Appendix C
Russian River Watershed Resilience Pilot Study Vulnerability Assessment

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Contents

1. Introduction 1-1

2. Vulnerability Assessment Summary 2-1

2.1 Surface Water Supply 2-3

2.2 Groundwater Supply 2-3

2.3 Flood Management 2-3

2.4 Water Quality 2-4

2.5 Ecosystems 2-4

2.6 Recreation 2-5

2.7 Hydropower 2-5

2.8 Community and Equity 2-5

3. Qualitative Vulnerability Assessment 3-1

3.1 Purpose 3-1

3.2 Methodology 3-1

3.2.1 Sensitivity Rating 3-1

3.2.2 Adaptive Capacity Rating 3-2

3.2.3 Vulnerability Rating 3-2

3.3 Results 3-2

4. Quantitative Vulnerability Assessment 4-1

4.1 Purpose 4-1

4.2 Methodology 4-1

4.2.1 Climate Projections and Hydrologic Responses from the Watershed 4-1

4.2.2 Vulnerability Indicators and Metrics 4-4

4.2.3 Analytical Tools 4-6

5. Surface Water Supply Vulnerability Assessment 5-1

5.1 Purpose 5-1

5.2 Methodology 5-1

5.3 Results 5-4

5.4 Summary 5-12

6. Groundwater Supply Vulnerability Assessment 6-1

6.1 Purpose 6-1

6.2 Methodology 6-1

6.2.1 GSFLOW Watershed Analysis 6-1

6.2.2 Groundwater Sustainability Plan Summaries 6-2

6.2.3 DWR's Water Shortage Vulnerability Analysis 6-5

6.3 Results ... 6-5
6.3.1 GSFLOW Analysis of the Russian River Watershed ... 6-5
6.3.2 Results from the Eight Climate Change Simulations ... 6-7
6.3.3 Groundwater Sustainability Plan Summaries ... 6-12
6.3.4 DWR's Water Shortage Vulnerability ... 6-16
6.4 Summary ... 6-20
7. Flood Management Vulnerability Assessment ... 7-1
7.1 Purpose ... 7-1
7.2 Methodology ... 7-1
7.2.1 Russian River HEC-HMS (Hydrologic Model) ... 7-4
7.2.2 Santa Rosa Creek HEC-HMS (Hydrologic Model) ... 7-5
7.2.3 Russian River HEC-ResSim (Reservoir Operations Model) ... 7-6
7.2.4 Russian River HEC-RAS (Hydraulic Model) ... 7-6
7.2.5 Santa Rosa Creek HEC-RAS (Hydraulic Model) ... 7-7
7.3 Results ... 7-7
7.4 Summary ... 7-13
8. Water Quality Vulnerability Assessment ... 8-1
8.1 Purpose ... 8-1
8.2 Methodology ... 8-1
8.2.1 Model Description ... 8-1
8.2.2 Simulation Plan ... 8-3
8.2.3 Model Inputs ... 8-3
8.3 Results ... 8-4
8.3.1 Lake Mendocino Outflow Temperature ... 8-5
8.3.2 Russian River at Cloverdale Temperature ... 8-7
8.3.3 Lake Sonoma Outflow Temperature ... 8-8
8.3.4 Russian River at Hacienda Bridge Temperature ... 8-9
8.3.5 Russian River at Cloverdale and Hacienda Bridge Dissolved Oxygen ... 8-10
8.4 Summary ... 8-12
9. Ecosystem Vulnerability Assessment ... 9-1
9.1 Background ... 9-1
9.2 Purpose ... 9-3
9.3 Methodology ... 9-4
9.3.1 Mainstem Russian River and Tributaries ... 9-5
9.3.2 Russian River Estuary ... 9-7
9.4 Results ... 9-12

9.4.1 Mainstem Russian River and Tributaries ... 9-12
9.4.2 Russian River Estuary ... 9-29
9.5 Summary ... 9-32
10. Recreation Vulnerability Assessment ... 10-1
10.1 Purpose ... 10-1
10.2 Methodology ... 10-1
10.3 Results ... 10-4
10.4 Summary ... 10-7
11. Hydropower Vulnerability Assessment ... 11-1
11.1 Purpose ... 11-1
11.2 Methodology ... 11-1
11.3 Results ... 11-1
11.4 Summary ... 11-3
12. Community and Equity Considerations ... 12-1
12.1 Purpose ... 12-1
12.2 Methodology ... 12-1
12.2.1 Sensitivity Indicators ... 12-2
12.3 Results ... 12-3
12.3.1 Flooding ... 12-3
12.3.2 Wildfire ... 12-7
12.3.3 Extreme Heat ... 12-9
12.3.4 Water Supply ... 12-11
12.4 Summary ... 12-12
12.4.1 Recommendations for Implementation ... 12-13
13. References ... 13-1

Attachment

Attachment C-1 Overview of Analytical Tools Used in the Russian River Watershed Resilience Analyses

Tables

3-1. Vulnerability Scoring Matrix ... 3-2
3-2. Qualitative Vulnerability Assessment Ratings ... 3-5
4-1. Summary of CMIP6 LOCA2-Hybrid GCMs ... 4-3
4-2. Climate Vulnerability Indicators and Metrics by Sector ... 4-5

4-3. Overview of Analytical Tools by Water Sector ... 4-6

6-1. Groundwater Models, Project Time Periods, and Assumptions Associated with Groundwater Sustainability Plan Future Projections ... 6-3

6-2. Average Annual Groundwater Budget under Historical, Current, and Projected Conditions for the Ukiah Valley Subbasin ... 6-13

6-3. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Santa Rosa Plain Subbasin ... 6-14

6-4. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Petaluma Valley Subbasin ... 6-15

6-5. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Sonoma Valley Subbasin ... 6-16

7-1. Historical Flood Events and Peak Flows ... 7-3

8-1. Model Water Quality Constituents ... 8-2

8-2. LOCA2-Hybrid Selected Scenarios ... 8-3

8-3. Model Meteorological Data Inputs ... 8-3

8-4. Model Meteorology Input Locations ... 8-4

8-5. Daily Average Temperature Results for Lake Mendocino Outflow, Cloverdale, Lake Sonoma Outflow, and Hacienda Bridge Model Locations ... 8-5

8-6. Daily Average Dissolved Oxygen Results for Cloverdale and Hacienda Bridge Model Locations ... 8-11

9-1. Water Temperature Upper Tolerance Threshold for Russian River Salmonids by Life Stage ... 9-6

9-2. Projected Sea Level Rise Scenarios for Point Reyes (feet) ... 9-11

10-1. Lake Mendocino Reservoir Elevation Thresholds ... 10-1

10-2. Lake Sonoma Reservoir Elevation Thresholds ... 10-2

10-3. Russian River Flow Thresholds for Recreation Analysis ... 10-2

10-4. Public Access Points along Assessed Reaches of the Russian River ... 10-3

12-1. Hazard-Specific Social Indicators ... 12-2

12-2. Overview of Climate Hazard Metrics, Definitions, and Reference Periods ... 12-3

12-3. Flood Sensitivity Distribution Across Russian River Watershed Population ... 12-5

12-4. Distribution of Population Sensitivity to Wildfire ... 12-7

12-5. Distribution of Population Sensitivity to Extreme Heat ... 12-9

12-6. Distribution of Population Sensitivity to Vulnerable Water Supply ... 12-11

Figures

2-1. Key Vulnerabilities Across the Russian River Watershed Resilience Pilot Study Planning Area ... 2-2

4-1. Application of Climate Projections in Vulnerability Assessment ... 4-2

5-1. Russian River ResSim Schematic ... 5-3

5-2. Lake Mendocino September 30 Storage Across All Scenarios by Water Year Period ... 5-5

5-3. Lake Sonoma September 30 Storage Across All Scenarios by Water Year Period 5-7

5-4. Lake Mendocino and Lake Sonoma Storage Volume for Future Projection EC-Earth3 5-8.5 for Two Baseline Scenarios: (1) No PVP, which ends Eel River transfers starting in 2035, and (2) NERF Operations, in which PVP transitions to NERF beginning in 2035 5-8

5-5. Annual Russian River Diversions at Mirabel and Wohler facilities Across All Scenarios by Water Year Period 5-9

5-6. Total Marin Surface Storage September 30 Values Across All Scenarios by Water Year Period 5-10

5-7. Stafford September 30 Storage Values Across All Scenarios by Water Year Period 5-11

5-8. Total Sonoma Water Retail Customer Annual Shortage Volumes Across All Scenarios by Water Year Period 5-12

6-1. Eight GCM Climate Future Scenarios Simulated by the RRIHM Plotted as Departure from Historical Mean Precipitation and Temperature Values 6-2

6-2. Spatial Distribution of Streamflow Depletion Factors, Simulated for the 1990–2015 Simulation Period 6-6

6-3. Seasonal Precipitation Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed 6-7

6-4. Seasonal Runoff Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed 6-8

6-5. Seasonal Evapotranspiration Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed 6-8

6-6. Seasonal Changes in Groundwater Storage Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed 6-9

6-7. Seasonal Groundwater/Surface Water Exchange Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed 6-9

6-8. Simulated Cumulative Groundwater Storage Change for Aquifer Systems Along the Upper Russian River and Dry Creek During a Hypothetical 5-year Drought Period 6-11

6-9. Simulated Net Surface-Groundwater Exchange for Aquifer Systems Along the Upper Russian River and Dry Creek During a Hypothetical 5-year Drought Period 6-11

6-10. Simulated Cumulative Net June to October Surface-Groundwater Exchange for Aquifer Systems Along the Upper Russian River and Dry Creek, Partitioned by Years in Which Lake Mendocino Drops Below Dead Pool Storage 6-12

6-11. (a) DWR's Water Shortage Physical Vulnerability Total Score Within the RRWRP Study Area. (b) DWR's Water Shortage Physical Vulnerability Total Score Filtered to Only Include Bedrock Areas and Areas with Domestic Well Users. 6-17

6-12. Exceedance Plot of Physical Vulnerability Total Score used to Assign Qualitative Vulnerability Ranking's for the Areas Dependent on Bedrock Groundwater Supplies 6-18

6-13. Map of Ranked Physical Vulnerability for Bedrock Areas of RRWRP Study Area 6-19

7-1. Model Schematics for Russian River HEC-HMS, HEC-ResSim, and HEC-RAS 7-2

7-2. Increase in Precipitation in the Russian River Watershed 7-4

7-3. Sample of Structures at Risk near Geyserville with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event) 7-9

7-4. Sample of Structures at Risk near Guerneville with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event) 7-9

7-5. Sample of Structures at Risk near Healdsburg with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event) 7-10

7-6. Sample of Structures at Risk near Cloverdale with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event) 7-10

7-7. Sample of Structures at Risk in Santa Rosa (east of 101) with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event [585]) 7-11

7-8. Sample of Structures at Risk in Santa Rosa (west of 101) with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event [585]) 7-12

7-9. Increase in Modeled Residences at Risk in Russian River Watershed for 25-, 50-, and 100-year 24-hour Storm 7-12

7-10. Increase in Modeled Residences at Risk in Santa Rosa Creek Watershed for 25-, 50-, and 100-year 24-hour storm 7-13

8-1. Russian River Water Quality Model Network 8-2

8-2. Lake Mendocino Outflow Daily Average Temperature 8-6

8-3. Average Seasonal Lake Mendocino Outflow Temperature and Storage EC-Earth3-Veg SSP5-8.5 8-6

8-4. Average Seasonal Lake Mendocino Outflow Temperature and Storage MRI-ESM2-0 SSP3-7.0 8-7

8-5. Cloverdale Daily Average Temperature 8-8

8-6. Average Seasonal Cloverdale Water Temperature and Air Temperature EC-Earth3-Veg SSP5-8.5 8-8

8-7. Average Seasonal Lake Sonoma Outflow Temperature EC-Earth3-Veg SSP5-8.5 8-9

8-8. Hacienda Bridge Daily Average Temperature 8-10

8-9. Average Seasonal Hacienda Water Temperature and Air Temperature EC-Earth3-Veg SSP5-8.5 8-10

8-10. Daily Average Dissolved Oxygen Results for Cloverdale Model Location 8-11

8-11. Daily Average Dissolved Oxygen Results for Hacienda Model Location 8-12

9-1. Site Map Showing the Location of the Russian River Estuary Within the Russian River Watershed 9-3

9-2. Longitudinal Maps of the Russian River Estuary Showing Interpolated Temperature, Salinity, and Dissolved Oxygen Fields, Based on Boat-based Profiles Collected by UC Davis for a Specific Closed River Mouth (inlet) Condition on September 30, 2014 9-9

9-3. Example Wave Frequency Distribution Change from USGS CMIP6 Future Wave Dataset 9-12

9-4. Modeled Average Daily Discharge at Russian River HEC-ResSim Nodes 9-14

9-5. Modeled Average Daily Discharge for the Dry Creek at its Confluence with the Russian River HEC-ResSim Node 9-14

9-6. Percent Change in Total Annual Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) 9-16

9-7. Percent Change in 99th Percentile Annual 1-day Maximum Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) 9-16

9-8. Percent Change in 99th Percentile Annual 3-day Maximum Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) 9-17

9-9. Percent Change in Total Fall (October through December) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) ... 9-17

9-10. Percent Change in Total Winter (January through March) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) ... 9-18

9-11. Percent Change in Total Spring (April through June) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left) ... 9-18

9-12. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During the Adult Migration Period (October–March). ... 9-20

9-13. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During the Spawning and Incubation Period (November–April) ... 9-21

9-14. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During Salmonid Juvenile-rearing Period (April–November) ... 9-22

9-15. Modeled Average Daily Minimum Dissolved Oxygen at Russian River Nodes ... 9-23

9-16. Modeled Average Daily Minimum Dissolved Oxygen at Dry Creek ... 9-24

9-17. (a) Cumulative Annual Precipitation (cm) by Water Year (October–September) at the Venado Weather Station near Healdsburg, California. (b) Proportion of Total Tributary Channel Length Surveyed from 2012–2025 in the Russian River and Dry Creek Watersheds Classified as Wet, Intermittent, or Dry at the Time of Late-season Surveys ... 9-27

9-18. Modeled Inlet Closure Seasonality Within Each Epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]) ... 9-29

9-19. Suitable Steelhead Rearing Habitat Availability per Month in Acre-days for Historical (1981–2010), Mid-Future (2041–2070), Late-Future (2071–2100) Epochs ... 9-31

9-20. Temperature Range by Month Under Closed Conditions in the Estuary for Historical (1981–2010), Mid-Future (2041–2070), Late-Future (2071–2100) Epochs with the Suitability Threshold for Juvenile Salmonids Defined by Boughton et al. (2017) ... 9-32

9-21. Average Monthly Discharge Across All Water Years Simulated by the 41 Climate Models for Each Epoch (Historical, Mid-Future, and Late-Future) at the Four Focal Nodes ... 9-34

9-22. Average Maximum Daily Temperature Average by Month Across all Water Years Simulated by the Three Climate Models for Each Epoch (Historical, Mid-Future, and Late-Future) at the Three Water Quality Nodes ... 9-35

9-23. Average Minimum Daily Dissolved Oxygen Average by Month Across all Water Years Simulated by the Three Climate Models for each Epoch (Historical, Mid-Future, and Late-Future) at the Three Water Quality Nodes ... 9-36

10-1. Comparison between the Number of Annual Days at Lake Mendocino Reservoir Elevation Thresholds between May 1 and September 30 ... 10-4

10-2. Comparison between Median Annual Days for Lake Mendocino Reservoir Elevation Thresholds between May 1 and September 30 ... 10-5

10-3. Comparison between the Number of Annual Days at Lake Sonoma Reservoir Elevation Thresholds between May 1 and September 30 ... 10-6

10-4. Comparison between Median Annual Days for Lake Sonoma Reservoir Elevation Thresholds between May 1 and September 30 ... 10-6

10-5. Comparison between the Number of Annual Days for Recreational Activities at Various Locations along the Russian River ... 10-7

10-6. Summary of Recreation Vulnerability Assessment Findings 10-8
11-1. Lake Mendocino Change in Daily Average Turbine Flow per Month 11-2
11-2. Lake Sonoma Change in Daily Average Turbine Flow per Month 11-2
11-3. Lake Mendocino Change in Annual Total Hydropower Generation 11-3
11-4. Lake Sonoma Change in Annual Total Power Generation 11-3
11-5. Summary of Hydropower Vulnerability Assessment Findings 11-4
12-1. Late-Future Conditions Climate Impacts Mapping 12-4
12-2. Population Sensitivity to Flooding 12-5
12-3. Comparison of Present and Future Exposure to Flooding 12-5
12-4. Population Sensitivity and Exposure to Wildfire 12-8
12-5. Comparison of Present and Future Exposure to Wildfires 12-8
12-6. Population Sensitivity to Extreme Heat 12-10
12-7. Comparison of Present and Future Exposure to Extreme Heat 12-10
12-8. Population Sensitivity to Drought 12-12

1. Introduction

Through the Russian River Watershed Resilience Pilot Study, an integrated vulnerability assessment was conducted to evaluate how climate hazards are projected to impact a series of eight water-related sectors across the planning area. These sectors include surface water supply, groundwater supply, flood management, ecosystems, water quality, recreation, hydropower, and community and equity considerations. Evaluation of sector-specific vulnerabilities to climate change supports identification of key areas of climate sensitivity and characterization of projected impacts.

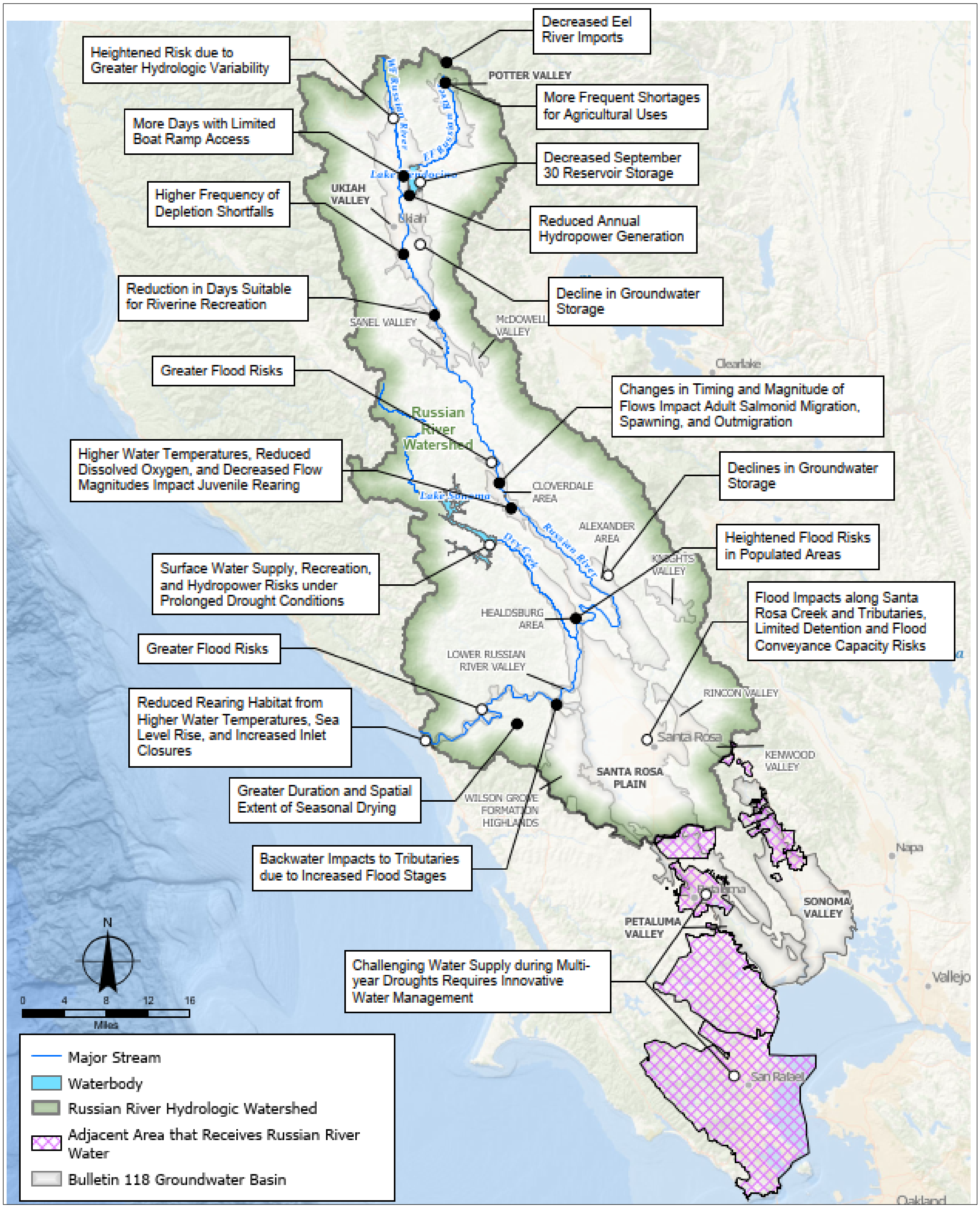
The vulnerability assessment is characterized by both qualitative and quantitative evaluations. The qualitative vulnerability assessment employs a scoring framework to characterize effects of climate hazards on individual components of water sectors throughout the planning area in terms of sensitivity, adaptive capacity, and vulnerability. The quantitative assessment builds on these qualitative findings to identify vulnerabilities through application of a projection-based modeling framework coupled with a series of indicators and metrics for each water-related sector.

This appendix documents the approaches, data, and tools used for conducting both the qualitative and quantitative vulnerability assessments, as well as the methodologies and findings of sector-specific evaluations. Additional details for each of these assessments are described in Sections 3 and 4, respectively. Sector-specific evaluations are discussed in Sections 5 through 12.

2. Vulnerability Assessment Summary

The Russian River Watershed Resilience Pilot Study assessed climate vulnerabilities across eight water-related sectors, including surface water supply, groundwater supply, flood management, ecosystems, water quality, recreation, hydropower, and community and equity. In general, changes in climate are characterized by increasing ambient temperatures across the planning area, more frequent and severe extreme precipitation events, and a consolidation of precipitation during the wet season. These changes drive several responses across the watershed, including reductions in fall, spring, and summer baseflows; higher peak flows in the winter; warmer water temperatures; increased wildfire risk; and more frequent and prolonged drought events and extreme heat days. Sector-specific vulnerabilities to these changes are varied and are often influenced by existing infrastructure and operations. Key vulnerabilities across the planning area that have been identified through this assessment are summarized in Figure 2-1. Additional details on sector-specific conclusions are noted in the sections below.

Figure 2-1. Key Vulnerabilities Across the Russian River Watershed Resilience Pilot Study Planning Area



2.1 Surface Water Supply

Surface water supply vulnerabilities are primarily driven by the reduction in Eel River transfers in the Upper Russian River. Transfers decline due to the planned transition from the Potter Valley Project to the New Eel-Russian Facility, the loss of snowpack in the upper watershed, and more variable Eel River and East Fork Russian River hydrology. This results in increased stress for surface water management at Lake Mendocino, signaled by declines in end of year storage, a higher frequency of years falling below critical storage thresholds, and additional challenges meeting needs for downstream water users and ecosystems. The West Fork Russian River is projected to experience similar increases in hydrologic variability and faces higher risks associated with seasonal extremes and post-fire debris flows due to the lack of an upstream regulating mechanism. Water users in the Upper Russian River are projected to experience an increase in depletion shortfalls under future conditions, particularly for agriculture in the Potter Valley.

In the Lower Russian River, fewer direct impacts from climate change are present. However, longer and more severe drought conditions would result in reduced water stored in the reservoir at Lake Sonoma and a small number of depletion shortfalls when these drought events occur, particularly when local Marin surface water supplies experience multi-year drought conditions promoting an increase reliance on Russian River supplies.

2.2 Groundwater Supply

Historical groundwater conditions within the planning area highlight a close interconnection of surface water and the alluvial aquifer systems along the Russian River. These alluvial aquifer systems have low groundwater storage capacity relative to the large seasonal swings in precipitation and streamflow. Groundwater storage is typically replenished to capacity each winter season by recharge and stream leakage, and is depleted by groundwater pumping, groundwater discharge to surface water, and groundwater evapotranspiration (ET) during the subsequent dry season. Given the close interconnection of these systems, future increases in seasonal and interannual hydrologic variability, more frequent and severe drought events, and reduction in Eel River transfers that impact surface water supplies will also drive vulnerabilities for groundwater resources. Under future climate conditions, increased temperatures and earlier onset of ET demands amplify seasonal groundwater depletions.

Potential future reductions in the reliability of Lake Mendocino due to changes in Potter Valley Project (PVP) transfers introduces an additional vulnerability for groundwater resources along the Upper Russian River. For example, if dry -season releases cannot be made from Lake Mendocino to the Upper Russian River, groundwater recharge from stream leakage to the aquifer would be substantially reduced, amplifying dry-season groundwater storage declines under multi-year drought conditions, could contributing to large year -over -year storage declines for those aquifer systems.

2.3 Flood Management

Vulnerabilities to climate change for the flood management sector are primarily driven by increased magnitude and duration of peak flows during the wet season. In general, the hydrologic responses to increases in annual precipitation volumes and a higher frequency of extreme precipitation events within the planning area include a consolidation of flow volumes in the wet season and an increase in 1-day and 3-day flood magnitudes. Flood-related vulnerabilities are significant in residential areas in and near Santa Rosa. Many of these residential communities are out of the current 100-year floodplain, however, increased runoff from projected future storm events are expected to increase the size and extent of the floodplain. Impacts are also projected in more populated areas along the Russian River, such as

Guerneville and Healdsburg. Backwater impacts of increased flood stages in the Russian River are also seen in the Laguna de Santa Rosa, Mark West Creek and Green Valley Creek, resulting in more frequent occurrences of flooding along these tributaries under future climate relative to historical conditions. Following wildfire events, post-fire debris flows mobilized during high-flow storms can further reduce channel and bridge conveyance, amplifying flood risk for downstream riverine and tributary communities in the Lower and Middle Russian River, particularly Guerneville, Monte Rio, and low-lying areas of unincorporated Sonoma County.

2.4 Water Quality

Under future climate conditions, the water temperature being released from Lake Mendocino and Lake Sonoma is expected to increase due to warmer inflows from increases in air temperature. For Lake Mendocino, there is a projected increase in the frequency of fall water temperature spikes due to the depletion of cold-water pool earlier in the fall season from lower reservoir storage. These increases in water temperature from reservoir releases may have an impact on reservoir hatchery operations as well as salmon and steelhead lifecycle stages downstream.

For the Russian River, both Cloverdale in the Upper Russian River and Hacienda Bridge in the Lower Russian River are projected to see an increase in water temperature of approximately 2 to 3 degrees Celsius throughout the year, on average, due to warmer local natural flow, warmer reservoir releases, and greater heat absorption while flowing downstream from increasing air temperatures. Both locations are also expected to experience a decrease in dissolved oxygen in the river due to higher water temperature and lower river flows. These changes also have the potential to impact salmon and steelhead rearing and spawning in the Russian River by decreasing the availability of suitable habitat.

2.5 Ecosystems

For ecosystems along the mainstem Russian River and its tributaries, climate change is expected to intensify seasonal habitat constraints, including increasing vulnerability for multiple listed salmonid life stages. In the mainstem Russian River, projected reduced early-fall flows increase the risk of delayed adult migration at critical riffles, especially for Chinook salmon. Higher and more variable winter peak flows elevate the likelihood of streambed and redd (spawning nests) scour for Chinook salmon, and to a lesser degree, steelhead and coho salmon. Warmer late-winter and early-spring temperatures advance incubation threshold exceedances, shortening the window of suitable egg development conditions at upstream locations.

The most consistent and severe vulnerability is projected during juvenile-rearing periods. Mainstem summer temperatures already approach or exceed thermal thresholds under historical conditions and increase under future conditions. Dissolved oxygen concentrations are also projected to fall below critical suitability thresholds beginning in late spring and remain depressed through summer, compounding potential for thermal stress associated with increasing water temperatures. Reduced late-spring flows may further constrain juvenile outmigration, rearing habitat, and associated survival to the Pacific Ocean.

For tributaries within the planning area, empirical evidence identifies longitudinal disconnection and reduced wetted habitat as primary drivers of juvenile mortality, with “days of disconnection” strongly associated with survival. Projected warming and declining baseflows in the fall, spring, and summer are expected to increase the duration and spatial extent of seasonal drying, particularly in lower alluvial reaches of tributaries. Although groundwater-supported pools provide localized refugia, their persistence may diminish under intensified drought conditions.

For the Russian River Estuary, future climate conditions increase risk to multiple salmonid life stages. Climate projections indicate reduced early-fall, early-winter, and spring flows and longer or more frequent inlet closure events. This conclusion does not take into account coastal storm changes but does consider potential changes in ocean swells. See future wave analysis below that shows no obvious change in wave conditions. This analysis considers a compound effect of climate induced changes in river conditions, sea level rise, and wave conditions. Conditions toward the end of the century also project higher winter peak flows. Increases in air temperature are expected to elevate river temperatures entering the estuary, and monitoring data confirm that estuary temperatures closely track upstream river conditions, particularly during closed-mouth periods. Increased closure duration and higher river temperatures are projected to reduce suitable juvenile steelhead rearing habitat during rearing months between May and mid-October.

2.6 Recreation

The Russian River, Lake Mendocino, and Lake Sonoma offer opportunities for water-based recreation within the planning area. These opportunities are dependent on annual surface water supplies, reservoir management, and downstream diversions from the Russian River. As such, recreation-related vulnerabilities are closely tied to the changes noted for the surface water supply sector. For Lake Mendocino, the annual median number of days between May 1 and September 30 with optimal (i.e., no negative impact on any recreational activities) conditions for boat-based recreation increases by approximately 1 week relative to historical trends. This change occurs due to a decrease in the number of days with higher reservoir elevations that exceed thresholds that preclude recreation in and around Lake Mendocino. However, the annual median frequency of boat launch closures that fully prohibit motorized boating also increases by roughly 2 weeks due to a higher prevalence of lower reservoir storage under future conditions. For Lake Sonoma, median conditions are relatively unchanged by future climate conditions, with only a 1- to 2-day reduction in optimal reservoir elevations that result in access limitations at only one of the three boat ramps. Along the Russian River, the median frequency of water-based recreationally suitable days under future climate conditions are projected to decrease relative to historical conditions, regardless of location and activity (i.e., boating or fishing).

