was not a useful metric for distinguishing between various levels of habitat suitability in this watershed. We developed an alternative and likely more stringent set of habitat suitability criteria for summer rearing habitat conditions as follows:

- Maintain RCTDs threshold for portions of the summer in the 10-yr average condition (always > 0.1-ft)
- Maintain RCTD threshold continuously in the 10-yr average condition
- Maintain RCTD threshold for portions of the summer in drought years (always > 0.1-ft)
- Maintain RCTD threshold continuously in drought years

We then assigned each 1,000-ft stream reach in the model with a score of zero through four based on the number of these criteria that were met to develop flow-based habitat classification maps for smolt outmigration and juvenile rearing.

Although water temperature analysis was not part of our project scope, preliminary review of available temperature data revealed that elevated water temperatures may be an even more important limiting factor for juvenile rearing habitat than flow in this watershed, therefore we compiled available temperature data from Sonoma RCD, CA Sea Grant, Trout Unlimited, and CDFW to facilitate incorporating temperature into the habitat classification. We calculated the Maximum Weekly Maximum Temperature (MWMT) from continuous temperature datasets at 15 locations in Mark West Creek. Each location had between one and five years of data between 2010-2019, however many locations had only one year of data and most years had only a few locations, complicating the interpretation of spatial and temporal patterns. Nevertheless, the data was sufficient to perform a preliminary water temperature classification based on the

MWMT and various levels of temperature impairment. Based on previous work, a threshold of 18.0 °C was used to represent impaired conditions, 21.1 °C to represent severe impairment, and 23.1 °C to represent conditions that may be lethal for salmonids given prolonged exposure (NCRWQCB, 2008).   Each reach was assigned a score from zero to three based on the number of the following criteria that were met:

- Maintain MWMT < 23.1 °C
- Maintain MWMT < 21.1 °C
- Maintain MWMT < 18.0 °C

In addition to sufficient flow to enable passage, maintain water quality, and support benthic macroinvertebates, there are many other important factors for maintaining suitable salmonid habitat. These include presence of pools with sufficient depth and cover, suitable spawning gravels, and availability of refugia from high velocity winter flows, among others. To account for some of these factors in our classification, we compiled Stream Inventory Report data collected by CDFW in 1996 and ranked each of the five reaches described in the report based on the relative quality of pool habitat and spawning habitat. Although we did not collect detailed pool or substrate data, we incorporated our general observations of these conditions in our interpretations of the resulting rankings. Our observations suggest that even though the inventory data described conditions more than 20 years ago, the relative quality of habitat conditions between reaches described by the data appears to be fairly consistent with current conditions. Finally, we compiled summer snorkel survey data collected by CA Sea Grant to understand which reaches have been utilized by salmonids in recent years.

We then produced a generalized multi-factor habitat classification map by combining the flow- and temperature-based classifications and making adjustments and interpretations based on the pool and spawning habitat rankings as well as our general observations about other factors such as off-channel habitat availability and potential for redd scour, and recent patterns of salmonid utilization. The resulting maps are intended to delineate the reaches providing the best overall habitat value for salmonids in the watershed as well as the reaches where conditions are likely unsuitable due to one or more critical limiting factors.

Results

The flow-based habitat classification results indicate that most reaches are impaired with respect to flow both in terms of smolt outmigration and summer rearing (Figure 60). Both the juvenile rearing and smolt outmigration classifications show similar patterns overall. Upstream of Van Buren Creek either one or zero of the four flow criteria are met, most reaches between Humbug Creek and Porter Creek meet two or three of the criteria, and most reaches below Porter Creek meet three or four criteria (Figure 60). Notable exceptions to this include short reaches upstream of Porter Creek and between Leslie and Riebli Creeks which are more flow-limited than adjacent upstream and downstream reaches (Figure 60).

Two of the three temperature criteria are met upstream of Van Buren Creek, one of the criteria are met between Van Buren and about 2-miles upstream of Porter Creek, and none of the criteria

are met (MWMT > 23.1 °C) in the reach upstream of Porter Creek (Figure 61). No continuous temperature data was available farther downstream. The available water temperature data shows an overall pattern of increasing temperature in the downstream direction with all reaches being temperature-impaired at times to varying degrees (Figure 62). In the upper watershed, maximum water temperatures generally occur in mid-July, whereas the reach above Porter Creek follows a similar trend in general but superimposed on this is a period of elevated temperatures resulting in maximum temperatures about a six weeks earlier in early June; this behavior may reflect a contrast in the timing of response to solar radiation inputs (Figure 63).

We examined the temporal variations in temperatures relative to streamflows observed at the stream gauges in the watershed and found no obvious correlations between flow and temperature at the most temperature-impaired locations. In fact, the highest temperatures in these reaches generally occur during June and begin to improve by August and September, whereas flows are generally declining throughout this period. In the reach above Porter Creek, June/July water temperatures ranged from 14.4 to 23.1 °C when flows were very low (< 0.2 cfs) and exhibited a similar range of variability (14.5 to 24.3 °C) when flows were relatively high (> 1 cfs) (Figure 64). This suggests that flow is not the primary control on temperature and that even significant streamflow enhancement is unlikely to mitigate elevated temperatures.

We also examined the relationship between pool depth and temperature in six pools monitored by CDFW upstream and downstream of Humbug Creek in 2017. Pools with depths greater than 3.5-ft maintained significantly lower temperatures than shallower pools less than 2.5-ft deep (Figure 65). Although based on a limited sample size from a single year, this suggests that deep pools likely provide critical refugia for salmonids in Mark West Creek when extreme temperatures occur in shallower pool habitats (Figure 65).

The CDFW inventory data indicates that the best pool habitat occurs in the reach above and below Humbug Creek (CDFW Reach 5) and above and below Riebli Creek (CDFW Reach 2) (Figure 66). It is important to remember that this is a relative ranking and pool conditions in these reaches are likely still impaired. The CDFW data indicates that these reaches have relatively low shelter ratings (mean of 40), shallow pools (2.5-ft mean maximum depth), and very little Large Woody Debris (1% occurrence) (Table 14). The best spawning habitat as indicated by the CDFW data occurs in the middle and lowest reaches (CDFW Reaches 2 and 4) (Figure 66). Upstream of Van Buren Creek, spawning suitability is limited by high embeddedness and the predominance of bedrock and cobble-sized substrate conditions (Table 14). Not captured in the CDFW data are considerations of potential for redd scour which is likely to increase significantly below Porter Creek due to increased stream power and sediment mobility. Therefore, the most suitable spawning habitat is likely to occur in the reach of Mark West Creek between Van Buren Creek and Porter Creek. It is important to remember that the inventory data is more than 20 years old and as such may not be reflective of current conditions other than in generally describing reach-to-reach variability.

Summer snorkel survey data is available from 2016-2019. Very few (<10) coho were observed in Mark West Creek during 2016 and 2018 and interpreting the data from 2017 is complicated by a spring release of juvenile coho in the upper watershed. Therefore, the 2019 data is the most useful for examining which reaches have been utilized by coho in recent years. Nearly all (98%) of the 734 observed coho were found in pools between Humbug Creek and Porter Creek. Within this reach, coho were highly concentrated in a relatively small number of pools, with 72% of the coho located in just 11 pools and the remaining 28% distributed between 33 additional pools (Figure 67).
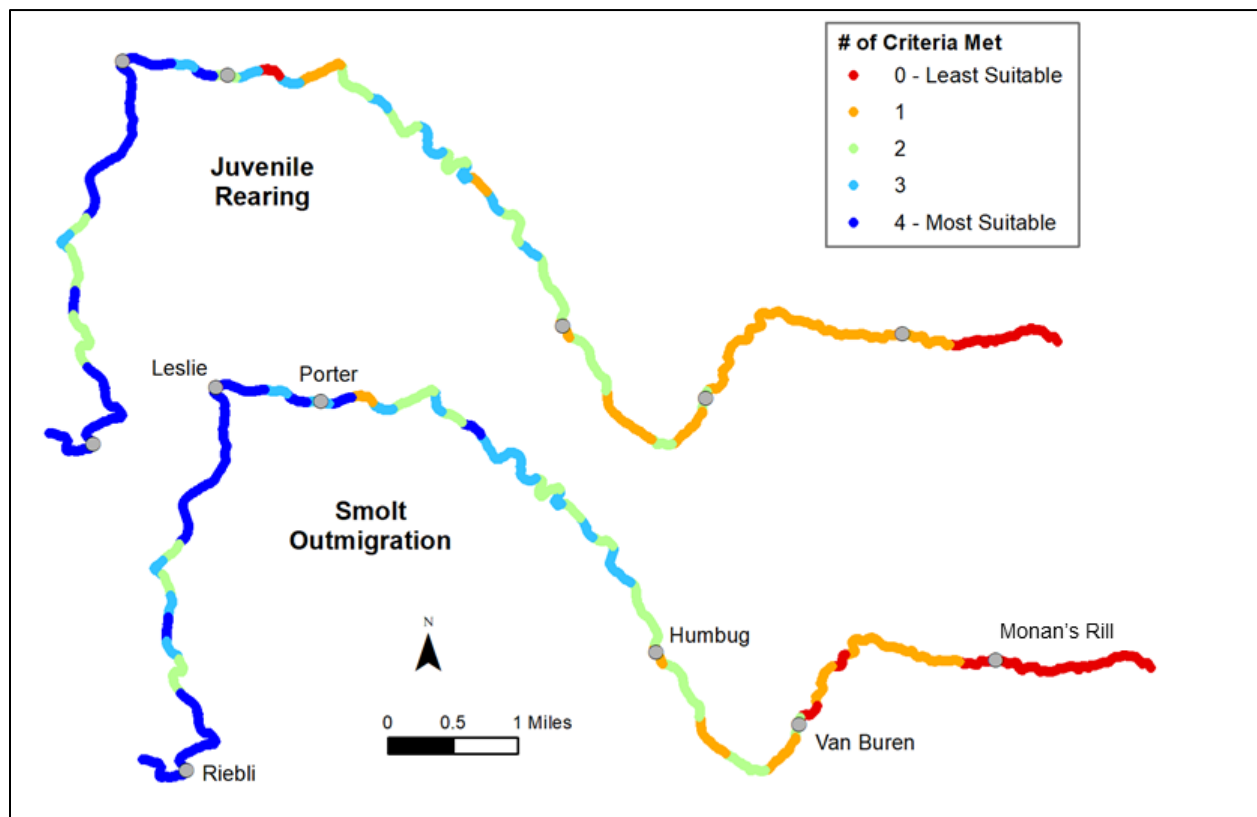
Figure 60: Flow-based habitat suitability classifications for juvenile rearing and smolt outmigration.
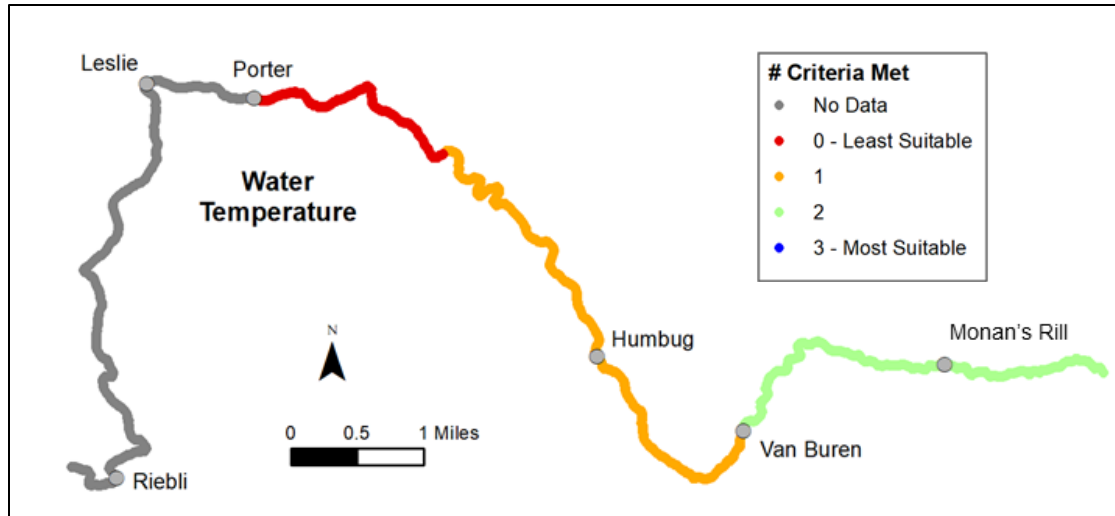
Figure 61: Water temperature-based habitat suitability classification.
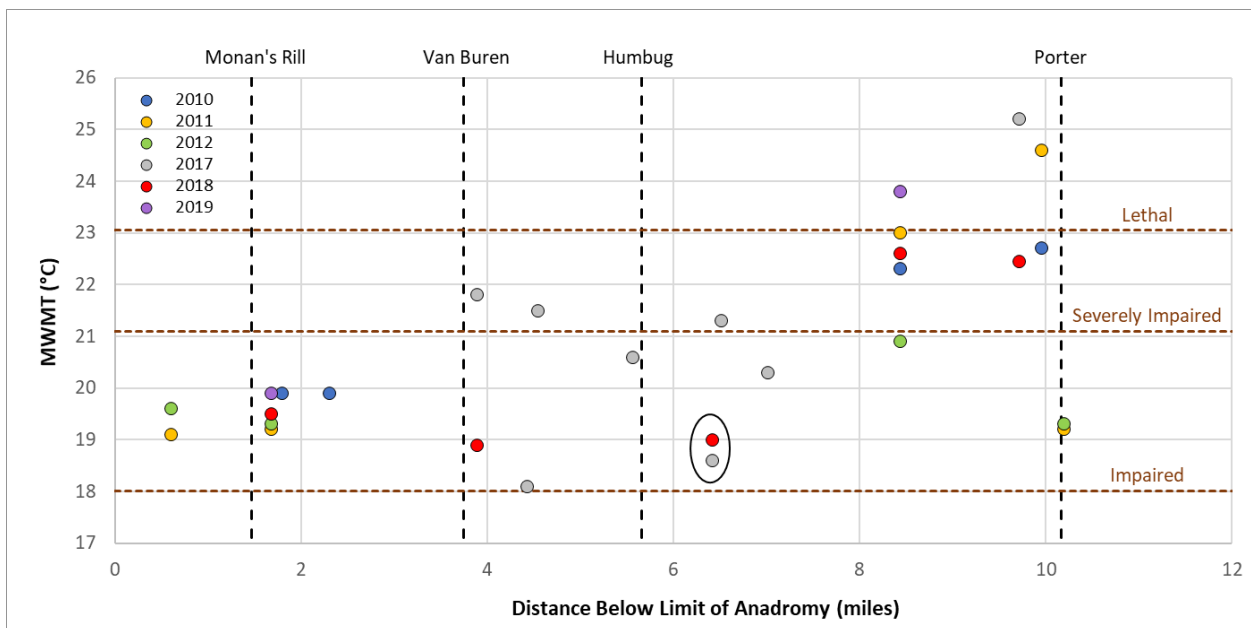
Figure 62: Longitudinal and temporal variations in Mean Weekly Maximum Water Temperature (MWMT) derived from continuous temperature data at 15 stations between 2010 and 2019, black oval indicates location of deep pool cold water refugia; temperature data from CDFW, Sonoma RCD, CA Sea Grant, and TU.
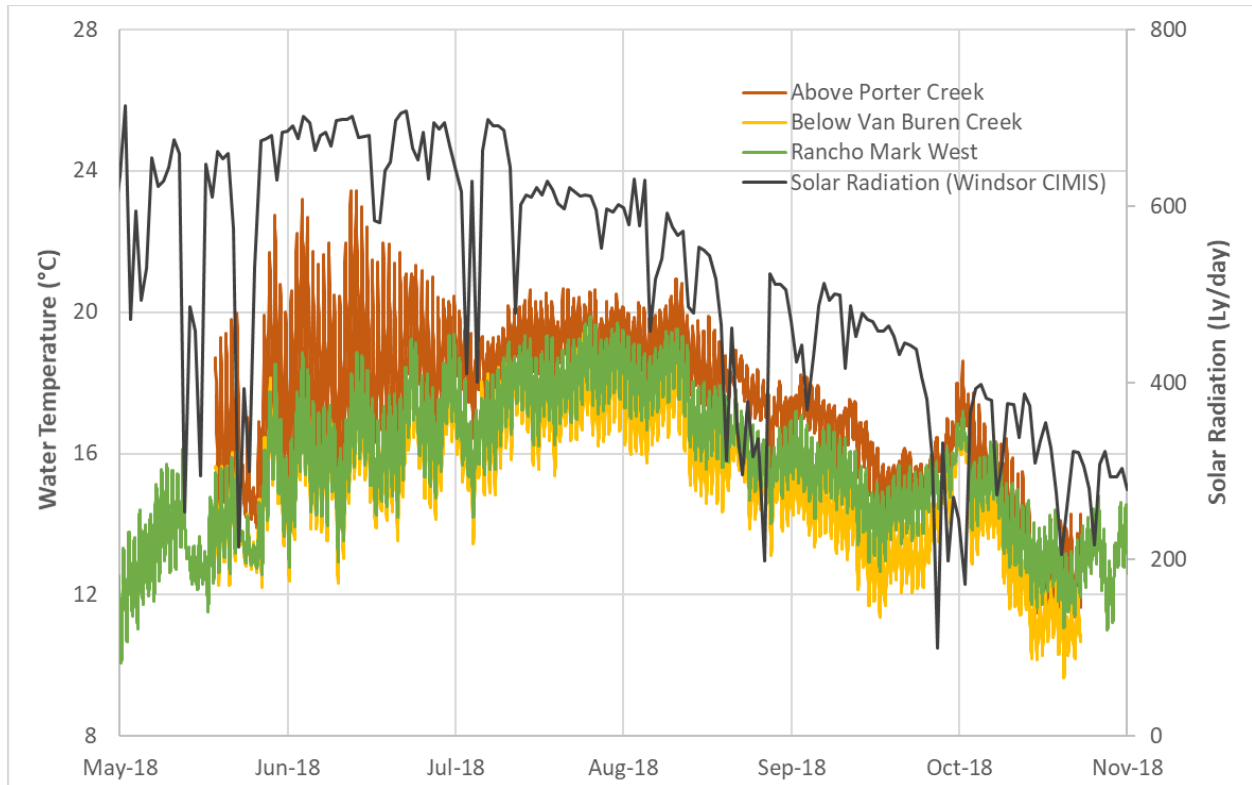
Figure 63: 15-minute interval water temperature data at three locations in Mark West Creek for 2018 and solar radiation data from the Windsor CIMIS station.
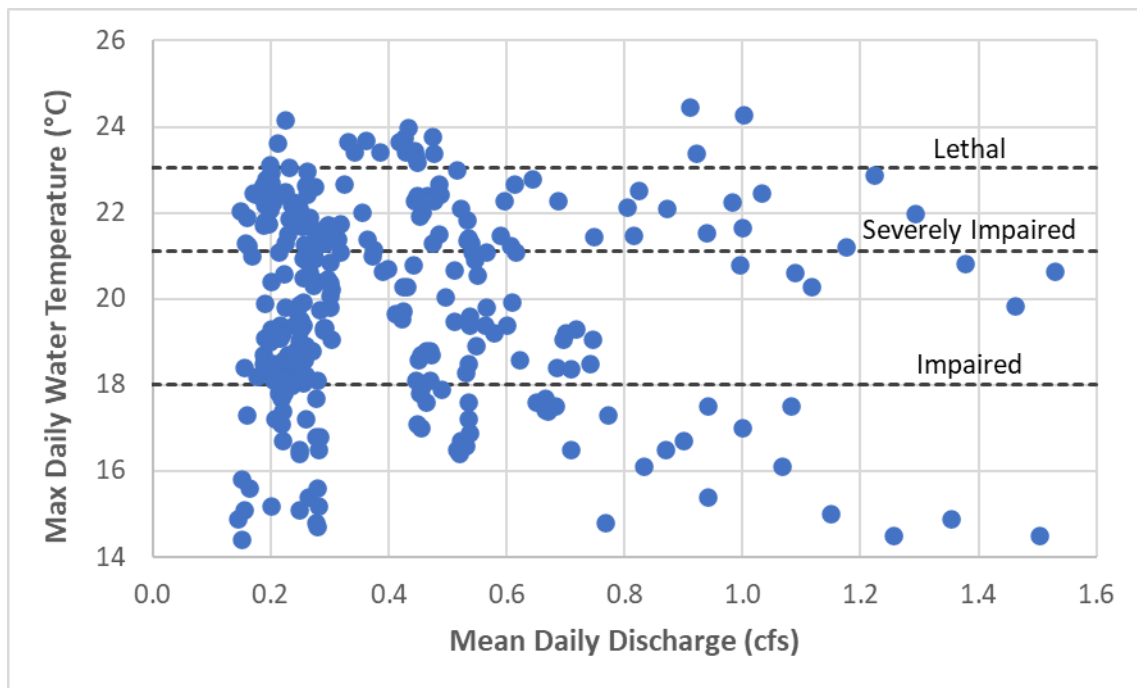
Figure 64: Comparison between Maximum Daily Water Temperature above Porter Creek during June and July of 2010-2012 & 2018-2019 and corresponding discharges as measured at the Rancho Mark West gauge.
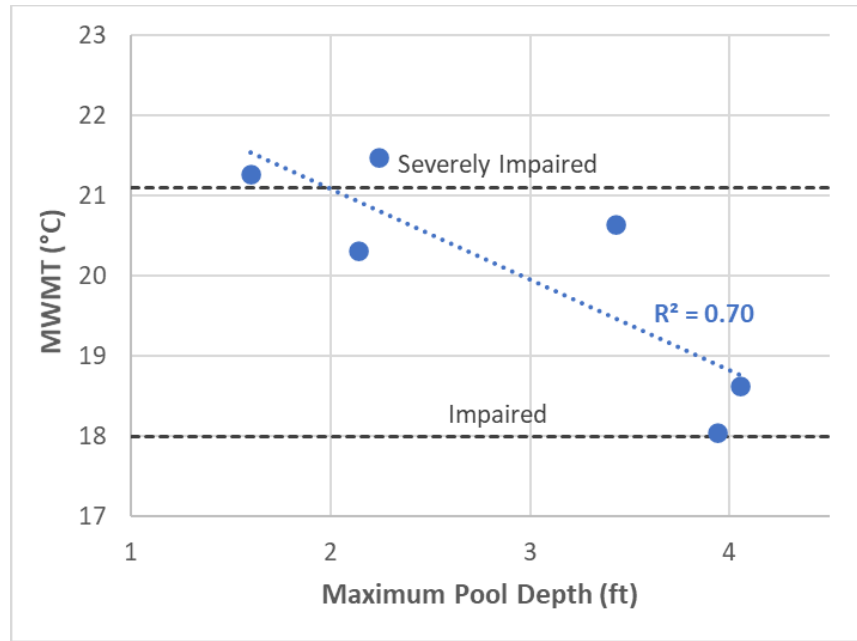
Figure 65: Relationship between maximum residual pool depth and 2017 MWMT for six pools above and below Humbug Creek, data from CDFW.
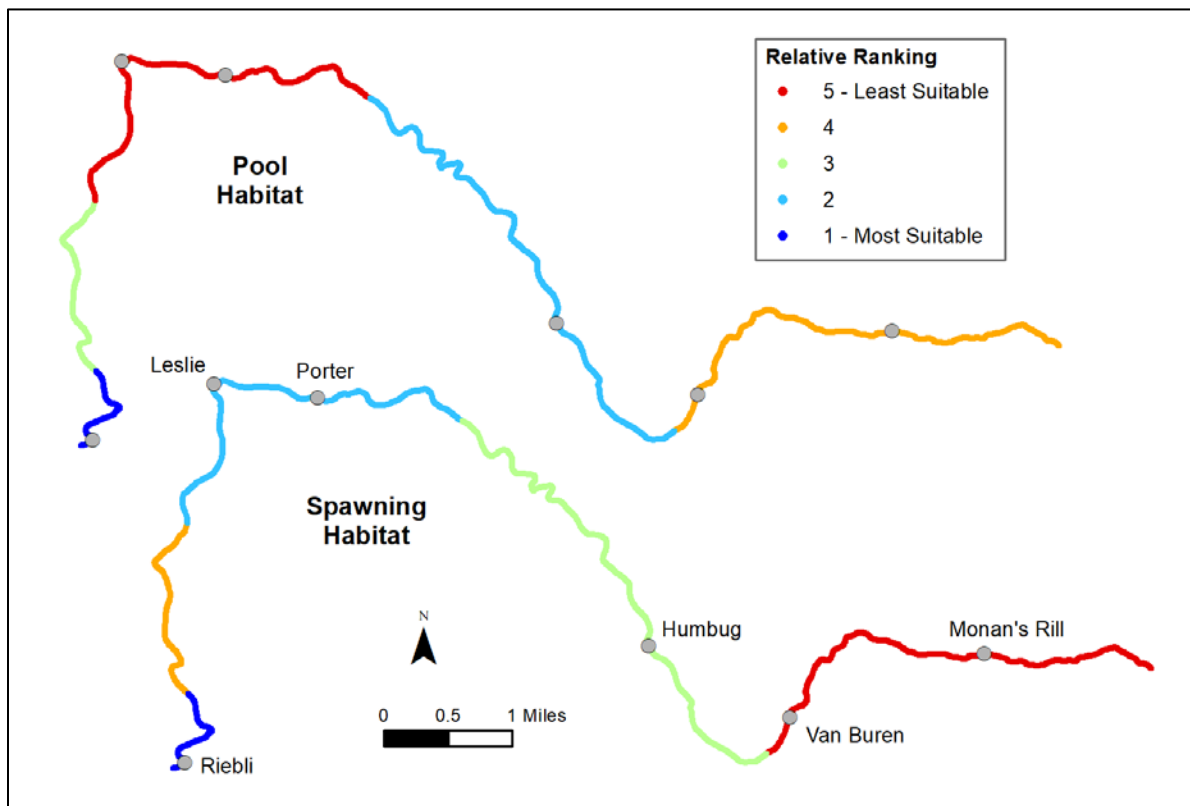
Figure 66: Pool and spawning habitat quality ranking based on the 1996 CDFW Stream Inventory Report.

Table 14: Summary of various pool and spawning habitat indicator metrics compiled from the 1996 CDFW Stream Inventory Report and used to develop the rankings presented in Figure 66.

CDFW reach #	Pool Habitat Indicators								Spawning Suitability Indicators		
	Pools as % of total length	Pools >3-ft as % of total length	Mean maximum residual depth (ft)	Residual maximum depth (ft)	Mean residual pool volume (ft^3)	Mean Shelter Rating	% occurrence of LWD	Pool Ranking	% gravel dominant	% embedded-ness 1 or 2	Spawning Ranking
6	39%	7%	2.0	5.0	379	47	3.1	**4**	14	1	**5**
5	37%	11%	2.5	8.1	751	42	1.0	**2**	12	33	**3**
4	32%	8%	2.2	3.9	784	28	2.7	**5**	32	33	**2**
3	34%	12%	2.7	5.7	1,412	33	0.2	**3**	19	19	**4**
2	49%	11%	2.6	8.9	2,562	38	1.0	**1**	33	64	**1**
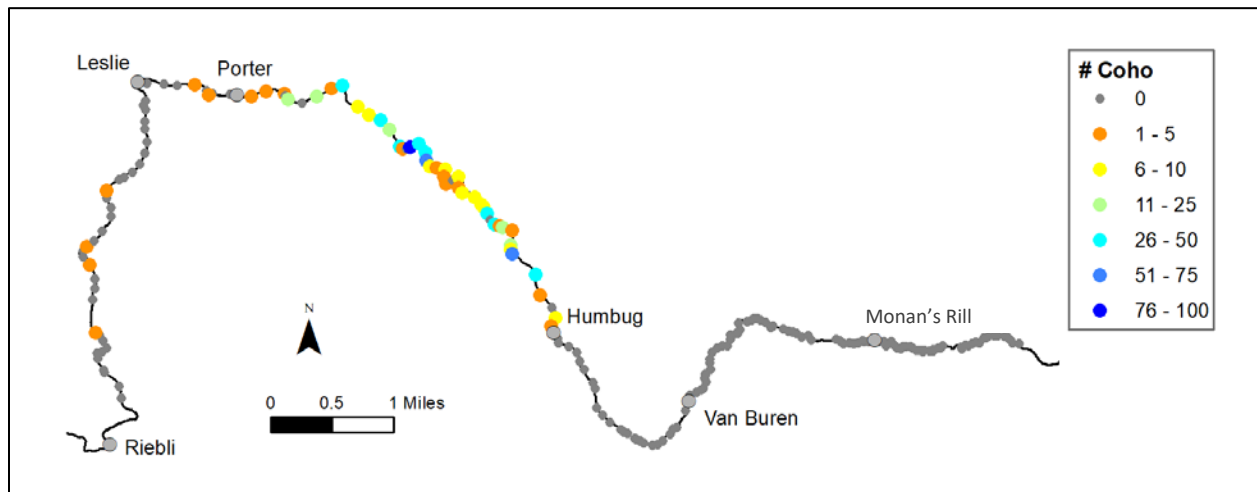
Figure 67: Snorkel survey data showing the distribution of juvenile coho observed in Mark West Creek during June/July of 2019, data from CA Sea Grant and Sonoma Water.

Restoration Prioritization & Recommendations

The overall salmonid habitat classification identifies a ~four mile reach of Mark West Creek between about 0.2 river miles upstream of Alpine Creek (~0.5 miles downstream of Van Buren Creek) and about two river miles upstream of Porter Creek as providing the best overall habitat for salmonids in the watershed (Figure 68). This reach (hereafter referred to as the high priority reach) is considered most suitable because it represents the best combination of flow and water temperature conditions and is also consistent with available data and observations about other

indicators of habitat quality such as pool and spawning conditions. Upstream of this reach, no more than one of the four established flow criteria are met, spawning conditions are suboptimal, and natural bedrock controls limit deep pool development and pose migration challenges. The two-mile reach upstream of Porter Creek experiences very high temperatures (>23.1 C) which may be lethal for salmonids and portions of this reach also experience very low RCTDs and periodic pool disconnection making overall conditions problematic for juvenile salmonids. We are aware of anecdotal reports of steelhead trout using the reach upstream of Van Buren Creek, despite the evidence of poor habitat. Less is known regarding temperature conditions farther downstream below Porter Creek, however it is unlikely that conditions improve dramatically and high stream power in this reach is expected to be problematic for spawning success owing to risk of redd scour.

Although the high priority reach we identified (see Figure 68) has the highest overall habitat quality in the watershed, it is still impaired with respect to both flow and temperature, and pool habitat is also likely limited by insufficient cover and large wood. Most of the coho observed in the watershed in recent monitoring were in this reach, further supporting the importance of this reach. Although not the focus of this study, field observations suggest there are multiple opportunities for enhancing off-channel habitat (SRCD has completed a design for an off-channel habitat design project in the reach) and improving pool habitat with LWD projects within this critical reach. We recommend that restoration projects aimed at enhancing both pool and off-channel habitat be implemented in this high priority reach where they are likely to provide the greatest benefits to salmonids.

Additional data and analyses are required to better understand the controls on stream temperatures; nevertheless, our preliminary assessment of available data suggests that daily and seasonal fluctuations in temperatures are driven primarily by fluctuations in incoming solar radiation rather than by quantity of streamflow. Preliminary evidence suggests that deeper pools maintain significantly lower water temperatures than surrounding habitats. The degree of temperature-impairment in the identified high priority reach is severe enough that salmonid survival may only be possible in a relatively small number of deeper pools capable of providing cold-water refugia. Given the importance of water temperature for salmonid survival in Mark West Creek, actions to increase shading through riparian vegetation projects and actions to maintain and enhance deep pools with good cover are likely to provide the greatest benefits for salmonids in Mark West Creek. Additional water temperature investigation is also warranted to better understand the controls on water temperatures and identify the most critical pool habitats within the identified ~4-mile high priority reach.
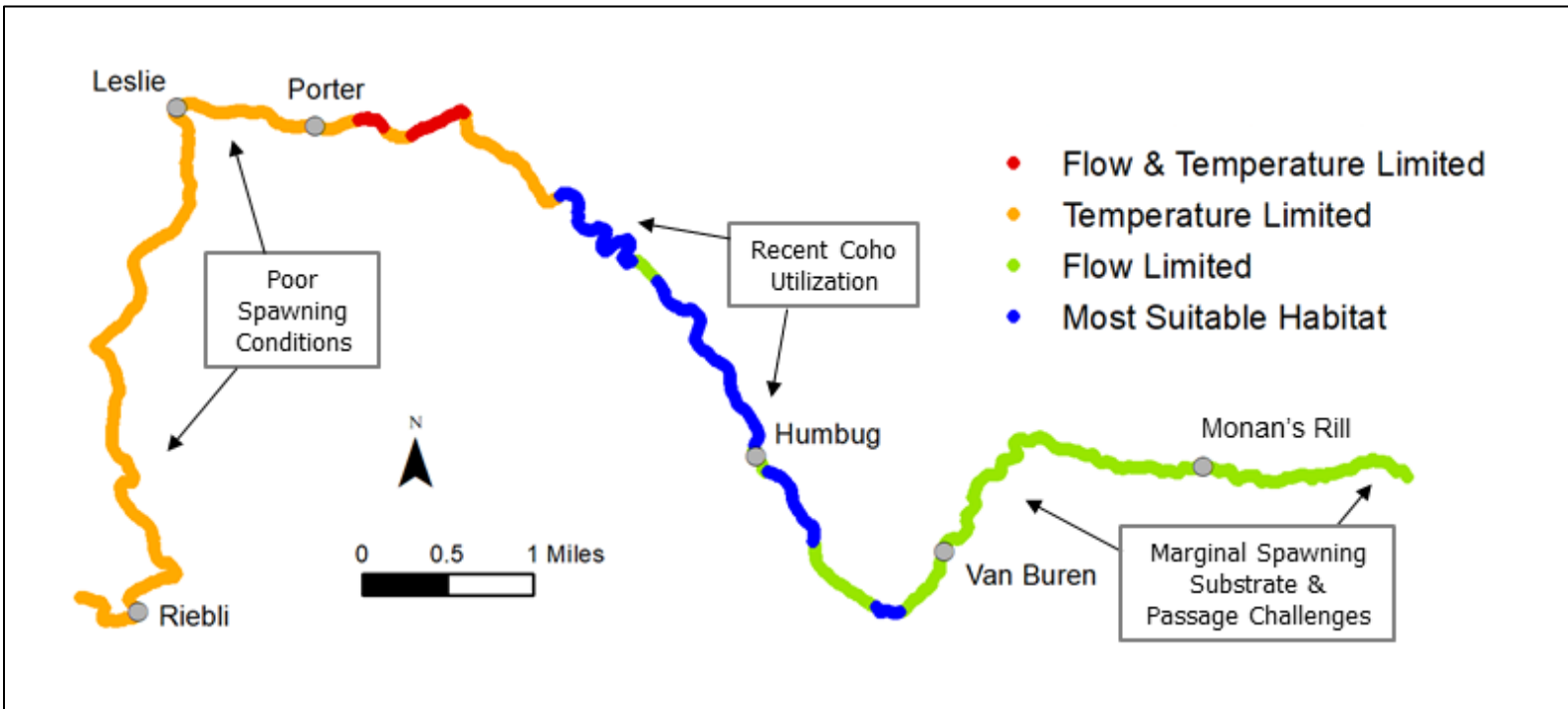
Figure 68: Final overall habitat suitability classification for Mark West Creek identifying the high priority reaches with the most suitable overall habitat conditions in blue.

Chapter 8 – Scenario Analysis

Overview

Efforts to sustain and enhance streamflow conditions have become a recent focus of restoration practitioners working in tributaries of the lower Russian River. Some actions have already been implemented such as pond and flow release projects in Green Valley, Dutch Bill, and Porter Creek (not the Porter Creek in Mark West watershed), and rainwater and diversion storage projects aimed at reducing dry season water use in Mark West Creek watershed and other tributaries. On the other hand, the watershed is subject to increasing water use pressure as new vineyard, winery, cannabis, and residential development projects are proposed, and local and state regulatory agencies are grappling with how best to regulate new groundwater use to avoid detrimental effects on streamflows and associated instream habitat. These challenges are further complicated by ongoing global climate change and the uncertainties associated with future hydrologic conditions. There is a clear need to be able to quantitatively evaluate the relative benefits of various flow enhancement strategies as well as the cumulative effects of land development and water-use on the landscape, and to do so within the context of future climate predictions so that more informed and effective management outcomes can be achieved.

To assist in meeting this need, we developed a series of model scenarios designed to provide an understanding of the hydrologic sensitivity of various hypothetical management and restoration actions as well as the effects of global climate change.   There are a total of 19 scenarios grouped in four primary categories: Water Use, Land/Water Management, Climate Change, and Mitigated as described in detail below (Table 15). Each scenario was implemented by changing one or more model inputs and comparing model results to existing hydrologic conditions as simulated with the calibrated model described in previous chapters.

Approach

Water Use Scenarios

Three water use scenarios were developed to estimate the cumulative effects of diversions and groundwater pumping in the watershed: 1-No Diversions, 2-No Groundwater Pumping, and 3-No Water Use. Implementation of these scenarios was a simple matter of turning off well and diversion inputs in the model. Irrigation associated with wells and diversions was also turned off. To examine the factors that influence the degree to which a given well results in streamflow depletion, we developed four additional scenarios where we turned off between 125 and 150 wells (~17% of all wells) based on various criteria (Figure 69). These scenarios included: 2B-wells located within 500-ft of a stream and screened entirely within the upper 200-ft of aquifer material, 2C-wells located within 500-ft of a perennial spring (as simulated in the existing conditions model) regardless of screen depth, 2D-wells screened in tuffaceous materials in the upper 300-ft of aquifer material, and 2E-wells located more than 1,200-ft from a stream or spring, not completed in tuffaceous materials, and not screened in the upper 200-ft of aquifer material. Minor adjustments were made to the selected well distributions to allow for an approximately equal volume of pumping between the four scenarios (Figure 69).

Table 15: Overview of the scenarios evaluated with the MWC hydrologic model.

Scenario Category	Scenario #	Scenario Name	Brief Description
Water Use	1	No Diversions	All surface water diversions turned off
	2	No Groundwater Pumping	All groundwater pumping turned off
	2B	No Pumping Near Streams	Wells within 500-ft of streams and screened in upper 200-ft turned off
	2C	No Pumping Near Springs	Wells within 500-ft of springs turned off
	2D	No Pumping From Tuff	Wells screened in surficial tuffaceous materials turned off
	2E	No Distal Pumping	Wells distal to streams/springs/tuff and not screened in upper 200-ft turned off
	3	No Water Use	All surface diversions and groundwater pumping turned off
Land/Water Management	4	Forest Management	Forest treatment on 7,054 acres of oak and Douglas Fir forests
	5	Grassland Management	Application of organic matter on 2,874 acres of grasslands
	6	Runoff Management	Manage runoff from 310 acres of developed lands to maximize infiltration
	7	Summer Pond Releases	Release water from three ponds with a total release of 0.19 cfs from June 15th to Sept 15th
	7B	Spring Pond Releases	Release water from three ponds with a total release of 0.82 cfs from May 7th to May 28th
	8	Combined Management	Combination of Scenarios 4 through 7
Climate Change	9	CNRM Climate Change	2070-2099 timeframe future climate as predicted by the CNRM model under the rcp8.5 emmisions pathway
	10	CCSM4 Climate Change	2070-2099 timeframe future climate as predicted by the CCSM4 model under the rcp8.5 emmisions pathway
	11	GFDL Climate Change	2070-2099 timeframe future climate as predicted by the GFDL model under the SRES B1 emmisions pathway
	12	MIROC esm Climate Change	2070-2099 timeframe future climate as predicted by the MIROC esm model under the rcp8.5 emmisions pathway
Mitigated	13	GFDL & Pond Releases	Combination of Scenarios 11 & 7 or 7B
	14	GFDL & Combined Management	Combination of Scenarios 11 & 7 or 7B

Figure 69: Distributions of wells excluded in Scenarios 2B-2E.

<u>Land/Water Management Scenarios</u>
Six scenarios were developed to evaluate the potential streamflow enhancement resulting from large-scale application of landscape management actions including: 4-Forest Management, 5-Grassland Management, 6-Runoff Management, 7-Summer Pond Releases, 7B-Spring Pond Releases, and 8-Combined Management (Table 15).

Forest Management
In the aftermath of the 2017 Tubbs Fire which burned through a large swath of the watershed and the 2019 Kincade Fire which burned along the north edges of the watershed, there is a very high level of awareness and interest in managing forests for reduced fuel loads. Many of the oak woodlands in the watershed are experiencing encroachment by Douglas Fir, and many Douglas Fir forests are characterized by high tree densities and abundant ladder fuels. This scenario is designed to represent wide-scale application of forest treatment strategies such as thinning and controlled burning (both of which are already occurring in portions of the watershed) and the effects of forest treatment on hydrologic conditions and streamflows.

In consultation with long-time watershed resident and forest manager Rick Kavinoky, we performed a forest condition mapping exercise on the Monan's Rill community property in the upper watershed. We mapped boundaries for nine 0.3-0.7 acre forest stands selected to represent a range of species compositions and treatment needs (determined based on qualitative assessment of tree densities and health, ladder fuel conditions, and presence of encroaching species). We sampled the Leaf Area Index data discussed in Chapter 4 to determine the mean LAI for each of the nine plots. There was a clear relationship between the stand type/treatment need categories and the mean LAI (Table 16). We used these differences to identify forested areas needing treatment throughout the watershed and to adjust the LAI values in the model to reflect implementation of treatment work.

The forest mapping indicated that stands of Black Oak and Oregon Oak not requiring treatment had a mean scaled LAI value of 3.1 and that those stands requiring minor or major treatments had mean values of 4.8 and 9.2 respectively. Douglas Fir stands not requiring treatment had a mean scaled LAI value of 7.3 and those requiring minor or major treatment had mean values of 9.5 and 14.8 respectively. The existing conditions model uses these three forest condition categories for oaks and Douglas fir forests along with these threshold LAI values (see Chapter 4), and the scenario was implemented by simply changing all minor and major treatment areas to no treatment values. Current forest conditions in areas burned by the Tubbs Fire are not captured in the LiDAR-derived LAI data and treatment needs within the burn area are unknown but may be expected to be reduced. We excluded the area of higher severity burn used to represent the Tubbs Fire in the calibration model (see Figure 12) from the identified areas needing treatment.

We used the proportional changes in LAI determined for Black/Oregon Oak and Douglas Fir to delineate treatment categories and estimate LAI for other species of oaks and for mixed Douglas Fir/Tanoak forest which were not included in the mapping at Monan's Rill. We also reduced rooting depths by 10% in the treated areas to better represent changes in transpiration not

Table 16: Forest plots mapped at Monan's Rill and associated treatment needs and Leaf Area Index (LAI) values.

Plot #	Stand Type	Treatment Needed?	Scaled LAI
1	Douglas Fir	No	7.3
7	Douglas Fir	Minor	9.5
3	Douglas Fir	Major	12.9
6	Douglas Fir w/ Tanoak	Major	16.5
5	Black Oak	No	3.0
8	Oregon Oak	No	3.2
4	Black Oak w/ Encroaching Douglas Fir	Minor	4.6
9	Oregon Oak w/ Encroaching Douglas Fir	Minor	4.9
2	Oregon Oak w/ Encroaching Douglas Fir	Major	9.2
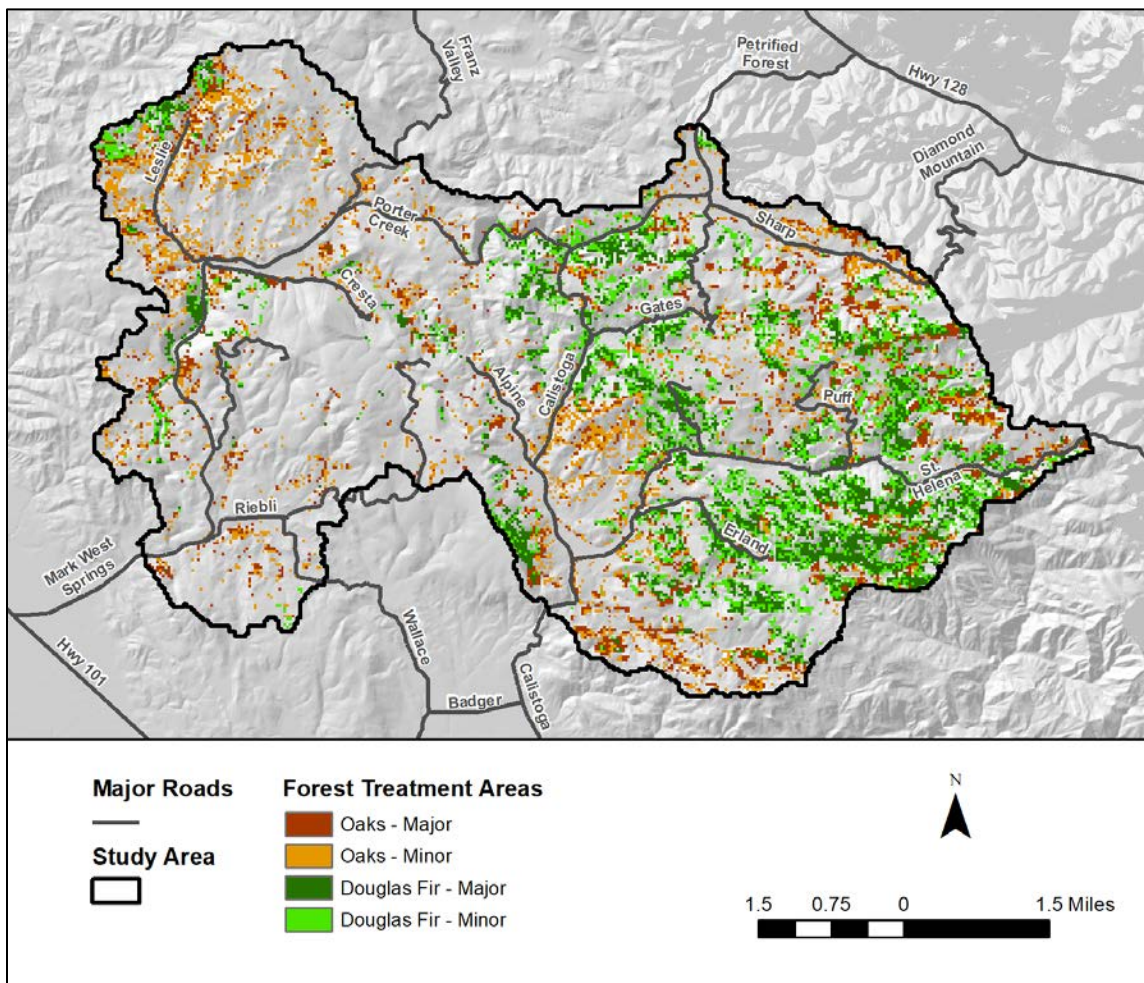
Figure 70: Areas of oak and Douglas Fir forest included as treated in the forest management scenario (Scenario 4).

captured by the LAI changes. The effects of forest treatment on other parameters such as overland roughness coefficients and detention storage are more uncertain and were assumed not to be affected by treatment for the purposes of this analysis. There are a total of 7,054 acres of treated forest represented in the model scenario which was divided approximately equally between various species of oaks (3,428 acres) and Douglas Fir (3,626 acres) (Figure 70).

Grassland Treatment

Increasing Soil Organic Carbon (SOC) on grasslands through compost application or strategic grazing practices has been identified as an important strategy for sequestering carbon (e.g. Ryals & Silver, 2013; Zomer et al., 2017). In addition to carbon sequestration benefits, increasing SOC may result in hydrologic benefits through increases in soil water availability and associated effects on seasonal soil water deficits and groundwater recharge. This scenario is designed to examine the potential hydrologic effects of large-scale adoption of grassland management practices designed to increase SOC. We assumed a 3% increase in SOC would be achievable (Flint et al., 2018) and related that change in SOC to a change in soil moisture contents at saturation, field capacity, and the wilting point based on data from 12 studies compiled by Minasny & McBratney (2018).

We implemented the grassland treatments in all grasslands in the model with more than a 2-acre contiguous area as identified in the fine-scale vegetation mapping (SCVMLP, 2017) covering a total of 2,874 acres (Figure 71). These grasslands were located in 14 different soil types as represented in the model (see Figure 15), and we classified each as fine, medium, or coarse and applied the associated mean estimates of the change in moisture contents from a 1% increase in SOC from Minasny & McBratney (2018). We scaled the estimates up to reflect a 3% increase in SOC which resulted in increases in soil moisture content at saturation, field capacity, and the wilting point of 0.10-0.14, 0.04-0.07, and 0.02-0.03 respectively, and increases in available water capacity (AWC) of 0.044-0.068. These estimates are generally consistent with the changes in AWC estimated for a 3% increase in SOC for soils of similar textures by Flint et al., (2018) which were based on the work of Saxton & Rawls (2006).

Runoff Management

Managing runoff from rooftops and impervious areas around residential and other developed areas to encourage infiltration has been recognized as an important best management practice for new development and is commonly referred to as Low Impact Development (LID). Most developed areas in Mark West Creek watershed were constructed prior to adoption of LID techniques. Traditional runoff management, on the other hand, is more likely to encourage runoff to flow quickly away from infrastructure and towards receiving water bodies via downspouts, drains, and ditches. This scenario is designed to examine the potential hydrologic benefits of large-scale adoption of LID practices on existing developed lands in the watershed.

We identified areas of contiguous impervious surface in the watershed from the developed category in our model land cover data. This spatial data is based on non-roadway impervious areas identified in the fine-scale vegetation map and resampled onto the 0.5-acre model grid.
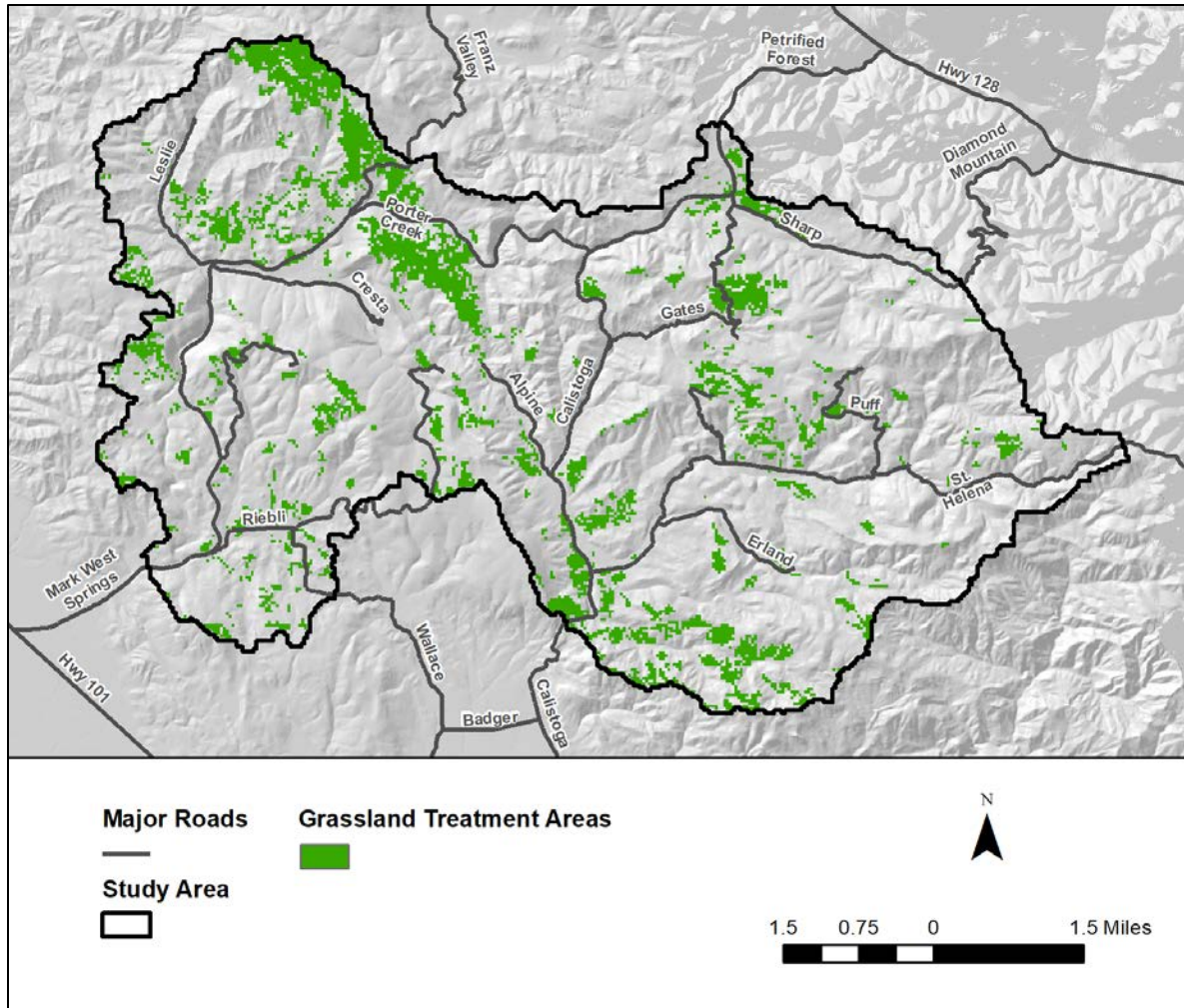
Figure 71: Treated grasslands included in the grassland management scenario (Scenario 5).

The resampling results in the exclusion of smaller impervious areas and the identification of the larger contiguous impervious areas most suitable for runoff management projects with potentially significant benefits. Roads are not represented in the scenario, although large-scale management of road runoff could have significant additional hydrologic benefits beyond what was simulated here. Development is most highly concentrated within the Riebli Creek watershed which is not considered to have high habitat value and contributes flow to Mark West Creek well downstream of the high priority reach. For these reasons, and to avoid dramatically increasing the scale of the scenario for potentially minimal benefit, we excluded Riebli Creek watershed from the analysis.