2.7 Hydropower

Releases from Coyote Valley Dam at Lake Mendocino and Warm Springs Dam at Lake Sonoma are used to generate hydropower in the Russian River watershed. Changes in the magnitude and distribution of reservoir inflows and subsequent reservoir releases throughout the year influence the quantity of hydropower production and the reliability of these energy supplies for municipalities and residents within the watershed. Similar to the vulnerabilities noted for the surface water supply and recreation sectors, Lake Mendocino annual total hydropower generation is projected to decrease by roughly 17% to 19% under median future conditions, primarily driven by reduced Eel River imports. Lake Sonoma median annual total hydropower generation demonstrates high resilience to future climate conditions, with up to a 2% decrease relative to historical trends.

2.8 Community and Equity

Russian River watershed communities are increasingly exposed to widespread and intensifying impacts from flooding, wildfire, extreme heat, and drought driven water supply disruptions. Climate hazard modeling and vulnerability analyses for other water-related sectors show that hazard footprints expand substantially under future conditions. Social vulnerability is already high across the region, with 40 to 50% of residents typically falling within the moderate to highest sensitivity tiers for each hazard. Many of the people who are most socially vulnerable live in places that face the greatest climate hazards, which means they experience disproportionate exposure today and in the future.

Findings underscore that hazard intensity, geographic reach, and exposure among high sensitivity communities all increase substantially across future climate projections. Results of this assessment indicate that the people and neighborhoods of Santa Rosa, the Ukiah Valley, the Cloverdale–Healdsburg–Windsor corridor, and the communities surrounding Lake Mendocino face the most significant and compounding climate pressures in the Russian River watershed.

3. Qualitative Vulnerability Assessment

3.1 Purpose

The qualitative vulnerability assessment captures water sector-specific drivers of risk and resilience with planning area nuance. Insights from this assessment are translated into scores and a composite index to support prioritization and provide a connection to the subsequent quantitative assessment. This structure allows regional interests to identify where climate stressors intersect with low adaptive capacity and high consequence potential enabling identification and prioritization of areas where early action and deeper analyses are most warranted.

3.2 Methodology

The qualitative assessment utilizes a vulnerability matrix that provides a structured framework for evaluating climate-related risks across multiple sectors of the planning area. This matrix organizes individual components of the Russian River watershed, such as ecosystems, hydropower facilities, water supply infrastructure, flood management assets, water quality receptors, agricultural zones, and recreation/tourism resources, against key climate stressors of extreme heat, drought, extreme precipitation and flooding, wildfire, and sea level rise, where applicable. Each entry combines concise narrative descriptions of climate sensitivities and adaptive constraints with standardized numeric ratings for sensitivity, adaptive capacity, and vulnerability to climate stressors. These narratives were informed by existing watershed management plans, agency reports, and subject-matter expertise, ensuring that local context and sector-specific drivers of risk were captured.

The assessment evaluates each water-related sector based on three dimensions:

- **Sensitivity** to climate stressors (e.g., ecological fragility, infrastructure limitations).
- **Adaptive capacity**, or the ability to respond and recover (e.g., through operational flexibility, redundancy, regulatory protections) to disruptions or impacts induced by climate stressors.
- **Vulnerability**, or a measure of the threat and susceptibility to the impacts of climate stressors given the qualities and state of individual components.

Each of these dimensions are discussed in further detail in the following subsections.

3.2.1 Sensitivity Rating

Sensitivity describes how strongly a component is affected when exposed to climate stressors such as extreme heat, drought, flooding, or wildfire. It reflects the degree to which climate conditions influence sector performance, function, or integrity.

Sensitivity is rated on a five-point scale:

- **1 – Low Sensitivity**: Climate variability and long-term climate change have little to no influence on the asset or its operations.
- **3 – Moderate Sensitivity**: Climate stressors influence performance or operations, but impacts are generally manageable or intermittent.
- **5 – High Sensitivity**: Climate stressors have a strong and direct influence on the asset or system, with high potential for performance degradation, failure, or loss of function.

3.2.2 Adaptive Capacity Rating

Adaptive Capacity reflects the inherent ability for a given component to respond to, cope with, or recover from climate-related impacts. This includes physical redundancy, operational flexibility, institutional authority, financial resources, regulatory protections, and the availability of alternative options.

Adaptive Capacity is also rated on a five-point scale, but inversely, such that higher numeric values indicate lower capacity:

- **1 – High Adaptive Capacity**: The component has substantial ability to adjust operations, recover quickly, or absorb climate impacts (e.g., multiple supply sources, strong institutional support).
- **3 – Moderate Adaptive Capacity**: The component has some ability to adapt, but responses may be constrained by cost, governance, or infrastructure limitations.
- **5 – Low Adaptive Capacity**: The component has little inherent capacity to adapt or recover, often due to single-source dependency, limited infrastructure, habitat constraints, or institutional constraints.

This inverse scale ensures that high sensitivity combined with low adaptive capacity results in the highest vulnerability ratings, consistent with widely accepted climate risk frameworks.

3.2.3 Vulnerability Rating

The combined Vulnerability Rating provides a synthesized view of how climate stressors interact with the sensitivity and adaptive capacity of individual watershed components. This rating, calculated by combining scores for sensitivity and adaptive capacity using a rating matrix (Table 3-1), helps identify which areas of the watershed are most vulnerable to climate changes. A rating of 1 or 2 indicates relatively low vulnerability, a rating of 3 indicates moderate vulnerability, and a rating of 4 or higher indicates high vulnerability. The components with highest vulnerability are often those both high sensitivity to climate impacts and limited capacity to adapt or recover.

Table 3-1. Vulnerability Scoring Matrix

Adaptive Capacity Rating	Sensitivity Rating				
	Low (1)	Low-Moderate (2)	Moderate (3)	Moderate-High (4)	High (5)
High (1)	1	1	2	2	3
Moderate-High (2)	1	1	2	3	3
Moderate (3)	1	2	3	4	5
Low-Moderate (4)	1	2	4	5	5
Low (5)	1	2	5	5	5

3.3 Results

Table 3-2 summarizes the results of the qualitative vulnerability assessment across planning areas, sectors, and system components. Each row represents a distinct component or asset, with corresponding ratings for sensitivity, adaptive capacity, and vulnerability. The qualitative vulnerability assessment revealed distinct patterns of climate risk across the watershed, highlighting both sector-specific sensitivities and systemwide stressors. Surface water supply, flood management, water quality, ecosystems, and community & equity show very high vulnerability hotspots (rating of 5), particularly where operations depend on inter-basin transfers, low gradient floodplains, estuarine mixing, and small or aging systems. Groundwater trends high (rating of 4) in multiple basins, with recharge limits, shallow aquifers, and salinity intrusion risks near bay margins elevating exposure under prolonged drought. Across sectors, atmospheric river flooding, post-fire debris and ash, drought/heat-driven low flows, and sea level rise in the lower watershed are the primary drivers of elevated vulnerability. A detailed list of the sectors and components that rated with the highest vulnerability ratings is below:

- **Upper Russian River**
  - **Surface Water Supply:**
    - Eel River Transfers **–** Critical water supply with low redundancy; warming reduces snow and hydrology becomes more variable on Eel River; drought/heat reduce diversion volumes while floods and wildfire may disrupt diversion operations.
    - West Fork Russian River **–** Small, largely unregulated tributaries with minimal storage; highly exposed to seasonal extremes and post-fire sediment/turbidity pulses.
  - **Groundwater Supply:**
    - Ukiah Valley groundwater basin **–** high dependence on Russian River flows to seasonally recharge basin, greater hydrologic variability affects this supply and refill
  - **Water Quality:**
    - Drinking Water & Quality **–** Upper Russian River and headwaters are vulnerable to drought and thermal loading and post-fire water quality concerns.
  - **Community & Equity:**
    - Ukiah, Redwood Valley, Hopland, and surrounding towns have census tracts designated disadvantaged communities –vulnerable communities with small water supply systems with limited redundancy face compounded heat, smoke, flood, and displacement risks.
- **Middle Russian River**
  - **Groundwater Supply:**
    - Alexander Valley groundwater basin may experience year-over-year storage declines due to reduced Russian River flows and respond more slowly to recovery
  - **Flood Management:**
    - Russian River Floodplain - Low gradient floodplain with legacy constraints due to mining; atmospheric river events and post-fire debris reduce flood water conveyance and increase inundation risk for communities.
  - **Community & Equity:**
    - Cloverdale, Healdsburg, Windsor, Geyserville **–** Frontline outdoor workers and small water supply systems with limited redundancy face compounded heat, smoke, flood, and displacement risks.
- **Lower Russian River**
  - **Flood Management:**
    - Russian River Floodplain **–** Low gradient floodplain with legacy constraints due to mining; atmospheric river events and post-fire debris reduce flood water conveyance and increase inundation risk for communities.

    - Central Sonoma Watershed Project – 1960s era flood detention reservoirs and engineered channels face capacity exceedance under atmospheric river storms and sediment laden flows, increasing downstream flood exposure.
  - **Water Quality:**
    - Regulatory Standards – Elevated exceedance risk for indicator bacteria, sediment, and dissolved oxygen within floodplain/estuarine systems under compound flood, drought, and heat stress.
  - **Ecosystems:**
    - Russian River Estuary – Estuarine salinity/mixing is highly sensitive to sea level rise and low river flows during drought; low flows combined with rising sea levels reduce habitat availability and degrade cold-water refugia.
  - **Community & Equity:**
    - Guerneville, Monte Rio, Forestville – Floodplain renters and mobile home residents with limited cooling and emergency access face compound flood, heat, smoke, and prolonged recovery barriers.
- **Transmission System and Adjacent Areas**
  - **Surface Water Supply:**
    - Marin and North Marin – Relatively small catchments capture runoff for local surface water; sensitive to shorter duration drought; limited access to groundwater to offset surface water deficits
  - **Groundwater Supply:**
    - Sonoma Valley Groundwater Basin – More sensitive to climate change than Petaluma or Santa Rosa Plain; more *Sustainable Groundwater Management Act* thresholds exceedances under future conditions reported; sea level rise may impact intrusion in the lower valley

Table 3-2. Qualitative Vulnerability Assessment Ratings

Sector	Planning Area	Component	Sensitivity	Adaptive Capacity	Vulnerability
Surface Water Supply	Upper Russian River	Headwaters	**4**	**3**	**4**
		East Fork Russian River	**4**	**3**	**4**
		PVP Diversions	**5**	**4**	**5**
		West Fork Russian River	**4**	**4**	**5**
		Lake Mendocino/Coyote Valley Dam	**4**	**3**	**4**
		Main Stem Russian River	**4**	**3**	**4**
	Middle Russian River	Headwaters	**4**	**3**	**4**
		Main Stem	**4**	**3**	**4**
		Lake Sonoma	**4**	**3**	**4**
		Dry Creek	**4**	**3**	**4**
		Alexander Valley	**4**	**3**	**4**
	Lower Russian River	Main Stem Russian River	**4**	**3**	**4**
		Windsor Wells	**3**	**3**	**3**
		Russian River Diversion Facilities	**4**	**3**	**4**
	Sonoma Water Transmission System	Transmission System	**4**	**3**	**4**
		Retail Customer Systems	**3**	**3**	**3**
		Marin Water System	**4**	**3**	**4**
		Lake Stafford	**4**	**3**	**4**

Sector	Planning Area	Component	Sensitivity	Adaptive Capacity	Vulnerability
Groundwater Supply	Upper Russian River	Potter Valley Groundwater Basin	**4**	**3**	**4**
		Ukiah Valley Groundwater Basin	**4**	**3**	**4**
		Sanel Valley Groundwater Basin	**3**	**3**	**3**
		McDowell Valley Groundwater Basin	**3**	**3**	**3**
	Middle Russian River	Alexander Valley Groundwater Basin (Cloverdale Area)	**4**	**3**	**4**
		Alexander Valley Groundwater Basin (Alexander Area)	**4**	**3**	**4**
		Healdsburg Area Groundwater Basin	**3**	**3**	**3**
		Knights Valley Groundwater Basin	**3**	**3**	**3**
	Lower Russian River	Lower Russian River Valley Groundwater Basin	**3**	**3**	**3**
		Santa Rosa Plain Groundwater Basin	**3**	**3**	**3**
		Rincon Valley Groundwater Basin	**3**	**3**	**3**
		Kenwood Valley Groundwater Basn	**3**	**3**	**3**
	Adjacent Areas	Sonoma Valley Groundwater Basin	**4**	**3**	**4**
		Petaluma Valley Groundwater Basin	**3**	**3**	**3**
Flood Management	Upper Russian River	Coyote Valley Dam/Lake Mendocino	**4**	**3**	**4**
		Russian River Floodplain	**4**	**3**	**4**
		Tributaries	**4**	**3**	**4**
	Middle Russian River	Warm Springs Dam/Lake Sonoma	**4**	**3**	**4**
		Dry Creek	**3**	**3**	**3**
		Russian River Floodplain	**4**	**3**	**4**
	Lower Russian River	Central Sonoma Watershed Project	**5**	**4**	**5**
		Tributaries	**4**	**3**	**4**

Sector	Planning Area	Component	Sensitivity	Adaptive Capacity	Vulnerability
		Laguna de Santa Rosa	4	3	4
		Russian River Floodplain	5	4	5
		Russian River Estuary	4	3	4
Water Quality	Upper Russian River	Ecological	5	2	3
		Regulatory Standards	4	2	3
		Drinking Water & Quality	5	3	5
	Middle Russian River	Ecological	4	3	4
		Regulatory Standards	4	3	4
		Drinking Water & Quality	4	3	4
	Lower Russian River	Ecological	5	3	5
		Regulatory Standards	5	3	5
		Drinking Water & Quality	4	2	3
Ecosystem	Upper Russian River	Aquatic Ecosystems	4	3	4
		Riparian Systems	4	3	4
		Forests and Headwaters	4	3	4
	Middle Russian River	Aquatic Ecosystems	4	3	4
		Riparian Systems	4	3	4
		Forests and Headwaters	4	3	4
		Dry Creek Restoration	4	3	4
	Lower Russian River	Aquatic Ecosystems	4	3	4
		Riparian Systems	4	3	4
		Laguna de Santa Rosa	4	3	4

Sector	Planning Area	Component	Sensitivity	Adaptive Capacity	Vulnerability
		Russian River Estuary	**5**	**3**	**5**
		Forests and Headwaters	**4**	**3**	**4**
Hydropower	Upper Russian River	PVP	**4**	**2**	**3**
		Lake Mendocino Plant at Coyote Valley Dam	**4**	**2**	**3**
	Middle Russian River	Warm Springs Dam (Lake Sonoma)	**4**	**2**	**3**
Recreation	Upper Russian River	Lake Recreation & Tourism (Lake Mendocino)	**3**	**3**	**3**
		River Recreation & Tourism	**3**	**3**	**3**
	Middle Russian River	Lake Recreation & Tourism (Lake Sonoma)	**3**	**3**	**3**
		River Recreation & Tourism	**4**	**3**	**4**
	Lower Russian River	River Recreation & Tourism	**4**	**3**	**4**
Community & Equity	Upper Russian River	Ukiah, Redwood Valley, Hopland, and Rural Towns, Healdsburg and Windsor	**5**	**4**	**5**
	Middle Russian River	Cloverdale, Geyserville, Vineyard /Farmworker Communities	**5**	**4**	**5**
	Lower Russian River	Guerneville, Monte Rio, Forestville, Renter Communities, Mobile Homes	**5**	**4**	**5**

4. Quantitative Vulnerability Assessment

4.1 Purpose

The quantitative vulnerability assessment builds upon the findings of the qualitative evaluation of potential climate impacts to water-related sectors by employing a projection-based modeling framework to explore a range of future climate conditions. This framework allows for shifts in the timing and magnitude of impacts to be evaluated under a range of plausible future conditions. Because individual climate models represent changes in temperatures, precipitation, hydrologic variability, and sea level rise differently, the quantitative vulnerability assessment approach characterizes uncertainties in future climate trajectories by considering 41 different climate projections.

For each water-related sector, a series of metrics and indicators are used to inform and evaluate climate vulnerabilities under future conditions. Results from the quantitative assessment provide a more detailed evaluation of vulnerabilities across the planning area, identifying areas where thresholds are projected to be exceeded, risks are evolving, and impacts are shared or cascading across individual sectors. Ultimately, these results provide a foundation for identifying and prioritizing adaptation strategies and subsequent planning efforts to address the impacts of climate change.

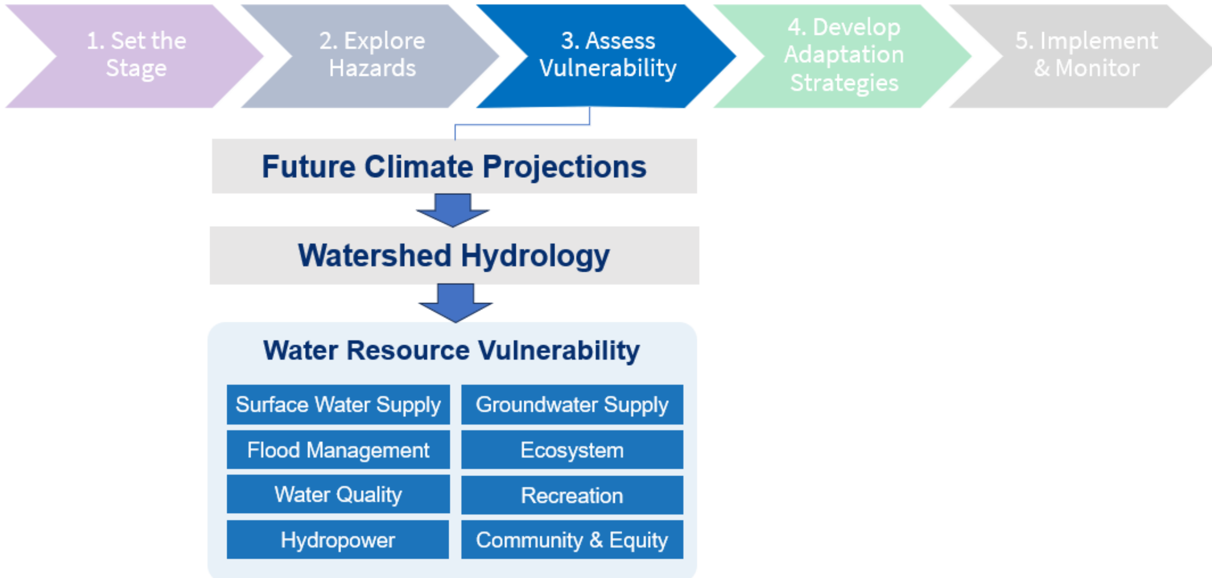
4.2 Methodology

The following subsections provide additional details for the development of climate projections and hydrologic responses to future conditions, the range of vulnerability indicators and metrics considered for each of the eight water-related sectors considered in this assessment, and the suite of analytical tools used to support characterization of future climate vulnerabilities.

4.2.1 Climate Projections and Hydrologic Responses from the Watershed

Figure 4-1 provides an overview of the application of 41 future climate change projections considered in the quantitative vulnerability assessment. In general, historical meteorological data and results from 15 climate models under coupled with three emissions pathways were used as inputs to the U.S. Geological Survey (USGS) Basin Characterization Model (BCM) to simulate historical and future hydrological processes throughout the planning area. Simulated hydrologic conditions were then used as inputs to a series of analytical tools to aid in sector-specific evaluations. The subsequent subsections provide further discussion for assumptions and approaches for representing future conditions under climate change.

Figure 4-1. Application of Climate Projections in Vulnerability Assessment



4.2.1.1 Historical Meteorological Data

Historical meteorology data between 1910 through 2024 was leveraged from the Parameter-elevation Regressions on Independent Slopes Model (PRISM; Daly et al. 1994; OSU 2025) dataset. PRISM data includes historical precipitation, and minimum and maximum temperatures, and was used as an input to the BCM hydrologic model.

4.2.1.2 Global Climate Models

To characterize future climate trends, Coupled Model Intercomparison Project Phase 6 (CMIP6) datasets from the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC 2021) were utilized. CMIP6 Global Climate Models (GCMs) feature higher spatial resolutions, with enhanced physical parameterizations and improved representations of synoptic processes relative to previous phases of the CMIP effort. Temporally, the CMIP6 GCMs typically cover a wide range of periods to represent both historical (e.g., 1950 to 2014) and future (e.g., 2015 to 2100) climate conditions. CMIP6 also considers a set of Shared Socioeconomic Pathways (SSPs), scenarios used to investigate how global societal trends (population growth, economic trends, policy considerations, etc.) might influence future greenhouse gas emissions and subsequent changes in climate. These SSPs are paired with various Representation Concentration Pathways (RCPs) to estimate the level of radiative forcing resulting from shifts in greenhouse gas emissions, land use, and other factors that drive changes in global temperatures. The five main SSP-RCP combinations used in CMIP6 are SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5 (Hausfather 2018). These are ultimately used as inputs to individual GCMs to characterize various trajectories of future climate conditions.

For the groundwater vulnerability assessment, Coupled Model Intercomparison Project Phase 5 (CMIP5) GCMs were used instead of CMIP6 models. Future climate downscaled datasets from CMIP5 were used as inputs to an integrated hydrology and river operations model (GSFLOW) for the Russian River watershed to simulate surface water-groundwater interactions (Adera et al. 2026). The existing model results from GSFLOW were leveraged for this effort; CMIP6 inputs were not used to generate new simulation results.

Additional details on the methodology for this sector-specific assessment are highlighted below in Section 6.

4.2.1.3 Downscaling

To translate the coarse resolution of GCMs into higher resolution for regional applications, California's academic institutions are advancing climate research by implementing hybrid-statistical downscaling methods. At UCLA, the Weather Research and Forecasting (WRF) Model is used for dynamic downscaling, producing several physically based projections available for public use and application. These projections are used to train the Localized Constructed Analogs Version 2 Hybrid (LOCA2-Hybrid) dataset at Scripps Institution of Oceanography (Pierce et al. 2023).

The LOCA2-Hybrid dataset includes bias-corrected GCM outputs that have been adjusted to align with meteorological station observations, offering a 3-kilometer resolution over California with temporal coverage between 1950 and 2100. For this dataset, downscaling is performed using a selection of GCMs that best capture the relevant characteristics of the climate in California. Recommendations for a set of GCMs for use in downscaling to support climate change analysis and applications in California are outlined in Krantz et al. (2021). This hybrid-statistical downscaling method has generated data for 15 GCMs with a total of 199 ensemble runs. A summary of this information is provided in Table 4-1.

Table 4-1. Summary of CMIP6 LOCA2-Hybrid GCMs

Item	Description
Downscaling Method	Hybrid-Statistically Downscaled / LOCA2-Hybrid
Institution	UCSD - Scripps Institute of Oceanography
Models	15 models: ACCESS-CM2, CESM2-LENS, CNRM-ESM2-1, EC-Earth3, EC-Earth3-Veg, FGOALS-g3, GFDL-ESM4, HadGEM-GC31-LL, INM-CM5-0, IPSL-CM6A-LR, KACE-1-0-G, MIROC6, MPI-ESM1-2-HR, MRI-ESM2-0, and TaiESM1
Bias Correction	15 models
Extent	1950 to 2100
Spatial Resolution	3-kilometers (California)
Temporal Resolution	Daily (native resolution) and monthly
Shared Scenario Pathways	SSP2-4.5, SSP3-7.0, and SSP5-8.5
Ensemble Runs	This downscaling method created data for 15 GCMs with a total of 199 ensemble runs.

4.2.1.4 Climate Projection Selection

The Russian River Watershed Resilience Pilot Study utilizes 41 individual climate projections to characterize a range of future conditions. These 41 climate projections are aligned with the combinations of SSPs and GCMs considered in the LOCA2-Hybrid dataset. It is important to note that not all of the three SSPs (i.e., SSP2-4.5, SSP3-7.0, and SSP5-8.5) are used as inputs for each of the 15 recommended GCMs for application in California. As such, the total number of climate projections considered in this assessment equates to 41 instead of 45.

To support assessments of water quality and Forecast-Informed Reservoir Operations (FIRO), a further subset of the 41 climate projections has also been used. The selection of this subset was based on the ability of individual projections to replicate the changes in selected climatic and hydrological metrics from the full list of 41 climate projections that are relevant for the water quality and FIRO assessments. The selection of the projection for the water quality assessment is primarily based on the ability to replicate projected changes in temperature and flow, while the projections for the FIRO assessment are based on the projected changes in flow and flood events. Three future climate scenarios (warm-wet, central tendency, and hot-dry) were also developed to characterize distinct ranges of projected hydroclimatic conditions. Recommended projections included in this subset are attributed to each of these climate scenarios to support characterization of a range of future conditions for the water quality and FIRO assessments.

4.2.1.5 Watershed Hydrology

Climate projections represent trajectories of temperature and precipitation changes over the planning area, but do not characterize watershed-specific responses to climate change. To understand these considerations under future climate conditions, a hydrologic model must be used. The Russian River and Upper Eel River BCM was developed by USGS in 2009 and serves as a regional water-balance model that simulates unimpaired streamflows and evapotranspiration under historical and future climate conditions. Several updates have been made over the years to expand spatial domains and improve representations of hydrologic processes; the most recent update in 2025 added the watersheds of the Marin County reservoirs. The BCM offers 270-meter spatial resolution and daily temporal resolution, with historical representation between October 1, 1910 to June 30, 2024 for the Russian River and Upper Eel River and October 1, 1981 to June 30, 2024 for portions of Marin and Napa counties. The future climate period represented by the BCM is inclusive of January 1, 2015 to January 31, 2100. To-date, the BCM has been used in several Russian River water supply planning studies, including the *Lake Mendocino Water Supply Reliability Evaluation Report* (Sonoma Water 2017), *Fish Habitat Flow and Water Rights Project Draft EIR* (Sonoma Water 2016a), and *Sonoma Water Climate Adaptation Plan* (Sonoma Water 2021).

PRISM data and LOCA2-Hybrid downscaled GCMs are used as historical and future inputs to the BCM, respectively. With each time step, the BCM characterizes unimpaired conditions by balancing precipitation and evapotranspiration, sublimation, runoff, recharge, and change in soil storage for each grid cell over the model domain. Excess water is infiltrated only when precipitation exceeds potential evapotranspiration. Recharge is represented as infiltration that percolates below the zone of evaporation. When soils are fully saturated, precipitation is ultimately represented as runoff. The distribution of recharge and runoff at each grid cell is dependent on local climate, land cover, and subsurface properties. BCM outputs ultimately serve as inputs to many of the analytical tools highlighted below in Section 4.2.2. Additional details of the BCM are provided in Attachment C-1. Assessment of various climatic and hydrologic metrics across the range of LOCA2-Hybrid downscaled GCM projections and BCM simulations are also discussed in detail in Attachment C-1.

4.2.2 Vulnerability Indicators and Metrics

To assess sector-specific climate vulnerabilities, a series of potential indicators and metrics were identified to serve as the basis for quantitative evaluations. Indicators represent observable aspects of a given sector that can be used to characterize that sector under historical and future conditions. Metrics incorporate quantitative measurements of certain components of a given indicator. As an example, an indicator for the recreation sector is recreational uses; metrics to evaluate this indicator include reservoir water levels and river flows that are sufficient for recreational activities. Regional input was also solicited throughout the development of the indicators and metrics used in quantitative vulnerability assessment to ensure that analyses covered key perspectives from interests throughout the Russian River watershed, where feasible.

The full list of indicators and metrics applied for each sector-specific assessment is provided in Table 4-2.

Table 4-2. Climate Vulnerability Indicators and Metrics by Sector

Sector	Indicator	Metrics
Surface Water Supply (SW)	Water Supply Reliability	▪ Russian River Collector Diversions ▪ Sonoma Water Retail Customer Shortages
	Reservoir Condition	▪ Annual and Monthly Distribution of Eel River Transfers ▪ Lake Mendocino Storage and Release Patterns ▪ Lake Sonoma Storage and Release Patterns ▪ Marin and North Marin Reservoir Storage Patterns
Groundwater Supply (GW)	Total Volume of Storage	▪ Groundwater-Surface Water Exchanges ▪ Groundwater Storage
	GSP Sustainable Management Criteria	▪ Santa Rosa Plain GSP Sustainable Management Criteria ▪ Petaluma Valley GSP Sustainable Management Criteria ▪ Sonoma Valley GSP Sustainable Management Criteria
Flood Management (FM)	Flood Inundation	▪ Floodplain Inundation Extent
	Asset Exposure	▪ Number of Structures in Floodplain
Water Quality (WQ)	Reservoir Condition	▪ Lake Mendocino Water Temperature Patterns ▪ Lake Sonoma Water Temperature Patterns
	River Condition	▪ Russian River Temperature and Dissolved Oxygen at Cloverdale ▪ Russian River Temperature and Dissolved Oxygen at Hacienda Bridge
Ecosystem (EC)	Ecological Flows & Geomorphic Processes	▪ Annual Flow Patterns for Mainstem Russian River ▪ Annual Flow Patterns for Russian River Tributaries ▪ Frequency of Tributary Drying ▪ Frequency and Duration of Rivermouth Closure
	Water Quality Impairments	▪ Daily Maximum Water Temperature Patterns ▪ Daily Minimum Dissolved Oxygen Patterns
	Salmonid Habitat Suitability	▪ Availability of Salmonid Habitat along Mainstem Russian River and Tributaries ▪ Availability of Salmonid Habitat in Russian River Estuary
Recreation (RC)	Recreational Uses	▪ Annual Days Suitable for Boating and Camping at Lake Mendocino ▪ Annual Days Suitable for Boating and Camping at Lake Sonoma ▪ Annual Days Suitable for Boating and Fishing along the River Russian

Sector	Indicator	Metrics
Hydropower (HP)	Hydropower Generation	▪ Annual and Monthly Hydropower Generation for Coyote Valley Dam ▪ Annual and Monthly Hydropower Generation for Warm Springs Dam
Community & Equity (CE)	Population Exposure to Risks	▪ Population Sensitivity to Floods ▪ Population Sensitivity to Wildfire ▪ Population Sensitivity to Drought ▪ Population Sensitivity to Water Supply

GSP = Groundwater Sustainability Plan

4.2.3 Analytical Tools

To evaluate the set of indicators and metrics for each water-related sector, a variety of analytical tools have been employed for each vulnerability assessment. Table 4-3 provides an overview of each of these tools and application for relevant sector-specific assessments. For additional details related to assumptions, inputs, outputs, and limitations, please refer to Attachment C-1, *Overview of Analytical Tools Used in the Russian River Watershed Resilience Analyses*. Further information on application and other relevant assumptions for each vulnerability assessment is provided in the methodology-focused subsections of Sections 5 through 12.