The developed areas represented in the scenario total 310 acres (Figure 72) which is about 76% of the total non-roadway impervious area in the watershed outside of the Riebli Creek drainage. There are multiple strategies possible for encouraging infiltration of runoff from these lands including use of level spreaders, bioswales, or infiltration basins. The most appropriate strategy
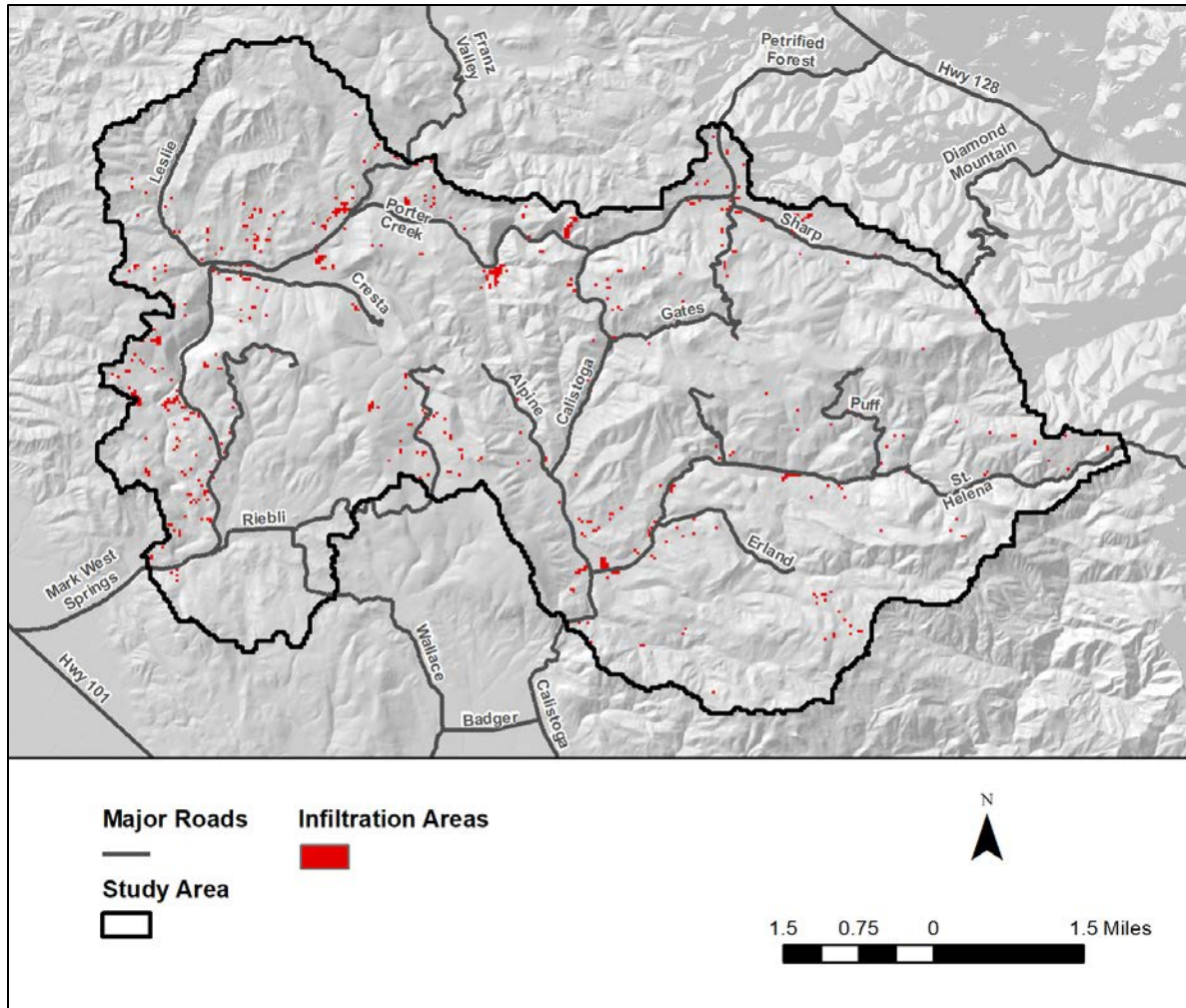
Figure 72: Developed areas included in the runoff management scenario (Scenario 6).

and design for a given location is highly site-specific and implementing the details of these stormwater management features is not practical at the 0.5-acre grid scale used in the model. Thus, for the purposes of this regional planning-level study we simply assumed that practices could be implemented to prevent all runoff generated directly from the identified developed lands from leaving the site. The scenario was implemented in the model by preventing runoff from entering or leaving each area through the use of the separated overland flow area option, and allowing water to pond, infiltrate, and evapotranspire according to the precipitation patterns and soil and evapotranspiration properties present at a given site.

The largest storm event in the 10-yr simulation was approximately a 10-yr event based on comparison to NOAA Atlas 14 precipitation frequency estimates. Thus, for projects to be equivalent to the model scenario they would need to be able to handle the peak flows and runoff volumes from a 10-yr storm. The model results indicate that in the upper watershed the 48-hr volume from this event over a 0.38 acre average per parcel developed area would be about 0.19

to 0.24 ac-ft. This would require a native soil basin on the order of 2,300 ft^2 or a gravel-filled basin of about 6,700 ft^2. These basins are large but likely feasible in many cases given the five acre average parcel size. Runoff management projects of a smaller scale are also possible; however, the goal of this scenario is consistent with the other scenarios in its focus on estimating the maximum potential benefits of runoff management projects.

Pond Releases

Releasing water from existing ponds has been recognized as a potentially important strategy for enhancing streamflows in the lower Russian River and several flow release projects have been implemented in recent years in Green Valley and Dutch Bill creeks among other locations. Most of the ponds in the MWC watershed are too small to allow for a viable release project, but we identified at least four ponds that appear large enough for such projects, and simulated releases for three of them. Out of respect for the privacy of landowners we are identifying these ponds only by their approximate locations. Available storage volumes for releases are approximate and were estimated using the LiDAR-captured water surface elevations as the late-summer residual (after water use and infiltration/evaporation losses) storage levels and a simple relationship between dam height approximated from the LiDAR and pond storage (USACE, 2018).

The three ponds include one in upper Mark West Creek with approximately 31.9 ac-ft of residual storage, one in upper Humbug Creek with approximately 5.2 ac-ft of residual storage, and one in upper Mill Creek with approximately 30.9 ac-ft of residual storage (Table 17). None of these ponds have significant consumptive water uses associated with them, therefore releasing water to augment streamflow is not expected to require new replacement water sources. Landowners we spoke with expressed concerns about fully depleting ponds because of the desire to maintain recreational and aesthetic value and maintain an emergency water source in the event of wildfire. To address these concerns, we have assumed that only half of the available residual storage could be released and the other half would be retained in storage for other uses. We also examined the simulated runoff volumes contributing to each pond and found that there is ample winter runoff to replenish the relatively small released volumes even during drought conditions and under future climate change scenarios.

We developed two flow release scenarios, one focused on enhancing summer juvenile rearing habitat (Scenario 7) and one focused on enhancing spring smolt outmigration (Scenario 7b). The summer release covers a 92-day period each year between June 15th and September 15th and release rates ranged from 0.014 – 0.088 cfs for a total release rate of ~0.19 cfs. The spring release covers a 21-day period each year between May 7th and May 28th and release rates ranged from 0.063 to 0.383 cfs for a total release rate of ~0.82 cfs (Table 17). These periods were selected based on review of historical conditions and targeted to increase minimum flow conditions during summer and the later portion of the primary outmigration period. We did not attempt to optimize the timing and release rates for this regional planning-level study, however it is likely that benefits greater than those simulated in this study could be achieved through adaptively managing releases in conjunction with real-time streamflow data which is available at several locations from Sonoma Water.

Table 17: Overview of the pond release volumes and rates included in Scenarios 7 and 7b.

Location	50% of Residual Storage (ac-ft)	Sceanrio 7 Summer Release Rate (cfs)	Scenario 7b Spring Release Rate (cfs)
Upper Mark West Creek	16.0	0.087	0.383
Upper Humbug Creek	2.6	0.014	0.063
Upper Mill Creek	15.5	0.085	0.371
Total	**34.0**	**0.187**	**0.817**

Climate Change Scenarios

Four model scenarios were developed to evaluate the effects of future climate changes on hydrologic and aquatic habitat conditions in the upper Mark West Creek Watershed. Each of these scenarios was based on projections of future climate for the 2070-2099 timeframe derived from a Global Circulation Model (GCM) scenario. The scenarios reflect changes in precipitation and temperature as predicted by each GCM, but do not address other aspects of climate change that may affect hydrologic and habitat conditions such as long-term changes in vegetation or irrigation demands that may occur in response to a modified future climate regime.

Global Circulation Model Selection

The selection of the four GCM scenarios ('futures') was based largely on the recommendations from the Climate Ready North Bay Vulnerability Assessment and the North Coast Resource Partnership's climate planning efforts (Micheli et al., 2016 & 2018). The vulnerability assessment selected a subset of six GCM futures from an ensemble of 18 futures analyzed by the USGS using the Basin Characterization Model (BCM) (Flint et al., 2013; Flint & Flint, 2014). These 18 futures were selected from the approximately 100 GCM futures included in the Intergovernmental Panel on Climate Change's (IPCC) Fourth and Fifth Assessment Reports (IPCC 2007; 2014) using statistical cluster analysis. The North Coast Resource Partnership study selected six of the eighteen futures included in the BCM, and our analysis focuses on four of these six (Figure 73 & Table 18).

The selection of these futures was designed to represent the full range of plausible changes to precipitation and temperatures, and to include a scenario representative of the mean projections (Micheli et al., 2016 & 2018). Three of the futures represent the "business as usual" emissions scenario (rcp 8.5) adopted by the IPCC's Fifth Assessment Report (IPPC, 2014). This pathway assumes high population growth and a slow adoption of clean and resource efficient technologies with atmospheric carbon dioxide concentrations rising to 936 ppm by 2100 (Hayhoe et al., 2017). One of the futures represents the "highly mitigated" emissions scenario (sres B1) reflecting a future with low population growth and the introduction of clean and resource efficient technologies; this pathway is comparable to rcp 4.5 with atmospheric carbon dioxide concentrations rising to 650 ppm by 2100 (Hayhoe et al., 2017).

Table 18: Overview of the four climate change scenarios evaluated with the MWC hydrologic model.

	GCM	Emissions Scenario	Change in Annual Precipitation (%)	Change in Maximum Temperature (°F)
Scenario 9	CNRM	rcp 8.5 (business as ususal)	37%	6.3
Scenario 10	CCSM 4	rcp 8.5 (business as ususal)	8%	5.4
Scenario 11	GFDL	sres B1 (highly mitigated)	-14%	3.7
Scenario 12	MIROC esm	rcp 8.5 (business as ususal)	-21%	11.0

Scenario 9 is a "Warm & High Rainfall" scenario based on the CNRM rcp 8.5 future, which projects a 37% increase in average annual precipitation and a 6.3°F increase in average maximum temperatures by the 2070 - 2099 timeframe relative to 1981 – 2010 (Table 18). Scenario 10 is a "Warm & Moderate Rainfall" scenario based on the CCSM4 rcp 8.5 future, which is close to the ensemble mean of the 18 futures selected for use in the BCM model and projects an 8% decrease in average annual precipitation and a 5.4°F increase in average maximum temperatures. Scenario 11 is a "Warm & Low Rainfall" scenario based on the GFDL sres B1 future which projects a 14% decrease in average annual precipitation and a 3.7°F increase in average maximum temperatures (Table 18; Figure 73). Lastly, Scenario 12 is a "Hot & Low Rainfall" scenario based on the MIROC esm rcp 8.5 future, which projects a 21% decrease in precipitation and an 11.0°F increase in temperature (Table 18).

Methodology

For all scenarios, precipitation and minimum and maximum temperature timeseries were derived from daily data from the World Climate Research Program's Coupled Model Intercomparison Project Phases 3 & 5 (CMIP3 & CMIP5) (USBR et al., 2013). The CMIP provides monthly and daily outputs from the GCMs included in the IPCC's Fourth and Fifth Risk Assessments statistically downscaled to a uniform 1/8th degree grid using a revised version of the bias corrected constructed analog method (BCCA v2).

Several studies have reported that GCMs are biased towards creating "drizzle" days with trace amounts of precipitation (Maurer et al., 2010). Mauer et al. (2010) claims that the BCCA method corrects this issue. However, when compared to observed precipitation records, downscaled precipitation timeseries still contained an un-representatively high number of days with trace precipitation. To address this documented issue, precipitation events with less than 0.02 in/day were removed from the precipitation timeseries. This removed between 50 and 105 trace events per year but changed average annual precipitation totals by only 0.6 – 1.2% over the 2070 - 2099 period. While this approach may not fully resolve the issue, it removes a
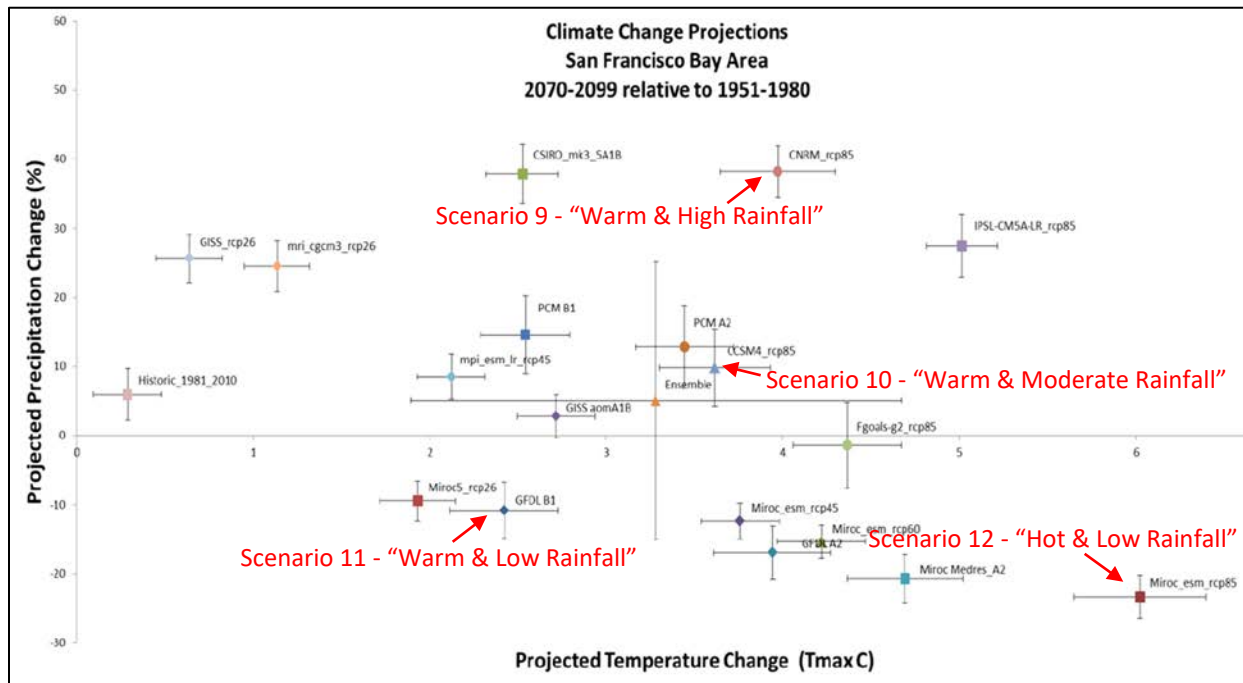
Figure 73: Projected regional changes in average annual precipitation and average maximum summer temperatures for the 18 GCMs analyzed using the Basin Characterization Model (BCM), modified from Micheli et al., 2016 to show the four scenarios included in this study.

significant number of trace precipitation events which if not filtered out could artificially increase simulated canopy interception and evapotranspiration.

Daily Potential Evapotranspiration (PET) timeseries were calculated from the CMIP minimum and maximum daily temperature timeseries using the Hargreaves-Samani Method (Hargreaves & Samani, 1982). These calculations used extraterrestrial solar radiation rates for a flat plane located at the model centroid and a KT value of 0.162 calibrated using reported temperature and evapotranspiration data from the Windsor CIMIS station. More details about the PET calculations can be found in Chapter 4.

As in the existing conditions model, precipitation and PET zone-based distributions were developed to account for the spatial variations in these parameters across the model domain. Precipitation zones are based on 1-inch average annual isohyets derived from the BCM 2070 - 2099 average annual precipitation dataset for each selected GCM future. Future PET distributions were created using the same methodology as the historic distribution discussed in the Chapter 4, in this case using average 2070 - 2099 monthly minimum and maximum temperature distributions from the BCM model. These distributions show similar spatial patterns to the historic distribution, although the range of values across each distribution varies significantly. Precipitation and PET timeseries were applied to these distributions using the same scaling factor approach as for historic conditions.

Scaling factors were calculated as the ratio of the value for each zone and the 2070 - 2099 means for the timeseries. Adjustments were made to the scaling factors applied for precipitation to correct for a high precipitation bias in the BCM dataset relative to historical conditions as observed at local climate stations (see Chapter 4 for further discussion). These adjustments were calculated such that simulated precipitation means preserve the percentage increases in mean annual precipitation between the 1981 – 2010 and 2070 – 2099 normals as estimated by the BCM.

To reduce computational requirements, each climate scenario uses timeseries from a continuous representative 10-year subset of the processed CMIP timeseries from the 2070 - 2099 period. These subsets were selected such that average annual precipitation was within 2% of the average annual precipitation estimated for the 2070 - 2099 normal for each future and such that each subset contained at least one extremely dry and one extremely wet year, as well as a multi-year drought (if present in the original 30-yr period). A summary of the annual and daily precipitation and PET inputs for the selected periods is shown in Figure 74-Figure 77. While the results of these scenarios will be compared against one another, it is not necessary for these time periods to match. GCMs simulate general climatic conditions, not specific weather events, and one would not expect conditions modeled for a given year to be comparable to conditions modeled for the same year using a different GCM.

Inputs Summary

Besides the changes in average annual precipitation and average maximum temperatures shown above in Table 18, the GCMs used as the basis for these scenarios predict several important inter- and intra-annual changes in precipitation and PET. Previous studies of large GCM ensembles have indicated that precipitation will become more volatile, that large precipitation events will become more frequent, and that the seasonal distribution of precipitation will concentrate in the core winter months (e.g. Swain et al., 2018). To assess the degree to which each of the selected GCM futures reflect these projected trends, several statistics were calculated. These include the frequency of historically wet and dry years (defined by the 80th and 20th percentile annual precipitation totals), the magnitude of large precipitation events (maximum 24-hr precipitation), and the seasonal distribution of precipitation (defined by the ratio of precipitation occurring during the core winter months of November - February and the peripheral months of October, March, and April). The baseline for these comparisons is the 2009-2019 simulation period, however as discussed in Chapter 4, conditions during this period are broadly representative of 1981-2010 conditions which is widely used as the baseline period for interpreting future climate changes.

The Scenario 9 (CNRM rcp8.5) future projects a general shift towards wetter conditions. Both the frequency and magnitude of wet years increases, as well as the frequency of higher intensity precipitation events (Table 19 & Figures 74-77). Much of this additional precipitation is projected during the core winter months, leading to a marked shift in the seasonal precipitation distribution. However, despite the large increase in average precipitation, the frequency and magnitude of dry years is projected to remain similar to historic conditions. Despite the low increase in average annual precipitation, the Scenario 10 (CCSM4 rcp8.5) future projects a large

increase in annual and seasonal variability (Table 19 & Figures 74-77). It projects the single highest annual precipitation total (80.2 in), the greatest inter-annual variability, and the strongest seasonal shift in precipitation towards the winter months. It also predicts individual dry years of similar frequency and magnitude to historical conditions, but more frequent multi-year droughts.

The Scenario 11 (GFDL sresB1) future projects a general shift towards drier conditions, with increases in both the frequency and intensity of droughts (Table 19 & Figures 74-77). Although the MIROC esm rcp8.5 future projects slightly drier average conditions, the GFDL sres B1 future projects the single driest year, with an average of 11.8 inches of precipitation. This future also projects the lowest precipitation intensities, with maximum daily rainfall totals of less than 2.0 in for most years. The Scenario 12 (MIROC esm rcp8.5) future also projects a general shift towards drier conditions with both the frequency and intensity of droughts increasing (Table 19 & Figures 74-77). Historically dry years are projected to become roughly twice as common and precipitation decreases by up to 30% during the driest years. Although no years with annual totals exceeding the historic 80th percentile are projected, moderately wet years with up to 47 inches of precipitation are still present. During these wetter years, maximum daily precipitation totals are projected to be similar to historic conditions, but much lower during normal and drier years.

Despite the large differences in future projections between the scenarios, all four scenarios share some commonalities. Regardless of the scenario, droughts are predicted to become more extreme and precipitation is predicted to have increased seasonality with more precipitation focused in the core winter months. Additionally, all four scenarios predict increases in PET which vary between scenarios based on the magnitude of the predicted increases in temperatures and represent increases of about 6-14% relative to historic conditions (Table 19 & Figures 74-77).

<u>Mitigated Scenarios</u>
To evaluate the scale of the predicted changes in hydrologic conditions under future climate relative to potential streamflow enhancement actions, we developed two mitigated scenarios. Scenario 13 combines the GFDL future climate simulation (Scenario 11) with the pond release scenarios (Scenarios 7 and 7B), and Scenario 14 combines the GFDL future climate with the combined management scenario (Scenario 8) (Table 15). To keep the number of scenarios to a reasonable level, we only ran the mitigation scenarios using future climate as predicted by the GFDL model. We selected this model because our results showed that it represented the second most extreme predictions of future changes in streamflows which we felt would provide the best overall picture of the degree of climate change induced impacts to streamflows that could be mitigated with the investigated management actions. A higher degree of mitigation would likely be possible if future climate more closely resembles the CNRM or CCSM4 model predictions and less mitigation would be possible if future climate more closely resembles the MIROC esm model predictions.

Table 19: Summary of key climate statistics for each climate scenario evaluated with the MWC hydrologic model.

	Historic	Scenario 9 CNRM	Scenario 10 CCSM4	Scenario 11 GFDL	Scenario 12 MIROC esm
Average Annual Precipitation (in)	36.0	49.3	38.9	30.9	28.6
Maximum Annual Precipitation (in)	61.2	75.2	80.2	46.9	47.3
Minimum Annual Precipitation (in)	19.5	18.6	17.6	11.8	13.3
Interannual Variability (in)	12.9	16.5	20.2	10.6	9.4
Frequency of 80th Percentile Historic Annual Precipitation	-	5	2	0	0
Frequency of 20th Percentile Historic Annual Precipitation	-	2	3	5	4
Seasonal Precipitation Distribution (Core:Periphery)	2.0	4.6	5.3	3.4	3.9
Maximum 24-hr Precipitation (in)	4.7	7.3	5.0	4.5	4.8
Average Annual PET (in)	45.4	50.1	49.5	48.0	51.7
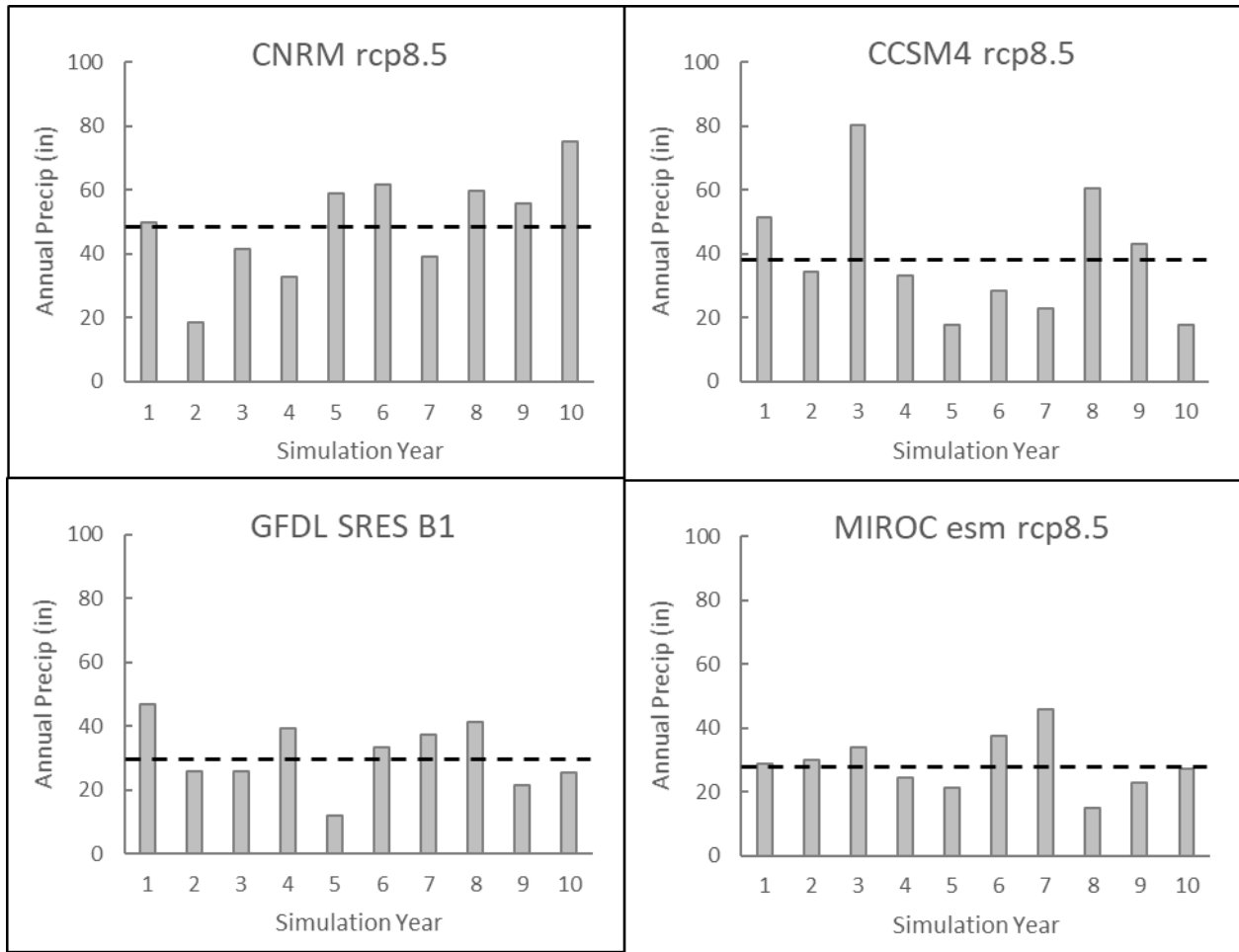
Figure 74: Spatially averaged annual precipitation within the model domain for each of the four selected climate scenarios (dashed black lines indicate the 2070-2099 mean).
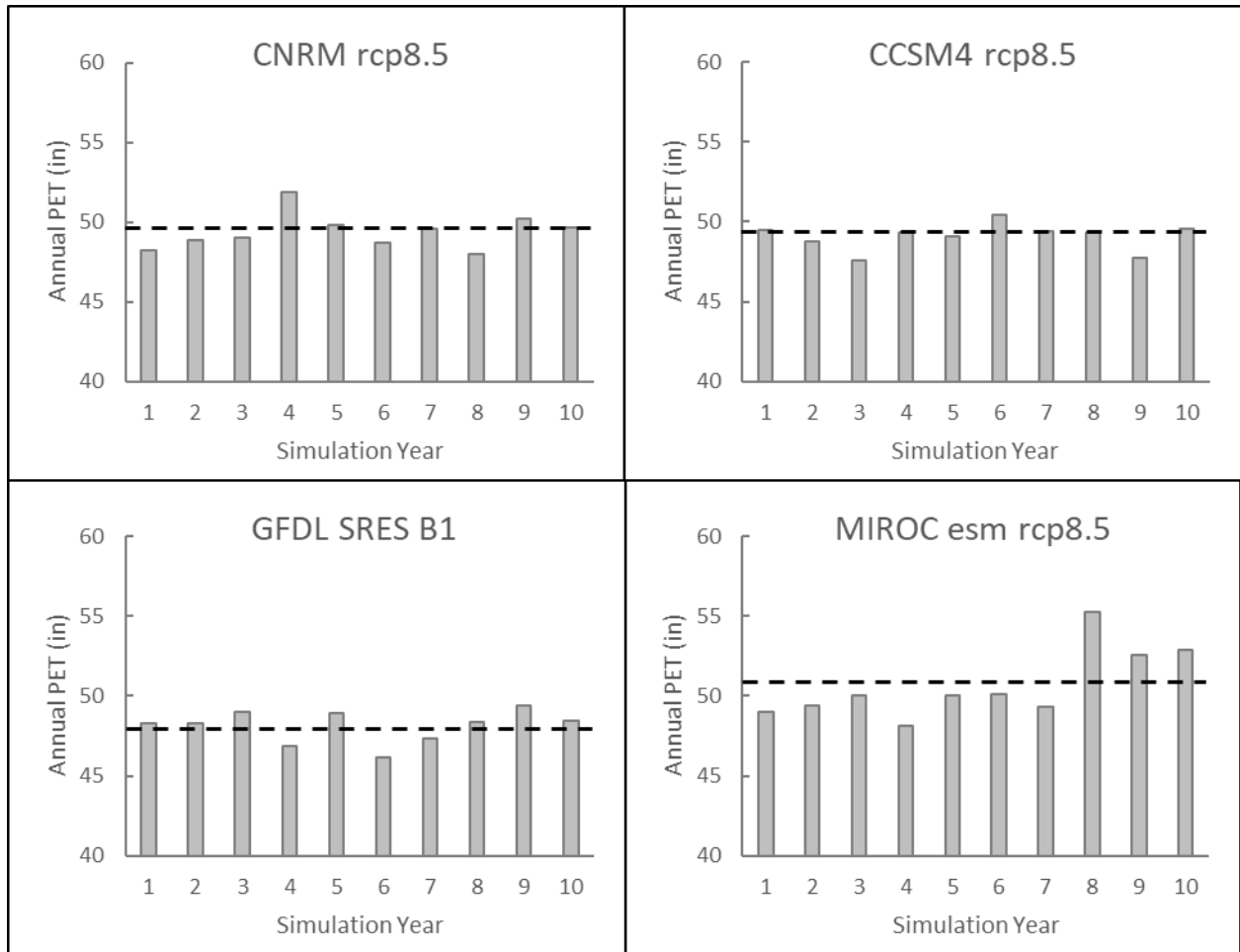
Figure 75: Spatially averaged annual Potential Evapotranspiration (PET) within the model domain for each of the four selected climate scenarios (dashed black lines indicate the 2070-2099 mean).
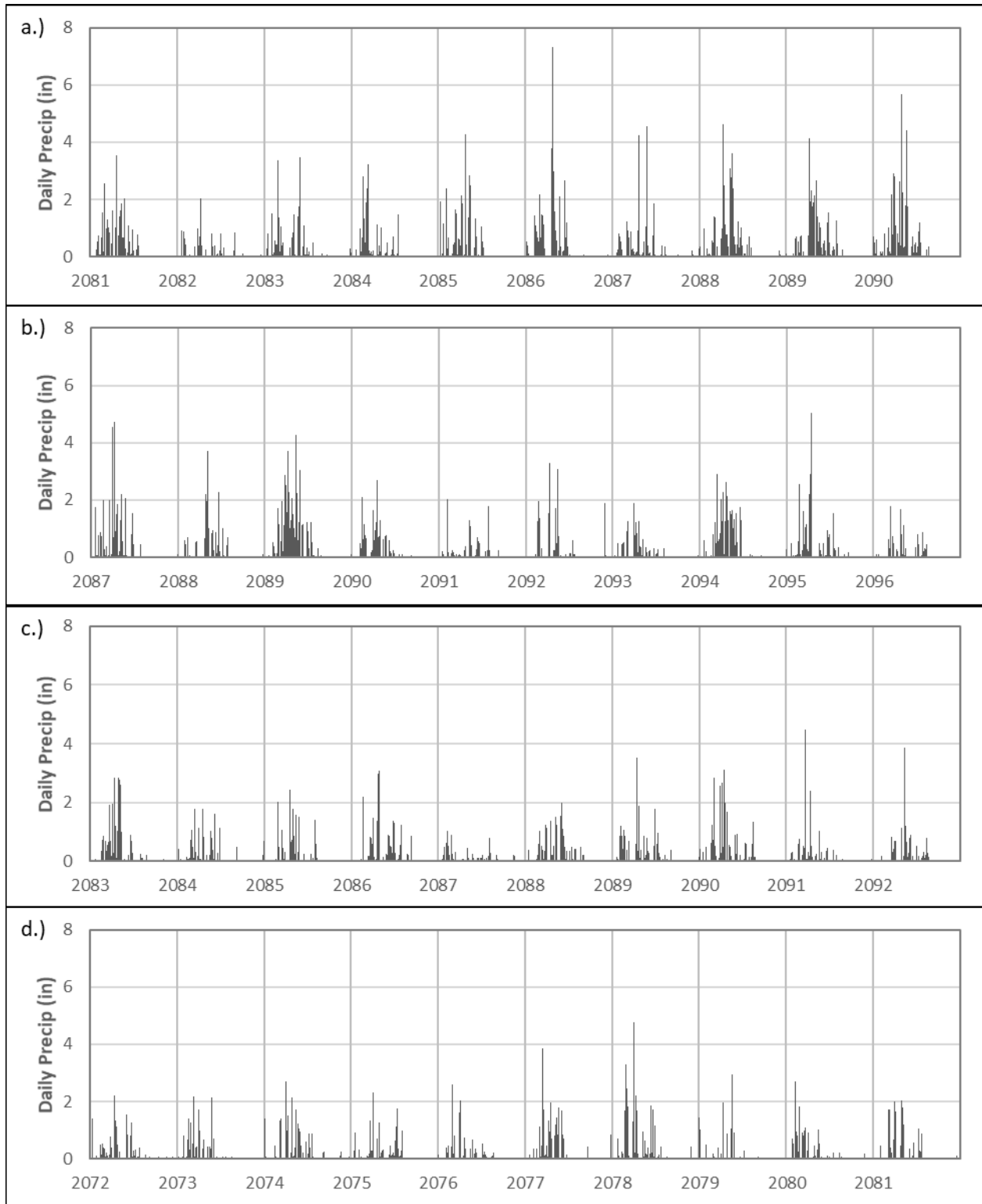
Figure 76: Spatially averaged daily precipitation used in scenarios (a) CNRM rcp8.5, (b) CCSM4 rcp8.5, (c) GFDL SRES B1, and (d) MIROC esm rcp8.5.
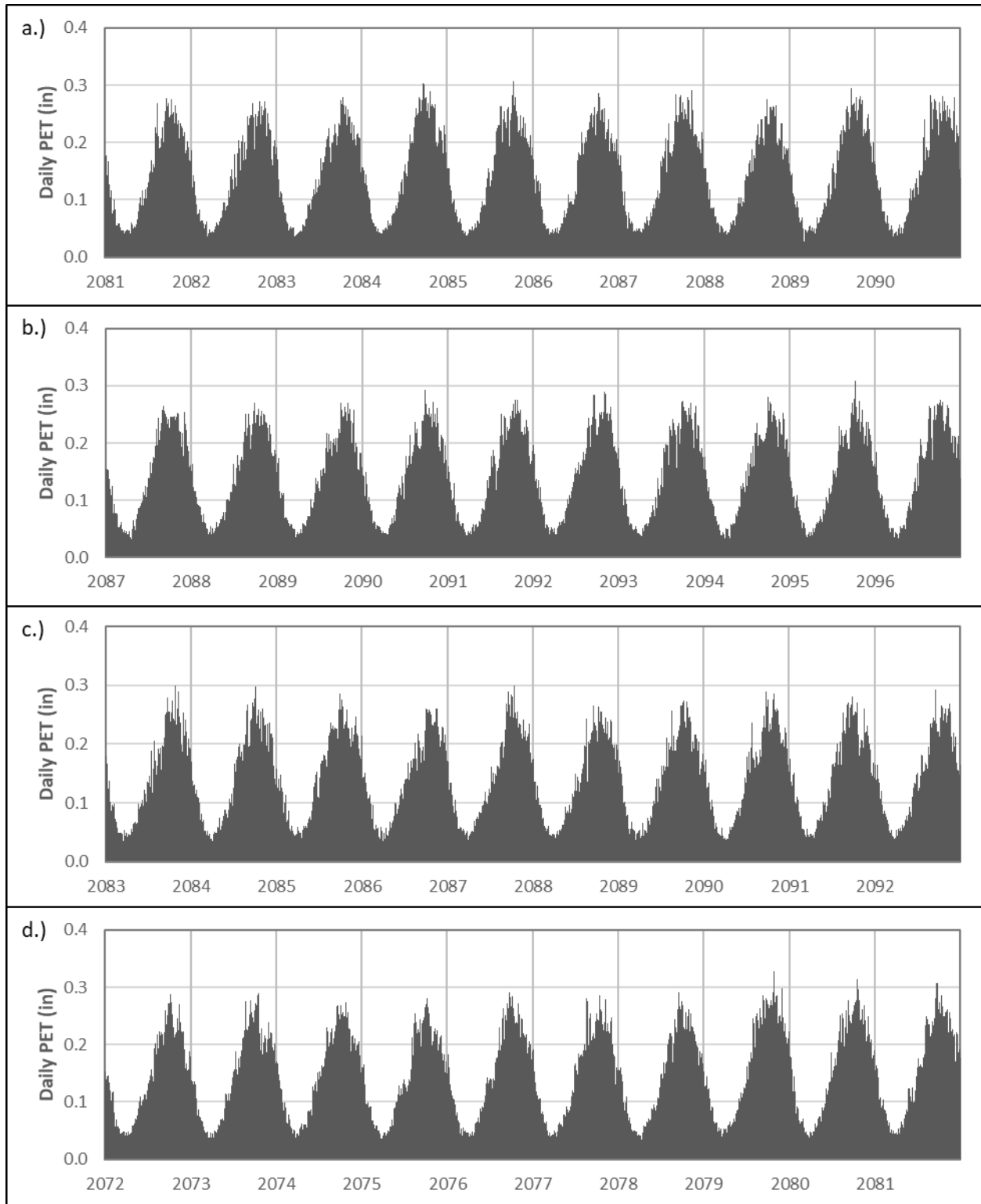
Figure 77: Spatially averaged daily Potential Evapotranspiration (PET) used in scenarios (a) CNRM rcp8.5, (b) CCSM4 rcp8.5, (c) GFDL SRES B1, and (d) MIROC esm rcp8.5.

Results

<u>Water Use Scenarios</u>

The no surface water diversion scenario (Scenario 1) revealed that the sustained cumulative effect of diversions in the watershed is relatively small. With diversions turned off, the average summer discharges increased by less than 0.01 cfs in most of the upper and middle reaches of Mark West Creek and by up to 0.03 cfs in the lowest reaches (Figure 78). The effects of diversions on mean springtime streamflow was similar but slightly greater than the summertime effects, with stream discharge increasing by 0.02-0.04 cfs at most locations downstream of Humbug Creek (Figure 81) with all diversions turned off. We compiled hourly discharge results to evaluate potential short-term diversion effects not captured with the mean summer discharge comparison. This revealed that diversions do have more significant short-term impacts on streamflow, with short-term increases in discharge under Scenario 1 of about 0.05 cfs upstream of Humbug Creek, 0.09 cfs downstream of Humbug Creek, and 0.07 cfs below Porter Creek (Figure 78).

The diversion impacts are discernable but minimal downstream of Monan's Rill and reach a maximum just downstream of Humbug Creek which has a high concentration of diversions (Figure 79). The timing of the simulated streamflow reductions is closely related to the model input assumptions regarding diversion timing and therefore the greatest changes occur on the first of each month when all diversions are active and are near zero during times when few diversions are active. Hence, it is likely that the short-term impacts are exaggerated given that the assumptions of coincident timing create a worst-case scenario. It is interesting to note that the fluctuations in flow throughout the summer due to other factors are generally larger than the fluctuations caused by diversions, therefore it would be very difficult or impossible to discern diversion impacts from examination of streamflow records alone (Figure 79).

The no groundwater pumping scenario (Scenario 2) revealed that the cumulative effect of groundwater pumping in the watershed is larger than that of surface water diversion but of modest magnitude. With groundwater pumping turned off, the average summer discharge increased by less than 0.01 cfs in the upper reaches of Mark West Creek and by up to about 0.06 cfs in the lowest reaches (Figure 80). Mean springtime discharge increases show a similar pattern to the summer increases with slightly larger changes (Figure 81). Examination of the water balance revealed that the aquifer system takes at least several decades to fully adjust to the change in pumping regime, and the reported flow increases represent the 10-yr period following 40-yrs of no pumping. Over the first 10-yr simulation cycle with no pumping, most of the volume that would have been pumped could be accounted for by increased groundwater storage, with only about 18% of the volume manifesting as increased groundwater discharge. During the fifth 10-yr cycle, the changes in storage were minimal and increased groundwater discharge accounted for about 76% of the pumped volume (Figure 82). Most of the remaining volume can be accounted for by increases in AET from the saturated zone and small decreases in recharge which serve to partially buffer the effects of pumping on streamflow (Figure 82).

We also examined the monthly changes in streamflow and other water balance components and found that volumetrically, the largest streamflow depletions occurred during December through April (~0.50 cfs at the watershed outlet) and the lowest rates occurred during July through September (0.06 cfs). This may seem counter-intuitive given that pumping rates peak in June and are at a minimum in January, however it is necessary to consider all of the effects of pumping on the water balance together to gain an understanding of the mechanisms behind the depletion seasonality. The largest month-to-month changes in the water balance occur as changes in storage. With pumping turned off and associated seasonal pumping drawdowns eliminated, not as much water enters storage during the recharge season resulting in more water available to contribute to groundwater discharge (Figure 83). Another significant but lesser effect is that higher groundwater elevations during the dry season result in more water available to riparian vegetation which serves to partially offset summer streamflow depletion through increases in AET from the saturated zone (Figure 83). This analysis suggests that strategies focused on deferring dry season pumping in favor of wet season pumping and storage (which may be effective in alluvial aquifers with short response time-scales) may not be very effective in bedrock aquifer settings like Mark West Creek. It is also important to note that the seasonal storage and AET effects from increasing levels of pumping may be expected to be asymptotic, and that since the total pumping volumes in the watershed are relatively low (~3% of annual infiltration recharge), the seasonality of streamflow depletion may be expected to become less pronounced under higher pumping stresses.

Results of the selective no pumping scenarios (Scenarios 2B-2E) indicate that the magnitude of summer streamflow depletion after 40-50 years of pumping does vary depending on distance from streams and springs, and likely also depending on well screen (perforated well casing) depth and hydrogeologic properties. To account for small differences in pumping volume reductions between the scenarios, we normalized the streamflow results by the change in pumping volume. Mean summer streamflow at the outlet of the watershed increased by 0.026 cfs per 100 ac-ft of pumping decrease for wells located within 500-ft of streams and screened within the upper 200-ft of aquifer material (Scenario 2B) (Table 20). This rate is approximately 137% of the rate determined for all wells from Scenario 2 (0.019 cfs/100 ac-ft of pumping decrease). The highest rate (0.029 cfs per 100 ac-ft of pumping decrease) was for wells located within 500-ft of springs (Scenario 2C). Wells screened within tuffaceous materials (Scenario 2D) showed streamflow effects similar to the average for all wells, and wells located more than 1,200-ft from streams and springs and not screened in the upper 200-ft of aquifer material (Scenario 2E) showed the smallest effects, with a rate of streamflow increase of 0.017 cfs per 100-ac-ft of pumping decrease which represents about 89% of the rate determined for all wells (Table 20).

This analysis suggests that proximity to springs and streams can be useful in determining the relative magnitudes of summer streamflow depletion within the 50-yr timeframe. However, it is important to note that all wells (including those distant from streams and screened at depth) may still be expected to result in streamflow depletion and the rate of depletion from near stream wells screened in the upper 200-ft was only about 1.7 times the rate for distant wells screened at depths greater than 200-ft (Table 20). It is also apparent that the 50-yr simulation

timeframe is not long enough for the system to fully adjust to a change in pumping regime, and over longer timeframes it may be expected that the differences between proximal and distal well impacts would decline.

Simulation results from the no water use scenario (Scenario 3) which represents conditions in the 10-yr period following 40-yrs without water use indicate that the cumulative effect of all surface and groundwater uses in the watershed is equivalent to approximately 8% of summer streamflow. With all water uses turned off, mean summer streamflow increased by 0.01 to 0.02 cfs upstream of Van Buren Creek, by 0.02 to 0.04 cfs between Van Buren and Porter Creeks, and by 0.04 to 0.09 cfs in the reaches downstream of Porter Creek (Figure 80).
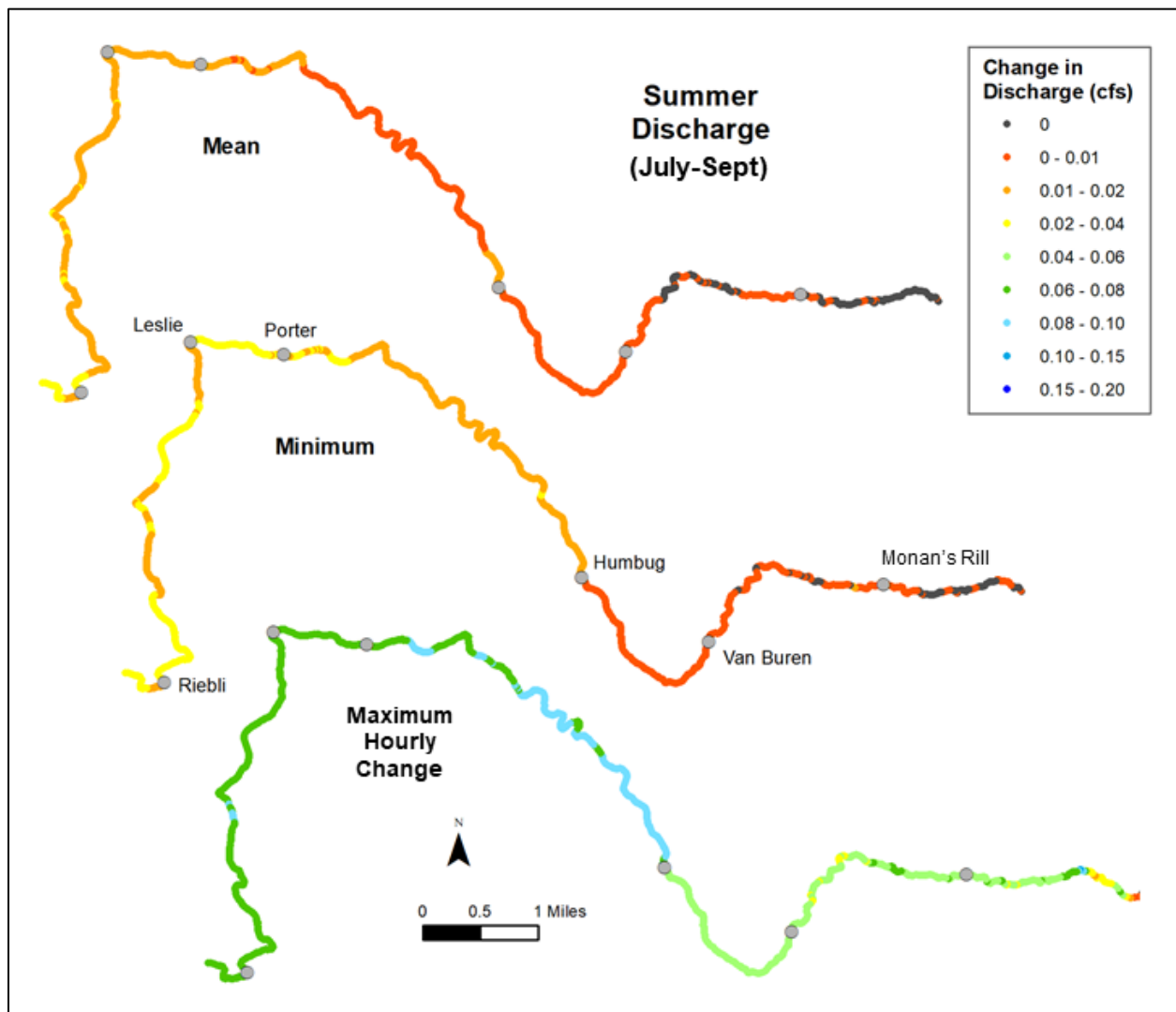
Figure 78: Changes to mean and minimum summer streamflow, and maximum hourly changes from cessation of all surface water diversions (Scenario 1).
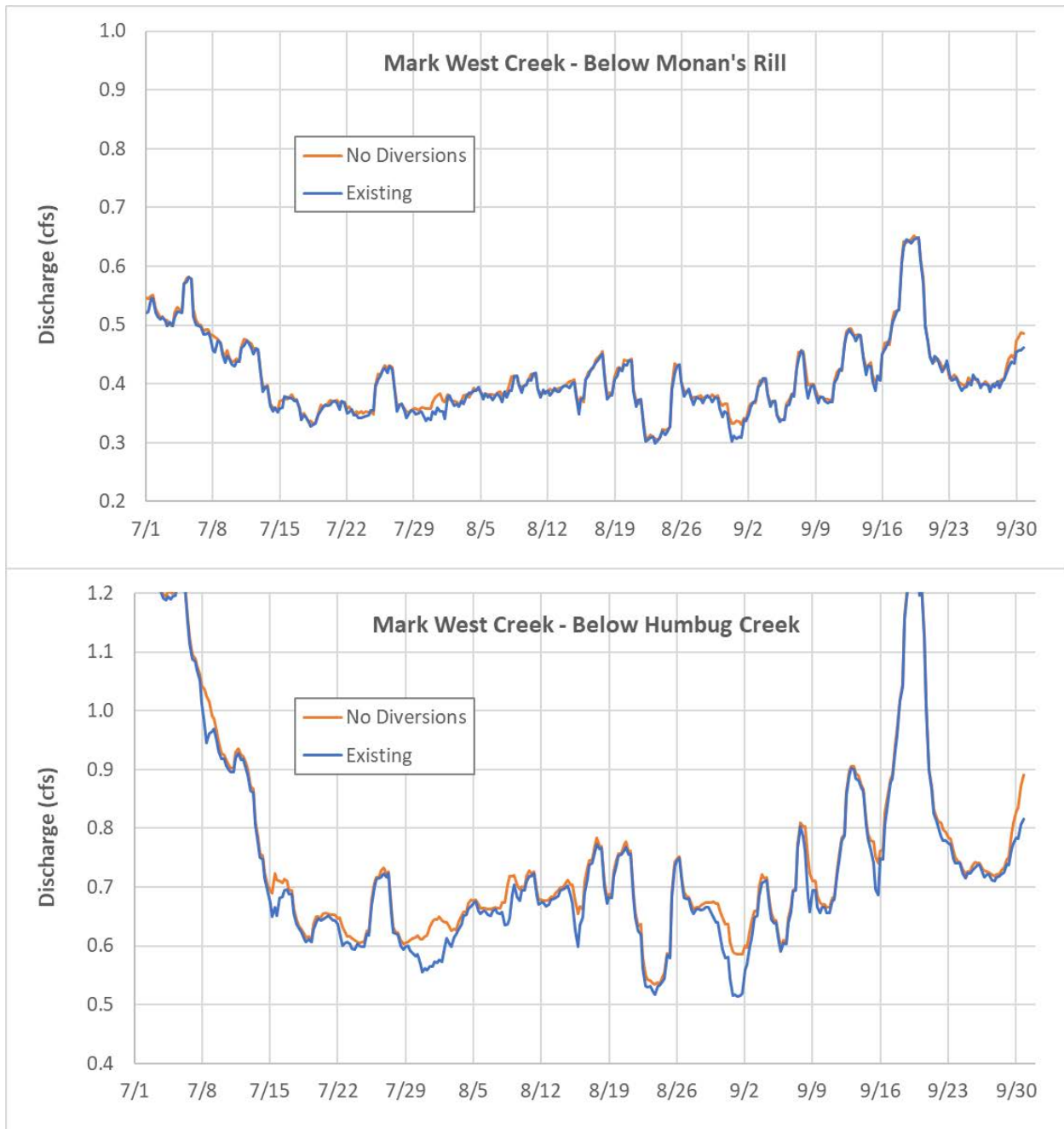
Figure 79: Simulated changes to hourly streamflow in Mark West Creek below Monan's Rill and below Humbug Creek resulting from cessation of all surface water diversions (Scenario 1).
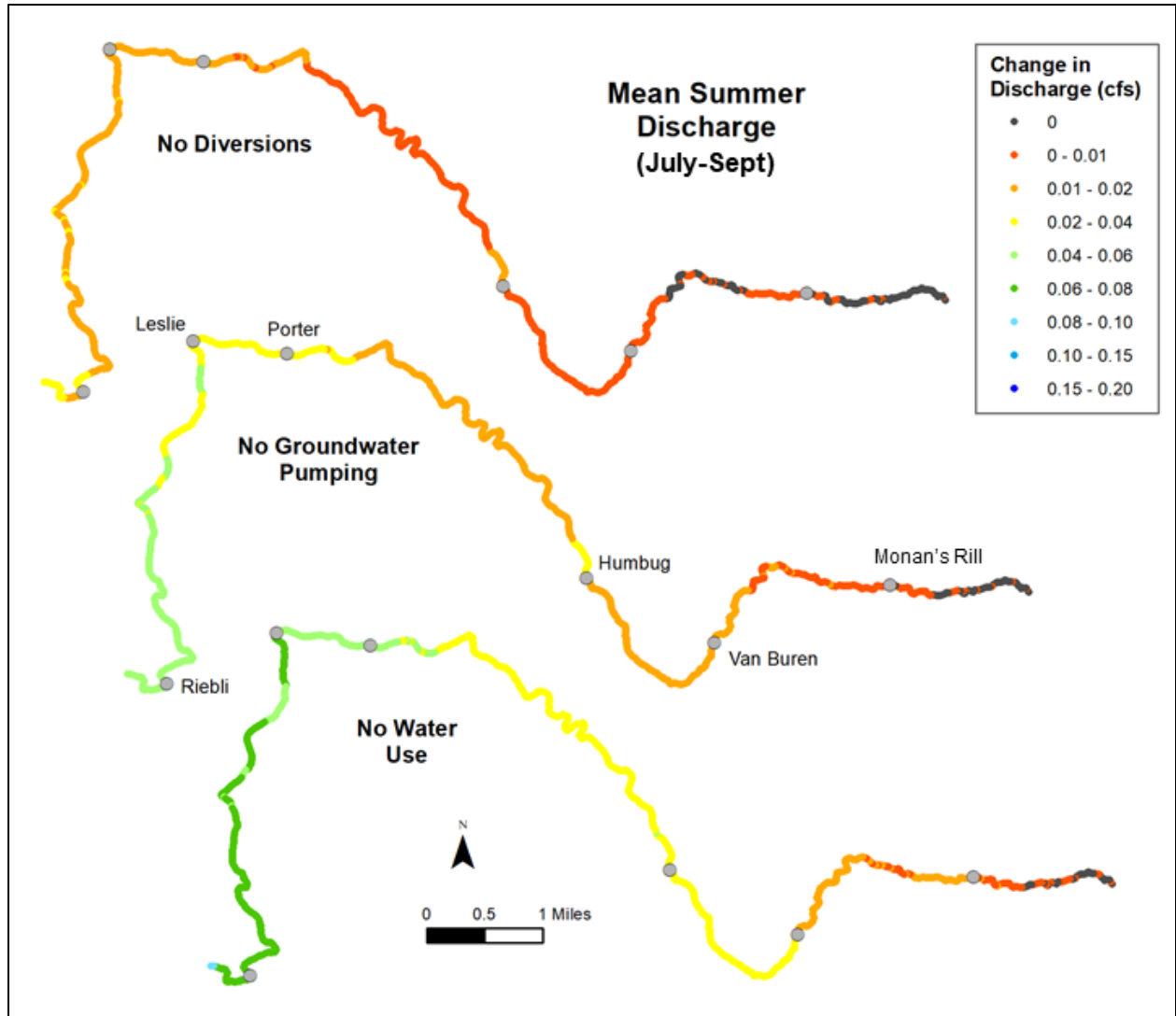
Figure 80: Simulated changes to mean summer streamflow for the three water use scenarios (Scenarios 1-3).
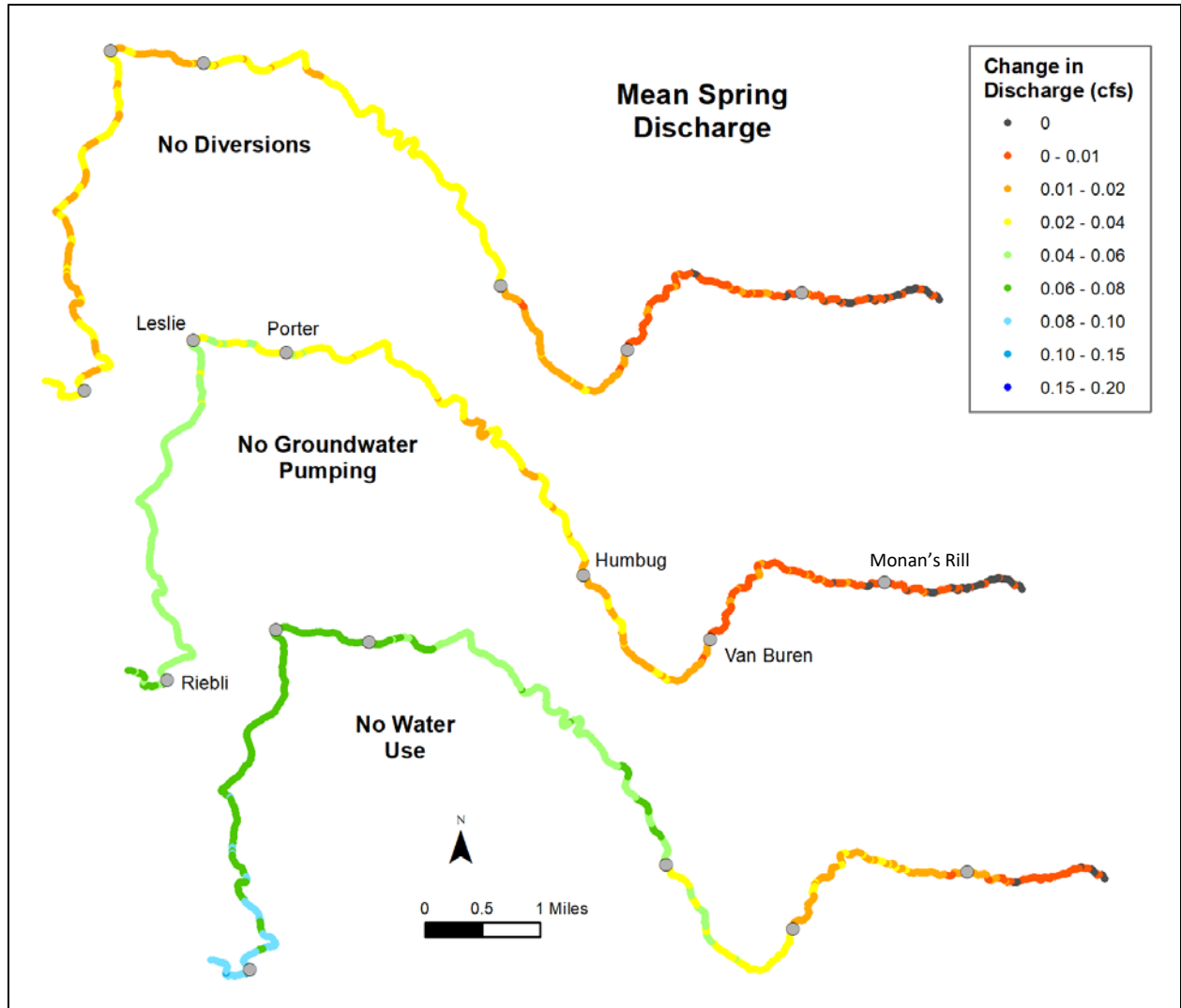
Figure 81: Simulated changes to mean spring streamflow for the three water use scenarios (Scenarios 1-3).
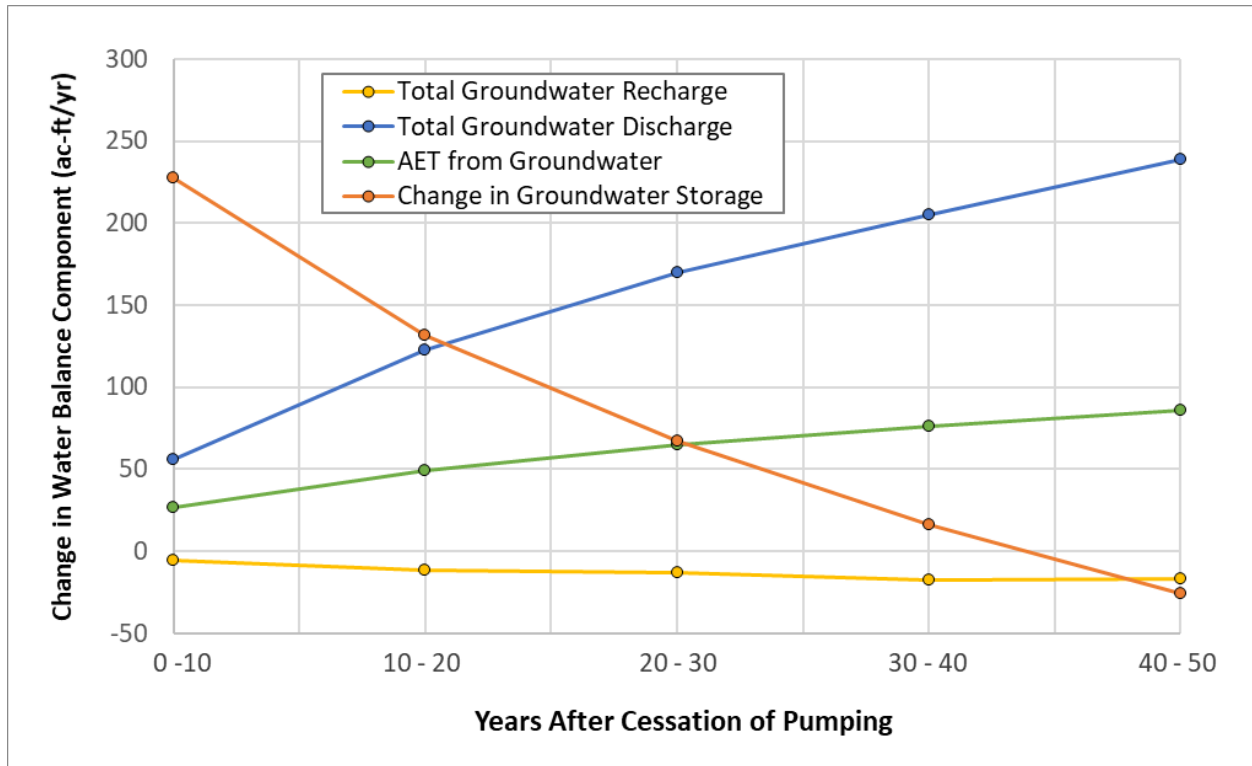
Figure 82: Changes to annual groundwater water balance components resulting from cessation of all groundwater pumping (Scenario 2) for each of the five 10-yr simulation cycles.
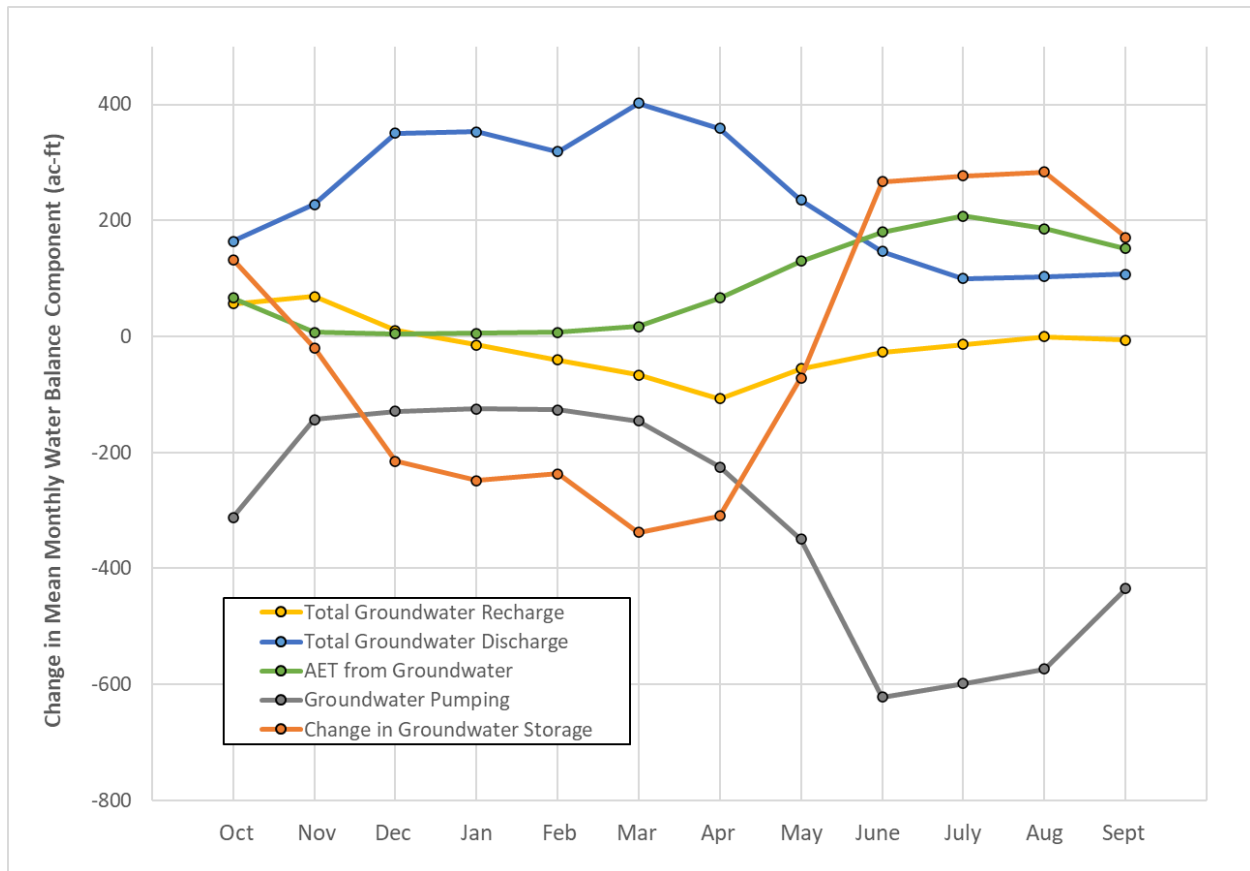
Figure 83: Mean monthly changes in the groundwater water balance resulting from cessation of all groundwater pumping (Scenario 2) for the fifth 10-yr simulation cycle.