Table 4-3. Overview of Analytical Tools by Water Sector

Tool	Use	Climate Model Projections	Sector(s)
BCM	Simulates historical and future climate unimpaired streamflows and evapotranspiration.	CMIP6	SW, FM, EC, RC
Russian River HEC-HMS	Simulates precipitation-runoff processes to support flood risk and reservoir operation studies for the Russian River and Santa Rosa Creek watersheds.	CMIP6	SW, FM
Santa Rosa Creek HEC-HMS	Simulates precipitation-runoff processes to support flood risk and reservoir operation studies for the Santa Rosa Creek watersheds.	CMIP6	SW, FM
Russian River HEC-ResSim	Simulates how water is stored and released from Lake Mendocino and Lake Sonoma, flows through the river system across various junctions and routing reaches, and is affected by human activities like water diversions and agricultural use.	CMIP6	SW, RC, HP, EC
Sonoma Water Decision Support Model	Simulates reservoir storage and releases, river diversions, aqueduct flows and capacity constraints, customer water demands, and alternative supply sources like groundwater and recycled water.	CMIP6	SW, RC, HP

Tool	Use	Climate Model Projections	Sector(s)
Russian River Integrated Hydrologic Model	An integrated surface water/groundwater hydrology and river operations model that represents surface-groundwater interactions and uses climate forcings to estimate dynamic water use demands.	CMIP5	GW
Potter Valley Integrated Groundwater-Surface Water Model	Simulates surface water flow, groundwater flow, groundwater-surface water interactions, evapotranspiration from shallow groundwater, and agricultural water use and irrigation dynamics for the Potter Valley Groundwater Basin.	N/A	GW
Groundwater Sustainability Plan Integrated Surface and Groundwater Computer Models	Integrated surface and groundwater computer models representing surface and subsurface movement of water supplies for the Petaluma Valley, Santa Rosa, Sonoma Valley, and Ukiah Valley groundwater basins.	CMIP5	GW
Russian River Flood HEC-ResSim	Simulates reservoir operations for Lake Mendocino and Lake Sonoma.	CMIP6	FM
HEC-RAS	Simulates river hydraulics in the Russian River and Santa Rosa Creek watersheds.	CMIP6	FM
HEC-ResSim Water Quality Model	Simulates water quality conditions throughout the Russian River watershed using flow, biochemical processes, and meteorological inputs.	CMIP6 (3 projections only)	EC, WQ
Quantified Conceptual Model	Simulates the hydrologic and morphologic behavior of bar-built coastal lagoons.	CMIP6	EC, WQ
Suitable Habitat Acre-day Model	Estimates the amount of suitable water-quality-based juvenile salmonid habitat available within the water column at different locations with the Russian River Estuary.	CMIP6	EC, WQ
Power Tools for Hydropower	Estimates hydroelectric power generation at Lake Mendocino and Lake Sonoma using daily reservoir storage elevation and release data.	CMIP6	HP
Vulnerable Communities Platform	Identifies areas of vulnerability to various climate hazards, including extreme heat, flooding, wildfire, and drought, and overlays information related to a range of socioeconomic factors.	CMIP5/CMIP6	CE

Notes:

CMIP5 = Coupled Model Intercomparison Project Phase 5

CMIP6 = Coupled Model Intercomparison Project Phase 6

HEC = Hydrologic Engineering Center
HMS = Hydrologic Modeling System

Tool	Use	Climate Model Projections	Sector(s)

N/A = not applicable
RAS = River Analysis System
ResSim = Reservoir System Simulation
USACE = U.S. Army Corps of Engineers

Sectors:

SW = Surface Water Supply
GW = Groundwater
FM = Flood Management
EC = Ecosystem
WQ = Water Quality
RC = Recreation
HP = Hydropower
CE = Community & Equity

5. Surface Water Supply Vulnerability Assessment

5.1 Purpose

This assessment uses two complementary simulation tools, the Russian River ResSim Model (RR ResSim) and the Sonoma Water Decision Support Model (DSM), to evaluate Russian River water supply performance and climate vulnerability. Russian RiverResSim is a rule-based model developed by Sonoma Water using HEC-ResSim code base developed by the U.S. Army Corps of Engineers that simulates reservoir storage, releases, and downstream flow routing based on operational priorities and river flow losses and gains. The Sonoma Water DSM is a system-level dynamic model that tracks water-balance processes across reservoirs, diversions, demands, and delivery systems to quantify reliability and long-term tradeoffs. Together, these models provide a consistent framework for simulating operations under historical variability and projected climate conditions. Detailed model documentation is available for both the RR ResSim model (Sonoma Water, 2016a) and the Sonoma Water DSM (Jacobs, 2025).

The modeling framework is designed to assess how reservoir and river operations perform across a wide range of hydrologic and operational conditions, with a focus on water supply reliability, flood control coordination, and environmental flow requirements. The models simulate existing and alternative operational strategies at key components including Eel River diversions, the Russian River mainstem, and coordinated operations at Lake Mendocino and Lake Sonoma. The DSM also represents the Sonoma Water transmission system and local retail supplies, including dynamic simulation of Marin Municipal Water District and North Marin Water District reservoir operations. This supports transparent evaluation of tradeoffs among municipal, agricultural, environmental, and hydropower objectives.

A primary application is to analyze how climate variability and change affect system performance, including shifts in inflow timing, extended drought, and evolving operational constraints. The framework tests sensitivities to operating rules, demands, and infrastructure under a suite of plausible future scenarios.

Model outputs support long-term planning by characterizing the frequency, magnitude, and duration of water supply shortages and other vulnerabilities. Subsequent phases will apply the models to evaluate alternative operational strategies to reduce those vulnerabilities. Results are structured to inform stakeholder discussions, compare scenarios on a consistent basis, and integrate water supply findings with related ecosystem, recreation, and hydropower analyses.

5.2 Methodology

Both Russian River ResSim and the Sonoma Water DSM represent the system as a network of reservoirs, river reaches, and junctions, including the Eel River to capture transfer flows from the PVP and the New Eel Russian Facility (NERF). In both platforms, Lake Mendocino and Lake Sonoma are modeled using explicit storage, elevation, and area relationships, along with evaporation, outlet and spillway characteristics, and operational constraints related to flood control, water supply, and environmental flows. The Sonoma Water DSM expands beyond the reservoir and river domain to simulate Sonoma Water’s transmission system, retail customer service areas, and local surface water supplies, including dynamic operations of Marin and North Marin reservoirs and associated delivery rules. The two platforms operate independently but use consistent operating rules within the Russian River domain to support comparable results.

Both models operate on a daily time step, which is appropriate for long-term storage dynamics, allocation decisions, and flow compliance. Simulations use an ensemble of 41 global climate model scenarios to represent a wide range of plausible hydrologic conditions. The models include a historical reference period and a future period conditioned by climate projections and are run continuously from water year 1950 to 2100. Vulnerability assessment results are summarized for three 30-year periods: 1981 to 2010 Historical period, 2041 to 2070 Mid-Future period, and 2071 to 2100 Late-Future period.

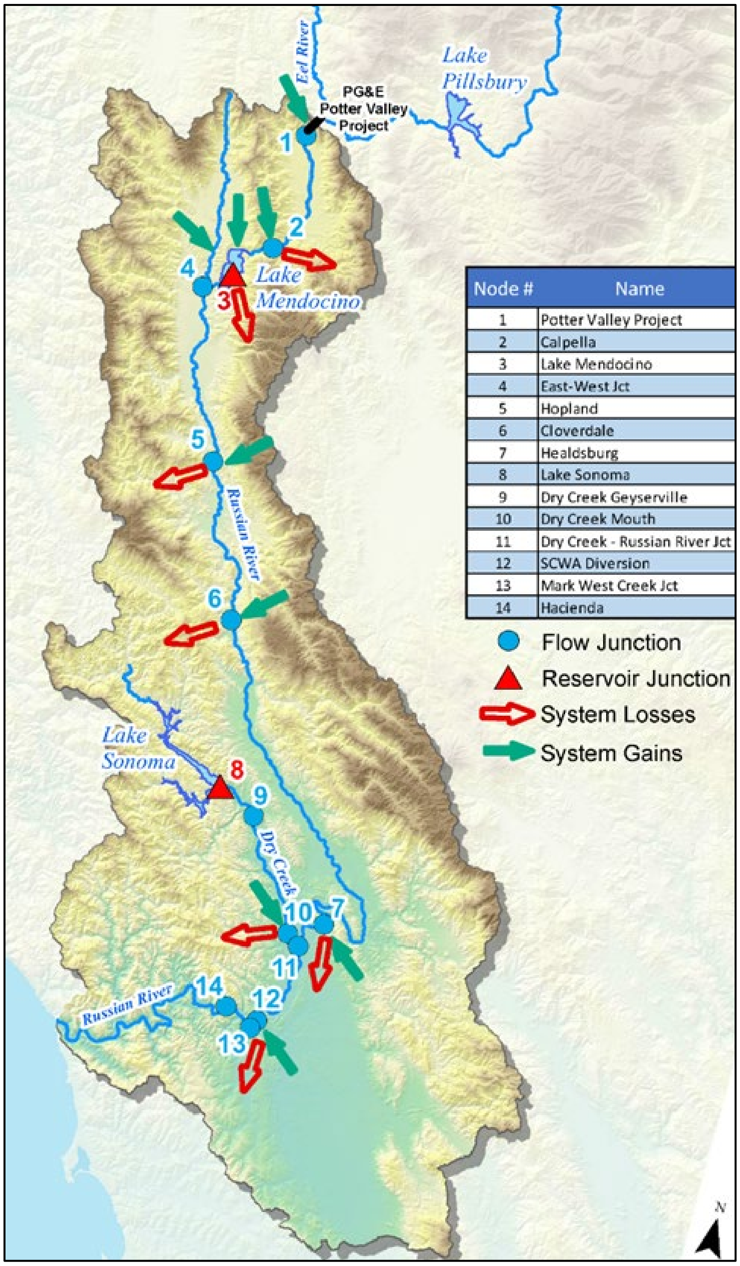
The Eel River transfers into the Russian River are represented in both models to capture availability, timing, and operational constraints. The Eel River domain includes Lake Pillsbury storage, minimum instream flows, and diversions to the Russian River watershed. Although logic exists for releases into the Eel River below Lake Van Arsdale, it is not considered for this assessment. Transfers through the PVP are simulated through 2035 consistent with the operations included in PG&E's application for a Non-Capacity License Amendment submitted in January 2025. Beginning in 2035, Lake Pillsbury is assumed to be decommissioned and drained as operations transition away from PVP. Following the decommission of PVP, two Eel River transfer operational scenarios were simulated to capture the range in uncertainty in Eel River transfers to the Russian River: (1) No PVP, which ends Eel River transfers starting in 2035, and (2) NERF, in which PVP transitions to NERF beginning in 2035. The PVP diversion capacity is assumed to be 240 cubic feet per second (cfs) and the NERF diversion capacity is assumed to be 300 cfs. No new storage capacity in Potter Valley to capture NERF diversions is assumed in the baseline simulations.

Reservoir and river operations are encoded using rule-based frameworks that reflect existing policies and regulatory requirements. Both platforms implement Lake Mendocino and Lake Sonoma flood control guide curves and FIRO storage zones. Release priorities reflect flood management, water supply, and environmental flow needs. Minimum instream flow requirements are consistent with Sonoma Water's water rights defined in Decision D1610, with a Biological Opinion required reduction in summer minimum instream flow requirements during Normal water supply conditions. The minimum instream flow schedules are set by a hydrologic index based on Lake Mendocino storage, which is consistent with operations defined in Temporary Urgency Change Petitions submitted by Sonoma Water and approved by the State Water Resource Control Board in 2023 through 2025. Initial model reservoir storage is set to observed values on September 30, 2025. Evaporation is based on climate model projections, with a unique evaporation series for each of the 41 scenarios. Storage elevation curves projected for 2050 are used to represent capacity changes from sedimentation.

The Sonoma Water DSM represents the Sonoma Water transmission system, including Mirabel and Wohler diversions, Santa Rosa Plain groundwater wells, pipelines, pump stations, storage tanks, and aqueduct turnouts. Each retail customer is represented with all available water sources, including aqueduct deliveries, local groundwater, recycled water, and local surface water. For North Marin Water District (NMWD) and Marin Municipal Water District (MMWD), the DSM dynamically simulates operations of Lake Stafford, and Soulajule, Nicasio, Kent, and Phoenix reservoirs. Source priorities and delivery limits are applied to reflect operational practice, with recycled water and groundwater generally prioritized in dry years.

Key inputs are harmonized across the two models. Hydrologic inputs include 41 historical and projected unimpaired flow series for 2 Eel River and 10 Russian River locations (Figure 5-1), and 7 additional inflows to MMWD and NMWD reservoirs in the DSM (described in Attachment C-1). System depletions include municipal, agricultural, riparian vegetation depletion, and losses to groundwater estimates along the Russian River and retail customer demands that account for local supplies. Retail customer supply and demand reflect 2025 observed conditions for 1950 to 2025 and follow 2020 Urban Water Management Plan projections through 2045, adjusted with recent population projections. After 2045, demands increase in proportion to Sonoma and Marin county population projections, with 86% of county populations assumed to be served by Sonoma Water. MMWD and NMWD local surface supplies are dynamically simulated throughout the period. For municipal depletion estimates along the Russian River, demand projections for 2025–2040 are based on supplier-specific data from their 2020 Urban Water Management Plans. For suppliers without an available 2020 Urban Water Management Plan, a regional growth assumption is made. From 2040 to 2100, demands are estimated solely based on the 2020–2040 population growth trajectory. Reach depletion estimates assume current depletion patterns from 1950 through 2025. After 2025, these current depletion patterns are then adjusted proportionally according to the projected net effects of evapotranspiration and precipitation under each climate scenario.

Figure 5-1. Russian River ResSim Schematic



Model outputs focus on performance indicators relevant to water supply vulnerability. Both platforms produce reservoir storage and release results and explicitly simulate supply shortfalls to Upper Russian River demands and Sonoma Water retail customer demands. Additional outputs include daily river flows for environmental, habitat, and recreation evaluations, as well as hydropower generation and turbine flows. These results support the vulnerability assessment and inform related study components, including the Russian River HEC-ResSim Water Quality Model, hydropower analyses in the DSM, and recreation and ecosystem evaluations.

As planning level tools, both models include simplifying assumptions. Real-time operational decision making and groundwater and surface water interactions are not explicitly represented. Performance under extreme high-flow conditions is less certain due to limited calibration data. River reach and distribution system travel times and losses are simplified. These limitations are addressed by emphasizing comparative results across scenarios and considering qualitative operational feasibility alongside quantitative outputs.

5.3 Results

This section summarizes simulated system performance for the Historical (1981–2010) baseline and climate-conditioned futures spanning the Mid-Future (2041–2070), and Late-Future (2071–2100) periods. Results focus on changes in hydrologic inputs, reservoir storage and release patterns, diversion behavior, and retail system reliability. Results are presented for the Upper Russian River (influenced by Eel River transfers and Lake Mendocino operations) and the Lower Russian River (influenced by Lake Sonoma operations, collector diversions, and retail/contractor behavior). Sensitivity analyses of Eel River transfer operations uncertainty are also summarized.

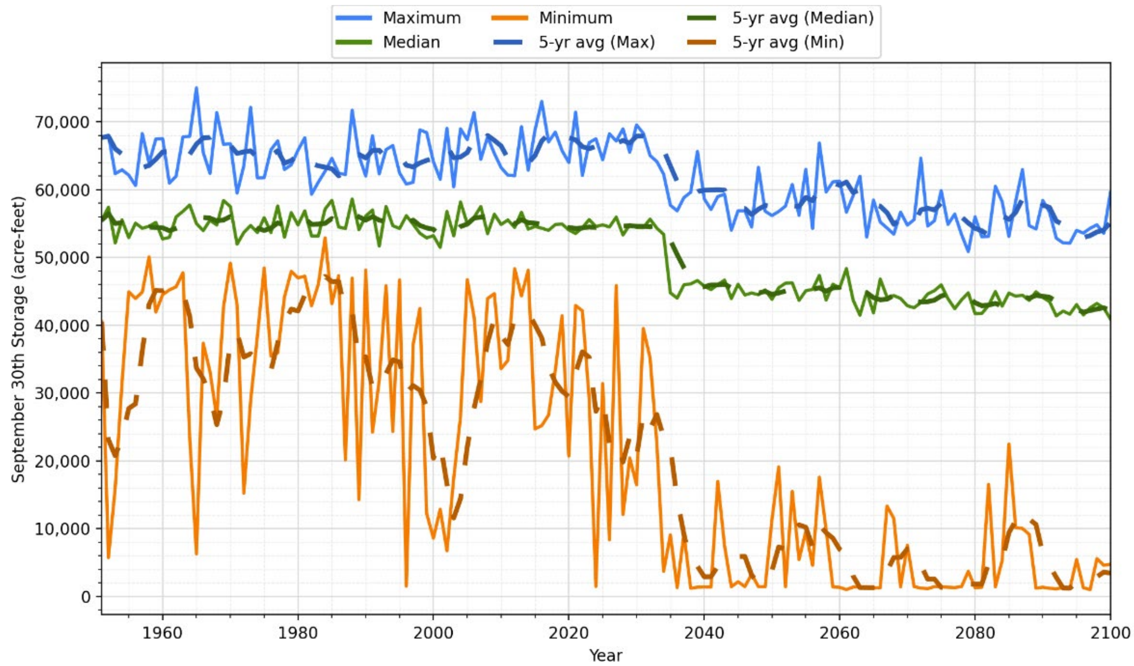
5.3.1.1 Upper Russian River

Lake Mendocino Storage and Release Patterns

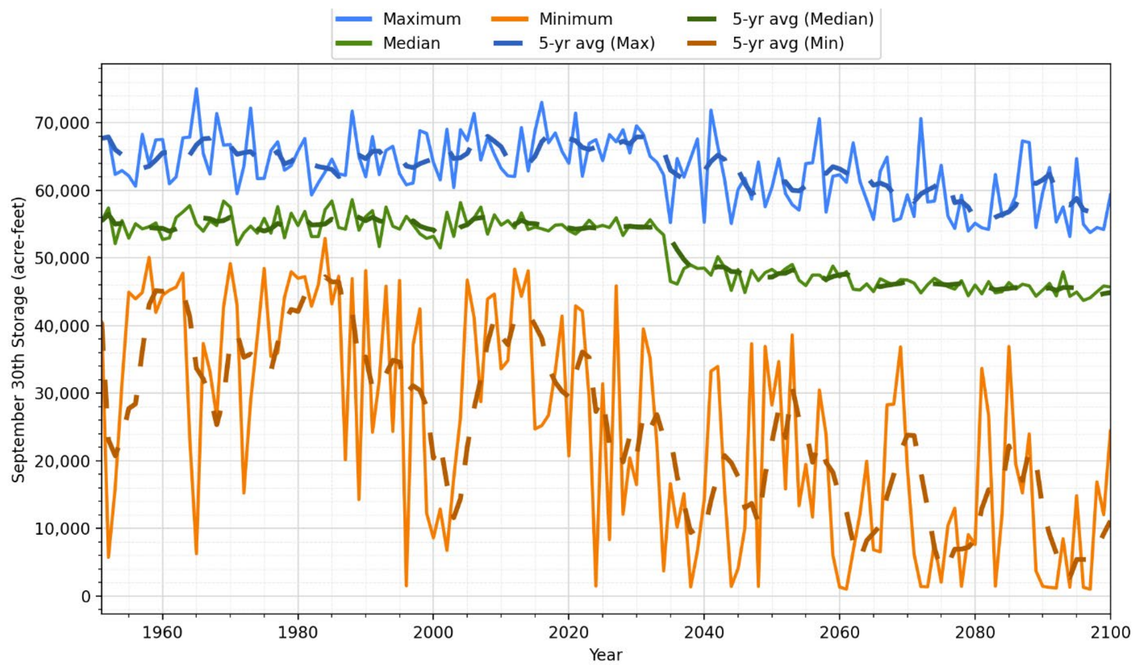
Figure 5-2 illustrates September 30 storage statistics for Lake Mendocino based on all 41 GCMs, comparing the Historical, Mid-Future, and Late-Future periods under both the No PVP and NERF Eel River transfer operational scenarios. Under the NERF scenario, median September 30 storage declines from about 62 TAF in the Historical period to roughly 50 TAF by the end of the Late-Future period. In the No PVP scenario, median storage decreases further to approximately 45 TAF. Years ending below critical planning thresholds, an indicator that may trigger operational or regulatory actions, account for 4%, 11%, and 16% of all NERF scenario observations across the three periods, respectively. Among the years that fall below this threshold, 21% in the Late-Future do not recover above 39 TAF in the subsequent year, occurring roughly three times more frequently than during the Historical period. This pattern points to an increasing likelihood of longer, multi-year drought sequences impacting Lake Mendocino.

Figure 5-2. Lake Mendocino September 30 Storage Across All Scenarios by Water Year Period

No Future Eel River Transfers (No PVP)



NERF Operations



Average annual Lake Mendocino releases declined by approximately 4% from the Historical period to the Late-Future period under NERF operations. Average summer-fall (June to October) releases declined by approximately 5% from the Historical period to the Late-Future period. These changes reflect both modifications to Eel River transfer operations and, secondarily, climate-driven hydrologic shifts.

The frequency of instream-flow-requirement shortfalls at the East–West Junction rises by 8% and 18% in the Mid- and Late-Future periods, respectively, when reservoir storage is low. These conditions are further exacerbated under the No PVP scenario.

Upstream of Lake Mendocino, under NERF operations, Potter Valley depletion shortfalls increase by 16% and 20% in the Mid- and Late-Future periods, respectively. Shortfalls downstream of Lake Mendocino to the Dry Creek confluence increase by 1% and 2% in the Mid- and Late-Future periods. These conditions are further intensified under the No PVP scenario.

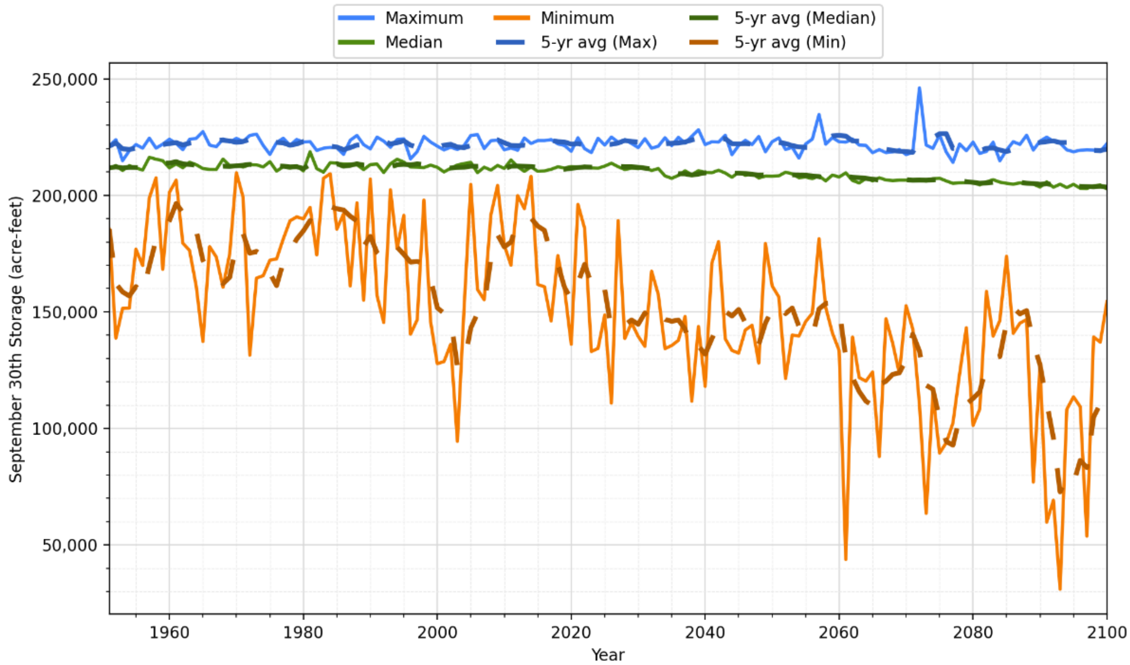
5.3.1.2 Lower Russian River

Lake Sonoma Storage and Release Patterns

Figure 5-3 illustrates September 30 storage statistics for Lake Sonoma based on all 41 GCMs, comparing the Historical, Mid-Future, and Late-Future periods under both the No PVP and NERF Eel River transfer operational scenarios. Median September 30 storage remains relatively stable across periods and Eel River transfer operational scenarios, resulting in a scenario-median value of 213 TAF in all periods and simulations, yet several future projections include years with storage lower than historical lows.
The frequency of years falling below critical planning thresholds, an operational and regulatory trigger for contingent demand reductions, remains very low across the three periods and all 41 scenarios. Only 1 scenario exhibits a multi-year excursion below this threshold, with storage remaining below 100 TAF for 2 consecutive years. Average annual release volumes decline by approximately 5% from the Historical period to the Late-Future period.

Figure 5-3. Lake Sonoma September 30 Storage Across All Scenarios by Water Year Period

No Future Eel River Transfers (No PVP)



NERF Operations

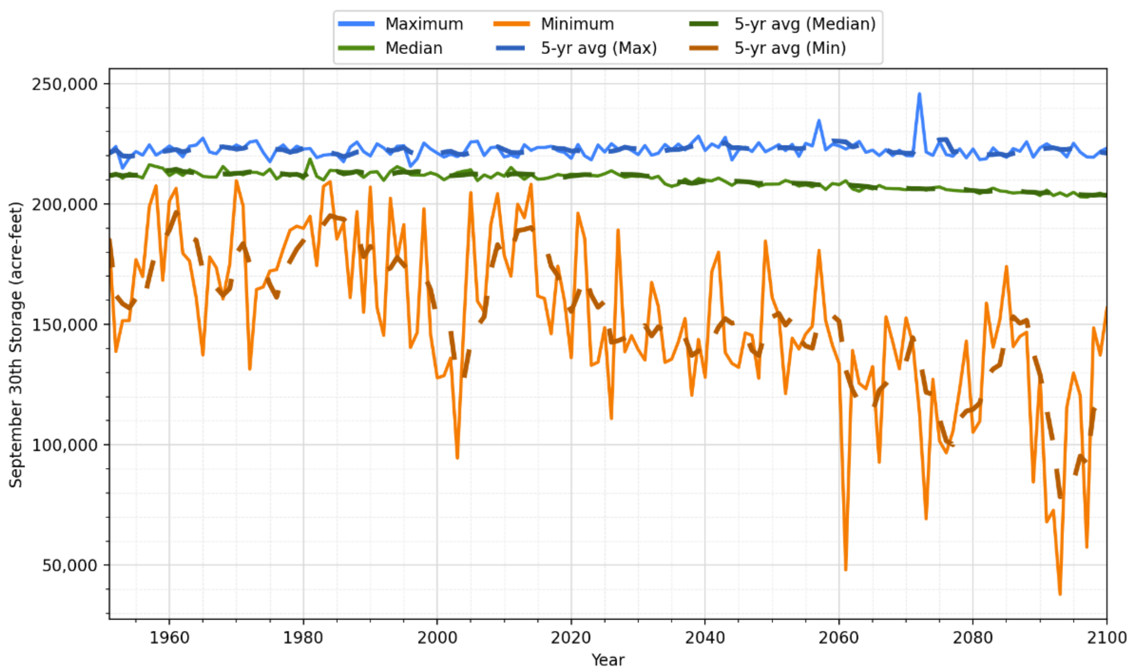
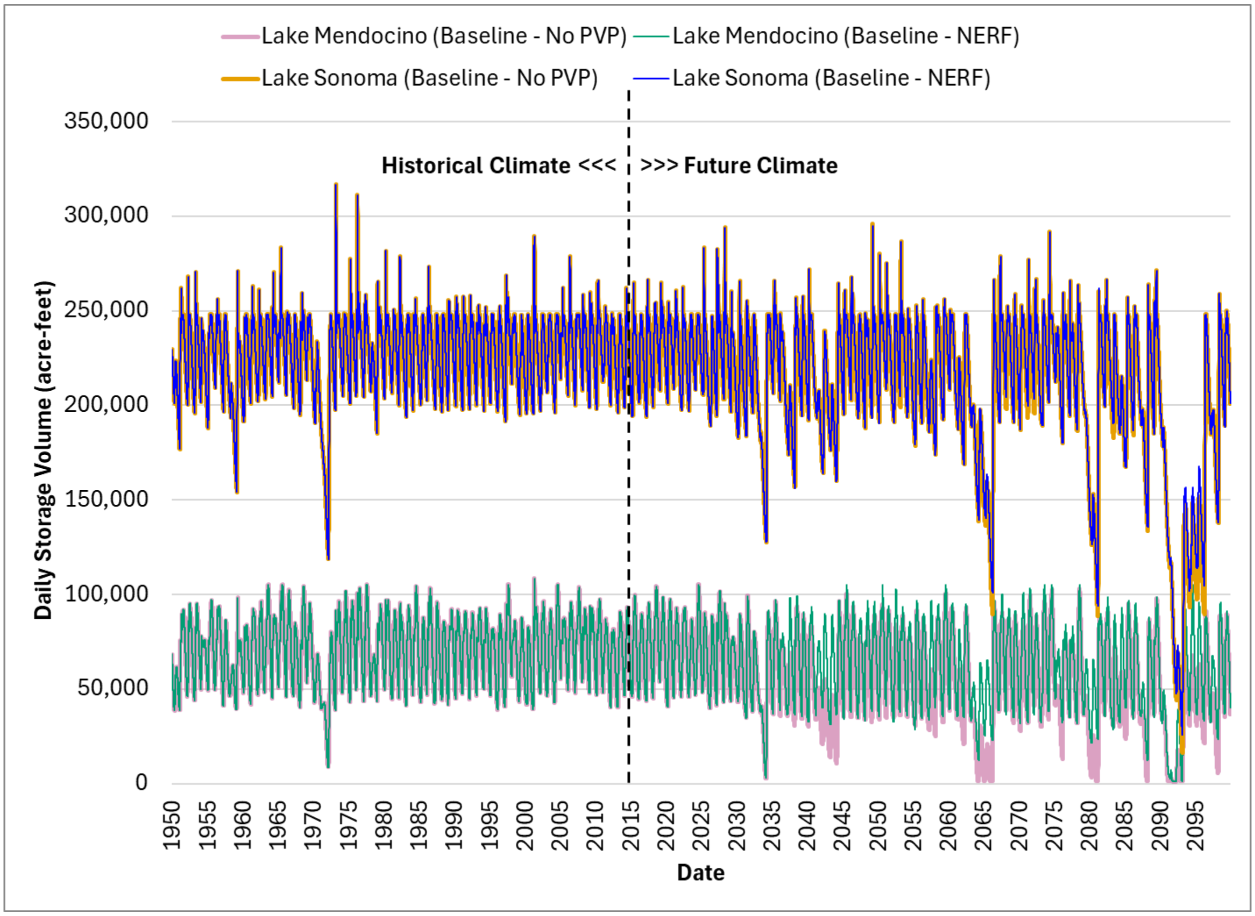


Figure 5-4 shows the simulated storage for Lake Mendocino and Lake Sonoma under one climate model projection (EC-Earth3 5-8.5) for both the No PVP and NERF scenarios. This figure illustrates a particularly notable future climate trajectory for the Russian River system in that the model produces three severe,

multi-year droughts that each persist for roughly 2 to 7 years, placing substantial strain on both Lake Mendocino and Lake Sonoma storage within only three decades.