Table 20: Summer streamflow depletion normalized by pumping volume for the various no pumping scenarios over the fifth 10-yr simulation cycle (Scenarios 2 & 2B-2E).

Scenario #	Scenario Name	Change in Mean Summer Discharge (cfs/100 ac-ft of pumping)
2	No Groundwater Pumping	0.019
2B	No Pumping Near Streams	0.026
2C	No Pumping Near Springs	0.029
2D	No Pumping From Tuff	0.019
2E	No Distal Pumping	0.017

Land/Water Management Scenarios

Forest, Grassland, and Runoff Management
The forest management scenario (Scenario 4) resulted in modest increases in mean summer discharges of 0.02 – 0.04 cfs throughout most of Mark West Creek upstream of Porter Creek and increases of 0.04 – 0.06 cfs below Porter Creek (Figure 84). These changes are equivalent to a 4-11% increase in mean summer flow depending on the location, and the average change over the full anadromous length of Mark West Creek was ~6%. The grassland management scenario (Scenario 5) resulted in smaller increases in mean summer flows of 0.02 or less throughout Mark West Creek (Figure 84). The runoff management scenario (Scenario 6) resulted in modest increases in mean summer discharges of less than 0.02 cfs upstream of Porter Creek. The majority of the area included in the scenario is located within and downstream of the Porter Creek watershed, and there is a substantial increase in the flow enhancement benefits below the confluence with Mark West Creek with mean summer discharges increasing by 0.06 - 0.12 cfs in the downstream reaches (Figure 86).

Increases in springtime streamflow for the forest management scenario were much larger than the changes for summer streamflow with increases of 0.5 - 0.6 cfs below Humbug Creek and 0.7 - 0.9 below Porter Creek (Figure 85); these changes represent 4 - 6% of the total flow. The changes in springtime streamflow for the forest management scenario are about three to five times larger than the changes for the other management scenarios. Springtime streamflow changes for the grassland management scenario were also larger than the summer changes with increases of 0.06 - 0.08 cfs below Humbug Creek and 0.10 - 0.18 cfs below Porter Creek (Figure 85). The runoff management scenario produced a similar but slightly greater increase in springtime streamflow relative to summer streamflow (Figure 87).

Comparison of the watershed-wide mean annual water balance between existing conditions and Scenarios 4 - 6 indicates that all three strategies (forest-, grassland-, and runoff-management) result in increases in infiltration recharge on the order of 2 - 4% on an annual basis (Figure 88). The mechanisms behind these increases are different for each case. Forest management results in about a 5% decrease in AET on treated lands which equates to a 1.4% decrease watershed-wide (579 ac-ft/yr) resulting in more water available for both runoff and infiltration recharge (Figure 88). In contrast, grassland management results in only minimal changes in AET and runoff and the increases in infiltration recharge are accomplished through increased soil water storage capacity which serves to extend the timeframe over which recharge can occur. Runoff management decreases runoff directly, resulting in both increases in infiltration recharge and AET (Figure 88).

The increases in infiltration recharge for all three scenarios represent a substantial volume of water (230-420 ac-ft/yr) which manifests in part through increases in groundwater discharge to streams as interflow, baseflow, and springflow (Figure 88). The springflow response is of particular interest in that springflow has been identified as the primary process generating summer streamflow in the watershed. The forest management scenario resulted in the largest increases in springflow (6.4%), followed by runoff management (3.9%), and grassland

management (1.9%). The relative influence of the management actions on springflow is controlled in part by the spatial distribution of treatment areas. For example, the forest management scenario generates the largest increase in springflow despite generating the smallest increase in infiltration recharge owing to the concentrations of both springs and treatment areas in the upper watershed.

It is apparent that location on the landscape influences how changes in infiltration recharge are expressed, with the forest management scenario resulting in the smallest increases in recharge but the largest increases in springflow due to both treated forest areas and springs being concentrated in the upper watershed. It is also important to note that the acreages involved in the three scenarios are intended to represent large-scale implementation based on existing potential on the landscape, therefore the locations and acreages involved are very different between the scenarios. To compare the relative hydrologic effects of these various management actions it is useful to normalize the results by acres of managed area. This exercise reveals that runoff management is by far the most effective strategy with per area increases in summer streamflow 36 times greater than forest management and 51 times greater than grassland management (Table 21). The level of effort required to manage stormwater from one acre is, however, expected to be significantly greater than the effort involved in management of one acre of forest or grassland. Additional discussion of comparisons between strategies is included below under the heading Summary and Comparison of Scenarios.

Pond Releases
The summer pond release scenario (Scenario 7) resulted in the largest increases in summer streamflow of any of the scenarios discussed thus far. Between the pond release in upper Mark West Creek and the confluence with Mill Creek where the lower release enters, mean summer discharges increase by 0.06 – 0.07 cfs with the exception of localized increases of up to 0.09 cfs just downstream of the confluence of Humbug Creek where the middle release enters. Below the lower release on Mill Creek, discharges increase by 0.14 to 0.16 cfs (Figure 85). Averaged across the full length of anadromy in Mark West Creek, the changes in streamflow represent an increase in mean summer streamflow of approximately 13%.

The predominance of gaining conditions in most reaches of the stream result in only limited flow losses downstream of the releases, which makes this strategy particularly well-suited for this watershed which is characterized by a lack of thick alluvial deposits. The increase in summer streamflow above the middle release at Humbug Creek is equivalent to about 80% of the upper release rate and the increase in streamflow at the watershed outlet is equivalent to about 84% of the total release rate from all three releases. The losing reach below Porter Creek does reduce the increase in streamflow locally by about 0.02 cfs, but this effect does not persist downstream since much of the water that infiltrates through the streambed in this reach discharges back to the stream downstream.

The spring pond release scenario produced a similar but slightly smaller increase in springtime flows (Scenario 7B) than in summer flows (Scenario 7) (Figure 87). The spring pond release scenario was designed to increase flows over a short (3-week) period coinciding with the timing

of the end of typical peak smolt outmigration in May. Examination of discharge and riffle depth hydrographs during the 2014 drought shows that the springtime releases substantially increase flows in the high priority reach during this critical time period extending the duration of passable conditions by approximately two weeks (Figure 89). The summer pond release scenario increases riffle depths significantly over the critical summer low flow period, but these changes are not large enough to maintain depths above 0.2-ft (Figure 89).

Combined Management

When all the land/water management scenarios are combined (Scenarios 4 - 7), mean summer discharge in Mark West Creek increased by 0.05 – 0.10 cfs between Monan's Rill and Van Buren Creek and by 0.10 – 0.15 between Van Buren Creek and Porter Creek. Downstream of Porter Creek streamflow increased by 0.25 – 0.35 cfs (Figure 90). These changes are similar but slightly less than the sum of the changes of the four individual scenarios. Averaged across the full length of anadromy in Mark West Creek, the changes in streamflow represent an increase in mean summer streamflow of approximately 23%.
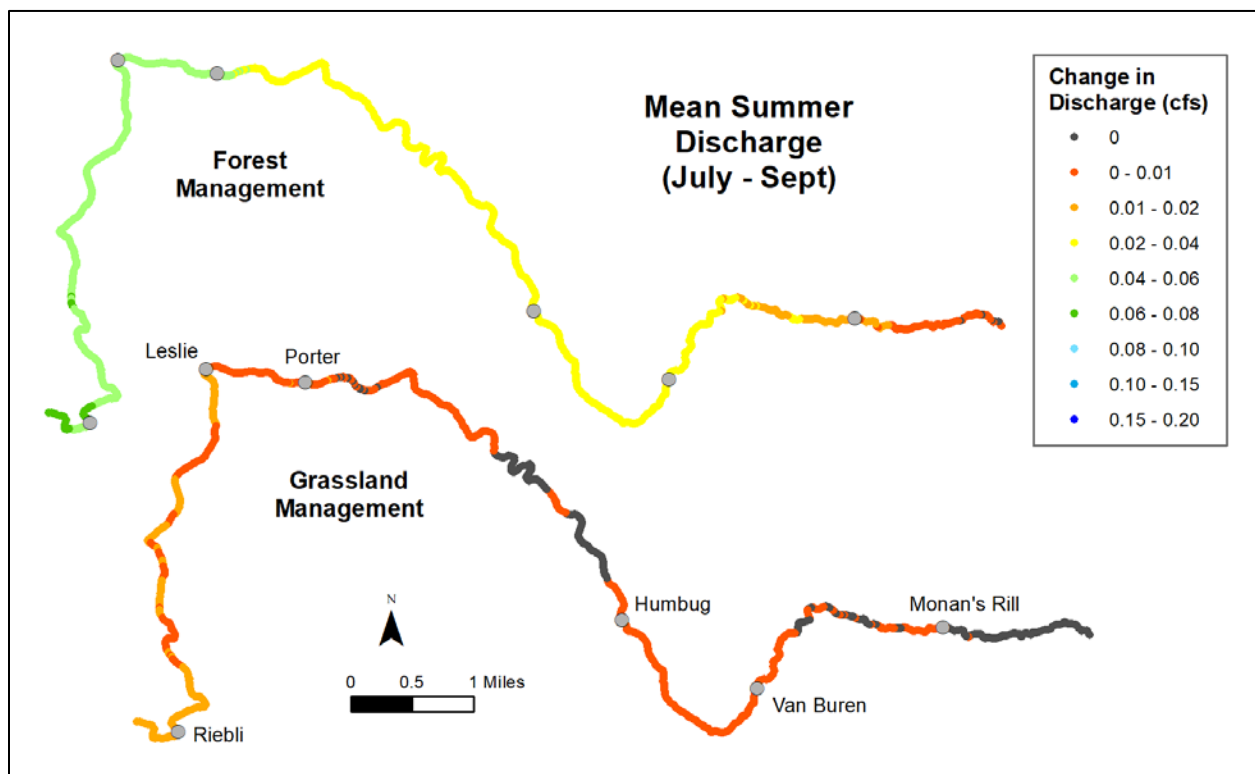
Figure 84 Simulated changes to mean summer streamflow for the forest and grassland management scenarios (Scenarios 4-5).
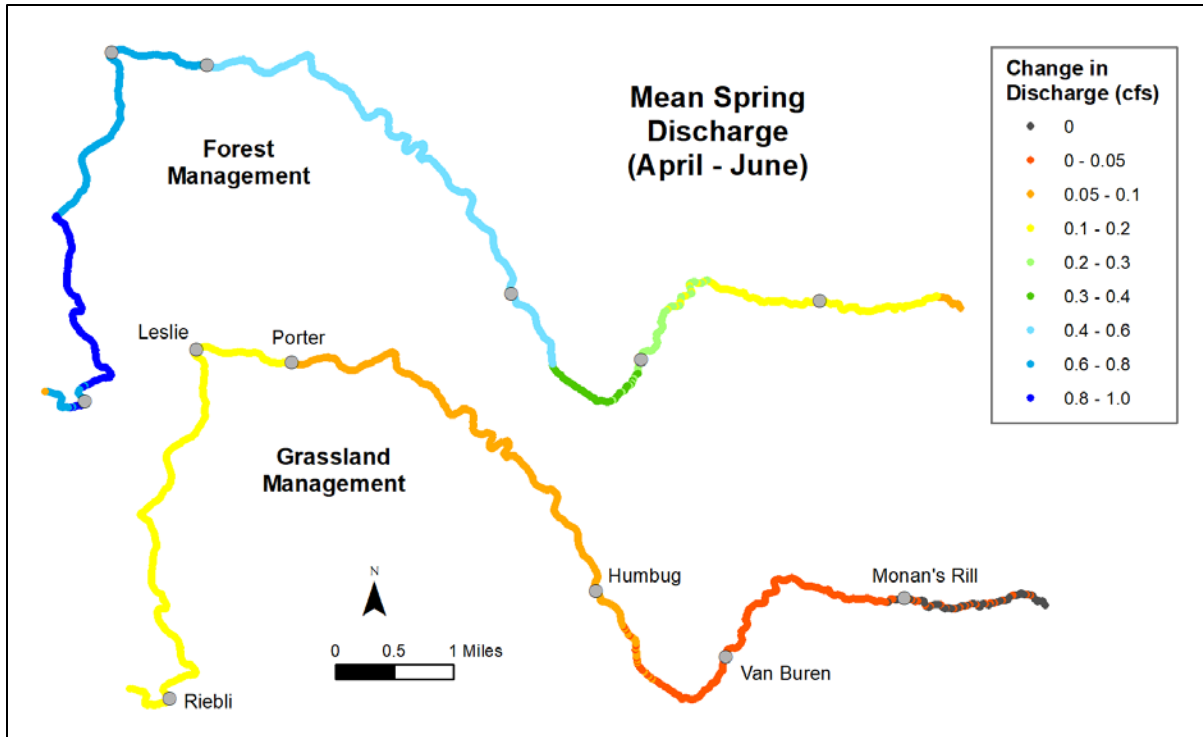
Figure 85: Simulated changes to mean springtime streamflow for the forest and grassland management scenarios (Scenarios 4-5).
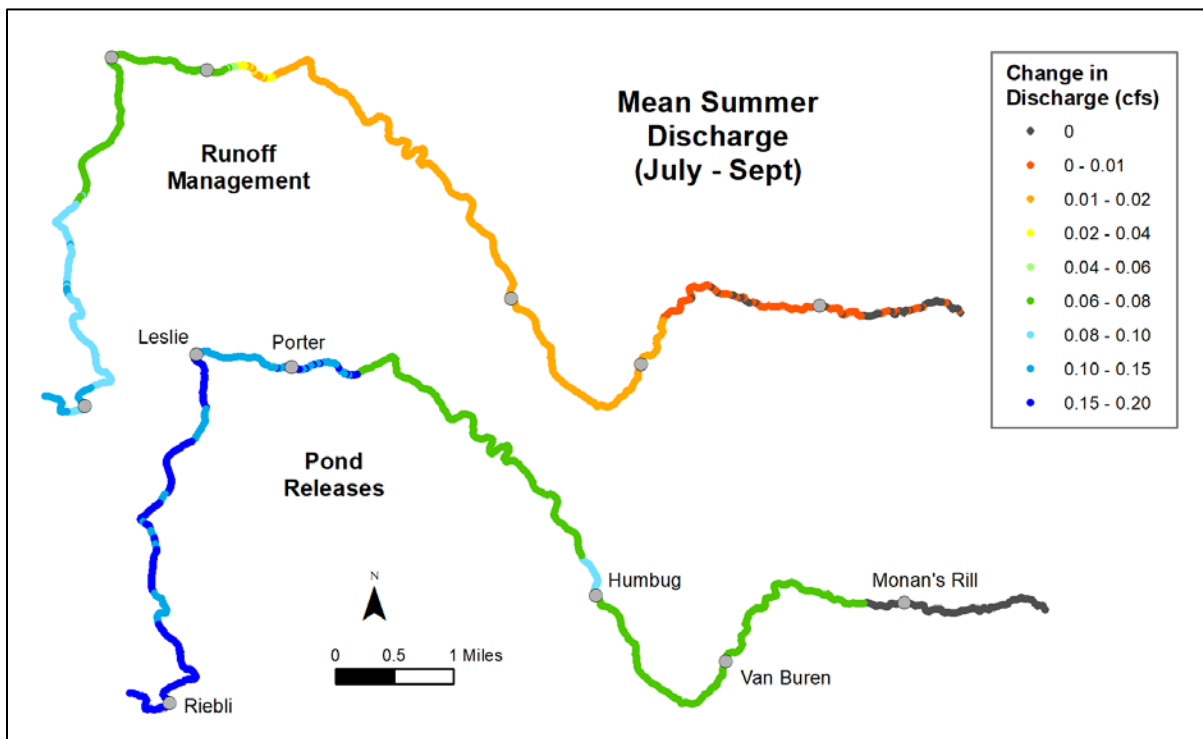
Figure 86: Simulated changes to mean springtime streamflow for the runoff management and summer pond release scenarios (Scenarios 6 & 7).
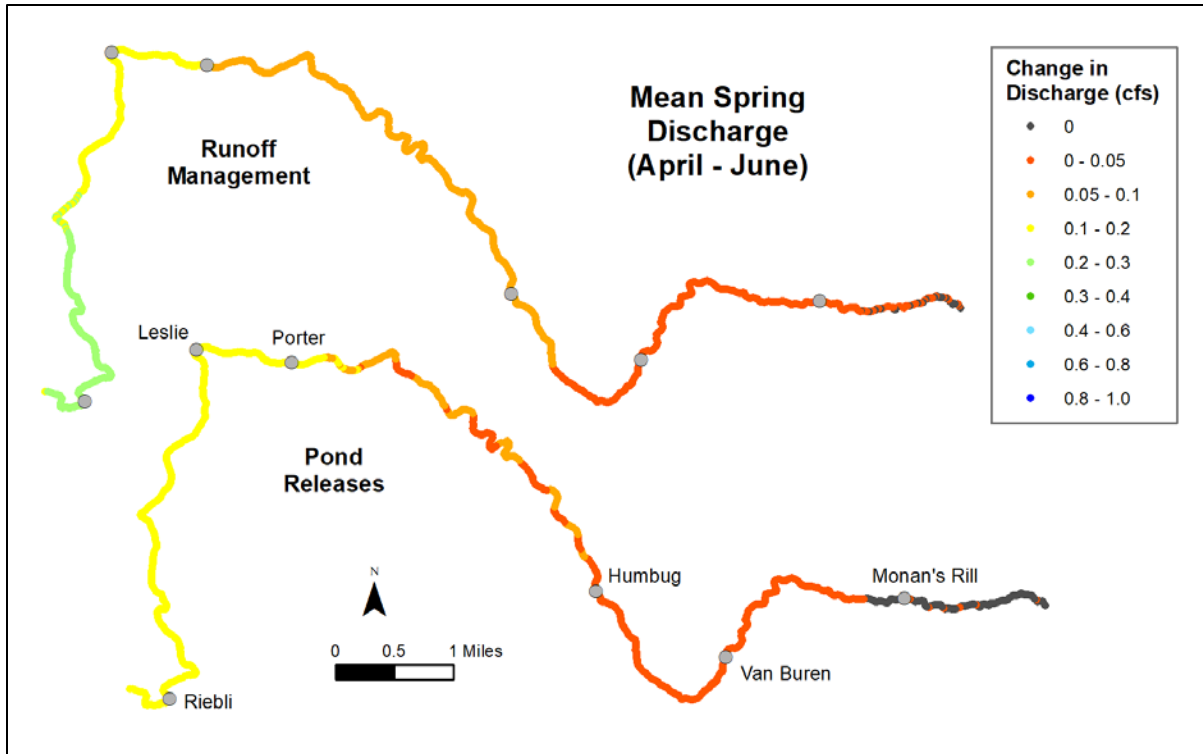
Figure 87: Simulated changes to mean springtime streamflow for the runoff management and springtime pond release scenarios (Scenarios 6 & 7B).
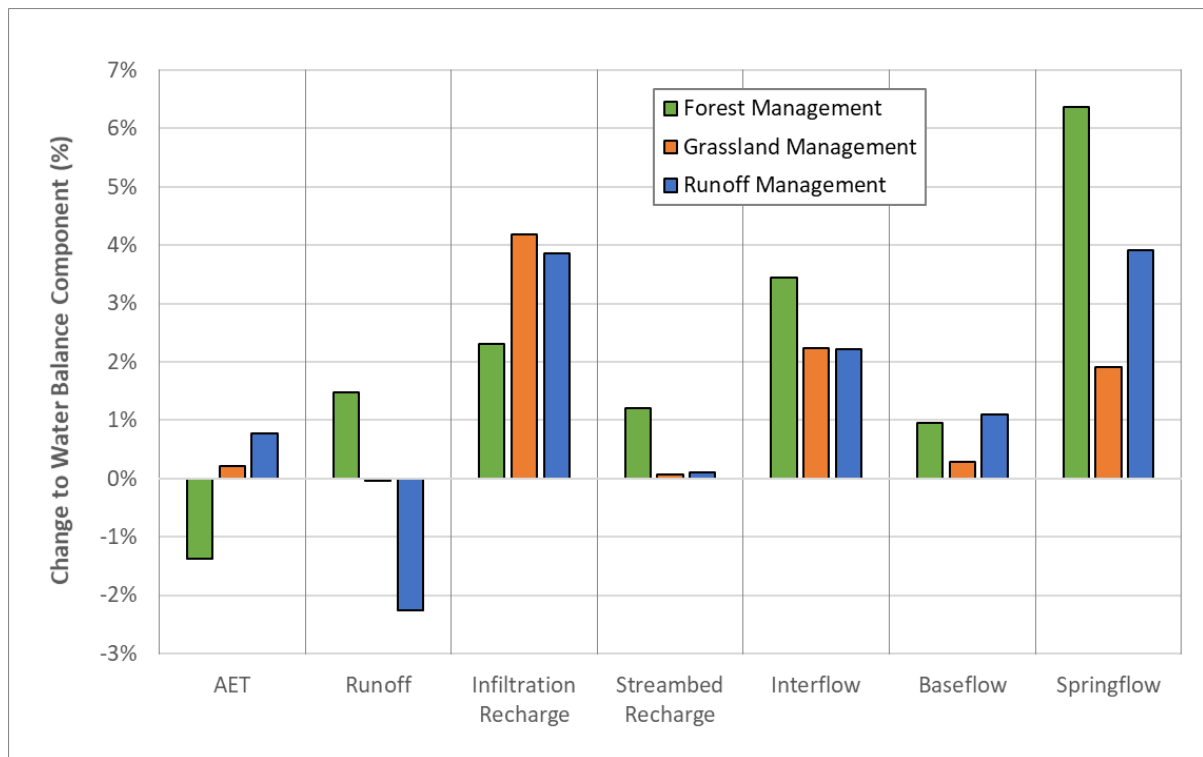
Figure 88: Percent change in select water balance components for Scenarios 4-6.
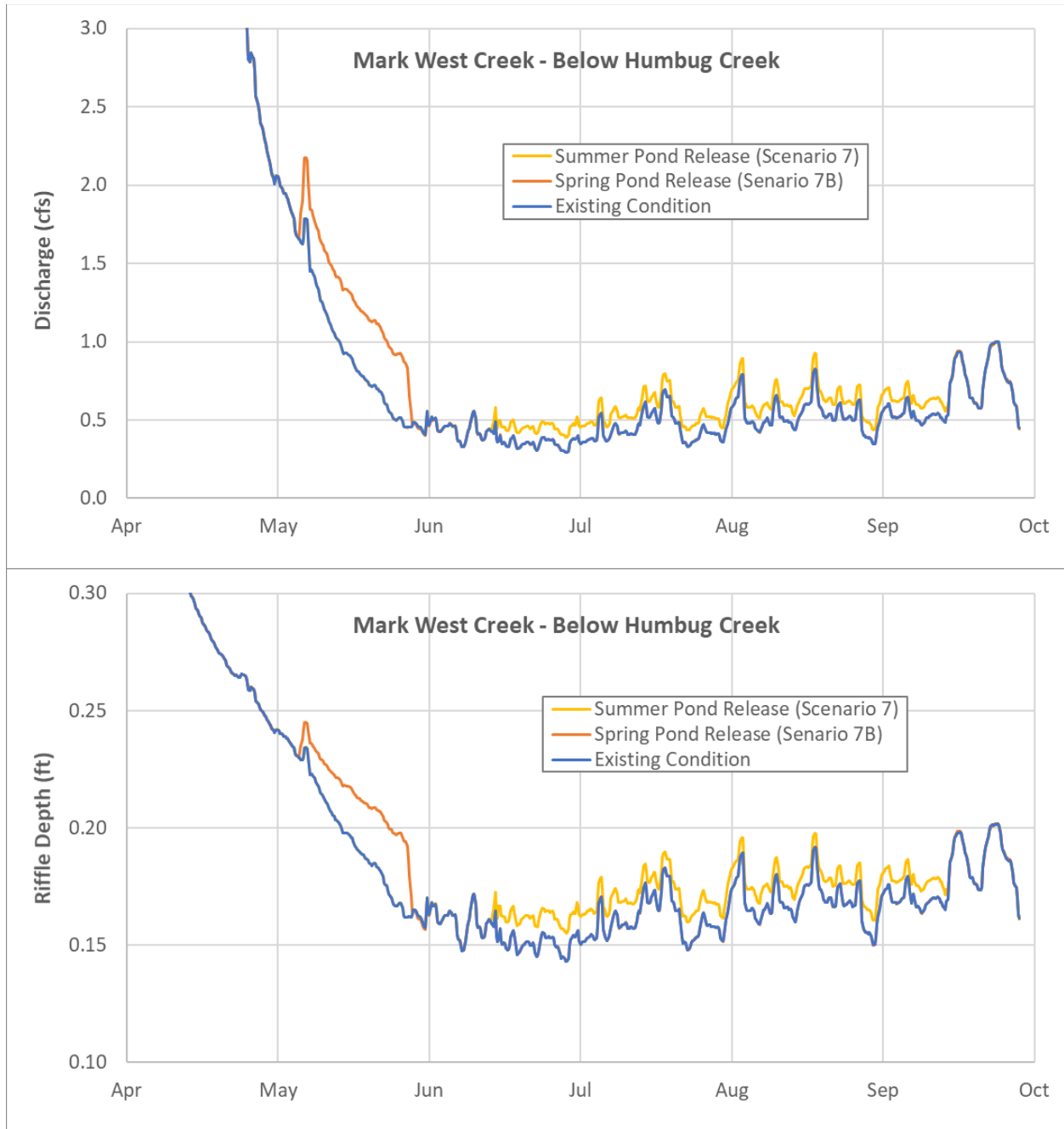
Figure 89: Spring and summer 2014 discharge (top) and riffle depth (bottom) in Mark West Creek below Humbug Creek for existing conditions and the spring and summer pond release scenarios (Scenarios 7 & 7B).