Figure 5-4. Lake Mendocino and Lake Sonoma Storage Volume for Future Projection EC-Earth3 5-8.5 for Two Baseline Scenarios: (1) No PVP, which ends Eel River transfers starting in 2035, and (2) NERF Operations, in which PVP transitions to NERF beginning in 2035



Under the EC-Earth3 5-8.5 climate scenario, the No PVP operational scenario (PVP through 2034 and no transfers afterwards) generally produces lower Lake Mendocino storage for most of the period from 2035 to 2100; about 85% of days are lower than under the NERF scenario (PVP through 2034 and NERF from 2035). On average, Lake Mendocino storage under the NERF scenario is approximately 6.4 thousand acre-feet higher (KAF). During late spring and summer, the storage under the NERF scenario averages about 7.2 KAF higher than the no-transfer scenario.

This effect is especially pronounced during multi-year droughts. In the 5-year drought occurring in the 2090s, storage under the no transfer scenario never rebounds above roughly 34 KAF, remaining substantially below NERF throughout the entire drought sequence and limiting opportunities for recovery between dry years. Taken together, the sensitivity indicates that the absence of Eel River transfers can compound climate-driven stress by keeping storage lower for longer periods, reducing late-season availability, and dampening rebound potential between dry years—context for operations that sits alongside (but is distinct from) the climate focused findings in this study.

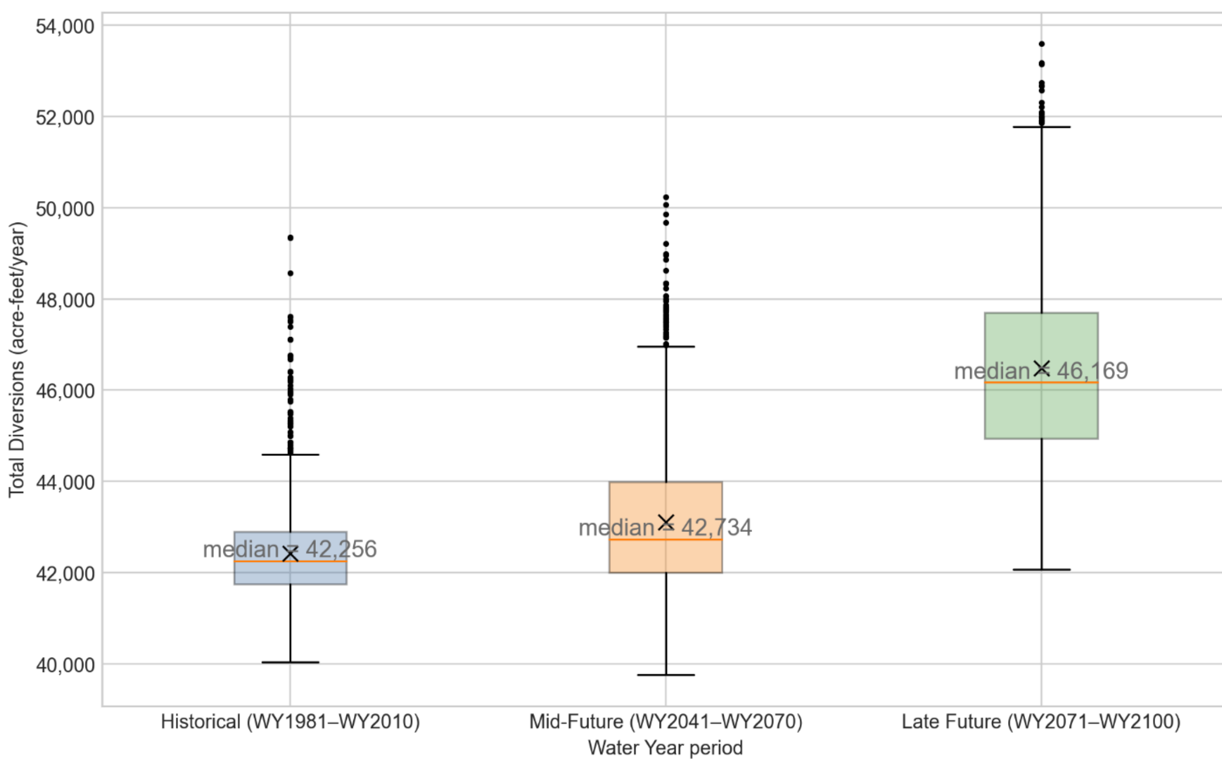
While this scenario highlights one plausible climate pathway, it represents only a single realization within a much broader ensemble. The previous figures (S-3 and S-4) summarize the maximum, median, and minimum projected storage conditions at Lake Mendocino and Lake Sonoma across all 41 climate scenarios to better reflect the full range of uncertainty in future hydrologic conditions.

Russian River Collector Diversions (Mirabel/Wohler)

Figure 5-5 presents the distribution of total annual diversions across the Historical, Mid-Future, and Late-Future periods from the Russian River at Mirabel and Wohler facilities.

Figure 5-5. Annual Russian River Diversions at Mirabel and Wohler facilities Across All Scenarios by Water Year Period

Boxes denote the interquartile range (25th to 75th percentiles), with the horizontal line indicating the median. Whiskers extend to the most extreme values within 1.5 times the interquartile range, and values beyond this range are shown as individual points.



Median annual diversions remain relatively consistent between the Historical and Mid-Future periods, 42.2 TAF and 42.7 TAF, respectively, indicating that mid-century hydrologic and operational conditions enable diversion volumes similar to those observed from 1981–2010.

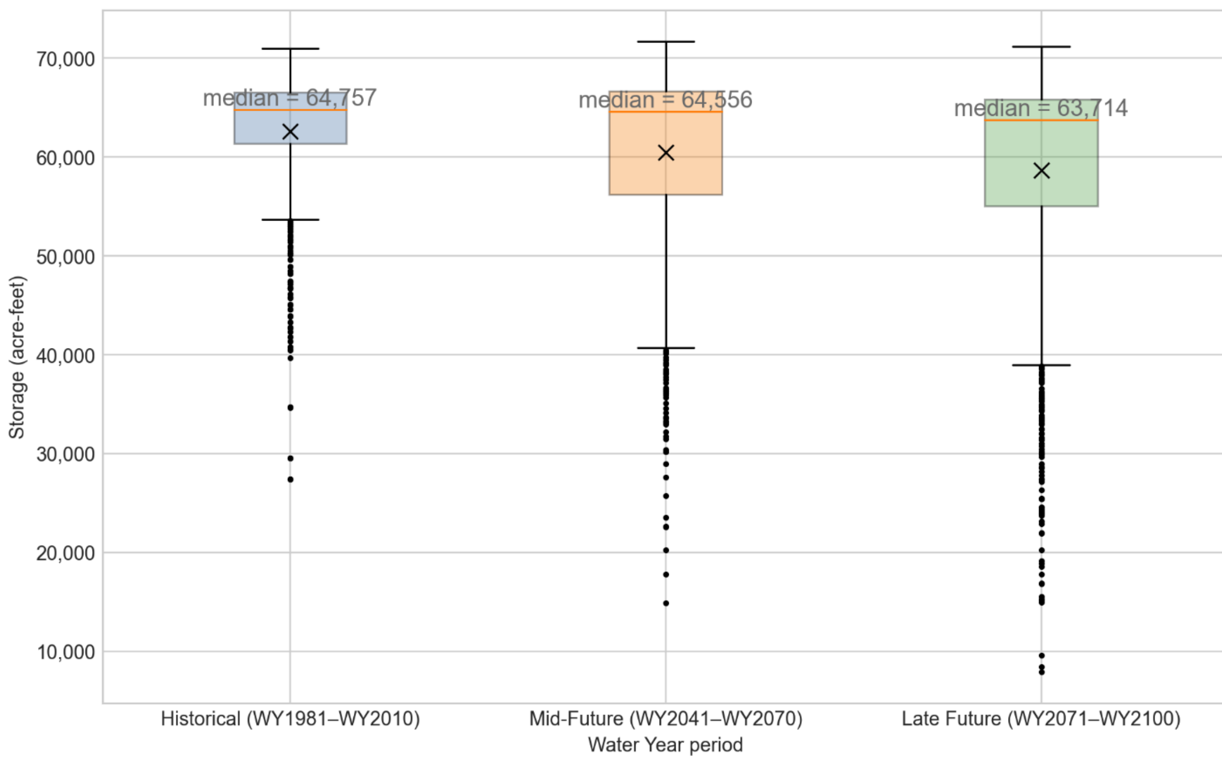
A more pronounced shift appears in the Late-Future period, where the median increases to approximately 46.2 TAF, representing an increase of around 9% relative to the Historical baseline. Peak-month diversions shift by +11% in the Late-Future, with peaks remaining in July.

The spread in annual diversion volumes also changes across periods. The Mid-Future distribution exhibits modestly wider variability, reflecting an increase in the frequency of both above-average and below-average diversion years. The Late-Future period shows even greater upper-range potential, with more years reaching diversions above 48–50 TAF. This is related to an increase in demand projections for this period, as well as MMWD's increased reliance on Russian River water supply under drier climates projected for MMWD's local surface supply systems (discussed further below).

Marin and North Marin Reservoir Storage Patterns

Figure 5-6 shows the distribution of total September 30 storage for the Marin Municipal system (total volume in Soulajule, Nicasio, Kent, Bon Tempe, Lagunitas, Alpine, and Phoenix reservoirs) across the Historical, Mid-Future, and Late-Future periods. Median storage values are similar across all three periods, with medians of approximately 64,757 acre-feet in the Historical period, 64,556 acre-feet in the Mid-Future period, and 63,714 acre-feet in the Late-Future period. The boxes representing the interquartile ranges remain relatively consistent in height, indicating similar spread in typical annual storage conditions.

Figure 5-6. Total Marin Surface Storage September 30 Values Across All Scenarios by Water Year Period

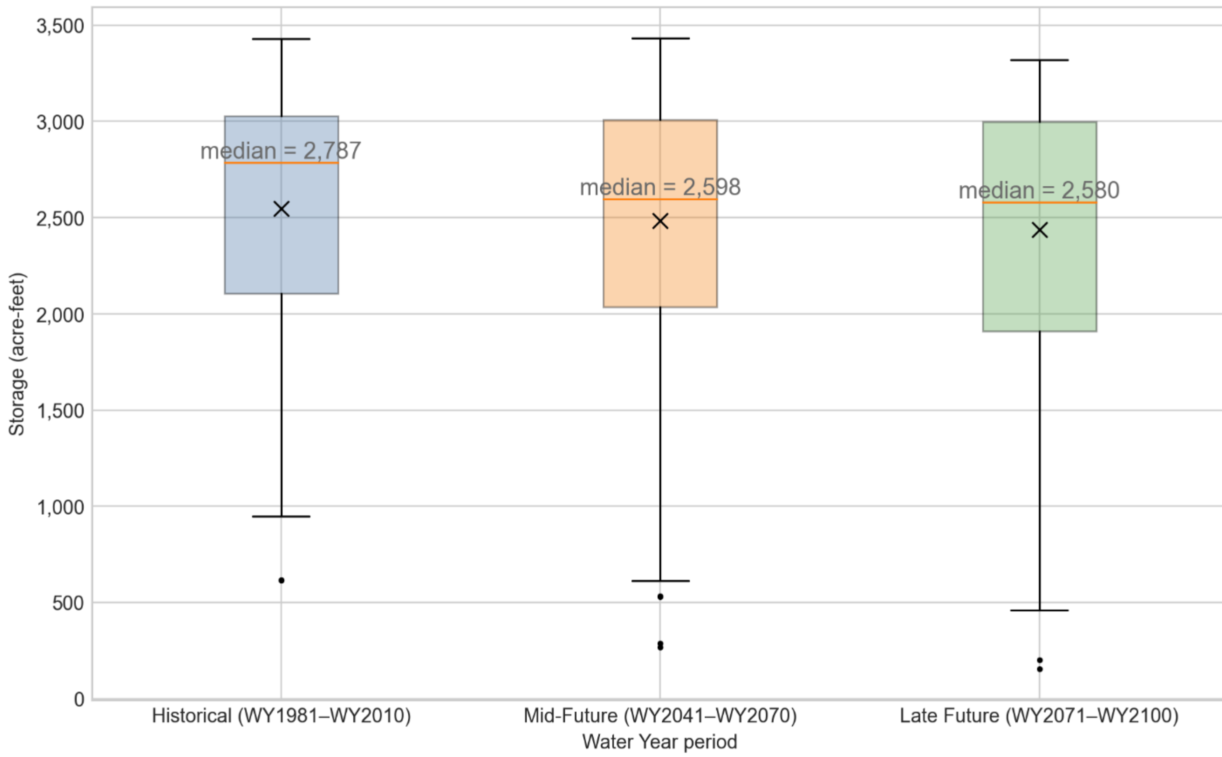


Each period also includes a wide range of annual outcomes, shown by the whiskers and individual outlier points. Upper-range storage values extend to roughly 68,000–70,000 acre-feet in all periods. Lower-range values include occasional years dropping below 30,000 acre-feet, which is the system's critical water supply planning threshold. These low-storage observations appear in each of the three periods, with an increasing trend into the Mid- and Late-Future periods. Several of the low-storage observations correspond to years where shortages occur in MMWD's service area, discussed in the subsequent shortages section.

Figure 5-7 shows the distribution of September 30 storage in Stafford Lake for the Historical, Mid-Future, and Late-Future periods. Median storage values remain similar across periods, with medians of approximately 2,787 acre-feet in the Historical period, 2,598 acre-feet in the Mid-Future period, and

2,580 acre-feet in the Late-Future period. The interquartile ranges are also comparable, indicating that typical annual storage levels are of similar magnitude throughout the modeled time horizons.

Figure 5-7. Stafford September 30 Storage Values Across All Scenarios by Water Year Period

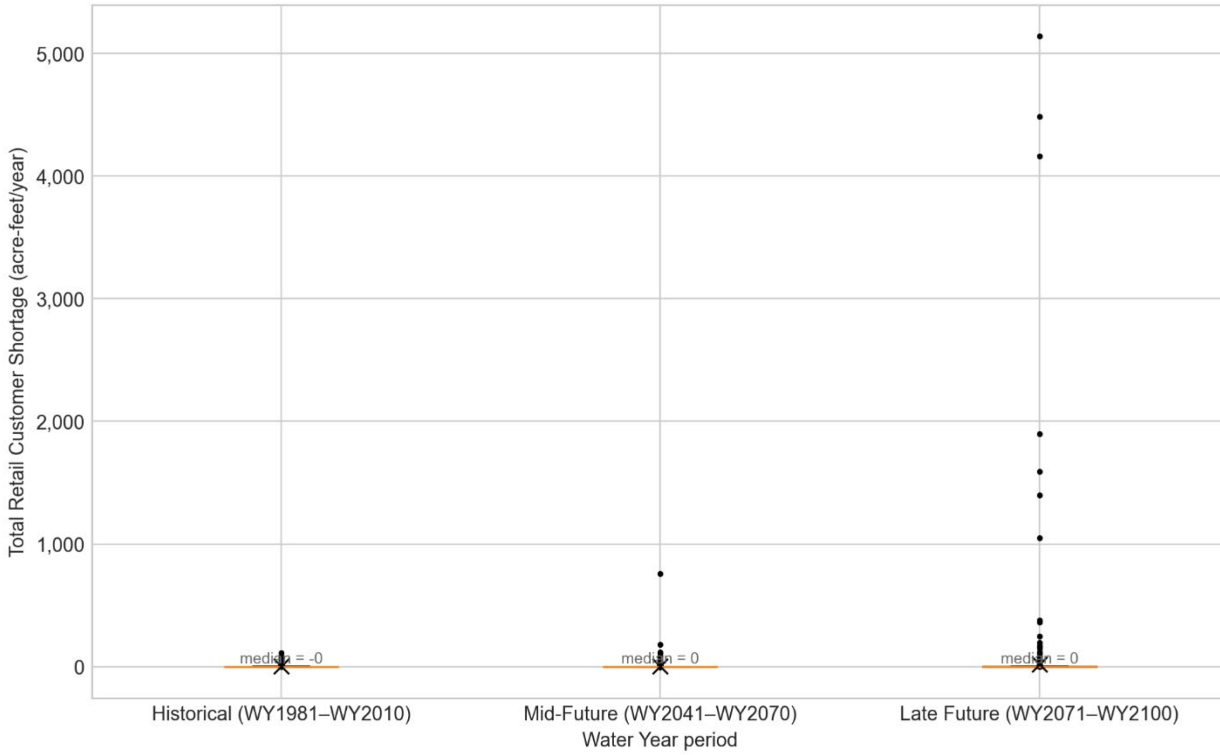


The whiskers and outlier points illustrate a broad range of annual storage outcomes in all three periods. Upper-range values reach roughly 3,400 acre-feet in the Historical and Mid-Future periods, with slightly lower upper bounds in the Late-Future period. Lower-range values drop into the several hundreds of acre-feet, including a small number of years near or below 500 acre-feet in the Mid-Future period and a greater frequency of such low-storage years in the Late-Future period.

Sonoma Water Retail Customer Shortages

Figure 5-8 shows the distribution of total annual Sonoma Water retail customer shortages for the Historical, Mid-Future, and Late-Future periods. Median shortages are zero in all three periods, indicating that most scenarios do not produce any annual shortage under modeled conditions. The interquartile ranges also remain at zero across all periods, reflecting that the majority of modeled outcomes cluster at no shortage.

Figure 5-8. Total Sonoma Water Retail Customer Annual Shortage Volumes Across All Scenarios by Water Year Period



The outlier points indicate that occasional shortages do occur, particularly in the Mid-Future and Late-Future periods. These events can reach several hundred acre-feet per year and a small number in the Late-Future period exceeding 1,000 acre-feet per year. A few extreme outliers occur in the Late-Future period, with the highest values approaching 5,000 acre-feet. A majority of these shortage volumes coincide with low local storage volumes in MMWD's reservoir system, the service area where a majority of the shortage volume occurs.

5.4 Summary

This assessment evaluates how the Russian River water supply system responds to a wide range of future hydrologic, operational, and climate conditions. Using coordinated RR ResSim and Sonoma DSM simulations, the analysis examines reservoir operations, Eel River transfers, retail system performance, and the relative vulnerability of the Upper and Lower Russian River. Results highlight growing challenges in maintaining reliable supplies, particularly in the Upper Russian River, where dependence on Eel River transfers and limited storage capacity increase sensitivity to climatic and operational change.

Reduced Eel River transfers are a major driver of vulnerability that exacerbate climate impacts. Transfers decline due to the planned decommission of the PVP, even under the NERF operational scenario, due to the loss of snowpack in the upper watershed, and more variable Eel River hydrology. Many future years produce significantly lower transfer volumes than the historical period, and NERF operations would shift transfer timing toward earlier in the water year. This reduces late-spring and summer availability for Potter Valley agriculture and increases the frequency of unmet depletion and minimum instream flow requirements.

Lake Mendocino is increasingly stressed across future scenarios. Annual September 30 storage declines relative to the historical period, and the frequency of years falling below critical planning thresholds increases. Longer and more severe drought sequences also emerge, reducing the ability to recover storage between dry years. As storage declines become more frequent, the ability to maintain releases for downstream water users becomes more challenging in some years. Sensitivity analyses confirm that reduced or highly variable Eel River transfers further amplify these challenges.

Upper Russian River water users face the greatest increases in shortage risk. Depletion shortfalls increase above historical levels in both mid- and late-century periods, and the frequency and magnitude of shortfalls are highest under scenarios with reduced Eel River transfers. Potter Valley agriculture is particularly vulnerable, with late-spring and summer supplies unavailable in many future years unless significant adaptation measures are implemented.

Lower Russian River water users experience fewer direct impacts but still face increasing pressures from longer and more severe drought conditions. Lake Sonoma storage remains relatively stable across most simulations, yet several future projections include years with storage lower than historical lows. Although most model scenarios continue to meet Sonoma Water retail demands without shortages, a small number of future years show shortfalls, particularly when local Marin surface supplies experience multi-year drought conditions and increase their reliance on Russian River water.

Despite these challenges, the analysis indicates that operational adaptation and water management actions can reduce impacts. Opportunities include refining reservoir operating rules, strengthening demand management, expanding local supply strategies, and improving coordination between upstream and downstream operational priorities. These strategies can help enhance system resilience and support long-term water supply reliability for communities, agriculture, ecosystems, and regional partners.

6. Groundwater Supply Vulnerability Assessment

6.1 Purpose

The purpose of the Groundwater Supply Vulnerability Assessment is to evaluate potential vulnerabilities to groundwater resources in response to projected changes in climate throughout the Russian River watershed area, as well as for underlying groundwater aquifers in areas that receive Russian River water in Sonoma Water's service areas (i.e., Adjacent Areas). The study area includes four groundwater basins managed by local Groundwater Sustainability Agencies (GSAs): that is, the Ukiah Valley Basin, Santa Rosa Plain, Petaluma Valley, and Sonoma Valley groundwater basins. A combination of studies, models, and data sources were used to assess potential groundwater vulnerabilities, including a groundwater modeling study of the Russian River watershed completed in 2025 by the U.S. Geological Survey (Adera et al. 2026), the GSPs developed for each of the four groundwater basins managed by their respective GSAs, and the Water Shortage Availability Analysis developed by the California Department of Water Resources (DWR).

6.2 Methodology

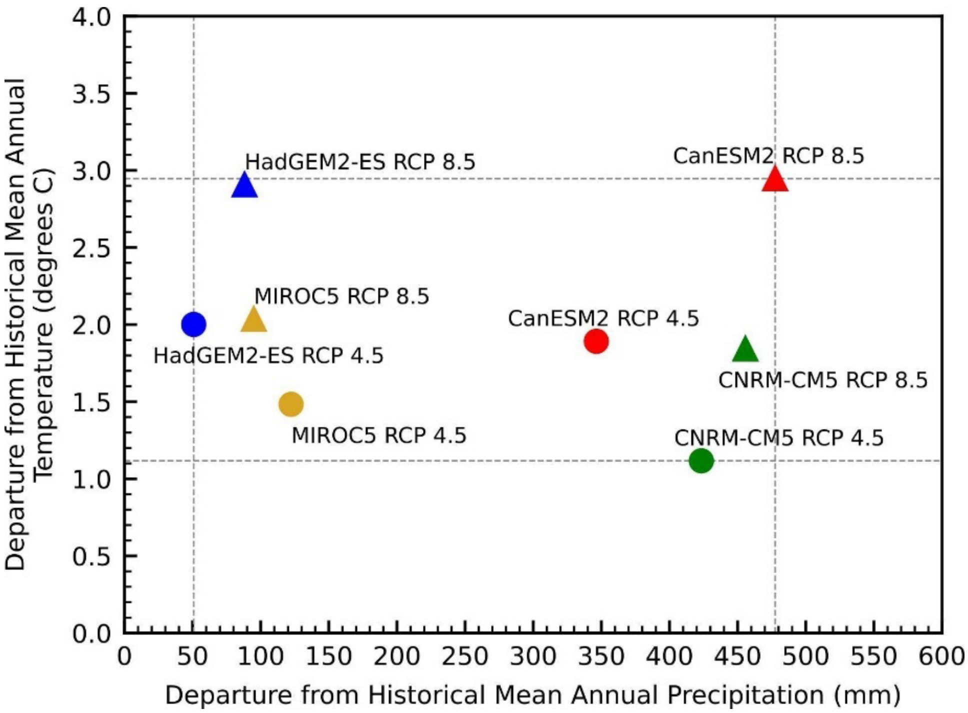
Evaluation of groundwater resources vulnerability relies on estimates of groundwater water budget components, including groundwater inflows (e.g., recharge, stream leakage, inflows from adjacent groundwater basins, etc.), groundwater outflows (e.g., groundwater discharge to streams, groundwater ET, outflows to adjacent basins, etc.) and changes in groundwater storage, each estimated under historical, current, and future climate conditions.

6.2.1 GSFLOW Watershed Analysis

For the Russian River hydrologic watershed area, groundwater resources vulnerability was assessed with the USGS's modeling study (Adera et al. 2026), which relies on an integrated surface-groundwater hydrology and river operations model, the Russian River Integrated Hydrologic Model (RRIHM). The RRIHM simulates surface-groundwater processes using GSFLOW (Markstrom et al. 2008), reservoir operations and priority-based water allocations using MODSIM (LaBadie 2005), as well as soil-moisture-dependent agricultural water allocation usings the AG Package (Niswonger 2020). The model simulates a historical period from 1990–2015, as well as future conditions (2015–2099) under eight CMIP5 climate forcings (Figure 6-1). Future climate simulations were run with no interbasin water transfers from the PVP. In addition, a variation of the historical scenario was also simulated with no PVP transfers to allow for direct comparison of hydrologic response for the historical period and under climate change.

Assessment of future groundwater vulnerabilities was achieved by comparing relevant groundwater budget components (e.g., groundwater storage, surface-groundwater exchange) under historical and climate change simulations.

Figure 6-1. Eight GCM Climate Future Scenarios Simulated by the RRIHM Plotted as Departure from Historical Mean Precipitation and Temperature Values



Source: Adera et al. 2026

6.2.2 Groundwater Sustainability Plan Summaries

During development of the GSPs for the Santa Rosa Plain, Petaluma Valley, and Sonoma Valley, separate groundwater flow models were developed for areas that encompass each groundwater subbasin to support development of water budgets (land, surface water, and groundwater), development of Sustainable Management Criteria, and to evaluate potential projects and management actions to support sustainable management of the groundwater subbasins. As part of GSP requirements, 50-year projections of future conditions were required to evaluate sustainability over the 50-year Sustainable Groundwater Management Act planning horizon.

Table 6-1 provides a summary of the groundwater models used and the projected time periods and climate assumptions used to develop the future projections, as part of GSP development, for each groundwater subbasin. Summaries based on the evaluation of these projected conditions in the GSPs will be summarized under Section 6.3 for each groundwater subbasin.