Table 21: Change in mean summer streamflow for forest, grassland, and runoff management (Scenarios 4-6) normalized to a 100-acre treatment area.

Scenario #	Scenario Name	Change in Mean Summer Discharge (cfs/100 acres of treatment area)
4	Forest Management	0.0010
5	Grassland Management	0.0007
6	Runoff Management	0.0355
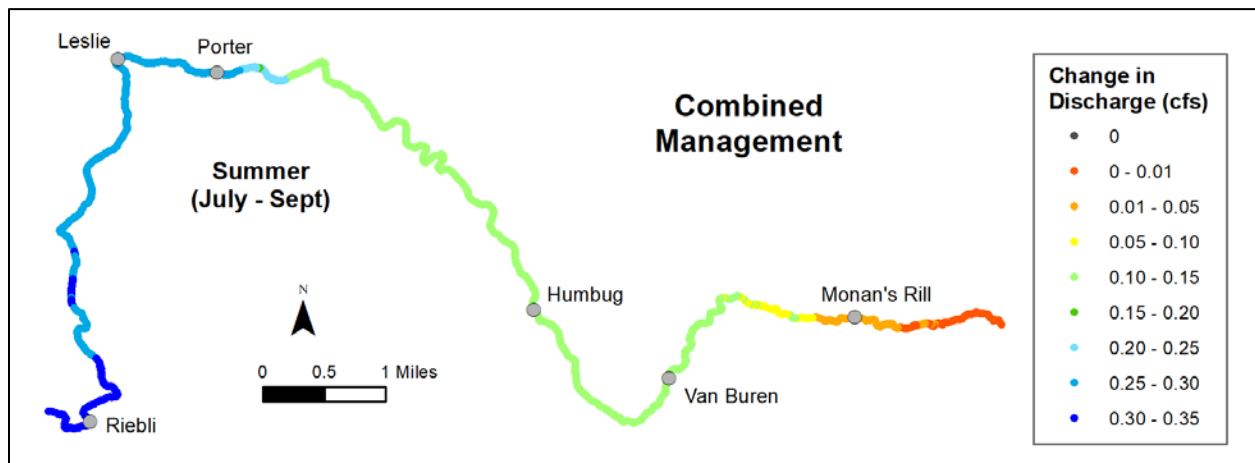
Figure 90: Simulated changes to the 10-yr average mean summer streamflow for the combined management scenario (Scenario 8; note the scale in the legend is different from previous figures for other scenarios).

Climate Change Scenarios

The four climate change scenarios (Scenarios 9-12) generated a wide range of predictions of future (2070-2099 timeframe) changes in discharge in Mark West Creek; nevertheless, there are some commonalities in the predictions of future streamflow trajectories. The average 10-yr mean monthly discharge is predicted to increase during late fall and winter in three of the four scenarios, with mean January flows in the CNRM scenario more than 2.5 times greater than existing conditions (Figure 91). All four scenarios show large decreases in discharge during spring with mean monthly flows during March decreasing by 48-71%. The predictions for summer flows are more variable with two scenarios predicting decreases in the mean monthly August flow on the order of 38-51% and one predicting increases of 26% (Figure 91). The future changes are even more extreme during drought conditions where winter flows are predicted to decrease dramatically in all four scenarios with high streamflow events becoming essentially non-existent

in the GFDL scenario (Figure 92).   The declines in springtime flows are also extreme with decreases in mean monthly discharge in March of 60-97% (Figure 92).

More careful review of the range of predicted changes in summer flows reveals that mean summer discharges increase in the CNRM scenario by about 0.1 - 0.2 cfs throughout Mark West Creek, whereas in the MIROC esm scenario, discharges between Van Buren Creek and Porter Creek drop from about 0.5 - 0.8 cfs to 0.3 - 0.4 cfs, and below Porter Creek flows drop from about 1.0 - 1.5 cfs to 0.6 - 0.8 cfs (Figure 93). In contrast to the variable predictions in mean summer discharges, all four models predict large decreases in mean spring discharges.   The CNRM scenario produces the smallest decreases with flows in Mark West Creek decreasing from 4-10 cfs to 0.5 - 1 cfs between Van Buren and Porter Creeks and from 10-20 cfs to 1 - 2 cfs downstream of Porter Creek (Figure 94). The MIROC esm scenario predicts even more dramatic decreases in springtime discharges with flow of <0.5 cfs between Van Buren Creek and Porter Creek and <1 cfs below Porter Creek (Figure 94).

Examination of the 10-yr mean annual water balance (representative of the 2070-2099 timeframe) reveals that the four climate scenarios predict very different changes to the mean annual water balance. Precipitation changes range from a 37% increase in the CNRM scenario to a 20% decrease in the MIROC esm scenario (Figure 95). The significantly higher precipitation in the CNMR scenario leads to increases in AET of about 13%, whereas the other three scenarios result in modest decreases in AET of between 2 and 7%.   Runoff is predicted to increase in the CNRM and CCSM4 scenarios by 26-69% and decrease in the GFDL and MIROC esm scenarios by 25 - 32% (Figure 95). The CNRM scenario predicts large increases in both infiltration recharge (44%) and streambed recharge (33%), the CCSM4 model predicts minimal changes in recharge, and the GFDL and MIROC esm scenarios predict significant decreases in infiltration recharge (29 - 40%) and streambed recharge (17 - 25%). Increased recharge in the CNRM scenario results in increases in groundwater discharge expressed as interflow (32%), baseflow (11%), and springflow (36%). Similarly, groundwater discharge decreases in the scenarios that predict decreases in recharge.   The largest decreases are predicted by the MIROC esm scenario where interflow, baseflow, and springflow are predicted to decrease by 30, 21, and 46% respectively (Figure 95).

Comparison of the water balance for the driest of the 10 years in each simulation reveals that the trajectories of the changes in the water balance between the four scenarios are more similar during drought conditions than for long term average conditions. AET is predicted to increase in all four models while runoff, infiltration recharge, and streambed recharge are predicted to decrease (Figure 96). The GFDL drought predictions are extreme with close to a complete loss of both runoff and infiltration recharge.   The groundwater discharge results remain variable between the scenarios with the CNRM and CCSM4 scenarios resulting in increased discharge during droughts and the GFDL and MIROC esm scenarios resulting in decreased groundwater discharge reflecting that groundwater discharge responds more to long-term fluctuations in climate rather than individual water year conditions (Figure 96).

All four scenarios indicate increases in Climatic Water Deficit (CWD). The mean CWD for the watershed over the 10-yr simulation period is predicted to increase from 26.0 in/yr under existing

conditions to between 30.3 and 33.9 in/yr under future climate conditions. Increases in CWD of this magnitude (17-30%) may be expected to lead to significant changes in vegetation communities and increases in fire risk. It is important to note that these simulations represent the hydrologic effects of changes in climate but do not include secondary effects that may be expected under a significantly altered future climate regime such as changes in vegetation cover and irrigation water demands.

Figure 91: Comparison of mean monthly streamflow averaged over the 10-yr simulation periods for existing conditions and the four climate change scenarios (Scenarios 9-12).
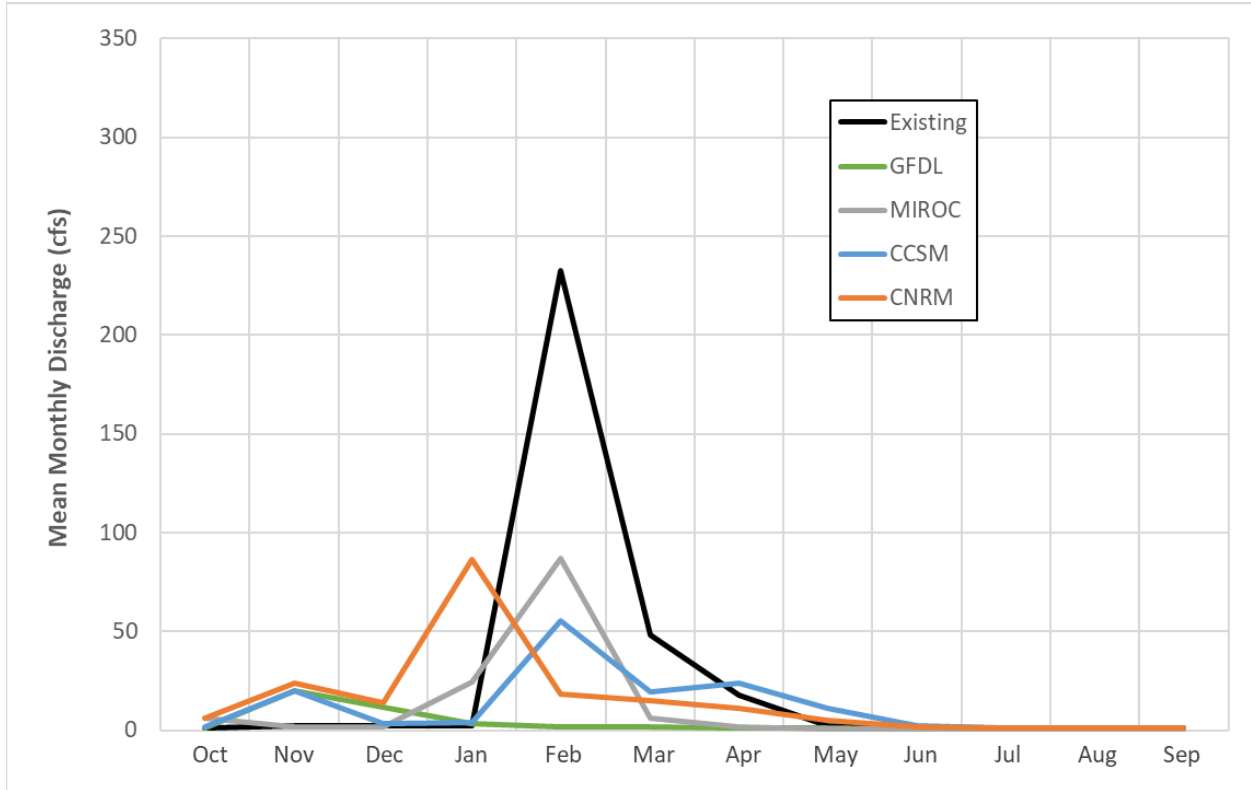
Figure 92: Comparison of mean monthly streamflow for the driest water year in each 10-yr simulation period for existing conditions and the four climate change scenarios (Scenarios 9-12).
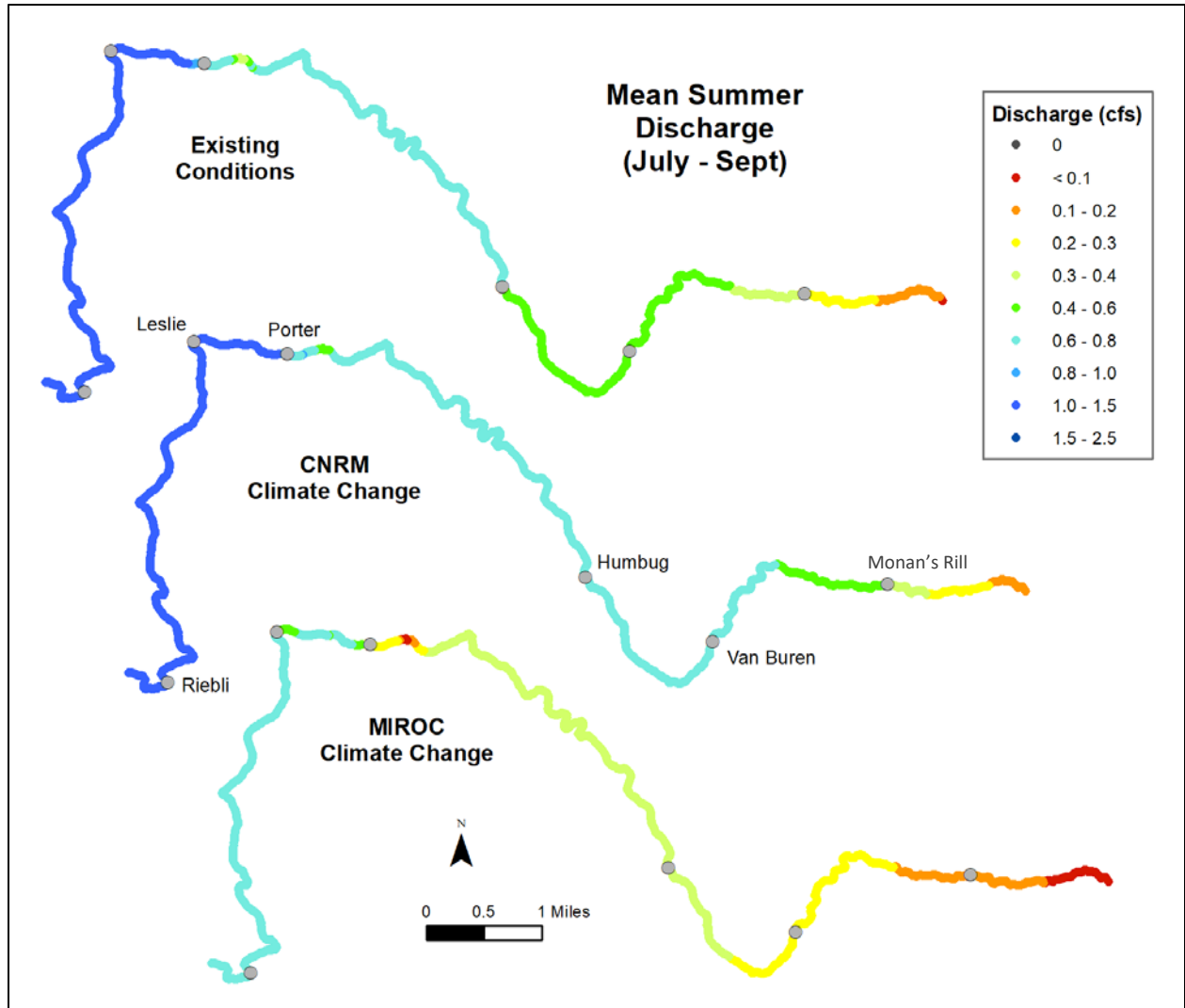
Figure 93: Simulated 10-yr average mean summer streamflow for existing conditions and the CNRM and MIROC esm scenarios (Scenarios 9 & 12) which represent the end-member predictions from the four climate change scenarios.
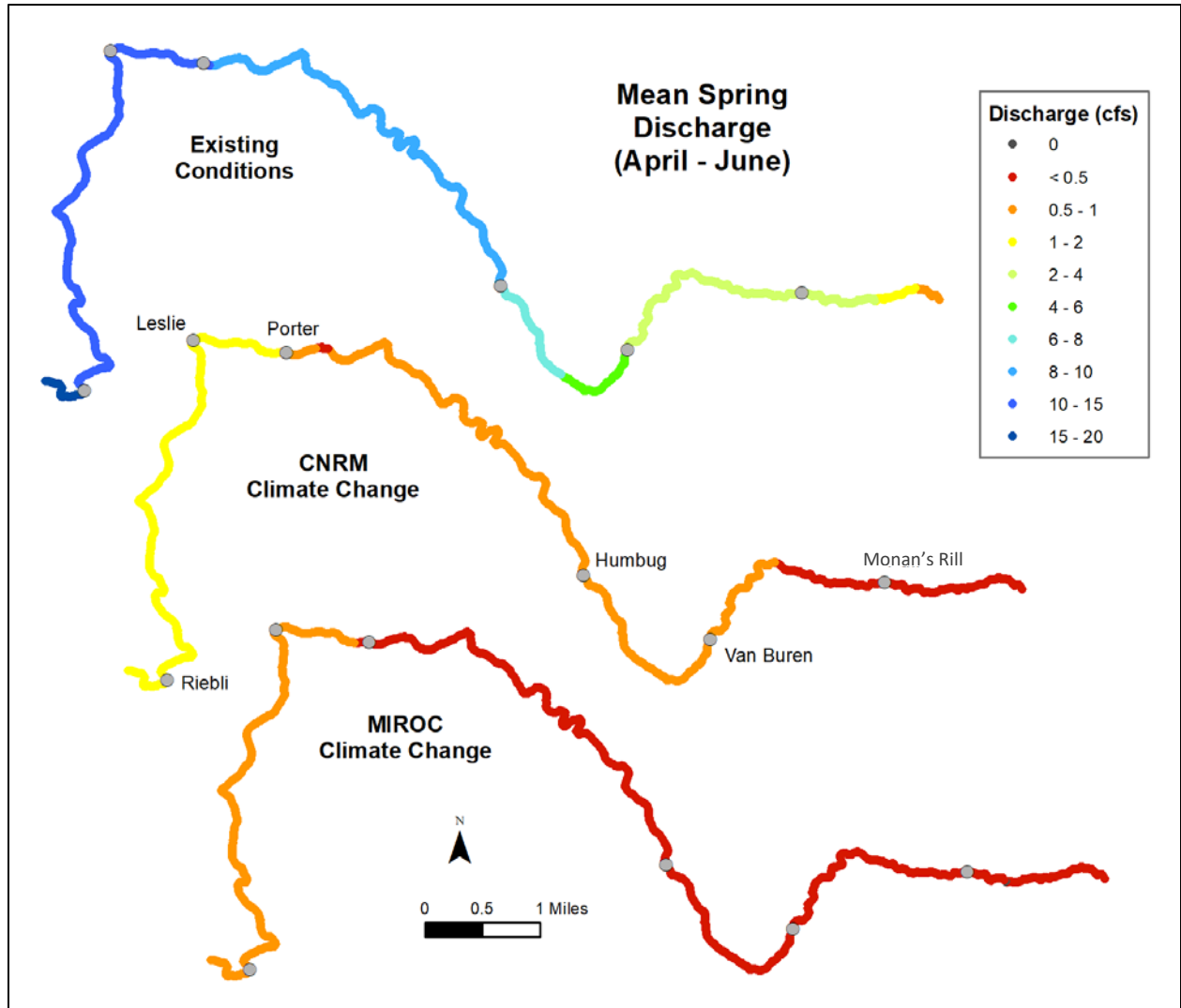
Figure 94: Simulated 10-yr average mean springtime streamflow for existing conditions and the CNRM and MIROC esm scenarios (Scenarios 9 & 12) which represent the end-member predictions from the four climate change scenarios.
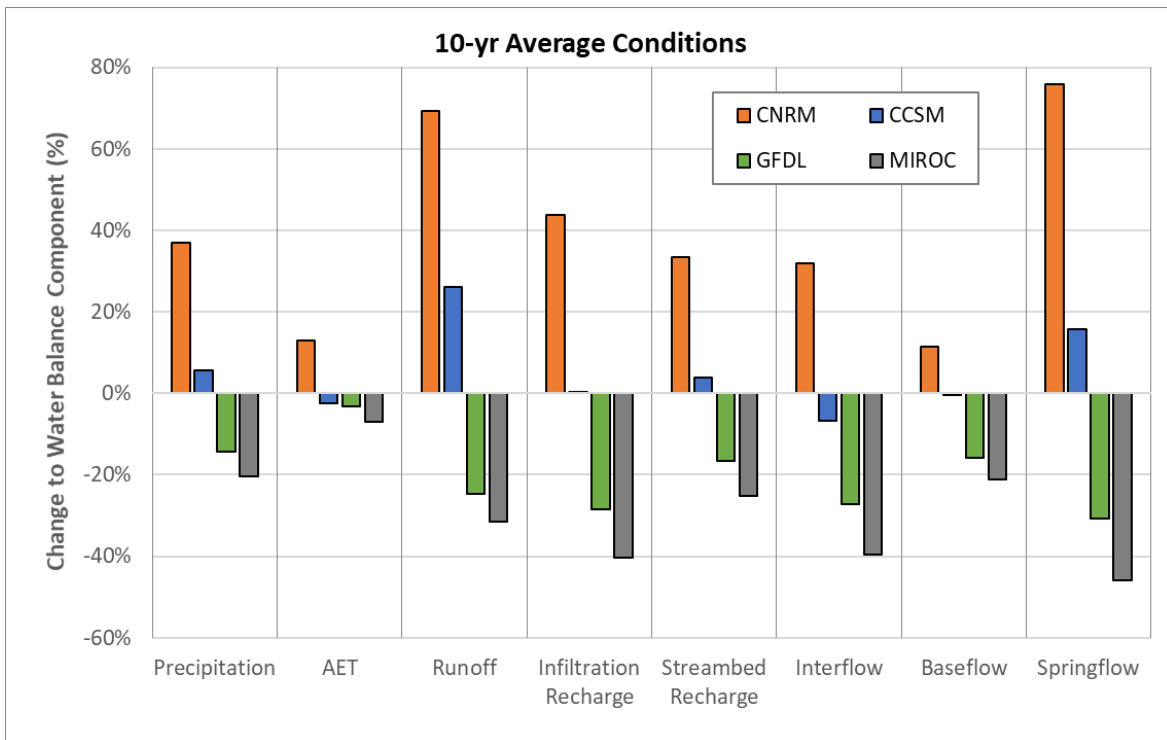
Figure 95: Percent change in various components of the water balance averaged over the 10-yr simulation periods for the four climate change scenarios relative to existing conditions.
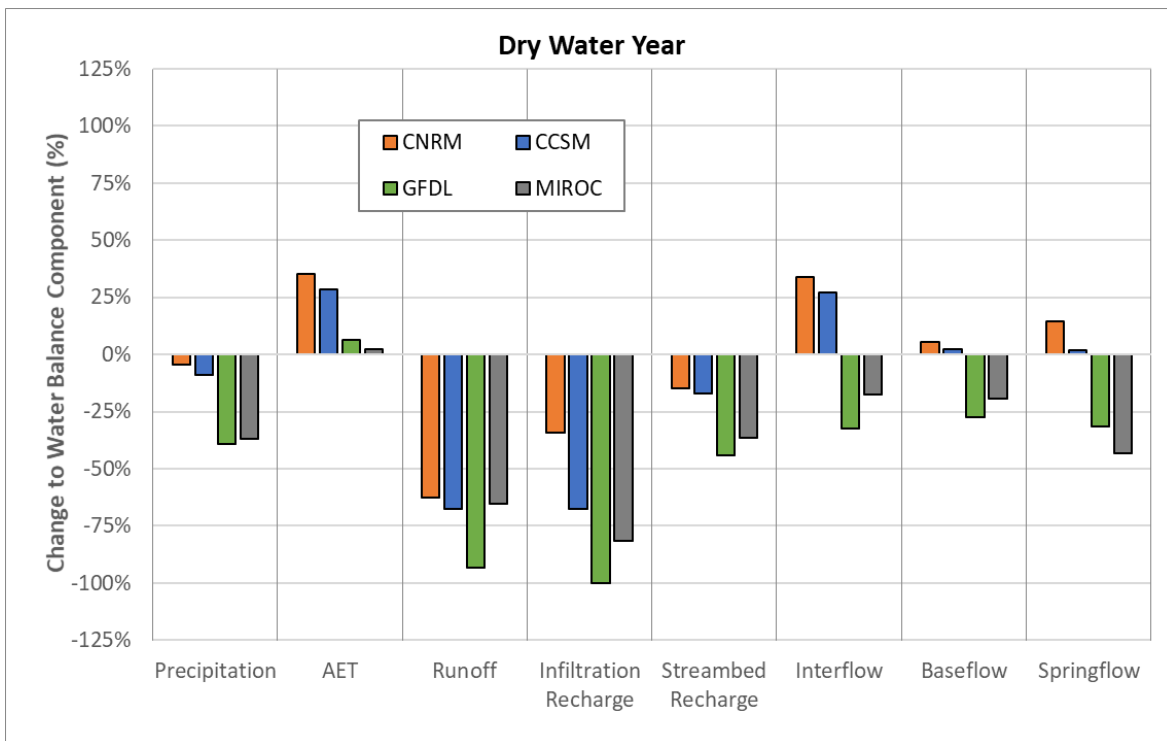
Figure 96: Percent change in various components of the water balance for the driest water year in each 10-yr simulation period for the four climate change scenarios relative to existing conditions.