Table 6-1. Groundwater Models, Project Time Periods, and Assumptions Associated with Groundwater Sustainability Plan Future Projections

Groundwater Subbasin	Groundwater Model used to Support Water Budget Development	Projected Water Budget Time Period	Projected Climate Input Assumptions
Ukiah Valley	Ukiah Valley Integrated Hydrological Model (UVIHM)	50-year baseline representing 2019 to 2070 with climate conditions consistent with 1969 to 2018 Climate variables adjusted to represent near-future climate (2030) and far-future climate (2070)	Adjusted precipitation and evapotranspiration using climate change factors developed by DWR to represent climate conditions centered around 2030 and 2070
Santa Rosa Plain	Santa Rosa Plain Hydrologic Model (SRPHM) Originally developed by U.S. Geological Survey (USGS) (Woolfenden and Nishikawa 2014) and updated by the USGS and Sonoma Water to support GSP water budget development (Alzairee and others 2025).	WY 2021 through 2070	Utilized projected climate conditions from the HadGEM2-ES GCM and RCP 8.5 Projected climate used to adjust inputs for: ▪ Precipitation ▪ Temperature ▪ Evapotranspiration ▪ Irrigated water demands ▪ Groundwater Pumping
Petaluma Valley	Petaluma Valley Integrated Groundwater Flow Model Developed by the USGS in conjunction with Sonoma Water (citation forthcoming)	WY 2021 through 2070	Utilized projected climate conditions from the HadGEM2-ES GCM and RCP 8.5 Projected climate used to adjust inputs for: ▪ Precipitation ▪ Temperature ▪ Evapotranspiration ▪ Irrigation water demands ▪ Groundwater Pumping Assumptions of sea level rise along San Pablo Bay based on guidance provided by the California Natural Resources Agency (CNRA 2018)

Groundwater Subbasin	Groundwater Model used to Support Water Budget Development	Projected Water Budget Time Period	Projected Climate Input Assumptions
Sonoma Valley	Sonoma Valley Integrated Groundwater Flow Model Version 2 (SVIGFM v2) SVIGFM was developed by Sonoma Water (Sonoma Water 2020a and 2020b)	WY 2021 through 2072	Utilized projected climate conditions from the HadGEM2-ES GCM and RCP 8.5 Projected climate used to adjust inputs for: ▪ Precipitation ▪ Temperature ▪ Evapotranspiration ▪ Irrigation water demands ▪ Groundwater Pumping Assumptions of sea level rise along San Pablo Bay based on guidance provided by the California Natural Resources Agency (CNRA 2018)

6.2.3 DWR's Water Shortage Vulnerability Analysis

In 2024, the California DWR updated their Water Shortage Vulnerability scoring for small water systems, rural communities, domestic wells, and other self-supplied residents (DWR 2024). As part of the Water Shortage Vulnerability scoring, a grouping of indicators was used to estimate physical water shortage vulnerability for rural communities based on projected climate change, conditions and episodic events, infrastructure, and observed shortage. Vulnerability indicators considered as part of the vulnerability scoring are as follows:

- Temperature shift
- Saline intrusion projected
- Wildfire risk
- Current year's precipitation
- Consecutive dry years
- Geology
- Water quality aquifer risk
- Subsidence
- Saltwater intrusion
- Overdrafted Basin
- Chronic declining water levels
- Surrounding land use
- Reported Household outages on domestic well

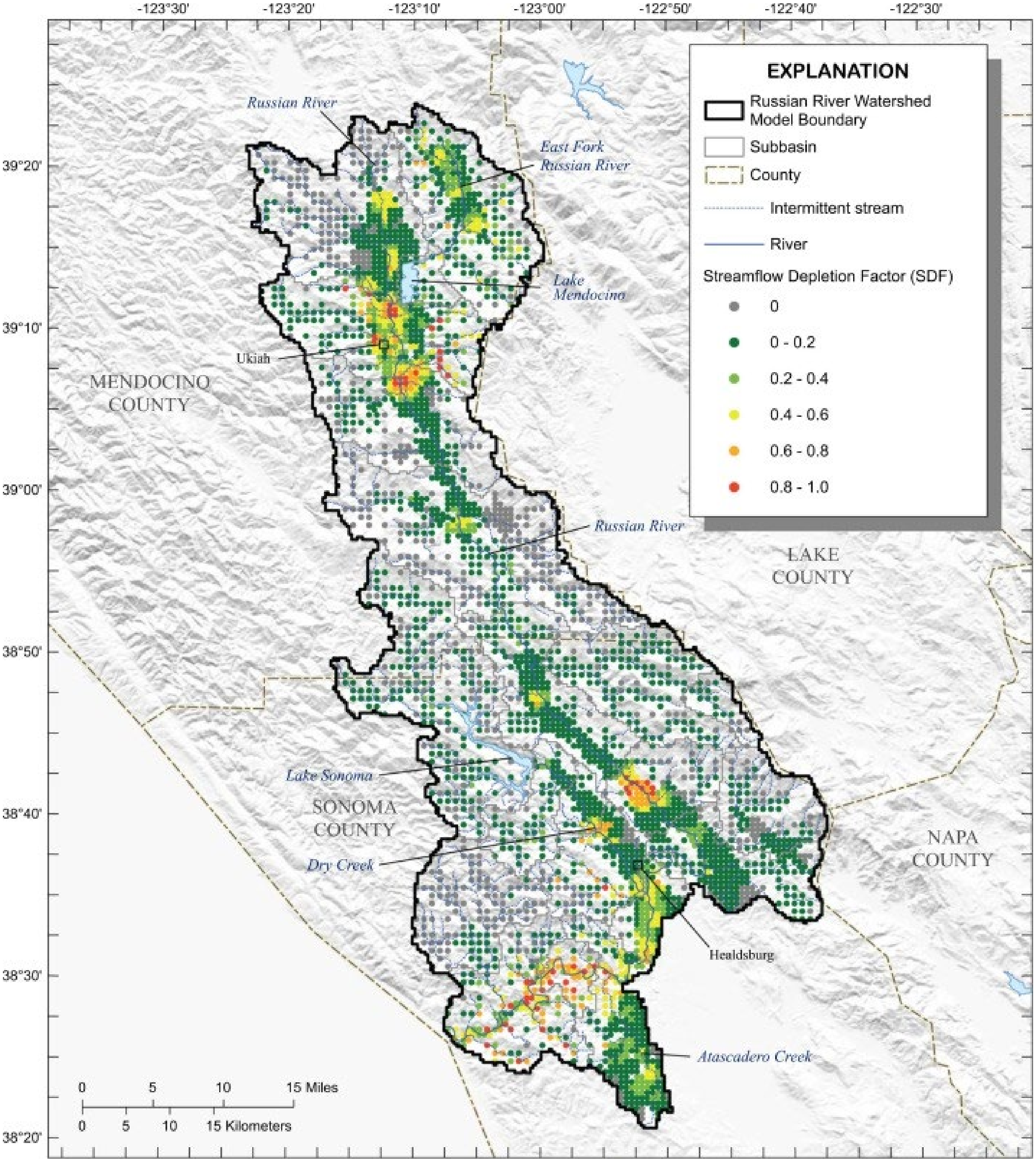
Based on the ranking of each indicator, a total weighted score was developed to represent the physical vulnerability. Full details on the methodology of scoring each indicator and the total score weighting scheme are described in DWR's methodology documentation (DWR 2024). The total score results from DWR's physical vulnerability analysis was further evaluated as part of the Russian River Watershed Resilience Pilot (RRWRP) to evaluate groundwater supply vulnerability of domestic wells users that reside in bedrock areas outside of major alluvial basins. The intent with including information on users outside of the alluvial basins is to supplement the vulnerability analysis from GSFLOW and the GSPs. Further discussion on the results of the groundwater supply vulnerability analysis of domestic wells in bedrock areas is discussed in Section 6.3.

6.3 Results

6.3.1 GSFLOW Analysis of the Russian River Watershed

Results from the RRIHM modeling study demonstrate the close interconnection between surface water and groundwater in the alluvial aquifer systems along the Russian River. These alluvial aquifer systems have low groundwater storage capacity relative to the large seasonal swings in precipitation and streamflow. These low-storage aquifer systems are typically replenished to capacity each winter season and are depleted by groundwater pumping, groundwater discharge to surface water, and groundwater ET during the subsequent dry season. Groundwater/surface water interactions vary dynamically along the Russian River and show large seasonal variations. Aggregated over the entire watershed and across all simulations, Adera et al. (2026) estimated that net surface-groundwater exchange was from streams to aquifers, with 5 to 12% of total streamflow contributing to stream leakage to groundwater. Additionally, Adera et al. (2026) estimated that 19% of pumped groundwater in alluvial aquifers along the Russian River is from stream leakage, with particular "hot spots" for streamflow depletion occurring in alluvial aquifers with favorable aquifer and streambed hydraulic properties, namely in portions of the Ukiah Valley, Alexander Valley, and the Lower River (Figure 6-2). These results demonstrate the close interdependence of surface water and groundwater in the watershed and highlight their shared vulnerabilities.

Figure 6-2. Spatial Distribution of Streamflow Depletion Factors, Simulated for the 1990–2015 Simulation Period



Source: Adera et al. 2026

6.3.2 Results from the Eight Climate Change Simulations

The eight climate change scenarios used to simulate hydrologic response under climate change vary in the magnitude of departure for both temperature and precipitation from historical baseline, with scenarios showing increases in mean temperature of 2.0 to 5.2°F and increases in mean annual precipitation of 2.0 to 18.7 inches for the 2015–2099 future simulation period as compared to historical baseline. Increases in precipitation primarily occur during the wet season (Figure 6-3). Future climate change simulations of the Russian River watershed show both greater seasonal and interannual hydrologic variability, with 59% longer and 54% more severe streamflow droughts, as well as lower dry-season and greater wet-season runoff (0.74× and 1.25× change from historical baseline, respectively; Figure 6-4). Increased temperatures result in an earlier seasonal onset of ET demands during the wet season as well as earlier declines in ET during the dry season (Figure 6-5).

Given the close interconnection between the Russian River and the alluvial aquifer systems along the river's corridor, increases in hydrologic volatility and attendant changes in streamflow response under climate change have follow-on impacts on groundwater resources. In general, groundwater response shows amplified seasonal swings in storage, with greater increases in storage during the wet season and greater reductions in storage in wet-to-dry and dry seasons (Figure 6-6). These larger-amplitude seasonal swings are driven by greater wet-season stream leakage and greater groundwater discharge to streams in wet-to-dry and dry seasons (Figure 6-7).

Figure 6-3. Seasonal Precipitation Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed

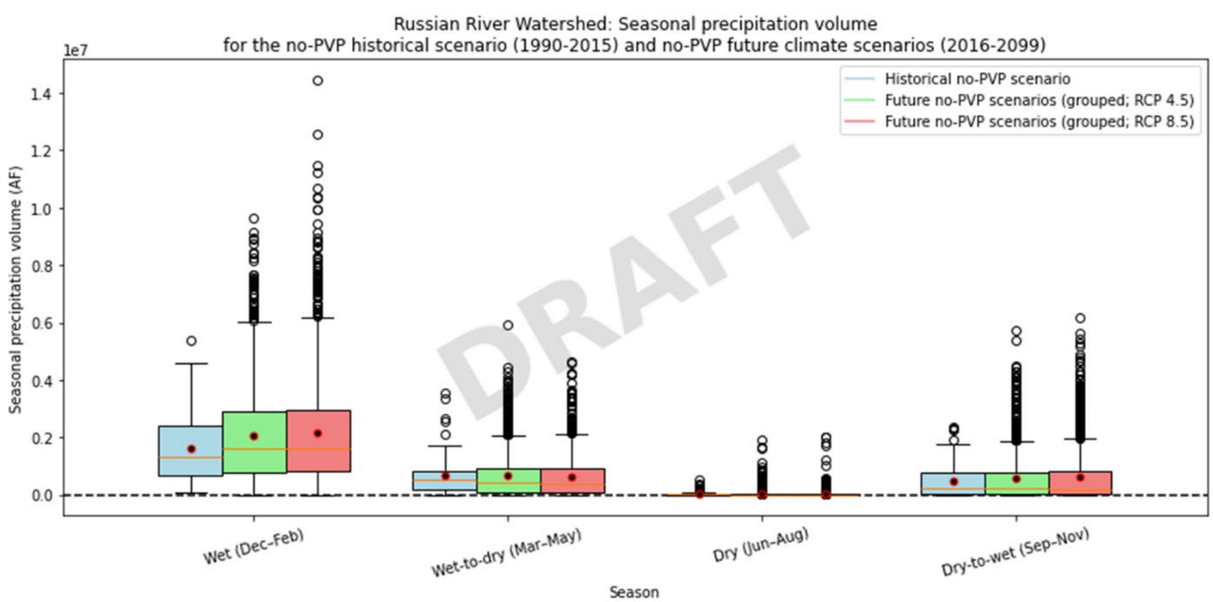


Figure 6-4. Seasonal Runoff Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed

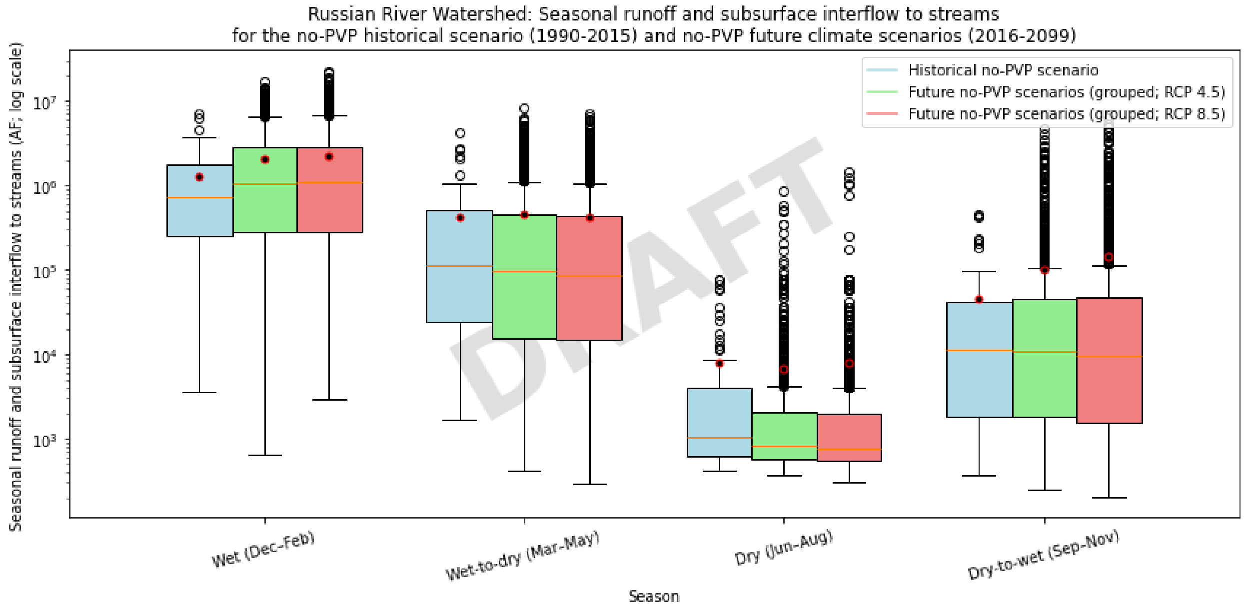


Figure 6-5. Seasonal Evapotranspiration Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed

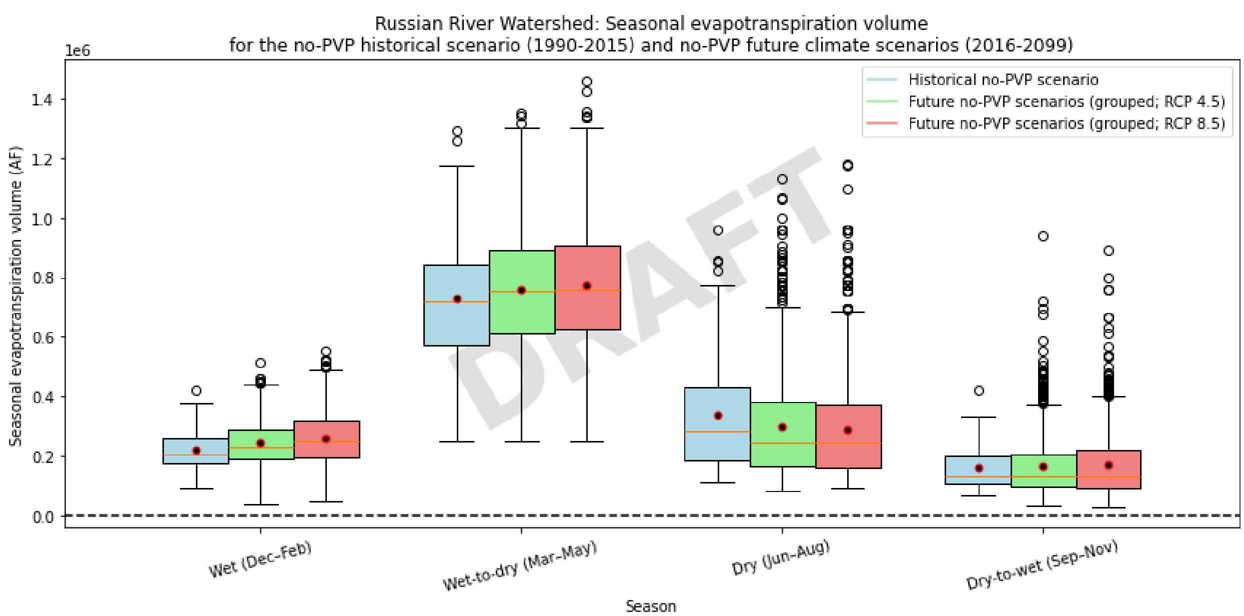


Figure 6-6. Seasonal Changes in Groundwater Storage Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed

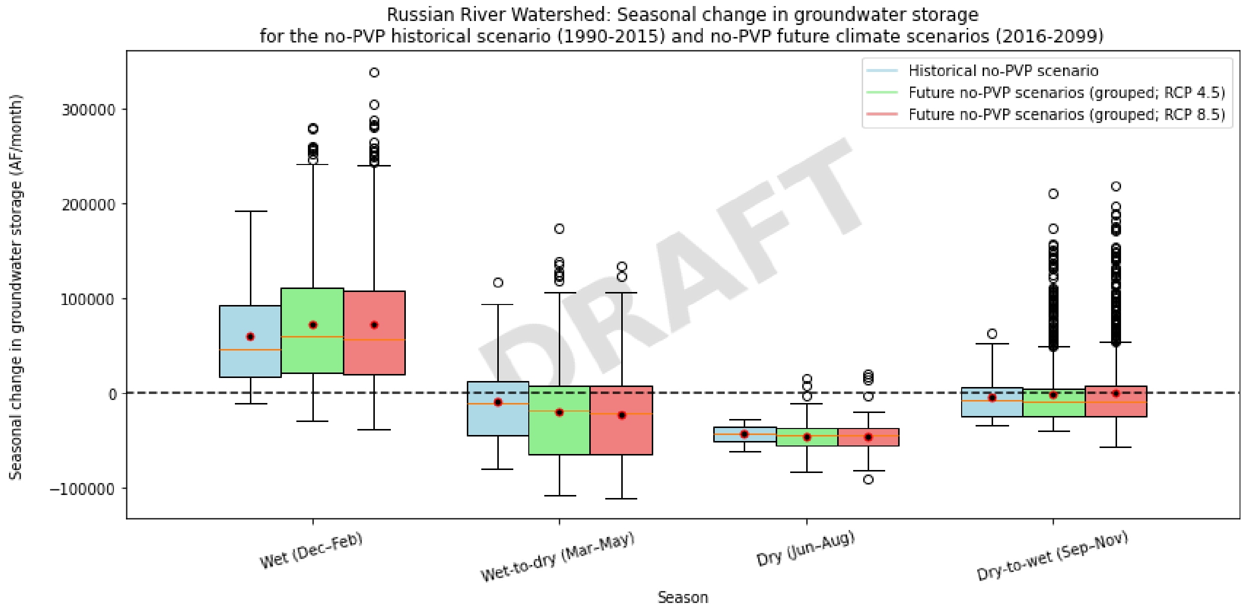
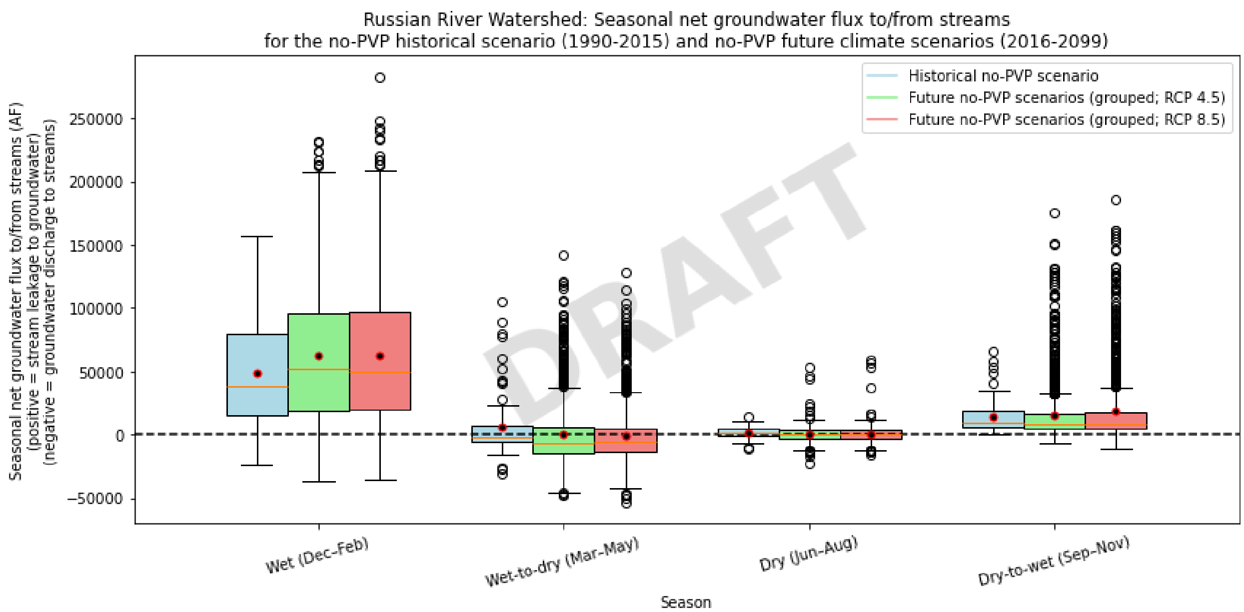


Figure 6-7. Seasonal Groundwater/Surface Water Exchange Volumes Under Historical and Future Climate Scenarios Across the Russian River Watershed



Future climate simulations show increases in the intensity and duration of multi-year droughts in the Russian River watershed. The ability of Lake Mendocino to make releases during the dry season has been shown to be sensitive to drought conditions and is exacerbated when interbasin transfers through the PVP cannot occur. Under the most extreme drought conditions, storage in Lake Mendocino may drop below dead pool storage, and no releases can be made to the Upper Russian River. Under these conditions, flows effectively drop to zero cfs until the confluence with Dry Creek where releases from Lake Sonoma (which is significantly more reliable) are able to sustain flow in Dry Creek and the Lower Russian River.

Future climate simulations with GSFLOW were used to assess impacts to groundwater resources under the combined pressure of (1) drought conditions and (2) in the absence of PVP transfers. Results show increased frequency of occurrence of Lake Mendocino reaching dead pool conditions where releases cannot be made as compared to a no PVP transfer scenario simulated under historical conditions. For the warmest and driest of the eight GCM forcings (HadGEM2-ES RCP 8.5), several intense multi-year droughts were simulated during the hypothetical 2015–2099 simulation period, including a 5-year drought (2019-2023) in which Lake Mendocino dropped below dead pool storage for a cumulative 524 days during a three-year period. This particular drought was selected to evaluate the impacts of drought and Lake Mendocino reliability on groundwater resources.

Under historical conditions, model results suggest that aquifer systems along the Russian River have little interannual groundwater storage variability, because seasonal groundwater storage losses accumulated during dry season are typically replenished to capacity each winter season. However, during drought conditions where Lake Mendocino drops below dead pool storage and releases cannot be made into the Upper Russian River (i.e., during the hypothetical 2019–2023 drought simulated with a the HadGEM2-ES RCP 8.5 GCM) significant year-over-year declines in groundwater storage are estimated for aquifer systems along the Upper Russian River (Figure 6-8). During the same period, only small year-over-year declines were estimated for aquifer systems along Dry Creek, where releases from Lake Sonoma sustained surface flows. This result highlights the vulnerability of Upper Russian River aquifer systems (e.g., the Ukiah, Sanel, and Alexander Valleys), which rely, in part, on stream leakage from the Russian River to modulate groundwater storage losses.

Figure 6-9 shows how surface-groundwater exchange shifts under dry-season conditions when releases can't be made into the Upper Russian River and surface flows effectively drop to zero cfs. Under these conditions, surface-groundwater exchange shifts from net positive to net negative stream-to-aquifer flux in the Upper River. When averaged over the entire 2015–2099 simulation period, June to October net surface-groundwater exchange volumes are reduced by roughly 3,000 ac-ft in years where Lake Mendocino drops below dead pool storage for more than one month and releases cannot be made into the Upper Russian River (Figure 6-10).

Figure 6-8. Simulated Cumulative Groundwater Storage Change for Aquifer Systems Along the Upper Russian River and Dry Creek During a Hypothetical 5-year Drought Period

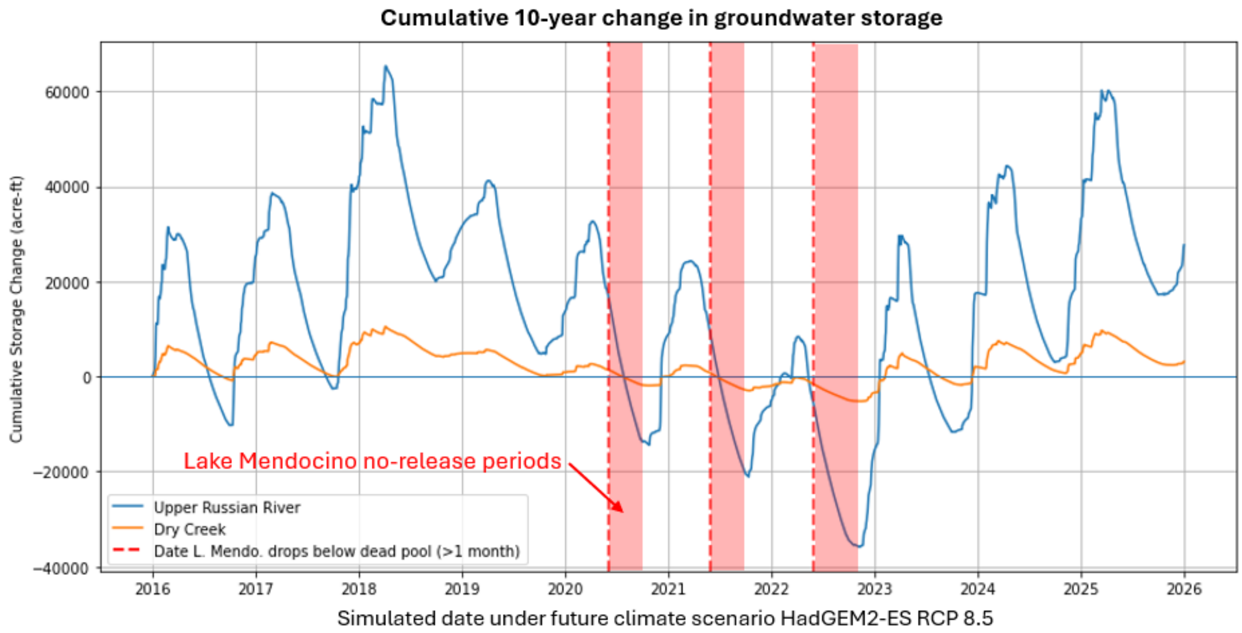


Figure 6-9. Simulated Net Surface-Groundwater Exchange for Aquifer Systems Along the Upper Russian River and Dry Creek During a Hypothetical 5-year Drought Period

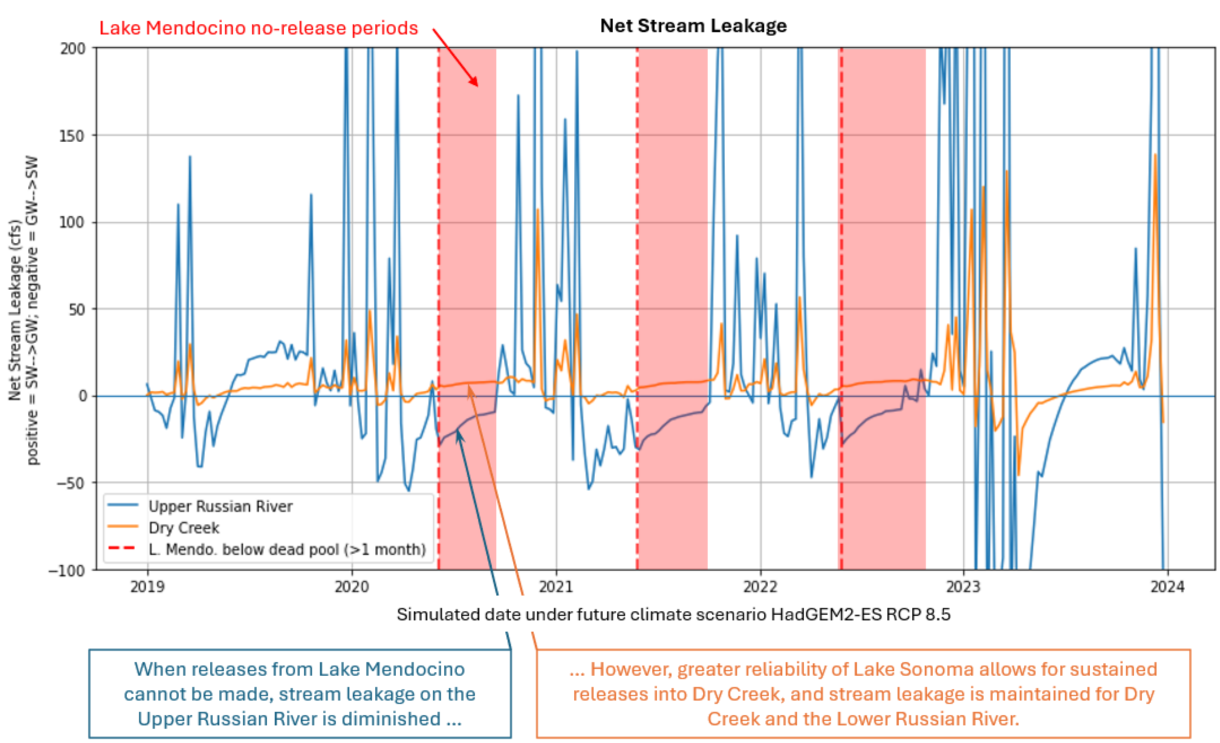
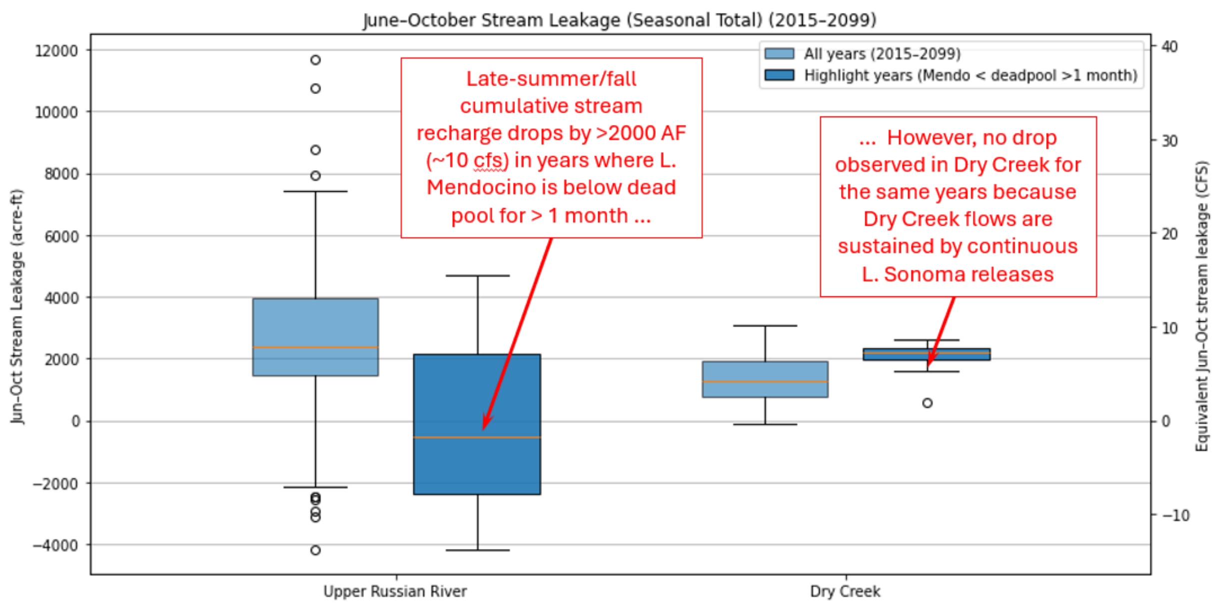


Figure 6-10. Simulated Cumulative Net June to October Surface-Groundwater Exchange for Aquifer Systems Along the Upper Russian River and Dry Creek, Partitioned by Years in Which Lake Mendocino Drops Below Dead Pool Storage



6.3.3 Groundwater Sustainability Plan Summaries

To support evaluation of groundwater supply vulnerability in the Study Area, summaries of groundwater conditions from the Ukiah Valley, Santa Rosa Plain, Petaluma Valley, and Sonoma Valley GSPs are provided in subsequent sections. It is important to note that GSAs are required to submit annual reports, periodic evaluations, and event amendments to the GSPs. The summaries provided herein are based on the GSPs that were published at the time of this study. As more data is collected, modeling tools are updated, and refinements are made to the understanding of historical and groundwater conditions in these subbasins, the groundwater conditions presented in the following sections are subject to change.