<u>Mitigated Scenarios</u>

We combined the pond release scenarios (Scenarios 7 & 7B) and the combined management scenario (Scenario 8) with the GFDL climate scenario (Scenario 11) to evaluate the degree to which the various management actions may be capable of mitigating the changes in streamflow associated with future climate. We selected the GFDL model because it represents the second lowest predictions of future spring and summer streamflow of the four climate scenarios which provides a good benchmark for evaluating the scale of the management effects. If future climate more closely resembles the CNRM or CCSM4 scenarios the mitigating effects of the management actions would likely be larger than what is shown here, whereas if future climate more closely resembles the MIROC esm scenario, less mitigation would likely be possible.

The GFDL scenario predicts decreases in mean summer discharge of about 0.20 – 0.42 cfs at most locations in Mark West Creek, and the summer pond releases are large enough to significantly reduce these declines down to about 0.15 – 0.25 cfs (Figure 97). The combined actions of summer pond releases and forest, grassland, and recharge management generate increases in flow that are large enough to fully offset the predicted effects of the GFDL future climate on summer streamflows (Figure 97). None of the actions are capable of fully mitigating against the large decreases in springtime flows predicted by the climate scenarios; nevertheless, springtime flow releases may provide a critical management strategy to provide passable flow conditions for short critical periods of time during smolt outmigration.

Examination of riffle depth hydrographs below Humbug Creek during the driest water year in each 10-yr simulation cycle shows that under the GFDL future climate, riffle depths only reach the 0.2-ft minimum fish passage threshold for brief periods during March through May (Figure 98). This represents a dramatic change in the passage conditions experienced by outmigrants. Under existing conditions depths remain above 0.3-ft until mid-April and above 0.2-ft until early May. Springtime pond releases appear to be large enough to allow for a more sustained (several week) period with riffle depths remaining around 0.2-ft; in this scenario, releases were targeted towards the end of the primary outmigration period in May (Figure 98). Greater riffle depths could likely be achieved over shorter periods by increasing release rates and decreasing durations. The combined actions of summer pond releases, forest, grassland, and runoff management also had an appreciable effect on summer riffle depths generating depths under GFDL future climate that resemble those for existing climate (Figure 98). These findings suggest that aggressive management is capable of offsetting most or all of the summer declines in streamflow predicted for the GFDL future climate.
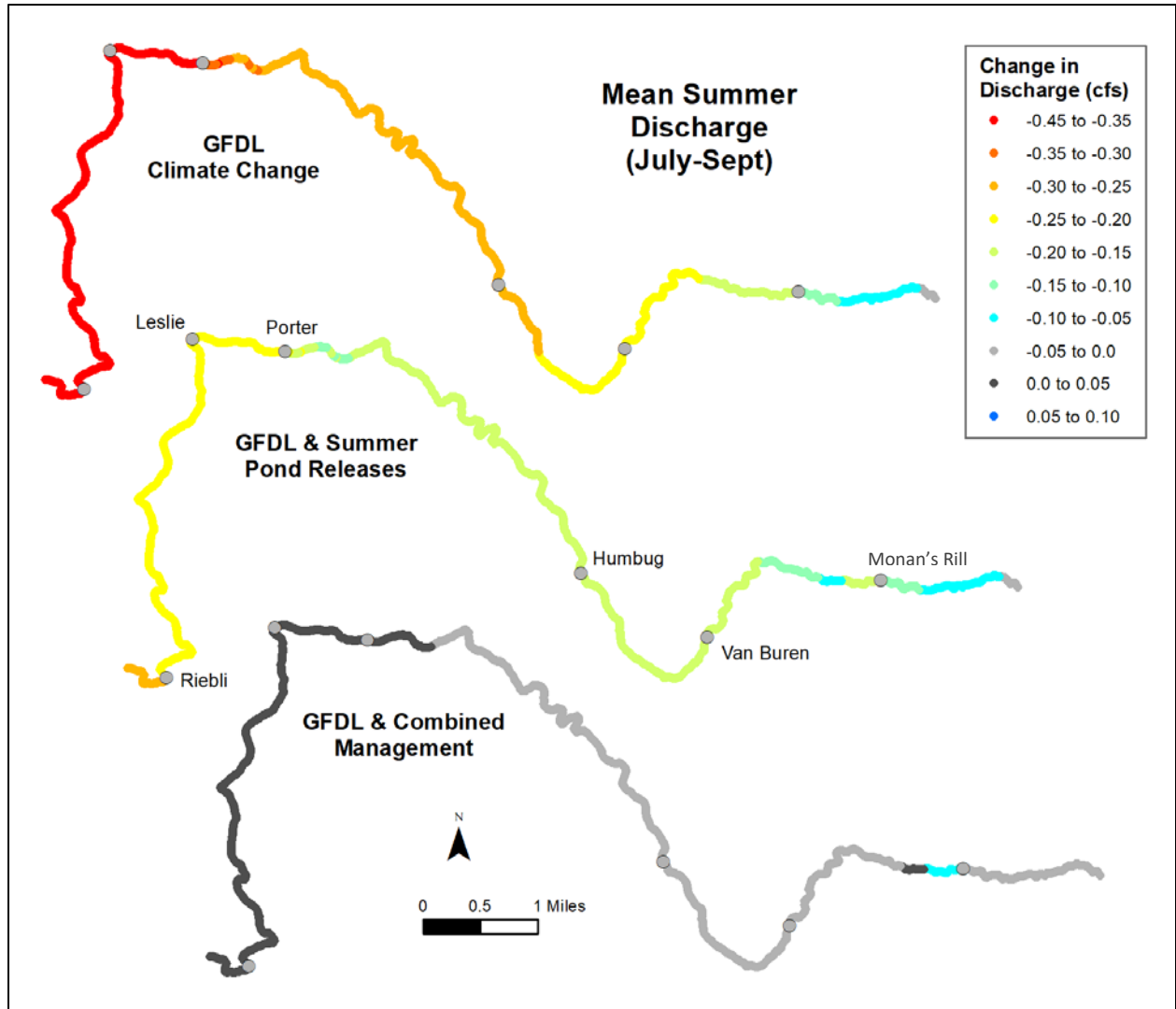
Figure 97: Simulated changes to the 10-yr mean summer streamflow for the GFDL future climate, the GFDL & spring pond release scenario (Scenario 13), and the GFDL & combined management scenario (Scenario 14).
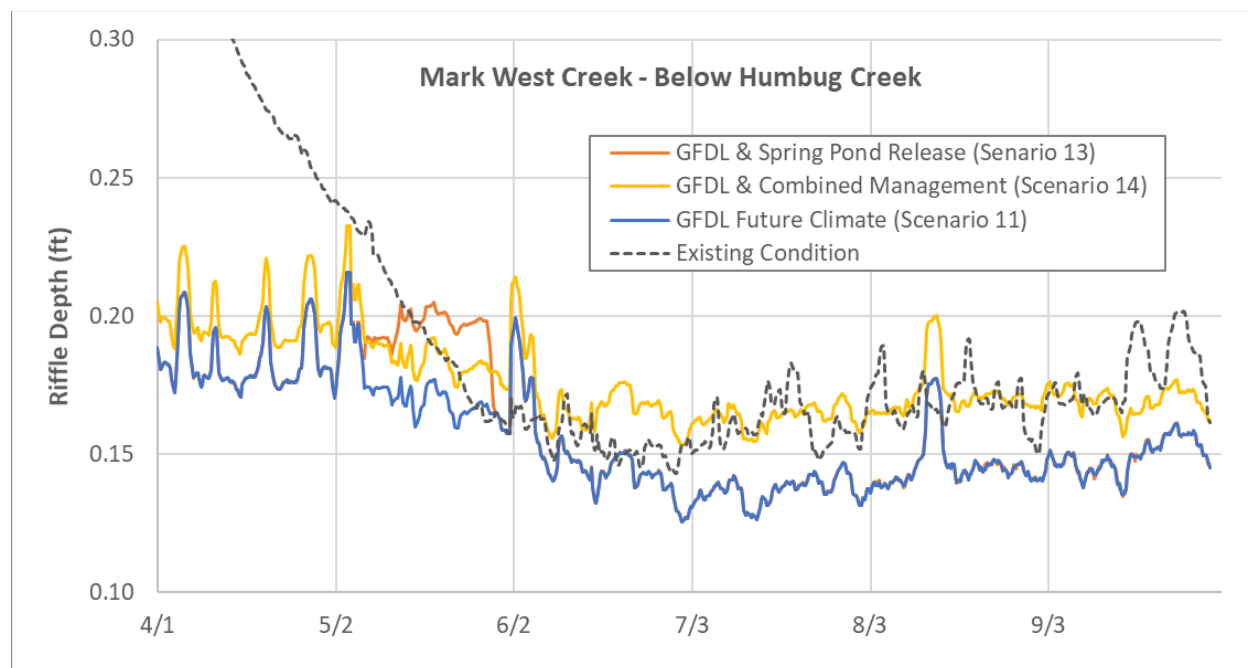
Figure 98: Spring and summer riffle depths for the driest year in the 10-yr simulation in Mark West Creek below Humbug Creek for existing conditions, GFDL future climate scenario (Scenario 11), the GFDL & springtime pond release scenario (Scenario 13), and the GFDL & combined management scenario (Scenario 14).

Summary and Comparison of Scenarios

Comparison of the changes in summer streamflow between the various scenarios indicates that the sustained cumulative effect of surface water and groundwater use are approximately equal and that cessation of all water use would eventually increase mean summer streamflow by about 6% in the ~4-mile high priority reach below Alpine Creek and ~8% at the watershed outlet (Figure 99). The pond release scenario generated the largest increases in summer streamflow of the stand-alone scenarios, with increases of about 13 - 14%. In the high priority reach, the next largest increases were from the forest management scenario, followed by the recharge management scenario (Figure 99). At the watershed outlet this order was reversed owing to the concentration of forest treatment areas in the upper watershed and the concentration of developed areas included in the runoff management scenario in the lower watershed. Runoff management generated about a 3% increase in summer streamflow in the high priority reach and a 10% increase at the outlet, whereas forest management generated about a 6% increase at both locations. The grassland management scenario generated the smallest increases in summer flows on the order of 2% (Figure 99).

The climate change scenarios generated a wide range of predictions with three of the four scenarios indicating decreases in summer streamflow of between 6 and 47% and one scenario indicating increases of about 15 - 19% (Figure 99). The mitigated scenarios indicate that pond releases can likely offset a significant portion of the projected decreases in summer streamflow predicted by some of the models and if combined with forest, grassland, and runoff

management, are likely large enough to completely offset the projected decreases (Figure 99). If future climate more closely resembles the predictions of the CNRM or CCSM4 models, pond releases and combined management would be expected to result in flow enhancement above existing conditions.

The various large-scale flow enhancement actions represented by the scenarios and the foregoing comparisons are intended to represent implementation of projects of a given type based on the maximum potential on the landscape. The scenarios vary widely in their scale, feasibility, and expected cost. To better understand the relative streamflow benefits of implementing a given project, we normalized the simulated increases in streamflow based on areas for a 'typical' parcel/project in the watershed (Figure 100). To normalize the surface water diversion scenario results, we assumed a new well would be drilled to replace the entire diversion volume with groundwater pumping. We divided the cumulative diversion effects by the total number of diversions and then subtracted the cumulative groundwater pumping effects normalized by the volume of diversion offset. In most cases it is not possible or practical to completely offset groundwater pumping with rainwater or runoff capture and storage. Installation of storage tanks is a common and practical means of offsetting groundwater pumping and we assumed 10,000 gallons of tank storage offset to normalize the groundwater pumping scenario results. The average per parcel acreages of forest treatment, grassland treatment, and impervious area represented by the scenarios was used to normalize the results for these three scenarios; these acreages were 5.6, 4.6, and 0.38 acres respectively. The pond release scenario was normalized by simply dividing the cumulative enhancement benefits by the number of release projects (three).

We also developed a rough cost estimate for each typical project and normalized the results again based on a $25,000 project cost. The six projects and estimated costs include:

- Groundwater Pumping Offset – installation of a 10,000 gallon rainwater catchment tank and associated reduction in groundwater pumping - $38,000
- Surface Diversion Replacement – replacement of a direct or spring diversion with a new groundwater well - $33,000
- Runoff Management – construction of an infiltration basin sized to capture the 10-yr 48-hr storm volume from a 3,000 ft^2 rooftop or other impervious area - $22,500
- Grassland Management – compost application on 4.6 acres of grassland (average per parcel acreage in the model scenario) - $7,000
- Forest Management – thinning and/or controlled burning on 5.6 acres of forested lands requiring treatment (average per parcel acreage in the model scenario) - $15,000
- Pond Release – summer flow release of 11.3 ac-ft from an existing on-stream pond (average release volume of the three ponds in the model scenario) - $20,000

This comparison revealed that pond releases are by far the most effective strategy for enhancing streamflows (Figure 100). On a cost basis, the streamflow benefits of one flow release project were found to be more than 50 times greater than an average surface water diversion replacement project and more than 500 times greater than an average grassland management

project (the second and third most effective strategies). Replacement of direct stream diversions or spring diversions of surface water with new wells is the second most effective strategy. Grassland and forest management showed a similar level of effectiveness on a cost basis and were about 3 - 4 times as effective as runoff management. Offsetting groundwater pumping with storage was the least effective of the six overall strategies considered.

It is important to recognize that runoff, forest, and grassland management may provide significant additional benefits besides streamflow enhancement compared to pond release and diversion replacement projects. These management strategies generate enhanced streamflow primarily via increasing groundwater discharge (see Figure 88), which may be expected to mitigate high water temperature, whereas flow releases from ponds may need to be carefully managed to avoid adverse temperature effects. These strategies also help reduce seasonal vegetation moisture stress which may decreases fire risk somewhat or at least help offset future increases in risk associated with climate change. In particular, the forest management scenario reduces actual evapotranspiration by about 5% on treated lands which represents a fairly large volume of water (615 ac-ft/yr), and the runoff management scenario results in a substantial decrease in the Climatic Water Deficit of about 25% on lands where they are implemented. These various benefits are in addition to the primary non-hydrologic benefits of forest and grassland management projects in reducing fuel loads and sequestering carbon respectively.

All four climate change scenarios representing the 2070-2099 timeframe indicate substantial decreases in springtime flows ranging from 35 - 62% (Figure 101). These changes greatly exceed the potential flow improvements associated with the various enhancement scenarios. Forest management generates the largest increases in mean spring discharges (~5 - 6%), and the other individual scenarios only increase spring flows by ~1 - 2% (Figure 101). As discussed above, while it may not be possible to significantly increase mean discharges during spring relative to the scale of expected decreases resulting from climate change, springtime pond releases lasting several days to weeks do provide a means of creating a period of passable flow conditions during critical outmigration periods which may be essential given the scale of the projected decreases in springtime flows (see Figure 98).
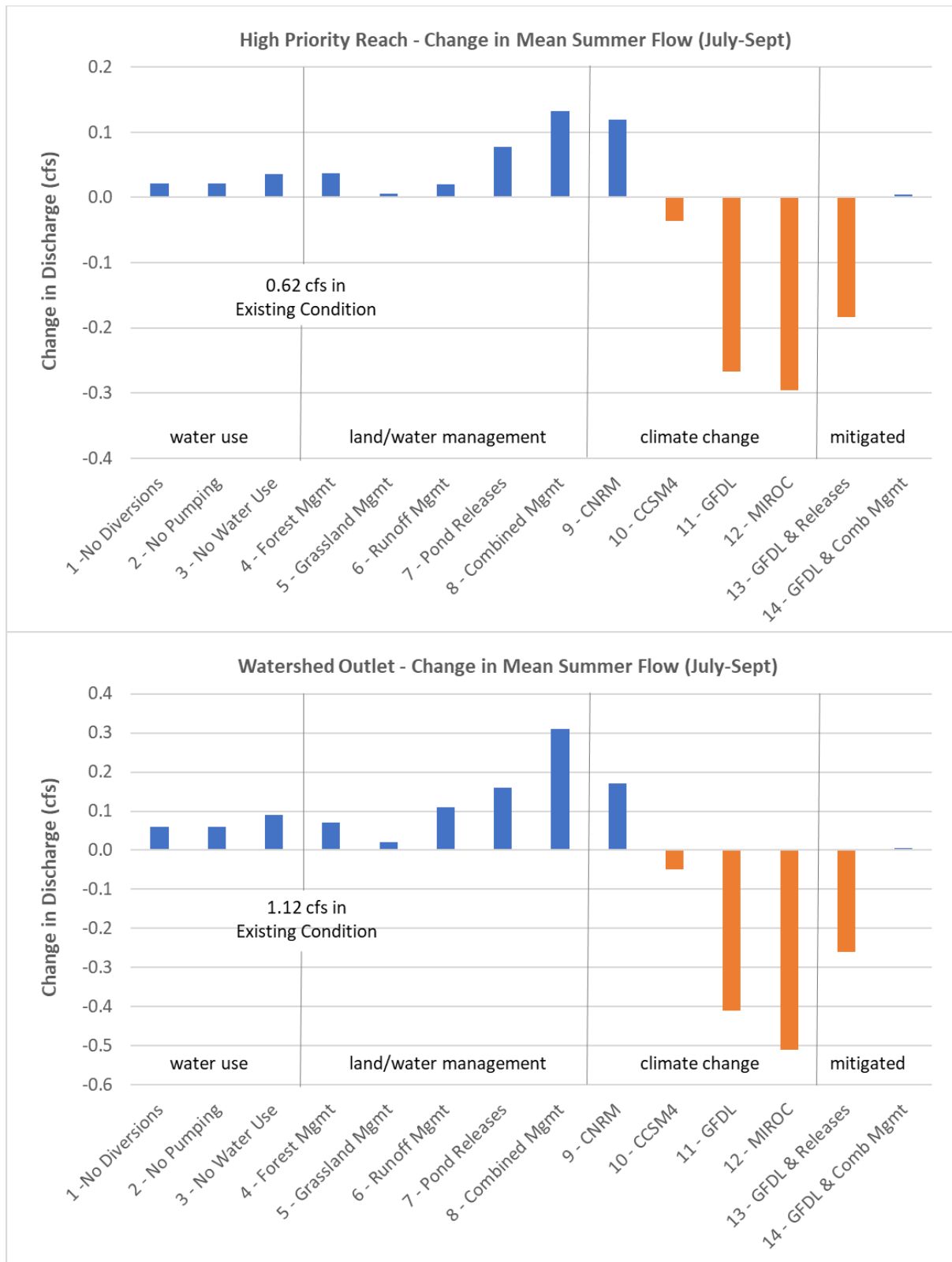
Figure 99: Summary of the simulated changes in mean summer streamflow for Scenarios 1-14 averaged over the high-priority habitat reach (top) and at the watershed outlet (bottom).
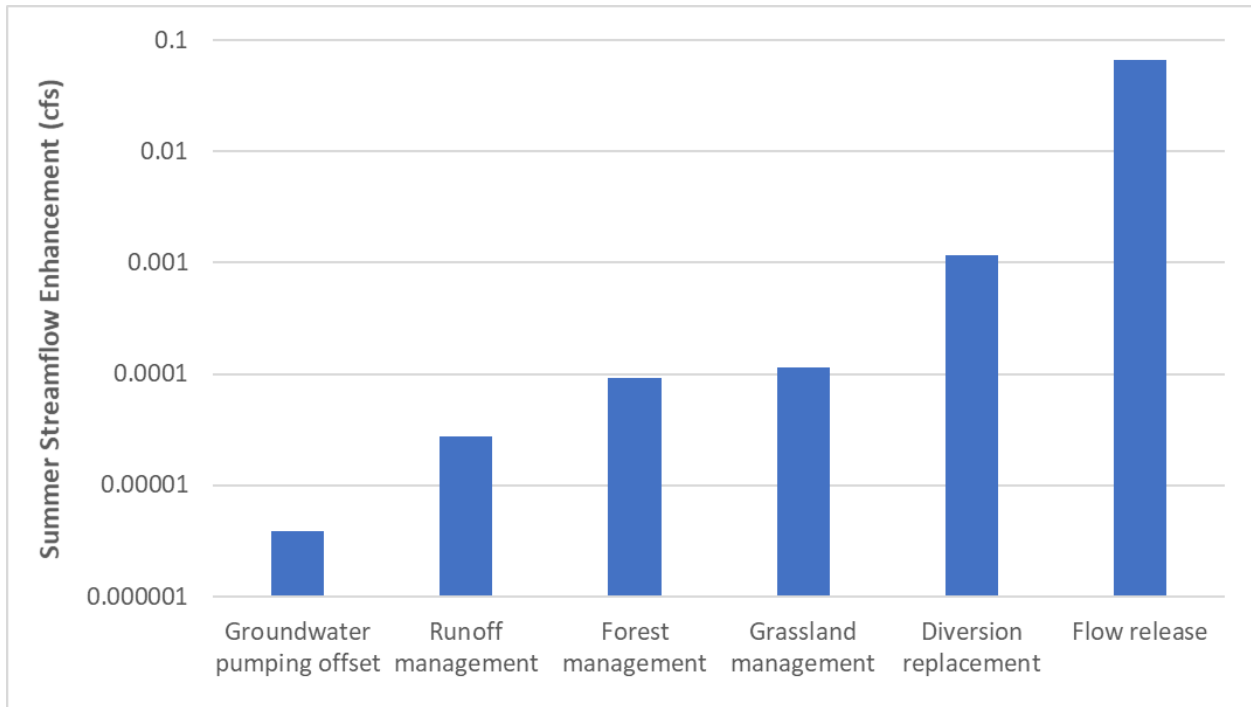
Figure 100: Summary of the simulated increase in mean summer streamflow for the six primary individual flow enhancement actions represented by the model scenarios normalized to a $25,000 project cost.
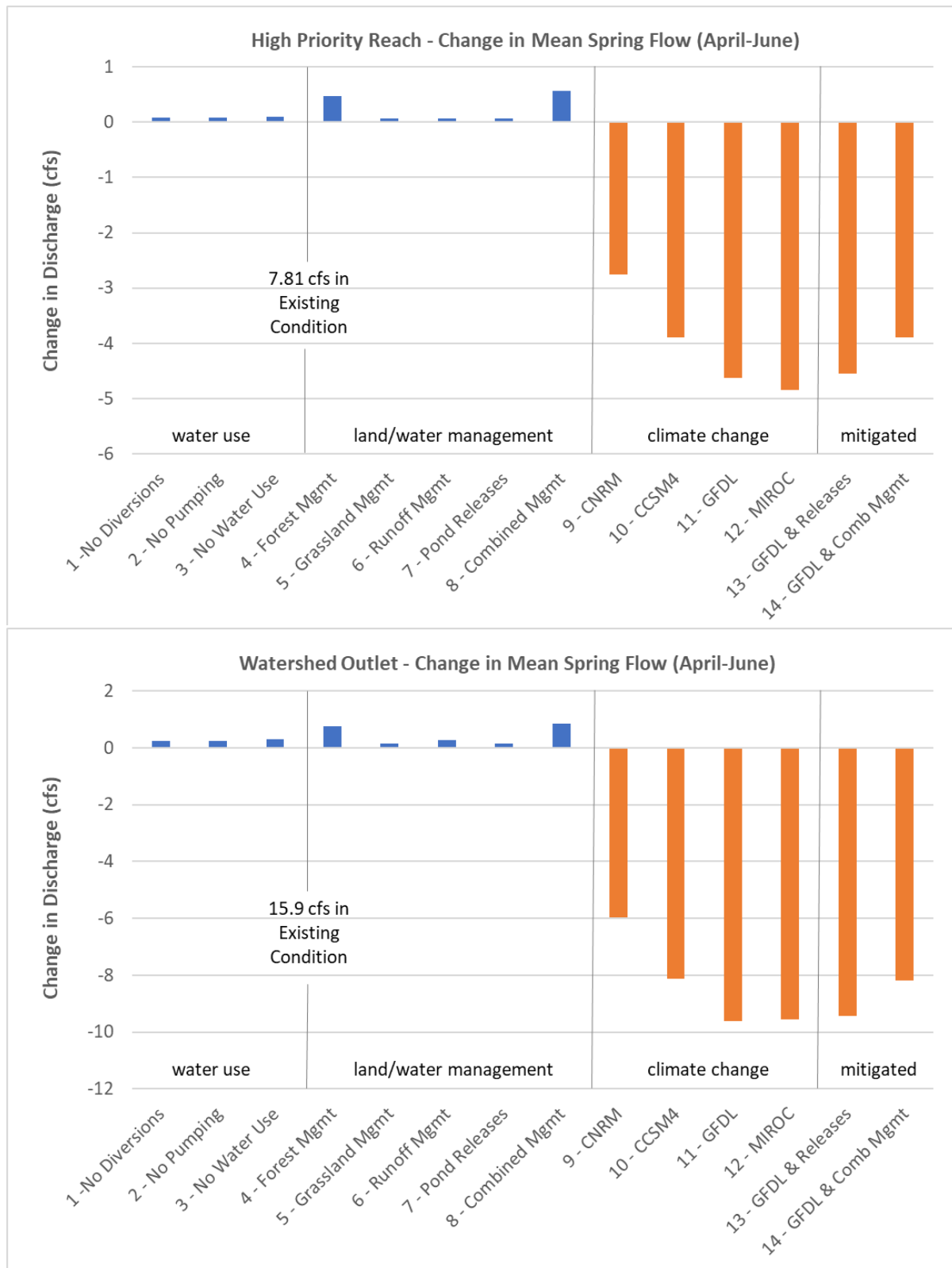
Figure 101: Summary of the simulated changes in mean springtime streamflow for Scenarios 1-14 averaged over the high-priority habitat reach (top) and at the watershed outlet (bottom).

Chapter 9 –Recommendations & Priority Restoration/Management Actions

Habitat Enhancement

Based on simulated riffle depth and observed water temperature data and informed by habitat inventory and fisheries monitoring data, the four mile reach extending from 0.2 miles upstream of Alpine Creek to 2.0 miles upstream of the Porter Creek confluence has the best overall habitat for salmonids (Figure 102). This analysis was focused on juvenile rearing and smolt outmigration; however, the identified reach is also believed to provide better spawning and winter rearing habitat conditions than upstream and downstream reaches. Conditions in the reach are far from optimal with impaired temperatures and insufficient summer streamflows. Nevertheless, the reach has the least impaired habitat conditions with significantly lower streamflows upstream and significantly higher temperatures downstream. We recommend that habitat enhancement projects be focused in this high priority reach where these efforts have the greatest likelihood of improving overall habitat conditions for salmonids.