6.3.3.1 Ukiah Valley

As part of GSP development, groundwater budgets were developed for the Ukiah Valley Subbasin to evaluate groundwater conditions under historical, current, and projected conditions. Table 6-2 presents a summary of average annual groundwater budget terms for the historical, current, and projected conditions for the Ukiah Valley Subbasin. These groundwater budget terms represent all inflows and outflows from the Ukiah Valley Subbasin as simulated in UVIHM. Comparison of historical, current, and future baseline groundwater budget terms indicates that less recharge and stream loss to groundwater is expected under future baseline conditions as compared to historical and current conditions. The recharge and stream loss to groundwater terms are projected to further decrease under the Climate Change 2030 and Climate Change 2070 scenarios. Projected municipal groundwater pumping is expected to remain similar to current conditions, while agricultural groundwater pumping is projected to increase under projected conditions.

Table 6-2. Average Annual Groundwater Budget under Historical, Current, and Projected Conditions for the Ukiah Valley Subbasin

Water Budget Term	Historical (WY 1992 to 2018) (AFY)	Current (WY 2015 to 2019) (AFY)	Future Baseline (WY 2019 to 2070) (AFY)	Climate Change 2030 Scenario (WY 2019 to 2070) (AFY)	Climate Change 2070 Scenario (WY 2019 to 2070) (AFY)
Groundwater Boundary Inflow	5.3	5.3	5.3	5.3	5.3
Deep Percolation/ Recharge	5,422.8	6,254.2	5,123.1	1,949.4	4,100.1
Stream Loss to Groundwater	3,660.7	3,137.3	818.8	1,363.7	1,031.8
Inflow From Upper Watershed	4,611.7	4,588	4,512.2	4,404.4	4,183
Municipal Pumping	1,854.7	1,069.5	1,069	1,069	1,069
Agricultural Pumping	4,630	4,429	4,914	4,914	4,914
Stream Gain from Groundwater	3,632.2	4,463.7	4,889.5	2,152	3,758.9
Groundwater Outflow from Basin	1	1	1	1	1

6.3.3.2 Santa Rosa Plain

As part of GSP development, groundwater budgets were developed for the Santa Rosa Plain subbasin to evaluate groundwater conditions under historical, current, and future conditions. As part of the groundwater budgets, a summary of the annual average change in groundwater storage for each summary period was presented. Table 6-3 provides a summary of the annual average change in groundwater storage for historical, current, and projected conditions. On average, the historical and current periods both show a negative change in groundwater storage with a larger magnitude in the change in groundwater storage under current conditions. The larger magnitude under current conditions is a result of recent dry drought periods contributing to larger declines as compared to the historical period. Similarly, the projected annual average change in groundwater storage for the first 20-years of the future period (WYs 2021 to 2040) and the full 50-year future period (WYs 2021 to 2070) both show negative changes in groundwater storage, on average. As described in the Basin Setting Chapter[1] of the GSP, the first 30-years of the projected period experiences a moderate increase in groundwater storage, followed by a more rapid decline from WYs 2046 to 2070. Elevated average precipitation in the first 30 years of the projected simulation contribute to the larger increases in groundwater storage as compared to the increasing warm and dry climate of the last 20-years of the simulation. Additionally, a 25% increase in groundwater outflows occurs during the projected period resulting from an increase in groundwater pumping and groundwater ET. Increased temperatures and drier conditions contribute to higher

[1] https://santarosaplaingroundwater.org/wp-content/uploads/Section-03_BasinSetting_SRP_GSP_Final_508.pdf

agricultural demands, along with increased agricultural acreages. Greater soil-zone ET is simulated due to increased temperatures and drier conditions, however, the increased consumption of soil moisture only decreased soil moisture by approximately 8%.

Table 6-3. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Santa Rosa Plain Subbasin

Summary Period	Average Annual Change in Groundwater Storage (AFY)
Historical (WY 1976 to 2018)	-600
Current (WY 2012 to 2018)	-2,100
Projected (WY 2021 to 2040)	-200
Projected (WY 2021 to 2070)	-1,400

As part of GSP development, the GSP must outline Sustainable Management Criteria (SMCs) for various Sustainability Indicators in order to evaluate sustainability and undesirable results. For the chronic lowering of groundwater levels SMC, minimum groundwater level thresholds (referred to as minimum thresholds) at representative monitoring wells throughout the subbasin are defined to represent "the minimum threshold for chronic lowering of groundwater levels shall be the groundwater elevation indicating a depletion of supply at a given location that may lead to undesirable results." An evaluation of minimum threshold exceedances was performed to support evaluation of projects and management actions in the GSP[2]. For the Santa Rosa Plain, minimum threshold exceedances did occur in some wells during the later period of the future project (WYs 2041 to 2070). While minimum threshold exceedances at a single well may occur, this may not indicate undesirable results, as defined in the GSP, however, it does provide some indication that portions of the subbasin may be vulnerable to changes in groundwater conditions. To evaluate improvements to minimum threshold exceedances, the GSP evaluated the following projects and management actions:

- Reductions in crop consumptive use
- Reductions in rural domestic groundwater pumping
- Stormwater managed aquifer recharge
- Aquifer storage and recovery

6.3.3.3 Petaluma Valley

As part of GSP development, groundwater budgets were developed for the Petaluma Valley subbasin to evaluate groundwater conditions under historical, current, and future conditions. As part of the groundwater budgets, a summary of the annual average change in groundwater storage for each summary period was presented. Table 6-4 provides a summary of the annual average change in groundwater storage for historical, current, and projected conditions. On average, the historical period indicated little to no change in groundwater storage suggesting groundwater levels were relatively stable through the historical period. The current period shows a small negative change in groundwater storage indicating a small decline in groundwater storage. Similarly, the projected annual average change in groundwater storage shows a small decline in groundwater storage over the 50-year projection period. As described in the Basin Setting[3] chapter of the GSP, the first 30-years of the projected period experienced increased precipitation and temperatures, rising sea levels, and declining total groundwater pumping resulting in a

[2] https://santarosaplaingroundwater.org/wp-content/uploads/6-A-SRP_Simulation-fo-Projects_Mgmt-actions_Appendix-6-A_NOV_AR_ada.pdf

[3] https://petalumavalleygroundwater.org/wp-content/uploads/Section-03_Basin-Setting_PV_GSV_Final_508.pdf

relatively stable trend in groundwater storage. However, starting in 2050, below-average precipitation causes larger groundwater storage depletions due to reduce runoff and areal recharge in the subbasin.

Table 6-4. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Petaluma Valley Subbasin

Summary Period	Average Annual Change in Groundwater Storage (AFY)
Historical (WY 1969 through 2018)	0
Current (WY 2012 to 2018)	-100
Projected (WY 2021 through 2070)	-200

Similar to the Santa Rosa Plain GSP, exceedances of groundwater level minimum thresholds were evaluated alongside evaluation of projects and managements[4]. For the Petaluma Valley subbasin, only a single well showed exceedances of its minimum threshold which supports the analysis of the change in groundwater storage where water levels tended to be relatively stable throughout the projected future period. Projects and management actions analyzed are part of the GSP included:

- A 20% reduction in rural domestic pumping
- A 10% reduction in vineyard irrigation

6.3.3.4 Sonoma Valley

As part of GSP development, groundwater budgets were developed for the Sonoma Valley subbasin to evaluate groundwater conditions under historical, current, and future conditions. As part of the groundwater budgets, a summary of the annual average change in groundwater storage for each summary period was presented. Table 6-5 provides a summary of the annual average change in groundwater storage for historical, current, and projected conditions. On average, the historical and current periods both show a negative change in groundwater storage with a larger magnitude change in groundwater storage during the current period. In part, the larger change in groundwater storage during the current period is due to drier conditions during the current period. Similarly, the projected annual average change in groundwater storage shows negative change in groundwater storage over the 50-year projection period. As described in the Basin Setting[5] chapter of the GSP, average annual precipitation during the projection period is slightly higher than historic precipitation. As a result, certain groundwater inflow terms, such as mountain-front recharge, is larger under the projected period as compared to the historical period.

[4] https://petalumavalleygroundwater.org/wp-content/uploads/Section-06_Projects-and-Management-Actions_PV_GSP_FINAL_508.pdf

[5] https://sonomavalleygroundwater.org/wp-content/uploads/Section-03_Basin-Setting_SV_GSP_Final_508.pdf

Table 6-5. Average Annual Change in Groundwater Storage under Historical, Current, and Projected Conditions for the Sonoma Valley Subbasin

Summary Period	Average Annual Change in Groundwater Storage (AFY)
Historical (WY 1971 to 2018)	-300
Current (WY 2012 to 2018)	-900
Projected (WY 2021 to 2070)	-300

Similar to the Santa Rosa Plain and Petaluma Valley GSPs, exceedances of groundwater level minimum thresholds were evaluated alongside evaluation of projects and managements[6]. For the Sonoma Valley subbasin, tended to show more wells with minimum threshold exceedances as compared to the Santa Rosa Plain and Petaluma Valley subbasins. While the annual change in groundwater storage shows relatively small declines in groundwater storage, on average, over the historical, current, and projected periods, the evaluation of groundwater level minimum thresholds gives some indication of potential vulnerabilities within the Sonoma Valley subbasin. Projects and management actions analyzed are part of the GSP included:

- Reductions in vineyard consumptive use
- Reductions in rural domestic pumping
- Recycled water deliveries
- Stormwater managed aquifer recharge
- Aquifer storage and recovery

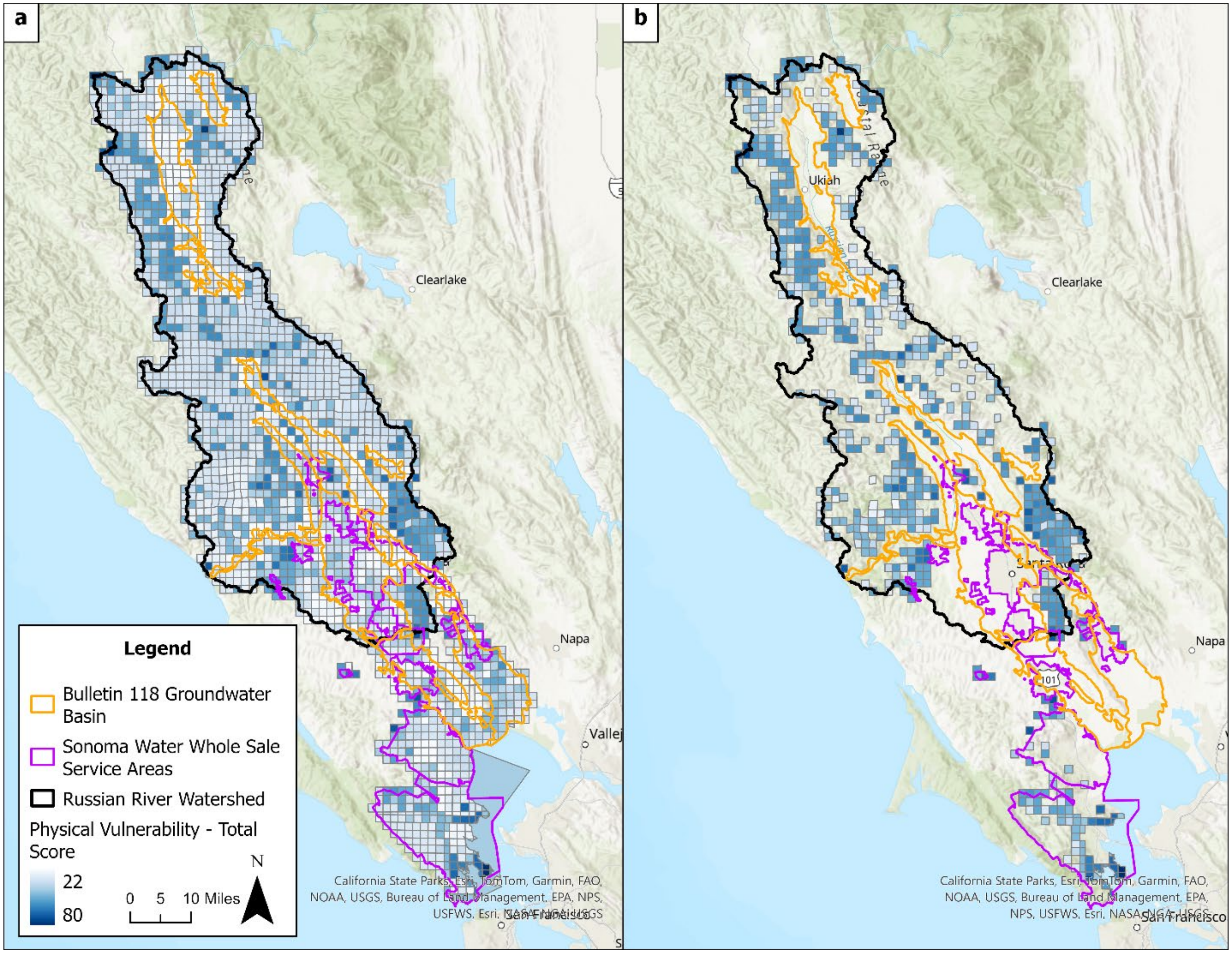
Additionally, the 2024 annual report for the Sonoma Valley Subbasin indicates the occurrence long-term declining trends in portions of the Sonoma Valley Subbasin. The annual report notes that the persistence and nature of these declines give indication that water levels are unable to rebound during a period of above-average precipitation due to groundwater pumping exceeding the rates of recharge to the deeper aquifer system (Sonoma Valley GSA 2025). As previously noted, the GSPs are continually collecting data and updating modeling tools to support further evaluation of groundwater conditions.

6.3.4 DWR's Water Shortage Vulnerability

To evaluate potential groundwater supply vulnerability in bedrock areas of the RRWRP study area, DWR's water shortage vulnerability dataset was processed to provide qualitative rankings of the total score for physical vulnerability. DWR's water shortage vulnerability dataset is a spatial dataset developed based around a 1-mile square grid to characterize physical vulnerabilities associated with state small water systems, rural communities, and domestic wells (DWR 2024). The publicly available spatial dataset was filtered down to the extent of the RRWRP study area (Figure 6-11a). For the purposes of supporting the qualitative water supply vulnerability analysis, the dataset was further filtered to only represent areas within the bedrock extents of the study area and to only include grid cells where the domestic well count is greater than one (Figure 6-11b). Vulnerabilities associated with the alluvial groundwater subbasins are evaluated based on the GSP summaries and GSFLOW model simulations. Therefore, DWR's water shortage vulnerability dataset is used to characterize groundwater supply vulnerabilities for user's not covered by the GSPs or GSFLOW.

[6] https://sonomavalleygroundwater.org/wp-content/uploads/Section-06_Projects-and-Management-Actions_SV_GSP_FINAL_508.pdf

Figure 6-11. (a) DWR's Water Shortage Physical Vulnerability Total Score Within the RRWRP Study Area. (b) DWR's Water Shortage Physical Vulnerability Total Score Filtered to Only Include Bedrock Areas and Areas with Domestic Well Users.



After limiting the extent of DWR's dataset to the RRWRP study area, and to only include the bedrock areas and areas where the domestic well count is greater than zero (Figure 6-11b), a percent exceedance plot of the total score was created to evaluate the distribution of the physical vulnerability total score in the study area (Figure 6-12). Using the exceedance plot, percent exceedance thresholds were selected to subdivide the distribution of physical vulnerabilities total scores into five distinct bins representing: Low, Moderate-Low, Moderate, Moderate-High, and High vulnerability. For example, total score values (y-axis on Figure 6-12) ranging from a value of 30 to 37 were assigned a Moderate-Low rank. Figure 6-13 shows the physical vulnerability rank throughout the RRWRP study area based on assigning the total score value one of the five vulnerability ranks based on where the total score value falls along the exceedance plot. In general, the areas where users are reliant on groundwater and reside in bedrock areas of the RRWRP study area are limited. However, in some cases there are broader extents of Moderate and Moderate-High physical vulnerability and only sparse distributions of areas with High physical vulnerability.

Figure 6-12. Exceedance Plot of Physical Vulnerability Total Score used to Assign Qualitative Vulnerability Ranking's for the Areas Dependent on Bedrock Groundwater Supplies

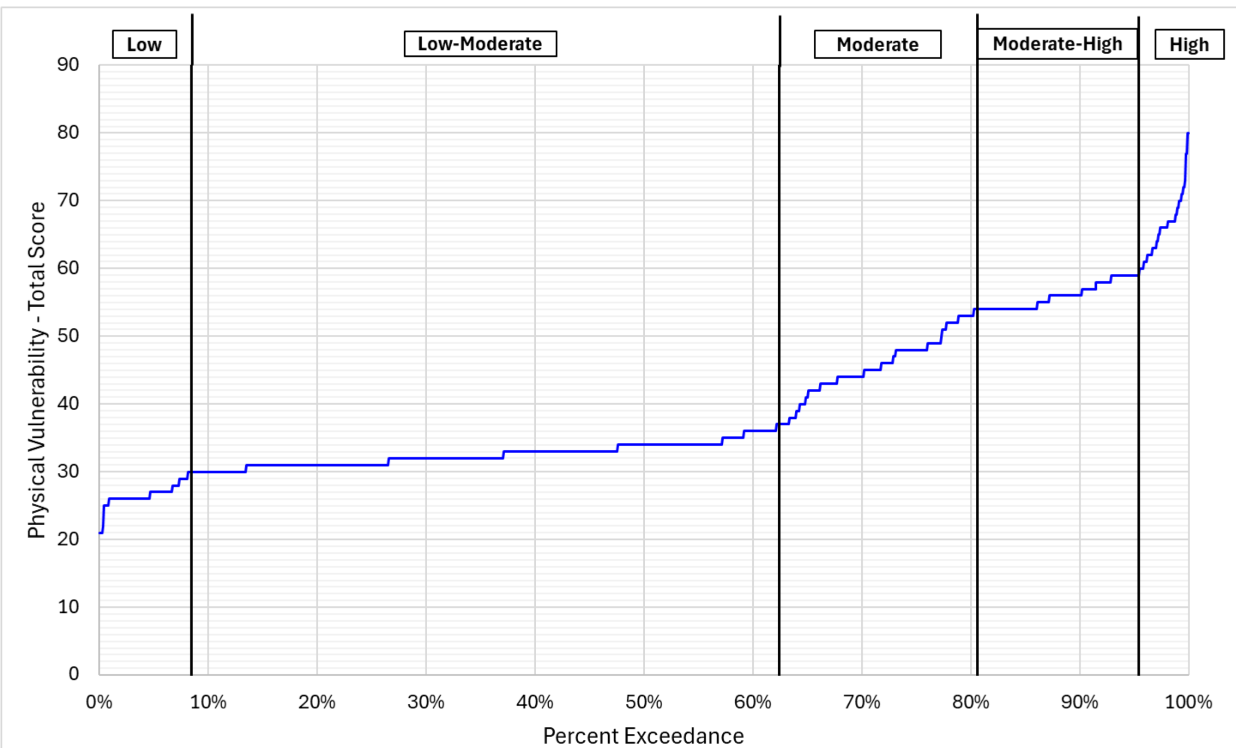
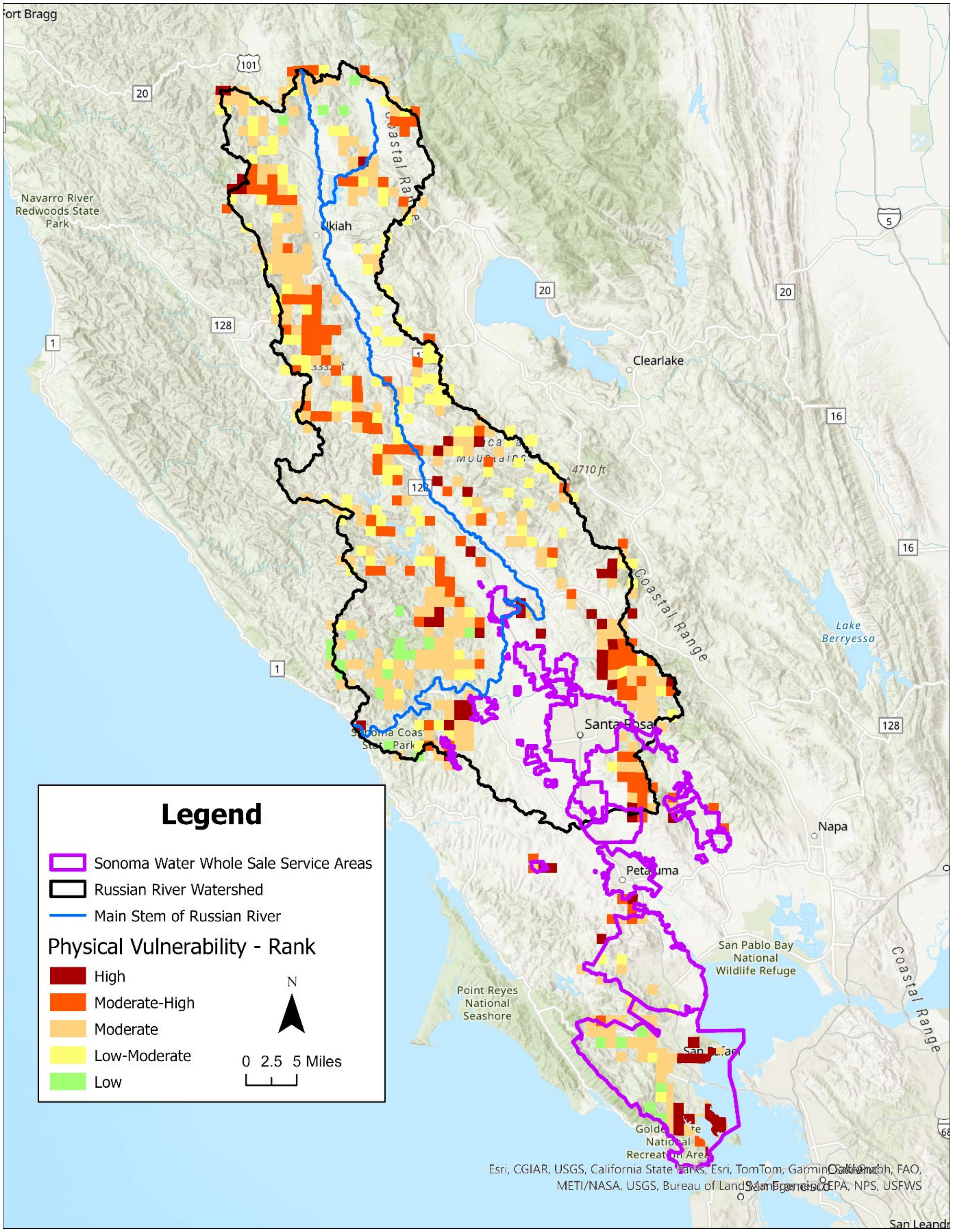


Figure 6-13. Map of Ranked Physical Vulnerability for Bedrock Areas of RRWRP Study Area



6.4 Summary

Results from the RRIHM modeling study show the close interconnection between surface water and the alluvial aquifer systems underlying and adjacent to the Russian River within the watershed. Under historical conditions, model results suggest that aquifer systems along the Russian River have little interannual groundwater storage variability because seasonal groundwater storage losses accumulated during the dry season are typically replenished to capacity each winter season. However, seasonal declines in groundwater storage can result in depletions in streamflow along the Russian River. In aggregate, net surface-groundwater exchange was from streams to aquifers, with 5 to12% of total streamflow contributing to stream depletion to groundwater. Model results also suggest that stream depletion by groundwater pumping is a significant component of the water budget for the alluvial aquifer systems along the Russian River, with an estimated 19% of pumped groundwater originating from stream depletion, with particular" hot spots" for streamflow depletion occurring in alluvial aquifers in portions of the Ukiah Valley, Alexander Valley, and the Lower River. These results demonstrate the close interdependence of surface water and groundwater in the watershed and highlight their shared vulnerabilities.

Future climate change simulations of the Russian River watershed show both greater seasonal and interannual hydrologic variability, with droughts occurring more frequently and with greater intensity. Given the close interconnection between the Russian River and the alluvial aquifer systems along the river's corridor, groundwater response follows these shifts, generally amplifying seasonal swings in storage, with greater increases in storage during the wet season and greater reductions in storage in wet-to-dry and dry seasons. Under the combined future stressors of (1) intensified drought conditions and (2) potential cessation of interbasin transfers of Eel River water, Lake Mendocino reliability is potentially reduced. GSFLOW simulates a significant increase in occurrences where Lake Mendocino drops below dead pool storage and releases cannot be made into the Upper Russian River. Under these conditions, groundwater replenishment from stream depletion is effectively cut off, amplifying dry-season groundwater storage declines and contributing to year-over-year storage declines in aquifer systems along the Upper Russian River. For aquifer systems along Dry Creek, where releases from the significantly more reliable Lake Sonoma sustain year-around flows, large year-over-year groundwater storage declines do not occur during the same simulated drought periods, highlighting the importance of surface water replenishment of groundwater in these systems.

Based on the evaluations performed to support GSP development, changes in groundwater storage are sensitive to climate and hydrologic conditions where increases in groundwater storage occur during the wet periods when recharge from precipitation and streamflow tends to be higher. Decreases in groundwater storage tend to occur during drier periods when recharge from precipitation and streamflow tends to be lower and when groundwater pumping to meet agricultural demands is higher due to increased temperatures. In summary, groundwater inflows are generally larger during wet years and smaller during drier years which has a larger influence on the change in groundwater storage over time. Additionally, increased temperature and decreased precipitation cause an increase in agricultural demand which can lead to increased groundwater pumping causing larger declines in groundwater storage during the drier periods. For the Petaluma Valley and Sonoma Valley, which are adjacent to San Pablo Bay, projected sea level rise assumptions were incorporated in the groundwater modeling used to support development of the GSP. Projected groundwater budgets for the Petaluma Valley and Sonoma Valley both suggest that inflow from the tidally influence Petaluma River and San Pablo Bay are projected to increase due to impacts of sea level rise. Increased inflow from San Pablo Bay could cause seawater to advance inland, however, available data does not indicate increasing trends in salinity at wells near San Pablo Bay.

The Ukiah Valley, Santa Rosa Plain, Petaluma Valley, and Sonoma Valley Subbasin GSPs have indicated other factors that can have an influence on groundwater storage conditions, such factors are as follows:

- Implementing demand reduction strategies to minimize reliance on groundwater pumping to meet agricultural and rural domestic demands.
  - Demand reduction strategies could include irrigation efficiency improvements and conversion of irrigated land uses to non-irrigated land uses, such as converting sports fields from irrigated turf to artificial grass surfaces
- Utilizing recycled water deliveries to offset demands can positively impact groundwater conditions by reducing the reliance on groundwater pumping.
- In wet years, when surface water supplies are abundant, opportunities for managed aquifer recharge can positively impact groundwater conditions by increasing groundwater storage for later use in the drier months and years when surface water supplies are less abundant.

7. Flood Management Vulnerability Assessment

7.1 Purpose

This study applied an integrated hydrologic–operations–hydraulic modeling suite to assess current and future flood management vulnerability under climate change conditions in the Russian River and Santa Rosa Creek watersheds. The framework links watershed runoff generation via the HEC HMS, reservoir flood control operations via HEC ResSim, and riverine and floodplain hydraulics via HEC RAS to provide a consistent, end-to-end assessment of flood behavior from storm precipitation through reservoir operations and ultimately downstream inundation. Historical precipitation patterns were used as the baseline hydrologic input and were systematically perturbed using climate change scaling factors developed for extreme precipitation events to represent potential future flood conditions.

The assessment focused on two decision-relevant questions:

1. How might flood magnitudes and inundation patterns in the Russian River and Santa Rosa Creek systems change under projected climate conditions? Simulations evaluated changes in the magnitude, timing, duration, and spatial extent of flood events using climate-adjusted precipitation inputs across recurrence intervals from the 2- to the 100-year event.

2. How can spatially explicit flood risk information under future climate scenarios inform adaptation strategy development? The integrated modeling framework can be used to:
    - Identify neighborhoods most vulnerable to increased flooding under projected climate conditions.
    - Identify risks to evacuation routes and quantify depths of flooding on critical roadways.
    - Estimate travel times of flood waves and overland flow through urbanized areas to support emergency response planning.
    - Identify areas of likely future flooding where land use planning, zoning, and development decisions should be informed by changing flood risk.

The framework supports multiple planning and policy needs including climate change vulnerability assessments that quantify sensitivity of hydrologic response, operations, and floodplain exposure to altered precipitation regimes. The integrated modeling analysis also supports long-term adaptation and capital planning, providing hydraulically explicit outputs for project scoping, benefit–cost screening, and prioritization of structural and non-structural measures.

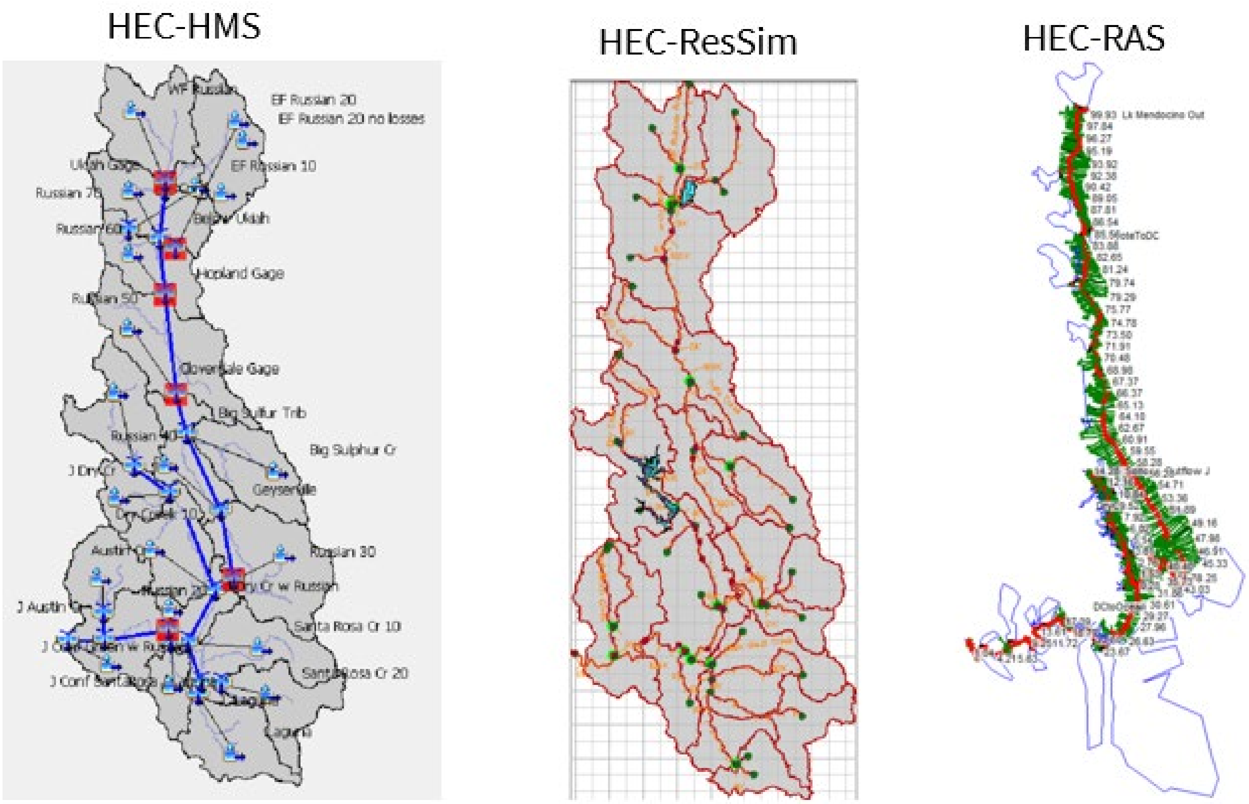
Geographic focus includes (a) the Russian River mainstem and contributing tributaries (with both HMS to ResSim to RAS and direct HMS to RAS pathways where appropriate), and (b) the Santa Rosa Creek watershed as a detailed sub-basin case where reservoir operations modeling is not required (HMS to RAS only). Detailed coverage of tributaries is limited to Dry Creek, although the lower portions of larger tributaries are included in the flood model mapping where they meet the Russian River. Focus areas were primarily constrained by those contained in existing flood models.

7.2 Methodology

The study employs a linked workflow that traces storm precipitation through watershed response, regulated system operations, and floodplain hydraulics whose schematics for the Russian River system are shown in Figure 7-1:

- HEC-HMS simulates climate-driven watershed runoff and unimpaired flows throughout the basin with local knowledge of precipitation patterns, soil characteristics affecting infiltration and runoff, and watershed slope.
- HEC-ResSim simulates reservoir flood control operations and regulated outflows for Lake Mendocino and Lake Sonoma using rule-based logic. For unregulated tributaries and for the Santa Rosa Creek system, flows from HEC-HMS are coupled directly to HEC-RAS (i.e., no operations model).
- HEC-RAS simulates river hydraulics, including unsteady 1D channel routing, floodplain inundation, depths, velocities, and arrival times.

Figure 7-1. Model Schematics for Russian River HEC-HMS, HEC-ResSim, and HEC-RAS



Projected impacts of climate change are represented via adjusted precipitation inputs to HEC-HMS. Extreme precipitation event perturbation factors derived from daily LOCA2-Hybrid downscaled data are applied to historical design storm hyetographs at the 2-, 5-, 10-, 25-, 50-, and 100-year recurrence intervals (ESA 2024), preserving storm temporal patterns while modifying event totals and intensities consistent with climate projections. The resulting HMS hydrographs propagate through ResSim (where applicable) and RAS, enabling consistent comparison of historical and climate-adjusted conditions at the operations and floodplain scales.

The study evaluated design storm events corresponding to the 2-, 5-, 10-, 25-, 50-, and 100-year return periods. For the Russian River model, representative historical high-flow events were selected based on observed event dates and peak flows at the Russian River at Hacienda Bridge near Guerneville (U.S. Geological Service gage 11467000). Peak flow events in 2002, 1982, 1997, 2006, 1995, and 1986 were chosen as closely representative of the 2-, 5-, 10-, 25-, 50-, and 100-year return period events as determined by a flow frequency distribution (Bulletin 17B) analysis of historic flows at Hacienda Bridge.

Historic hourly precipitation records were used to construct a six-year synthetic rainfall record that included the six return interval events in order from smallest to largest, using the full year of historical rainfall for each event. This approach allowed for a single 6-year long HMS simulation.

In Santa Rosa, the study estimated precipitation using target return interval flood events instead of historic events. The flow frequency analysis used modeled results from Santa Rosa Creek at the Pierson Street gage (Pierson Street, United States Geological Service gage 11466200) to quantify return interval flows summarized in Table 7-1. Since the return periods utilized in this study are based on flows at the Hacienda Bridge and Pierson Street locations, they may not correspond to the same recurrence intervals at other locations within the watersheds. The elongated shape of the Russian River watershed has a strong influence on the local return interval magnitude of a given storm, as a high rainfall event in the upper watershed might not coincide with a high rainfall event in the lower watershed. A 50-year event in Guerneville could be a 25 or 100-year event in Ukiah and Cloverdale.

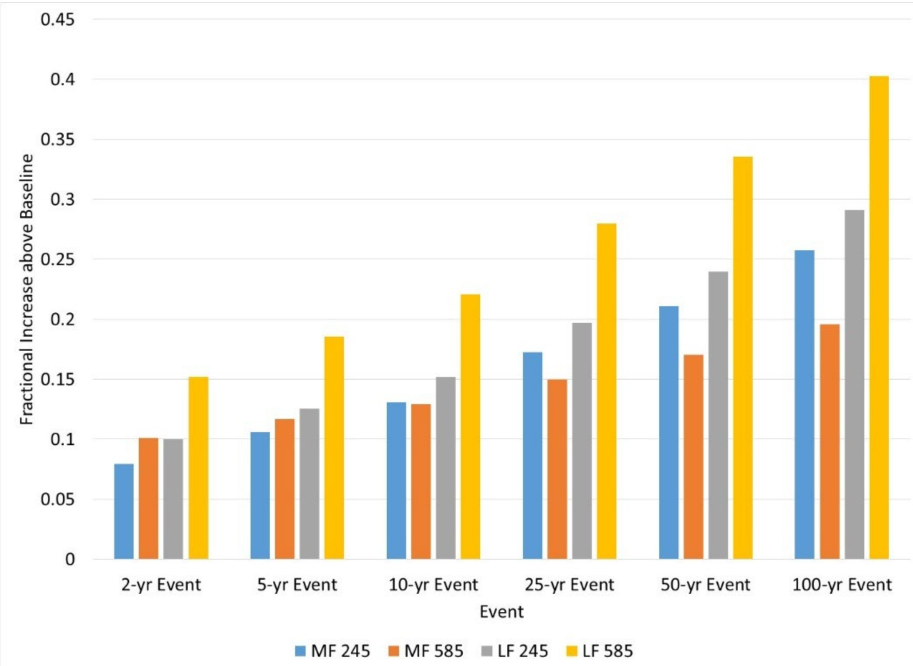
Table 7-1. Historical Flood Events and Peak Flows

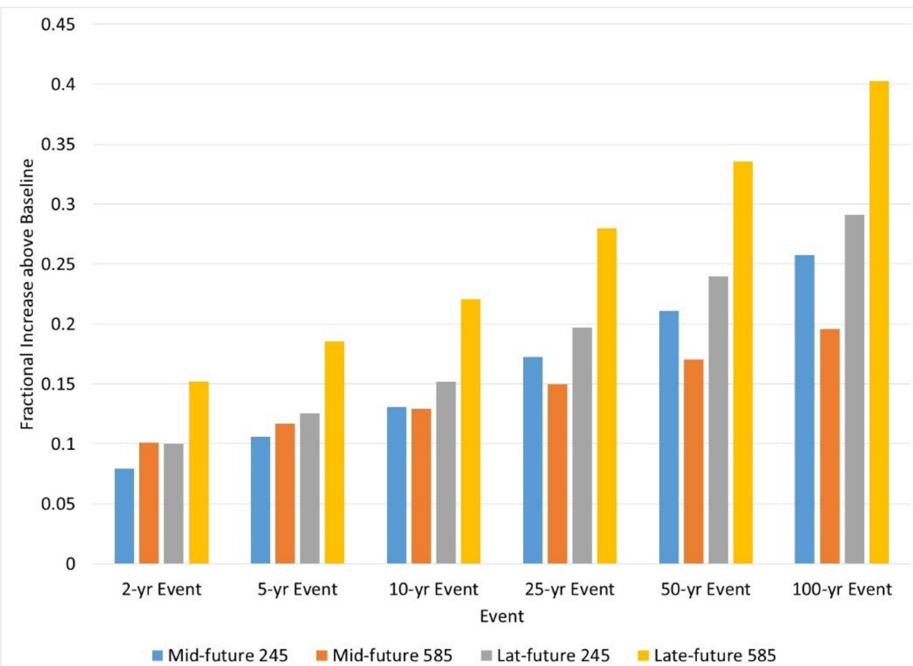
Return Period (year)	Event Date	Peak Flow (cfs)	Peak Stage (Gage Height, feet)*
Russian River at Hacienda Bridge Near Guerneville (USGS 11467000)			
100	2/18/1986	102,000	48.56
50	1/9/1995	93,900	48.01
25	1/1/2006	86,000	44.26
10	1/1/1997	82,100	44.99
5	12/2/1981	67,200	40.09
2	1/3/2002	44,000	33.43
Santa Rosa Creek at Santa Rosa (Pierson Street, USGS 11466200)			
100	N/A	10,170	145.1
50	N/A	9,800	144.7
25	N/A	8,570	143.7
10	N/A	6,780	141.8

* Hacienda Bridge Gage Height is 22.33 feet above NAVD88, Santa Rosa Creek elevations are feet NAVD.

Future climate change conditions were evaluated for two planning horizons, Mid-Future and Late-Future, under two SSP trajectories, SSP2-4.5 to capture an intermediate emissions pathway and SSP5-8.5 representing a high emissions pathway. This provides a bookend of likely results for the full range of future climate change conditions used in other facets of the vulnerability analysis. For each return period and climate scenario, the corresponding precipitation scaling factors for the 24-hour storm are summarized in Figure 7-2. These scaling factors were developed from estimates for future rainfall based on LOCA2-Hybrid downscaled CMIP6 GCMs developed by Environmental Science Associates (ESA) on behalf of Sonoma Water (ESA 2024). Scale factors were averaged from rasters covering the Russian River watershed into 19 sub-watersheds for the Russian River HMS model, and applied to each individual sub-basin in HMS. Figure 7-2 presents the watershed-averaged fractional increase in 24-hour precipitation for the four climate scenarios and six storm magnitudes. For the Santa Rosa Creek HMS model, scaling factors from the same source were applied to each of 76 individual subbasins for the baseline and future climate simulations.

Figure 7-2. Increase in Precipitation in the Russian River Watershed





7.2.1 Russian River HEC-HMS (Hydrologic Model)

The Russian River HEC-HMS model (USACE, 2018) provides the primary estimate of natural (unimpaired) tributary inflows across the basin. HMS outputs serve as hydrologic inputs to (a) HEC-ResSim for reservoir operations and (b) HEC-RAS for downstream hydraulic simulations. The model supports both historical and climate-adjusted storm simulations.

Runoff generation uses the Clark Unit Hydrograph to transform precipitation to direct runoff, coupled with Soil Moisture Accounting and Deficit & Constant methods to represent infiltration and losses across varying wetness conditions. Baseflow is simulated with linear reservoir methods. Evapotranspiration is represented using Penman-Monteith. Channel routing is performed with Muskingum-Cunge and Modified Puls where appropriate, providing stability and mass conservation for routed hydrographs.

Key inputs include the following:

- Precipitation: Hourly and daily data from 28 gages, spatially interpolated using GageInterp with PRISM-based bias grids; adjusted using extreme precipitation perturbation factors for 2- through 100-year events.
- Climate variables: Solar radiation, temperature, humidity, and wind sourced from U.S. Air Force and Automated Surface Observing System stations to support evapotranspiration and energy balance components.
- Physiography: Soils from USDA Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO), land use/land cover (USGS), and terrain from digital elevation models (DEM) to parameterize losses, routing, and drainage characteristics.

Key outputs utilized from the hydrology model include hourly unimpaired flow hydrographs at subbasin outlets for direct use by the Russian River HEC-ResSim (regulated segments) and HEC-RAS (unregulated reaches). The domain includes 42 subbasins covering roughly 1,485 square miles at an hourly time step. The historical simulation includes 6 years discussed previously to bracket flood risk analysis conditions.

The model does not include snowmelt processes, employs simplified channel geometry in select reaches, and does not explicitly resolve subsurface or localized (compound) flooding dynamics. These limitations are addressed by calibration, sensitivity checking, and reliance on HEC-RAS for floodplain detail. The HMS model has not been calibrated for extreme flood events such as the 100 year event that serves as the basis for quantification of future climate impacts.

7.2.2 Santa Rosa Creek HEC-HMS (Hydrologic Model)

The Santa Rosa Creek HMS is a local-scale hydrologic model developed to support flood risk analysis, Federal Emergency Management Agency (FEMA) Physical Map Revision studies, and NRCS watershed planning. Its outputs supply boundary inflows to the Santa Rosa Creek HEC-RAS model for event-based inundation mapping under both historical and climate-adjusted storms.

Direct runoff is represented with the Snyder Unit Hydrograph, with watershed losses modeled using the NRCS Curve Number method. Channel routing applies Muskingum-Cunge consistent with the Russian River HMS routing approach.

Key inputs include:

- Precipitation: Hourly and daily data at 19 gages from California Irrigation Management Information System (CIMIS) and California Data Exchange Center databases.
- Physiography: 2019 NLCD for land cover, NRCS SSURGO for soils, and DEM/LiDAR (2013) for drainage and routing.

Key outputs utilized for this effort include hourly hydrographs at subbasin outlets used as inflow boundary conditions for the Santa Rosa Creek HEC-RAS model. The model comprises 78 subbasins covering 77.7 square miles. Simulations use hourly time steps for 24-hour design storms at the 2-, 5-, 10-, 25-, 50-, and 100-year return periods. As with the Russian River HMS model, snowmelt is not represented. Select reaches use simplified channel geometry, and subsurface/compound flood interactions are not explicitly modeled.

7.2.3 Russian River HEC-ResSim (Reservoir Operations Model)

HEC-ResSim simulates flood control operations at Lake Mendocino and Lake Sonoma, translating HEC-HMS inflows into regulated outflows for downstream hydraulic modeling. The configuration supports both real-time forecasting workflows and planning-level scenario analysis. In the Russian River context, the Sonoma Water operational HEC-ResSim model described in Section 5 emphasizes long-term, planning-oriented simulations of water supply, environmental flows, and multi-objective reservoir management, whereas the USACE Flood Management HEC-ResSim model applied in the Flood Management context is designed for real-time, event-based forecasting and flood control decision-support with higher spatial resolution and Corps Water Management System integration. The model uses rule-based operation logic, applying flood control diagrams, storage targets, and release constraints. It represents operational decision-making under flood conditions, including spillway behavior and release ramping where applicable. The operations logic includes a simplified assumption of FIRO at Lake Mendocino where the total defined FIRO pool can be utilized for water supply storage without any flood control releases. These FIRO operations allow storage of 80,050 acre-feet between November 1st and February 14, an increase of 11,650 acre-feet over standard operational storage levels.

Key inputs to the reservoir operations model include the following:

- Hourly inflows from HEC-HMS (tributary and local inflows)
- Daily average inflows from the Eel River (via the Sonoma DSM described in Attachment C-1)
- Reservoir geometry and outflow characteristics (elevation–storage–area curves, outlet/spillway flow rating curves)
- Flood control and operational rules (seasonal diagrams of allowable storage, downstream constraints on reservoir releases)

The ResSim network covers the basin from upstream of Lake Mendocino and Lake Sonoma to the Russian River mouth, with 33 junctions representing key river and tributary nodes which allow incorporation of downstream river flows in reservoir operations so that reservoir releases do not exacerbate flooding during large flow events. Simulations use hourly time steps. Key outputs from the ResSim model include reservoir pool outflow hydrographs for mainstem boundary conditions and elevations/volumes for performance evaluation. Time series of reservoir releases are directly applied to the HEC-RAS hydraulic model.

To remain tractable for planning studies, the representation simplifies real-time operational complexity (e.g., external constraints, communication lags, and discretionary operator actions).

7.2.4 Russian River HEC-RAS (Hydraulic Model)

The Russian River HEC-RAS model (USACE, 2018) simulates unsteady 1D hydraulics to quantify stages, flood depths, velocities, arrival times, and inundation extents under both historical and climate-adjusted events. The Russian River model solves unsteady flow in 1D channel networks coupled to 1D floodplain storage areas representing floodplain areas just off the main stem of the river associated with tributaries. It computes water-surface profiles, stage–discharge relationships, and estimates velocity variations across the width of the flow field. Hydraulic structures (bridges, culverts) and ineffective flow areas are included to constrain conveyance and storage. The hydraulic model interpolated local water surface elevations onto the terrain model to develop inundation maps which can be exported as shapefiles for use in GIS analysis.

Key inputs to the hydraulic model include:

- Geometry: River channel cross sections and structures derived from USGS DEM and structural as-built plans.
- Boundary conditions: Flow hydrographs from HEC-HMS and regulated releases from HEC-ResSim.
- Roughness and coefficients: Spatially distributed Manning's n and structure parameters.

Key outputs from the hydraulic model utilized applied in the vulnerability analysis include:

- Time series of flow and stage at control points.
- Gridded maps of flood depth, depth–velocity, and arrival time.
- Inundation extents suitable for overlay with exposure and consequence datasets.

The 1D hydraulic model covers 100 miles of the Russian River, from just downstream of Lake Mendocino to the ocean. The terrain used to set model geometry originated from a USGS 10-meter DEM and used surveys and previous models for the low-flow channel. Simulated time steps were set at one minute. The model is calibrated to the historical flood event from December 2005 through January 2006.

Uncertain or limited bathymetry required manual channel adjustments in places. Performance is reduced for smaller flow events where local roughness and minor controls dominate. Uniform roughness assumptions in complex vegetated corridors and reliance on downscaled precipitation for climate perturbations introduce additional uncertainty. The Russian River HEC-RAS model has not been calibrated for large-scale flood events. Model calibration should be included in future studies before adaptation measures are developed and implemented.

7.2.5 Santa Rosa Creek HEC-RAS (Hydraulic Model)

The Santa Rosa Creek HEC-RAS model provides local hydraulic detail for climate-adjusted flood risk assessment in the Santa Rosa Creek watershed, driven by HEC-HMS inflows. Configuration mirrors the Russian River RAS approach, with unsteady 1D/2D hydraulics, floodplain exchange, and structure representation. The Santa Rosa Creek model does include extensive 2D overland flow areas unlike the Russian River model. High-resolution geometry is derived from 2013 LiDAR and 2006 field surveys. Outputs include time series at control sections and gridded depth/velocity/arrival time rasters for consequence analysis. The model spans the full Santa Rosa Creek watershed and floodplain. Simulations are event-based, using hourly or sub-hourly steps for the 24-hour 10-, 25-, and 100-year events, and are calibrated to historical floods in 2005, 2010, and 2019.

Limitations are generally consistent with the Russian River RAS model (geometry and roughness uncertainty, limited bathymetry). Gage coverage is sparse in some tributaries, increasing reliance on regionalization and calibration transfer.

7.3 Results

The primary results from the hydraulic model that serve as the basis for the vulnerability analysis are floodplain inundation maps for current and future design storms. Results of the Baseline 100-year flood simulation were compared to FEMA's National Flood Hazard Layer maps (FEMA 2026). In general, there is good agreement between the predicted flood extents with the FEMA maps. There are exceptions, particularly where the river canyon widens and includes more extensive floodplains. The FEMA map has a tendency in some areas to overestimate the width of the floodplain relative to the HEC-RAS model, particularly in the northern half of the system. Since the terrain data used in the HEC-RAS model is generally more recent, it is assumed that the detailed 1D model results generate accurate flood in the northern half of the system. FEMA maps in the Guerneville area have been recently updated and generally match well with the HEC-RAS model results.

Increases in peak flows through the system are significant under future climate scenarios, with peak flows at Hacienda Bridge projected to increase from 73,400 cfs in baseline conditions to 94,400 cfs under Mid-Future conditions and 118,900 cfs under Late-Future conditions for the 100-year precipitation event based on the 1986 precipitation dataset. These increases in modeled flow translate to peak stage increases of 3.8 and 4.7 feet near Guerneville for the 100-year flood.

Inundation maps were used to quantify impacts to both residences and population in the watershed through a GIS analysis. Sonoma Water provided a georeferenced database of all structures in the county, with classification information detailing residences, outbuilding, commercial, and other structures. FEMA's LandScan database provided population estimates on a raster grid covering the watershed. These two databases were used along with shape files of estimated inundation extents to quantify the number of structures, residences, and people within various floodplains, both under present and future climate conditions.

The elongated nature of the watershed and the relatively narrow floodplain complicate presentation of results for the full watershed, but representative samples are provided in the following figures. Figure 7-3 presents an example of structures in Geyserville at risk of flooding under future climate. Figure 7-3 shows three polygons of increasingly larger width indicating increased flows under baseline and two future climate scenarios. Multiple structures on the west bank are projected to be impacted by flooding under the late-future scenario despite being currently out of the 100-year floodplain. Similar examples of structures at risk under future climate are presented in Figure 7-4 (Guerneville), Figure 7-5 (Healdsburg), and Figure 7-6 (Cloverdale).

Figure 7-7 presents inundation maps for Santa Rosa, focusing on the area north of Santa Rosa Creek and East of Highway 101. The light green band reflects estimates of flooding under current climate at the 100-year return interval event. With increased precipitation by Mid-Future (585 scenario), flooding extends out to areas covered in yellow. With Late-Future precipitation (LF-585), flooding extends to areas shown in red. Figure 7-8 presents a similar image for the area west of Highway 101 and north of Highway 12.

Figure 7-9 and Figure 7-10 reflect projected changes to flood impacts on residential structures in the Russian River and Santa Rosa Creek watersheds. Results are presented as the percent increase in the number of residential structures flooded from the Baseline simulation to projected future simulations for the 25-, 50-, and 100-year events. Future scenarios considered include Mid-Future and Late-Future under high emissions (SSP5-8.5) climate scenarios. For the 25-year flood event, model results indicate that approximately 20% more structures in the Russian River watershed will flood under the Mid-Future scenario and 47% more in the Late-Future scenarios. For the 100-year flood event, increases could reach 24% by Mid-Future and 97% by Late-Future. The majority of impacted residences are in the lower Russian River, where homes are situated nearer to the river.

Figure 7-3. Sample of Structures at Risk near Geyserville with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event)

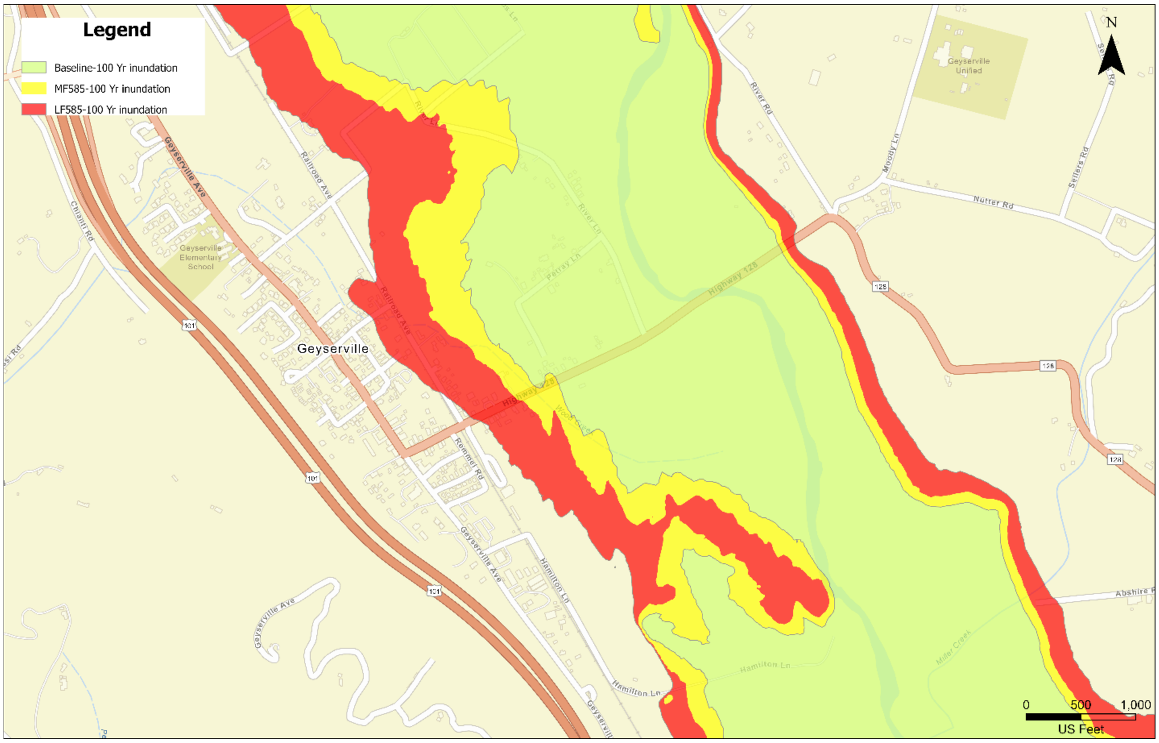


Figure 7-4. Sample of Structures at Risk near Guerneville with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event)

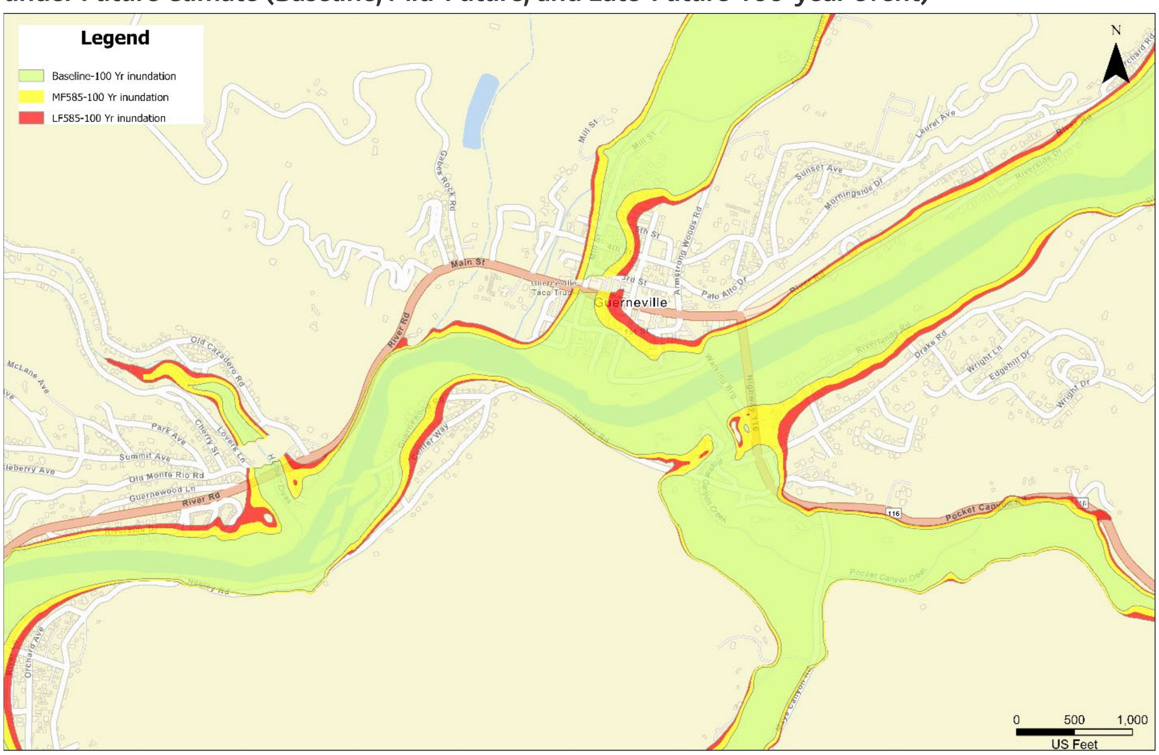


Figure 7-5. Sample of Structures at Risk near Healdsburg with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event)

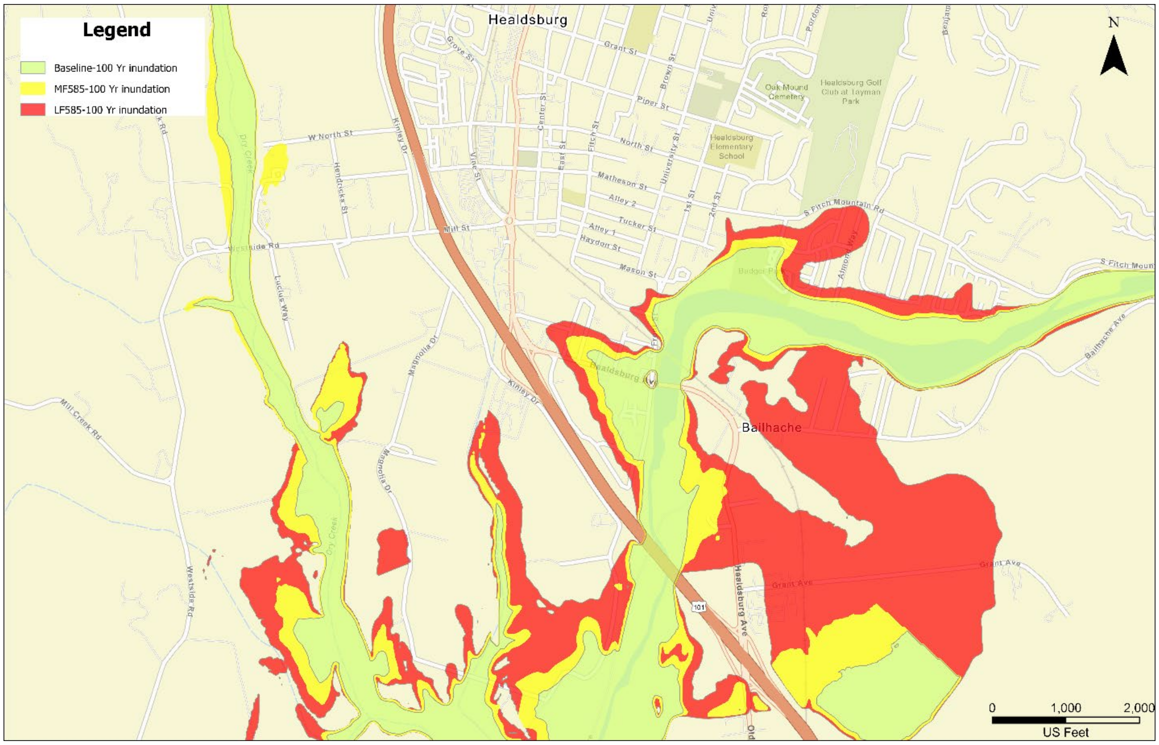


Figure 7-6. Sample of Structures at Risk near Cloverdale with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event)