Based on a limited number of sample sites, water temperatures in the high priority reach appear to remain below severely impaired levels in pools with depths above about 3.5-ft whereas severely impaired temperatures occur in shallower pools (see Figures Figure 62 & Figure 65). More temperature monitoring and pool inventory and analysis is recommended in the reach to identify pools providing critical temperature refugia. A temperature study is also warranted to better understand the factors affecting water temperature and to identify possible mitigation actions. Our preliminary findings suggest that streamflow is not the primary control on temperature and that encouraging formation of stable deep pools and maximizing shading are likely the most important immediate objectives. In-stream large wood (trees and logs) is very limited in Mark West Creek and installation of large wood on a broad scale at sites selected to encourage formation and protection of existing deep pools is recommended. Where needed, projects should also include riparian planting to maximize shading of the summer water surface. Opportunities for development of off-channel habitat projects to enhance winter rearing habitat are also available in the identified reach, and these types of projects are also recommended to support improved conditions in the reach for other limiting life cycle stages.

Flow Protection/Enhancement

Summer streamflow throughout Mark West Creek is generated primarily by spring discharge which most commonly occurs along streambanks with exposures of bedrock of the Sonoma Volcanics. Springflow is concentrated in the upper watershed with the watershed area upstream of Van Buren Creek supplying more than 55% of the total summer spring discharge in the watershed despite representing less than 17% of the total watershed area. We recommend that the various flow protection and enhancement actions described below be focused in the watershed area upstream of the Mill Creek confluence where they are more likely to provide flow benefits in the identified high priority reach. The watershed area upstream of Van Buren Creek could be considered even higher priority for flow protection and enhancement given the

disproportionate role the area plays in generating summer streamflow supplied to downstream reaches (Figure 102).

Given that groundwater discharge from the Sonoma Volcanics is the primary driver of summer streamflow, additional monitoring and analysis of subsurface geologic conditions and connectivity of springs and recharge source areas is warranted. Collection of data from a series of dedicated monitoring wells screened in specific geologic units and paired with springflow measurements is recommended to allow for an improved understanding of groundwater processes in the volcanics. Significant prior and ongoing effort has been given to collecting stage data and summer streamflow records, however limited effort has been dedicated to comprehensive rating curve development and generation of continuous streamflow records. Such data is critical to establishing baselines and understanding the effects of flow enhancement actions and ongoing climate change in the watershed and we recommend that a comprehensive long-term streamflow monitoring program be implemented for the watershed.

Releasing water from existing ponds was found to be by far the most effective individual strategy for enhancing streamflow (see Figure 100). The streamflow benefits of a cost-normalized flow release project were found to be more than 50 times greater than surface water diversion replacement projects and more than 500 times greater than grassland management projects (the second and third most effective strategies). Except in the reach upstream of Porter Creek, thick alluvial deposits are uncommon with many reaches of exposed bedrock and predominately gaining conditions persisting throughout the summer. These conditions are ideal for allowing released flows to provide flow benefits that persist in downstream reaches. Examination of existing ponds revealed that there are only three ponds upstream of the high-priority reach with sufficient storage to provide meaningful releases and we recommend that flow release projects be developed for these ponds if possible. There are many challenges that must be overcome to implement these flow release projects including landowner willingness, uncertainty regarding longevity, water quality and invasive species considerations, and permitting and water rights requirements.

There are many existing ponds that could likely be enhanced and new ponds could be built specifically to store water for streamflow enhancement. Given the disproportionate impact that pond releases are expected to have as a mitigation strategy for effects of climate change on streamflow, this somewhat controversial idea should be seriously considered. Water temperature and other water quality considerations should be an important aspect of planning flow release projects since water temperatures are already impaired and it is critical that flow releases do not further increase temperatures. There are various strategies for coping with elevated pond temperatures (e.g. bottom releases, surface shading, cooling systems) to the extent that this poses an issue during planning and design.

Our findings suggest that direct stream and spring diversions may have a significant impact on summer streamflow conditions at least over short periods when diversions are active; however, the cumulative effects of groundwater pumping in the watershed were relatively small. While we did find some relationship between the degree of streamflow depletion and the screen depth

and distance of wells from streams/springs, these differences were modest with a rate of depletion from near stream wells screened in the upper 200-ft about 1.7 times the rate from more distant wells screened at depths greater than 200-ft. We did not find any direct relationship between the timing of pumping and the timing of streamflow depletion with the primary effects of summer pumping manifesting largely as changes in water balance dynamics during the recharge season (see Figure 83). These findings suggest that replacing direct stream and spring diversions with storage and/or groundwater pumping is a viable approach for enhancing streamflow conditions but that offsetting groundwater pumping with storage or shifting the timing of pumping from summer to winter is unlikely to lead to appreciable improvements in flow conditions. Of the six general strategies considered, replacement of direct diversions is the second most-effective strategy after pond releases, whereas offsetting groundwater pumping was found to be the least effective strategy (see Figure 100).

Requiring new wells to be screened a set distance from a stream or spring or below a certain depth may extend the length of time before streamflow depletion occurs, but it will not prevent streamflow depletion from occurring. The long response timescale (decades) suggests that a volumetric approach to managing groundwater will likely lead to more successfully managing streamflow depletion compared to approaches focused on location or time of use. It is important to note that the total pumping stress in the watershed is relatively small (~3% of mean annual infiltration recharge) and that the limited degree of streamflow depletion under existing conditions should not be understood to suggest that significant streamflow depletion would not occur were the total volume of pumping to increase substantially in the future.

On a cost-normalized basis, grassland, forest, and runoff management all produced relatively small streamflow benefits with grassland and forest management being approximately 3-4 times as effective as runoff management (see Figure 100). These strategies also have important secondary hydrologic benefits in addition to enhancing streamflows in that they reduce seasonal vegetation moisture stress which may reduce fire risk. Specifically, forest management reduces actual evapotranspiration on treated lands by about 5% and runoff management decrease Climatic Water Deficits (CWD) in infiltration areas by about 25%; grassland management only resulted in a small decrease in CWD of about 1%. These benefits are in addition to the primary non-hydrologic benefits of these types of projects for reducing fuel loads (forest management) and sequestering carbon (grassland management).   There are also potential negative consequences of extensive forest management in terms of potential habitat loss for avian and terrestrial species which must be considered, and the forest treatments would only be effective in the long-term if periodically repeated to maintain the intended reduction in fuel load.

We recommend that a planning study be conducted for the upper watershed to identify parcels most suitable for grassland, forest, and runoff management projects and that these projects be implemented where feasible. Given that the streamflow benefits of these strategies are more than an order of magnitude less than those of diversion replacement and more than two orders of magnitude less than those of pond releases, the various types of management projects are considered a lower priority than pond release or diversion replacement projects. That said, the long-term maintenance of streamflow under future climate conditions may require all of the flow

enhancement strategies to be implemented and it is important to gain near-term experience with these management strategies and to attempt to monitor their effectiveness.

The optimal design and effectiveness of runoff management projects is highly site specific and it is recommended that projects be focused on parcels with significant impervious area that are currently well-connected to surface water features, have relatively high soil infiltration rates, and sufficient space and site conditions to allow for larger-scale infiltration features. Gravel-filled infiltration basins may be required in some cases to prevent ponding of stagnant waters for more than 72-hrs per Sonoma County vector control requirements. Native soil basins will likely work in some situations, and where space is limited basins can be combined or replaced with bioswales and/or features designed to distribute water evenly across the landscape.

In summary while runoff, forest, and grassland management may not result directly in substantial streamflow improvement, these efforts have multiple benefits and are likely important strategies for managing fire risk and mitigating climate change impacts as discussed in more detail below.

Climate Change Adaptation
Climate change is expected to result in a dramatic decrease in springtime flows particularly during drought conditions. Summer baseflows are also predicted to decrease in some simulations, however the future trajectory of summer flows is less certain with some scenarios predicting limited changes or modest increases. The decline in flows during spring is expected to have significant effects on salmonids particularly with respect to smolt outmigration with some of the climate scenarios predicting that in some years flows will fall below passage thresholds nearly continuously from mid-February through October. The only feasible means to at least partially mitigate this dire threat to salmonids appears to be the implementation of springtime pond releases. While it may not be possible to significantly improve conditions throughout the smolt outmigration period, relatively high release rates could be achieved for a period of several days to weeks to provide a period of passable flow conditions timed to coincide with expected peak smolt outmigration (see Figure 98). We recommend that flow release projects be developed and adaptively managed to provide a combination of larger pulses of streamflow during outmigration and enhanced streamflow during summer baseflow depending on conditions in a given year.

The runoff, forest, and grassland management strategies influence the quantity of streamflow from springs which in general is relatively cold, therefore these approaches may be expected to assist in mitigating elevated water temperatures whereas the more effective strategies (pond releases and diversion replacement) would not be expected to provide temperature benefits (see Figure 88). These strategies also help reduce vegetation moisture stress by increasing the quantity of water available to plants in the case of runoff and grassland management or decreasing water demand from the landscape for the case of forest management. This reduced moisture stress may be an important benefit for wildfire hazard reduction and the increase in wildfire hazard expected as a result of climate change.

In summary, implementation of runoff, forest, and grassland management projects are expected to help build resiliency to climate change by providing multiple benefits beyond potential

streamflow improvement and spring and summer pond releases provide a means of adaptively managing flow conditions for salmonids in the face of a changing climate.
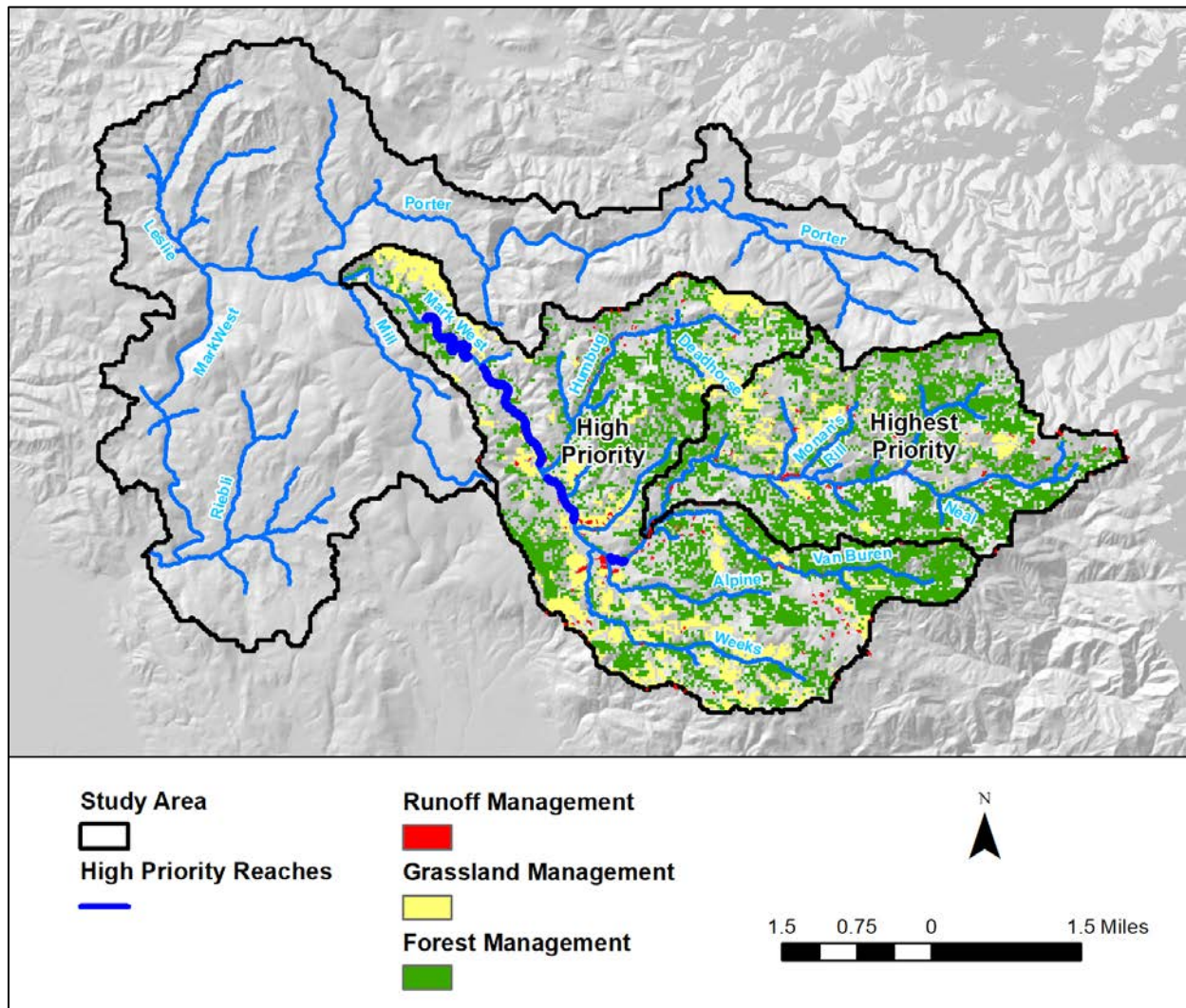
Figure 102: *Locations of the identified high priority reaches for habitat enhancement projects and high priority watershed areas for flow enhancement projects.*

Chapter 10 – Conceptual Design Development

The final phase of the project involved development of conceptual designs for two site specific streamflow enhancement projects. The projects focus on the approach of runoff management and were selected to take advantage of local site conditions and project opportunities on properties managed by our project partners the Pepperwood Foundation and Sonoma County Regional Parks. The projects illustrate two possible approaches to managing runoff for enhanced groundwater recharge and we anticipate similar approaches as well as other alternative methods could be applied on parcels throughout the watershed.

Goodman Meadow

Site 1 is located within the Pepperwood Preserve at the Goodman Meadow near the headwaters of Leslie Creek in the northwest corner of the watershed (Figure 103). The Goodman Meadow site consists of a relatively flat, approximately 12-acre natural basin perched on a topographic
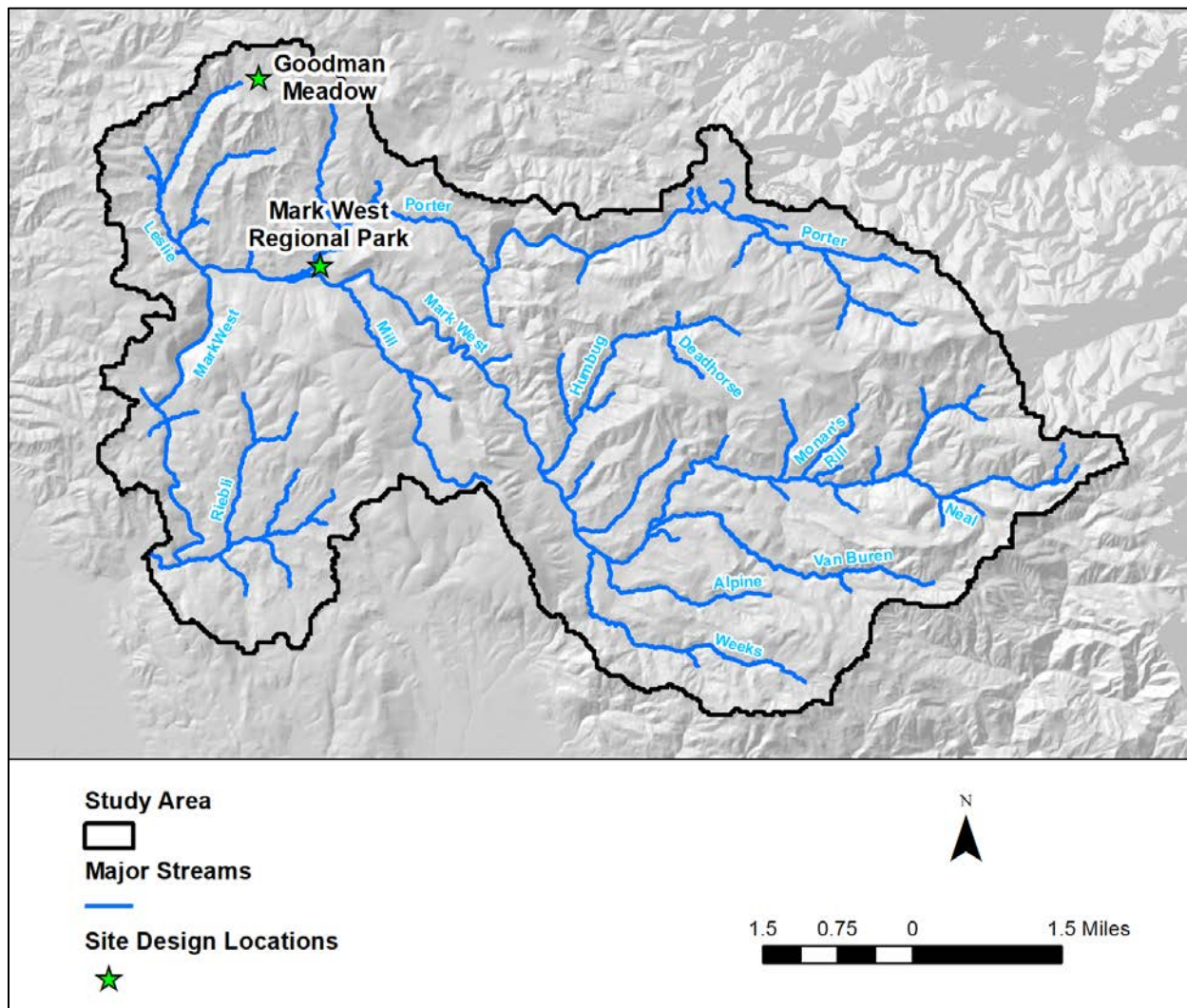

Figure 103: Locations of the two streamflow enhancement sites where conceptual designs have been developed.

bench and drained by an incised channel cutting through its western margin (see Appendix A, profile A to A'). The design consists of constructing a berm across the narrow valley at the basin outlet to retain winter runoff within the meadow and promote enhanced groundwater recharge. A channel exits the basin flowing southwest through a relatively narrow valley (approximately 60-ft wide at the base of adjacent slopes, see Appendix A section B to B') creating an optimal site for a berm or small dam. Approximately 94 acres of watershed area drain to the proposed berm site. The contributing area consists of mostly oak woodland and is not developed outside of an unpaved ranch road which traverses the hillside at the upper end of the meadow.

The basin outlet elevation will control the volume of water captured and stored within the basin. Various types of outlet structures are possible and for this conceptual design we assumed a 50-ft wide broad-crested weir with Low (1,128.0-ft) and High (1,132.5-ft) outlet elevation options (Appendix A). The Low elevation option would create an impoundment area of approximately 0.5 acres capable of storing approximately 1.1 ac-ft of water. Assuming 2-ft of freeboard above the outlet elevation, the Low elevation option would require a berm with an average height at the outlet of 4 feet above the meadow plain and a height of about 7-ft at the outlet above the incised channel bed. Based on existing LiDAR elevation data collected in 2013 (WSI, 2016), an ~98-ft long berm would be required. Assuming a 2H:1V berm side slope and a 4-ft berm top width, this would require approximately 274 yd^3 of fill (Appendix A). The High elevation option would create an impoundment area of approximately 1.4 acres and approximately 5.3 ac-ft of storage. The required berm would have an average outlet height of 8.5-ft above the meadow plain and a height of 11.5-ft at the outlet above the incised channel bed. Based on existing LiDAR elevation data, an ~132-ft long berm would be required. Assuming a 2H:1V berm side slope and a 4-ft berm top width, this would require approximately 692 yd^3 of fill (Appendix A).

A flow release structure should also be included near the base of the outlet to allow for drainage of retained water for maintenance purposes and/or for seasonal drainage if desired. An appropriate release schedule would be guided by Pepperwood Preserve's overall management strategy for the meadow and include consideration of the effects of the changed hydroperiod on grassland communities. These details would be further investigated and determined during subsequent design phases.

To evaluate the anticipated recharge and streamflow enhancement benefits associated with construction of the Goodman Meadow project, we implemented the conceptual design (using the higher of the two outlet elevations) as a scenario in the hydrologic model. The model represents the basin using a stage-storage relationship and calculates daily water levels as a function of simulated inflows from runoff and groundwater and simulated outflows across a broad-crested weir outlet structure and from evaporation and infiltration recharge.

The storage volume of the basin is relatively small compared to the available runoff and it fills to capacity during the first significant rainfall event of each year (typically in November or December). The basin remains near capacity throughout the rainy season with water levels typically beginning to decline in May or early June (Figure 104). Water levels typically reach a minimum in October by which point the upper portions of the basin are dry with 4-6-ft of water
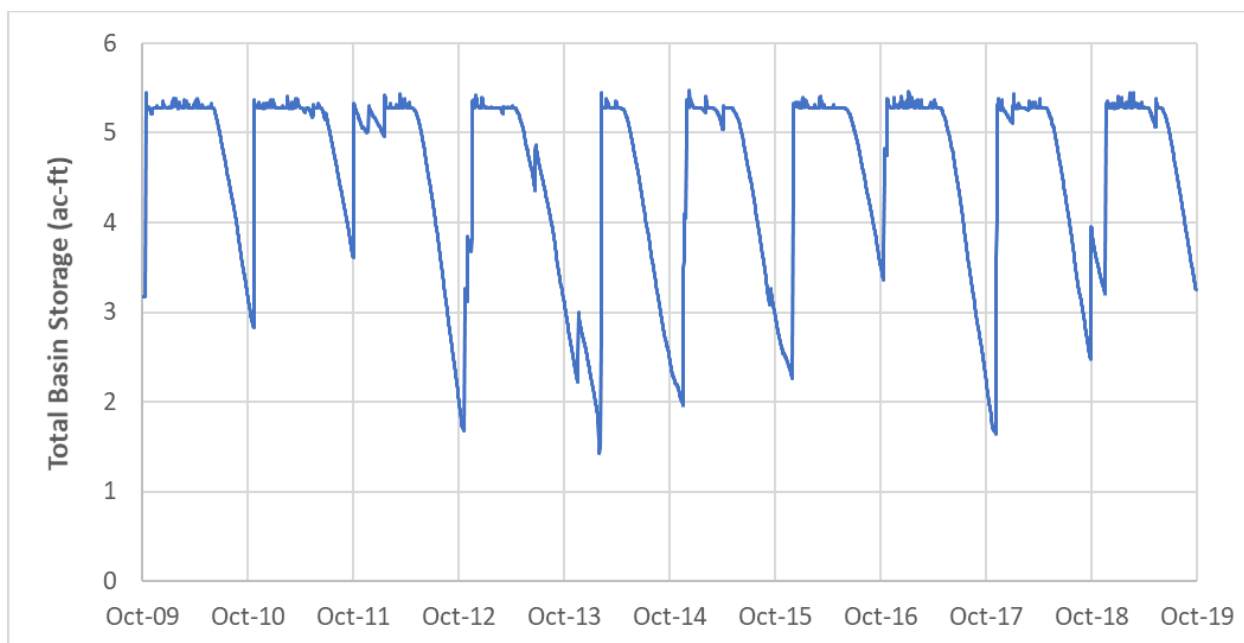
Figure 104: Daily fluctuations in storage in the Goodman Meadow recharge basin over the 10-yr hydrologic model simulation period.

remaining in the lower portions of the basin. The seasonal drawdown is dependent primarily on the duration of the dry season with minimum storage levels ranging from 1.4 to 3.6 ac-ft (26-68% of total capacity) (Figure 104).

Under existing conditions, mean annual infiltration recharge in the basin footprint was ~3.6 in/yr, and under proposed conditions this rate increases to ~18.7 in/yr. The total volume of additional recharge provided by the project is estimated to be about 1.9 ac-ft/yr. This additional recharge generates a modest increase in streamflow downstream in Leslie Creek. The upper reaches of the creek are intermittent and typically dry out sometime between late April and late June. The recharge enhancement serves to extend the length of time that the stream remains flowing each spring by between 12 and 21 days and the 10-yr mean streamflow over the April through June timeframe increases by about 0.01 cfs, representing about a 7% increase in flow.

Mark West Regional Park

Site 2 is located on a terrace on the east bank of Porter Creek just upstream of its confluence with Mark West Creek (Figure 103). The site is slated to be developed as the main entrance and parking area for the newly formed Mark West Regional Park operated by Sonoma County Regional Parks. Park facilities have not yet been designed in detail but are expected to be contained within approximately 3.1 acres currently occupied by a barn structure and an adjacent parking area and gravel road (Appendix B). The stormwater management design described here could become a part of the overall design for the park facilities and consists of collecting runoff from the developed portions of the park entrance in a network of diversion ditches and directing these flows into a series of two linear, gravel filled infiltration basins designed to maximize

groundwater recharge. These basins are also expected to provide ancillary benefits by reducing peak runoff and providing filtration of pollutants from the parking area.

The basin alignment corresponds to an existing ditch that runs along the base of the slope southeast of the barn and parking lot. The upper basin is approximately 130-ft in length and runs adjacent to the existing parking area maintaining the existing slope of 0.6%. The lower basin runs approximately 490-ft behind the existing barn and maintains the existing slope of 0.2%. The two basins are separated by a road crossing where a 2.5-ft diameter, 150-ft long culvert is proposed to transport flows (Appendix B).

In addition to runoff collected from the developed footprint, the basins and associated channel will also receive flows from the adjacent hillslope which encompasses approximately 15.4 acres. The main intent of this infiltration basin design is to detain runoff from the developed areas associated with the new Mark West Regional Park entrance facilities and as such the basin has been sized to provide storage for a volume associated with a representative design storm for that area. Typically, infiltration basins are not recommended to receive runoff from drainage areas greater than 2 acres of undeveloped area due to concerns of sediment clogging which, over time could lead to a reduction in basin storage and groundwater recharge potential. Preliminary field observations suggest that runoff from the hillslope likely occurs primarily as sheetflow rather than as concentrated flow which suggests that sediment delivery to the basin may be minimal. Nevertheless, subsequent design work should include measures to minimize concentrated flow and sediment delivery to the basin from the adjacent undeveloped area such as a vegetation buffer with erosion control features along the base of the hillslope parallel to and up-gradient of the basin.

Channel dimensions were based on capacity calculations associated with the 100-yr recurrence interval storm runoff from the combined areas of the developed park and the 15.4-acre hillside. A simple Rational Runoff model for this area estimated 100-yr peak flows from the 3.1 acres of park facility and the adjacent 15.4-acre undeveloped watershed to be approximately 28 cfs. The channel and culvert sizes needed to accommodate this peak discharge were determined using standard open-channel and culvert hydraulic calculations and representative cross sections. The design channel is 2-ft deep, has a bottom width of 5-ft, and has side slopes blending into the existing topography with maximum slopes of 2:1 (Appendix B). A 2.5-ft diameter circular culvert with a slope of 2% connecting the two basins is required to convey the 100-year event (Appendix B).

This design is preliminary and further work by Sonoma County Regional Parks would be necessary to confirm feasibility of this approach. Topographic surveys, soil analysis, and infiltration testing will be necessary to generate construction ready design plans and provide infiltration performance estimates. Typical stormwater retention designs are required to eliminate ponded surface water within 72 hours to prevent mosquitos from breeding; however, this is largely mitigated by the gravel-filled basin design. We did not explicitly simulate this design in the hydrologic model because the scale of the design features is too small to accurately resolve using the 0.5-acre regional model grid. Nevertheless, results from the Runoff Management scenario

described in Chapter 8 provide some context regarding the groundwater recharge enhancement and associated streamflow benefits expected from the project.

The regional scenario indicated that management of runoff from 98 acres in the Porter Creek watershed would generate approximately 73.4 ac-ft of additional infiltration recharge. The project design includes a storage volume equivalent to about 1.7% of the storage volume assumed in the regional scenario but only about 0.4% of the surface area. There are many additional factors that may increase or decrease the effectiveness of the design relative to the assumptions of the regional scenario. Nevertheless, these proportions serve as a general guide for estimating the recharge benefits of the proposed project and yield a range of expected additional recharge above background rates of between 0.3 and 1.2-ac-ft/yr.

The reach of Porter Creek adjacent to and downstream of the project site typically goes dry sometime between late May and late July depending on rainfall conditions. The regional modeling indicated that large-scale management of runoff in the Porter Creek watershed could extend the duration of streamflow adjacent to the project reach by 5 to 13 days and increase the mean April through June streamflow by about 0.05 cfs. As discussed above, the project would likely result in less than 2% of the recharge enhancement represented by the regional scenario suggesting that the streamflow benefits of the project by itself would be unlikely to significantly improve flow conditions in lower Porter Creek; though the project's proximity to the intermittent reach of Porter Creek suggests that it may provide greater streamflow benefits than projects located in upstream areas.

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