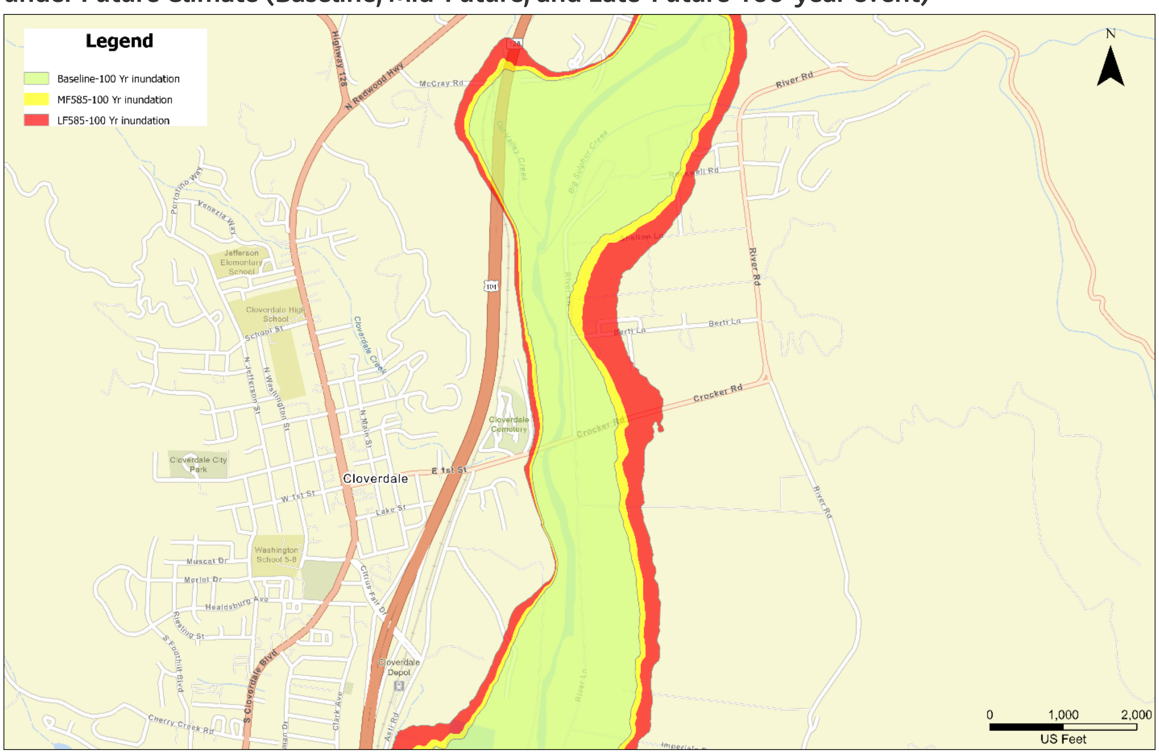


Figure 7-7. Sample of Structures at Risk in Santa Rosa (east of 101) with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event [585])

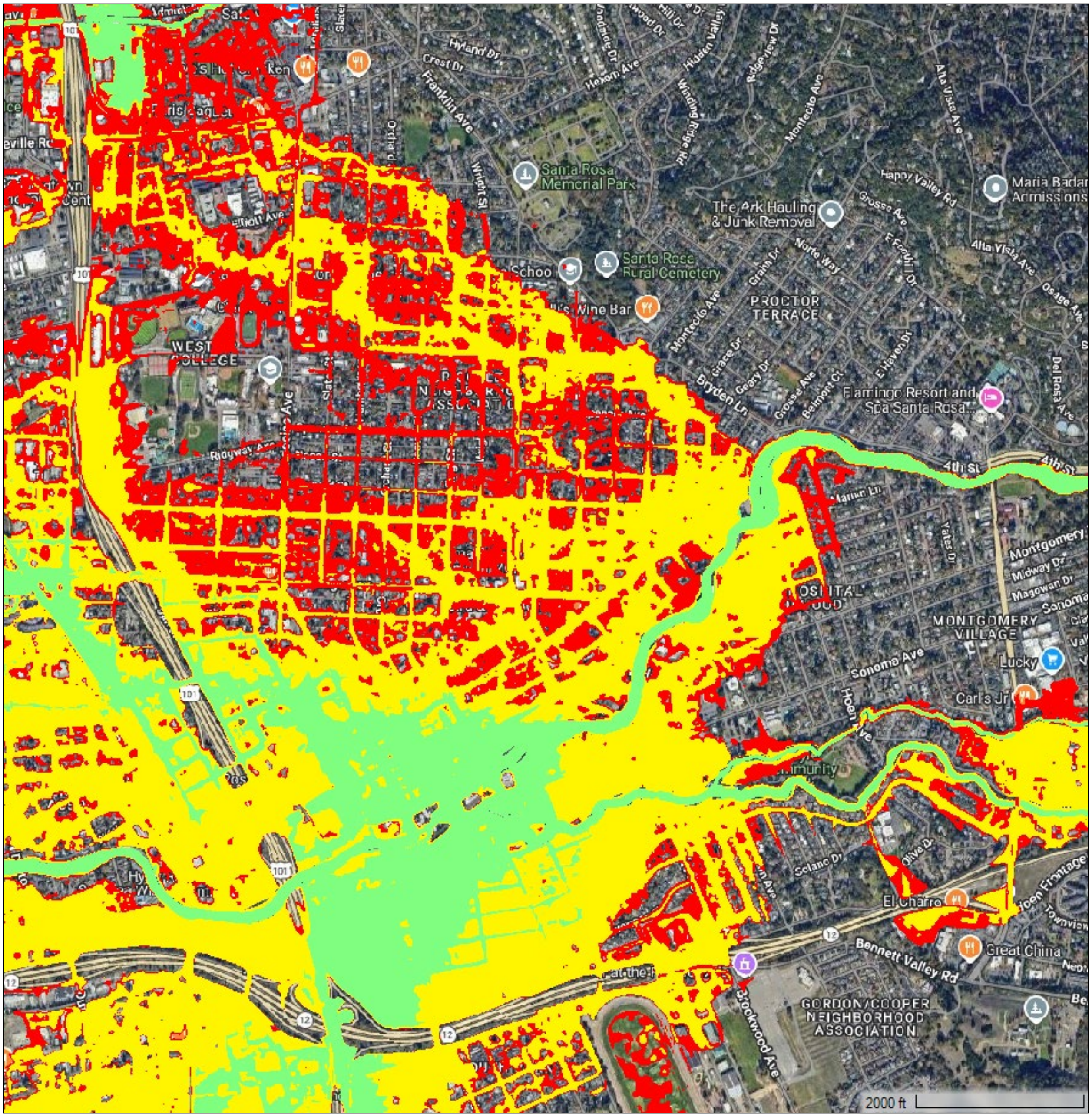


Figure 7-8. Sample of Structures at Risk in Santa Rosa (west of 101) with Modeled Increased Inundation under Future Climate (Baseline, Mid-Future, and Late-Future 100-year event [585])

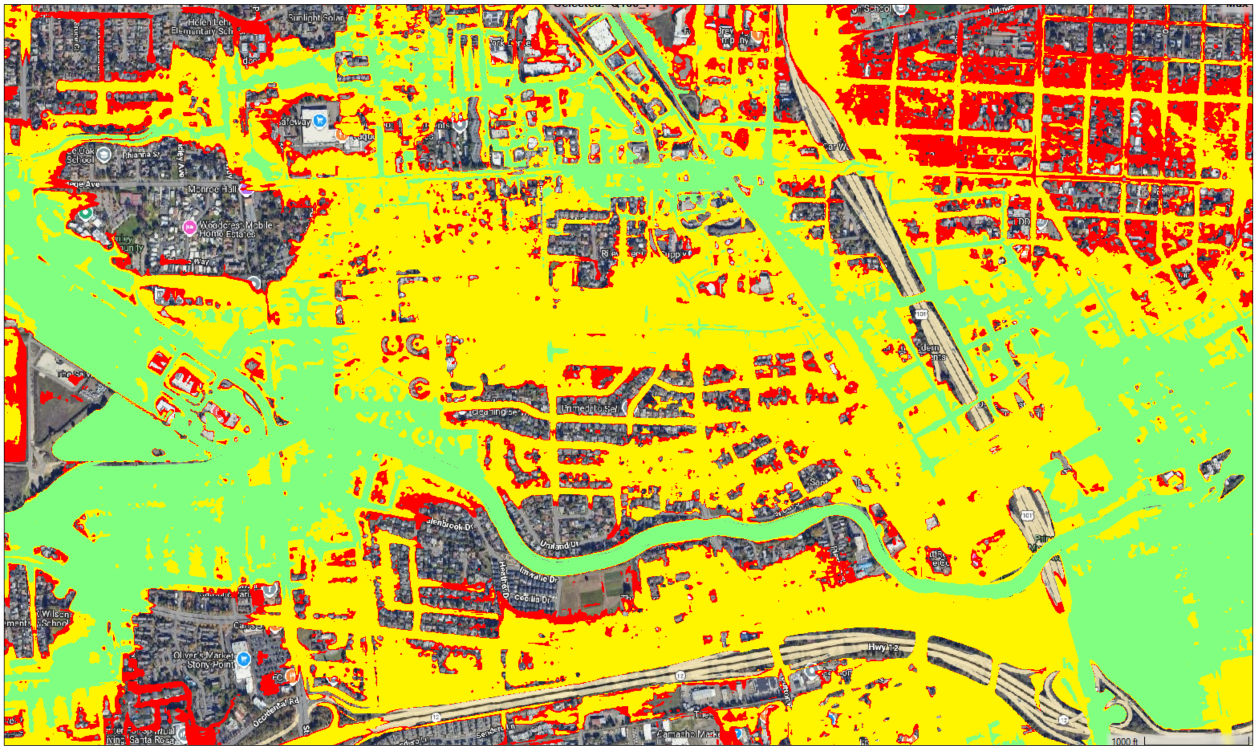


Figure 7-9. Increase in Modeled Residences at Risk in Russian River Watershed for 25-, 50-, and 100-year 24-hour Storm

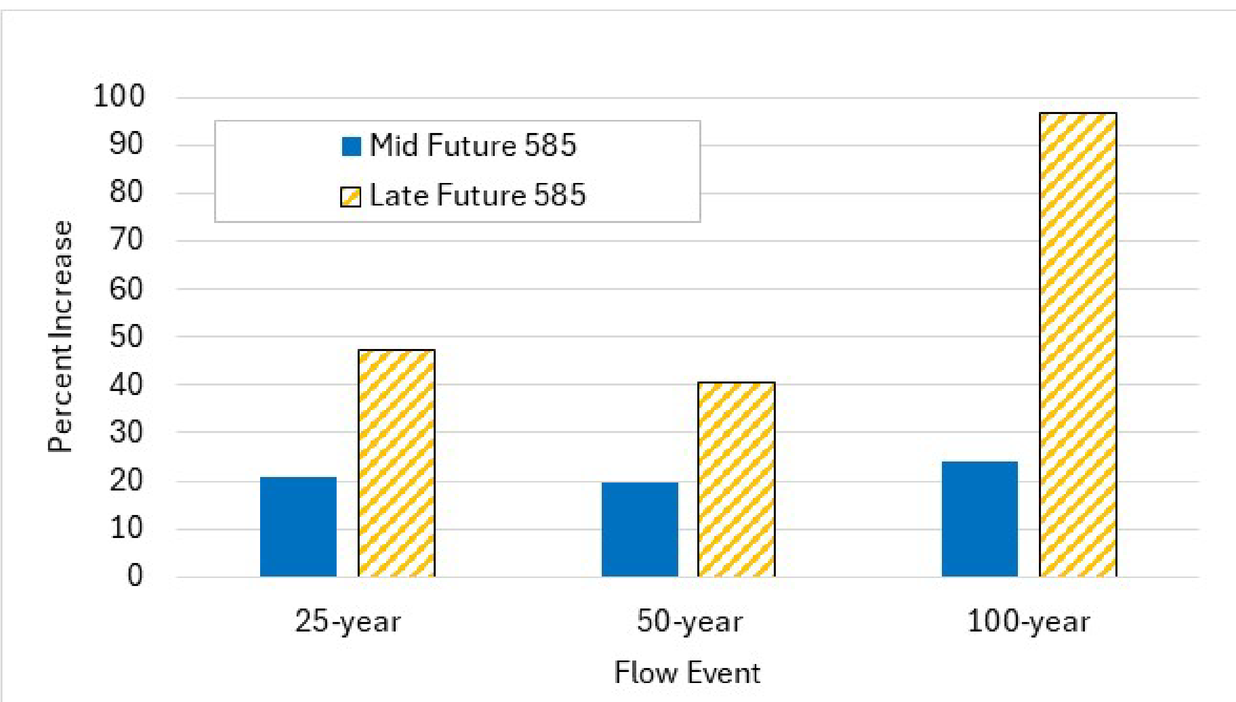
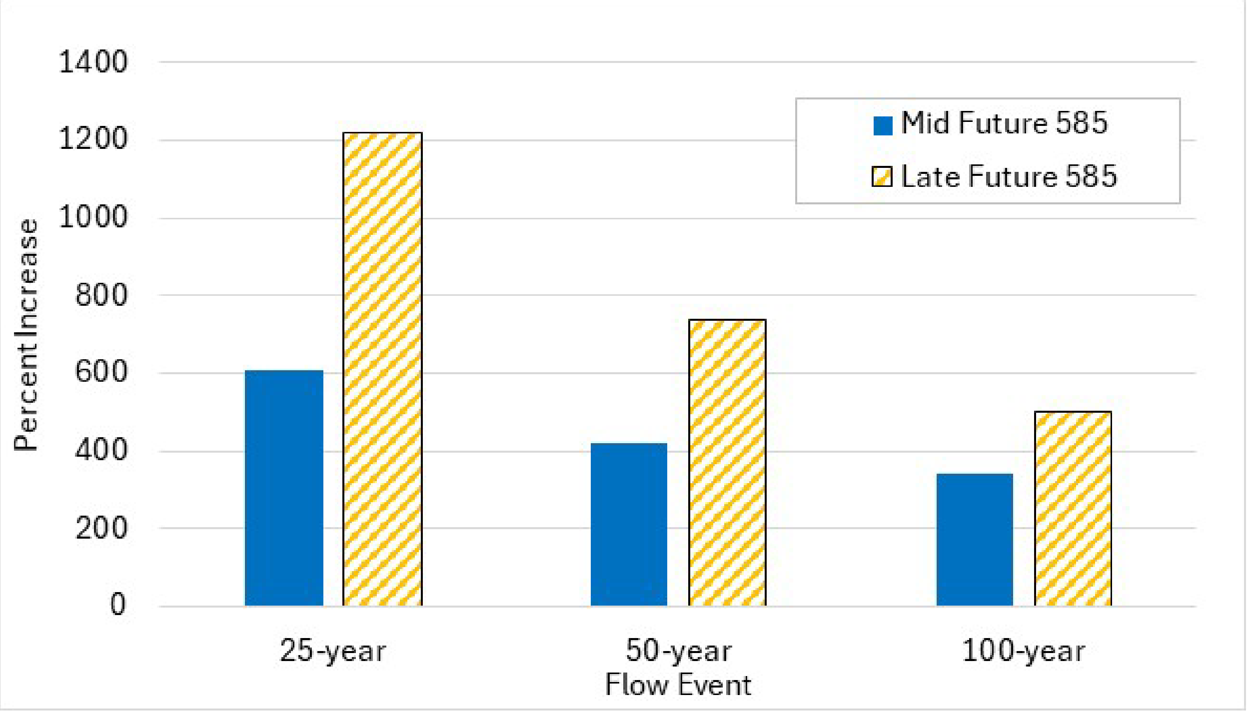


Figure 7-10. Increase in Modeled Residences at Risk in Santa Rosa Creek Watershed for 25-, 50-, and 100-year 24-hour storm



Projected flood impacts to housing in the Santa Rosa Creek watershed are significantly higher on a percentage basis, as Santa Rosa Creek does not have the conveyance capacity required to transport even the current 25-year flow without overtopping its banks. In the Mid-Future, models predict a 600 percent increase in the number of structures flooded by the 25-year flood, from under 500 structures to over 3,300 structures. In Late-Future conditions, results show a 1,200% increase in residences impacted, to over 6,200 structures. At the 100-year flood level, the increases are smaller in percentage terms but larger in number of structures impacted, increasing from 2,600 in the baseline to 11,600 in Mid-Future and 15,700 in Late-Future conditions. The Santa Rosa Creek watershed is more densely populated than the Russian River watershed, hence the large increases with increased flows under future climate scenarios.

Backwater impacts of increased stages in the Russian River are also seen in the Laguna de Santa Rosa, Mark West Creek, and Green Valley Creek. Although hydraulics were not explicitly modeled in these areas, as they are modeled as 1D storage areas connected to the Russian River, the model does know the local terrain and the water elevation in the Russian River and thus should provide a reasonable measure of inundation from a pure backwater influence.

7.4 Summary

Flood modeling was conducted to assess vulnerabilities associated with changing rainfall intensity and magnitudes suggested by future climate models. An integrated modeling suite comprised of hydrologic (HEC-HMS), reservoir operations (ResSim), and river hydraulic models (HEC-RAS) was applied to approximate future changes in flood risk. This suite of models is useful for approximating comparative changes in flood risk for historical and future climate. Spatial analyses of modeled future flood conditions can inform our understanding of the relative shifts in flood risk from current to future climates and lead toward improved understanding of measures to reduce these risks. Simulations with the integrated modeling suite were conducted for current conditions and for future climate consisting of increased rainfall magnitude and intensity. It is important to note that the flood modeling was performed specifically to support understanding of potential changes under a range of future climate and should not be viewed or used as definitive future outcomes. The flood analysis did not include updates to elevation mapping or refinements to models and should not be used to assess specific property risks. Flood risk management responsibilities are spread among multiple agencies in Mendocino and Sonoma counties and many of these are coordinating to advance analysis and response.

Along the Russian River, future climate is projected to nearly double the number of residences vulnerable to 100-year flood inundation. For the 100-year flood event, increases under future climate could reach 24% by Mid-Future and 97% by Late-Future. For the 25-year flood event, model results indicate that approximately 20% more structures in the Russian River watershed may flood under the Mid-Future scenario and 47% more in the Late-Future scenarios. The majority of impacted residences are in the lower Russian River, where homes are situated nearer to the river.

Projected flood impacts to residences in the Santa Rosa Creek watershed are significantly higher as Santa Rosa Creek does not have the conveyance capacity required to transport even the current lower flood flows without overtopping its banks. In Mid-Future conditions, models predict a 600% increase in the number of structures flooded by the 25-year flood event. In Late-Future conditions, results show a 1,200% increase in residences impacted. At the 100-year flood level, the increases are smaller in percentage terms but larger in number of structures impacted, increasing from roughly 2,600 in the baseline to 11,600 in Mid-Future and 15,700 in Late-Future conditions. The Santa Rosa Creek watershed is more densely populated than the Russian River watershed, hence the large increases with increased flows under future climate scenarios. Backwater impacts of increased stages in the Russian River are also seen in Mark West Creek and Green Valley Creek.

Flood vulnerabilities under future climate are significant in residential areas near Santa Rosa Creek. While such residences are not within the current 100-year floodplain, increased runoff from projected future storm events is expected to result in a larger floodplain. Impacts are also seen in more populated areas along the Russian River, such as Guerneville and Healdsburg. Backwater impacts of increased stages in the Russian River are also seen in Mark West Creek and Green Valley Creek.

Numerical models provide useful estimates of future conditions, but results must be interpreted with an understanding of potential limitations of the modeling analysis, including those associated with assumptions adopted by the model. The full modeling suite has not been calibrated to historic events as part of this analysis, and a cursory comparison to larger historic events indicates that the model underestimates peak flows and stages. This would likely lead to an underestimation of the structures and population at risk under future climate. A full calibration of the HMS and HEC-RAS models should be incorporated into future studies. Furthermore, the climate change factors for this assessment were developed using 24-hour daily precipitation data from LOCA2-Hybrid. A potential enhancement for future assessment could be to leverage climate datasets with higher temporal resolution to quantify and evaluate projected changes in storm durations less than 24-hours (ESA 2024).

8. Water Quality Vulnerability Assessment

8.1 Purpose

Future climate models project increases in air temperature and reductions reservoir storage and river flows, resulting in a high likelihood of changes to water quality patterns in the Russian River watershed. These changes in water quality can impact salmonids and steelhead that are listed under the Endangered Species Act, other aquatic species, and recreation in the Russian River. To assess these changes, this vulnerability analysis utilizes the Russian River HEC-ResSim Water Quality Model (RRWQM) developed by Resource Management Associates (RMA; now GEI Consultants) to model water quality under future climate projections.

The RRWQM is a new component of the Russian River HEC-ResSim system operations model that is described in the Surface Water Supply Vulnerability Assessment (Section 5). In addition to reservoir operations, river flows, and diversions, the model simulates hydraulic processes and dynamic biogeochemical processes to calculate various water quality constituents. The constituents are calculated at a sub-daily timestep along the main stem of the Russian River to simulate diurnal and seasonal patterns. Lake Mendocino and Lake Sonoma reservoir mixing and biogeochemical processes are also modeled to determine the water quality of releases into Dry Creek and the Russian River. Due to limited availability of tributary water quality data, the model focuses on processes in the mainstem of the Russian River.

Simulations under various future climate scenarios were used to assess the general trends in water quality under a changing flow regime and meteorology at specific locations of interest. These results will be utilized in the Ecosystem Vulnerability Analysis (Section 9) to estimate impacts to fisheries in the Russian River. The results also provide a baseline that potential adaptation measures can be compared against.

8.2 Methodology

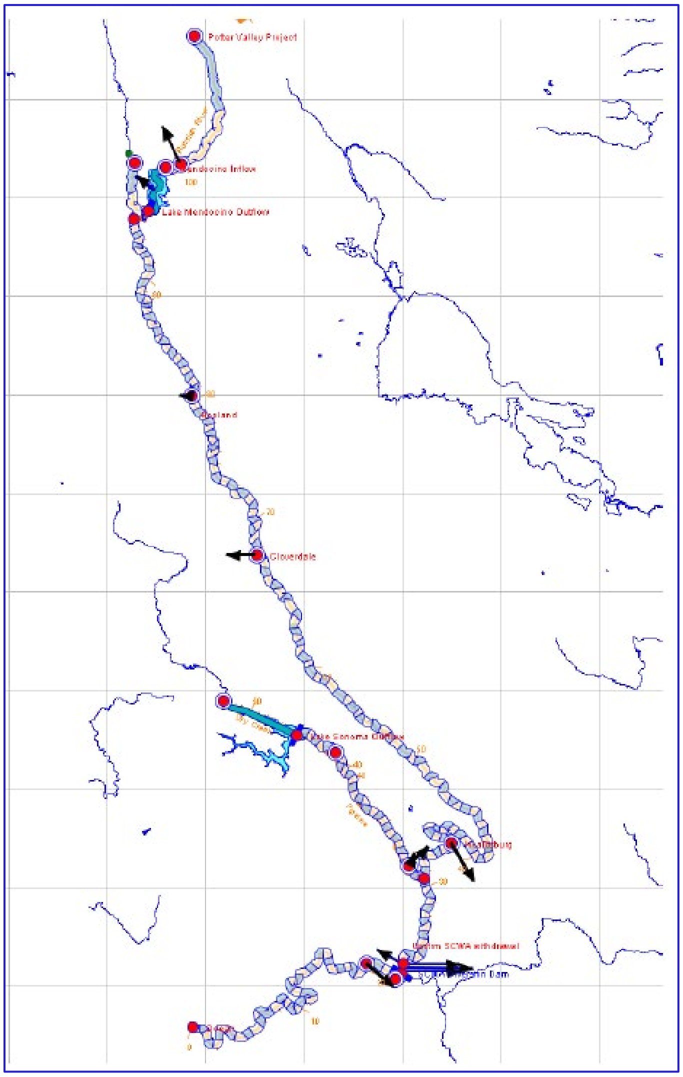
8.2.1 Model Description

The RRWQM simulates a range of water quality constituents within Lake Mendocino and Lake Sonoma reservoirs and along the mainstem of the Russian River for various reservoir storage and flow conditions (Table 8-1). To simulate the water quality constituents, the model uses a water quality module that is integrated into HEC-ResSim to represent the Russian River watershed (Figure 8-1). The water quality module includes calibrated parameters to simulate biogeochemical processes and river channel bathymetry and hydraulic parameters to calculate processes such as reservoir mixing and river velocity and stage. The RRWQM was developed and calibrated in 2021 by RMA and then subsequently updated and recalibrated in 2024 by RMA/GEI with updated observational data. A detailed description of the model with calibration results and calculation methods can be found in the HEC-ResSim Simulation of Water Quality in the Russian River Basin: 2024 Update report (RMA 2024).

Table 8-1. Model Water Quality Constituents

Model Constituent	
Water Temperature	Organic Phosphorous
Sediment Temperature	Phytoplankton
Dissolved Oxygen	Benthic Algae
Ammonium	Particulate Organic Carbon
Nitrate	Dissolved Organic Carbon
Organic Nitrogen	Dissolved Inorganic Carbon
Inorganic Phosphorus	Suspended Particulate Organic Matter

Figure 8-1. Russian River Water Quality Model Network



8.2.2 Simulation Plan

The RRWQM calculates processes at a 2-hour timestep, which is essential for modeling sub-daily water quality patterns and hydraulic routing of constituents. For this analysis, the model was run for calendar years 1981 to 2100 for three selected future climate scenarios. The simulation period is different than the Surface Water Supply Vulnerability Assessment due to the limitation of the sub-hourly climate data that will be described in the model input description section. The three climate scenarios were selected from the 41 total future climate scenarios provided by the Scripps Institute of Oceanography's LOCA2-Hybrid data products that represent a selection of the CMIP6 GCMs and SSPs. The three models selected represent distinct future climate outcomes for changes in temperature and precipitation: (1) Median, (2) Hot-Dry, and (3) Warm-Wet. The selected future climate outcomes represent a range of hydrologic and meteorological outcomes without having to simulate all 41 LOCA-Hybrid2 scenarios. The three selected scenarios are listed in Table 8-2.

Table 8-2. LOCA2-Hybrid Selected Scenarios

GCM	SSP	Climate Description
EC-Earth3-Veg	3-7.0	Median
EC-Earth3-Veg	5-8.5	Hot-Dry
MRI-ESM2-0	3-7.0	Warm-Wet

8.2.3 Model Inputs

The RRWQM requires multiple inputs to calculate water quality constituents. These inputs include hydrologic inputs to determine system inflows, reservoir operation rules and physical constraints to determine reservoir releases and storage, river diversions to determine system losses, water quality parameters to calculate biochemical processes, and meteorology (Table 8-3) to calculate atmospheric-influenced processes. For this vulnerability assessment the hydrologic inputs are derived from the BCM hydrologic model which is described in Attachment C-1. The reservoir operation rules and physical constraints and river diversions are consistent with the Russian River HEC-ResSim model description in the Surface Water Supply Vulnerability Assessment. The water quality parameters were determined in the updated model calibration of the RRWQM in 2024 (Sonoma Water 2024). While most of the model inputs were developed as part of other assessments or model calibration, the future climate meteorological inputs was processed specifically for the RRWQM.

Table 8-3. Model Meteorological Data Inputs

Parameter
Atmospheric Pressure
Air Temperature
Humidity
Solar Radiation
Wind Speed

The required meteorological inputs (Table 8-3) are provided by the LOCA2-Hybrid model outputs. The gridded outputs from these projections are available from calendar year 1950 through 2100 at a daily timestep and include minimum/maximum air temperature, minimum/maximum relative humidity, average solar radiation, and average wind speed. The RRWQM, however, requires hourly climate data to simulate water quality at a sub-daily timestep so these inputs needed to be converted into hourly values. For this conversion, a projection from UCLA's WRF future climate model dataset was utilized. Due to data availability at the time of this analysis, the CESM2 SSP3-7.0 scenario was selected from WRF dataset for the conversion process. The WRF model provides gridded hourly meteorological data from calendar years 1981–2100, for air temperature, wind speed, relative humidity, and solar radiation. Model values from the grid locations that correspond to the RRWQM meteorologic input locations (Table 8-4) were extracted to develop the raw input time series. This raw time series values were then bias-corrected against observed data to develop an adjusted hourly dataset that represents a base hourly meteorological climate projection. This base hourly time series was then scaled by the daily LOCA2-Hybrid daily values to develop the final input meteorological dataset for the RRWQM simulations used in this assessment. Since the WRF model only covered the model period of 1981 to 2100, the converted LOCA2-Hybrid timeseries was truncated to 1981 to 2100 instead of the full 1950 to 2100 period.

Table 8-4. Model Meteorology Input Locations

Station Name	Location
Lake Mendocino Met	Coyote Dam
Lake Sonoma Met	Warm Springs Dam
Windsor	At the site of the CIMIS Winsor Meteorological Station

8.3 Results

The processed inputs were modeled through the RRWQM to develop water quality outputs for the three LOCA2-Hybrid scenarios from 1981 to 2100 along the Russian River. For this assessment, water temperature was analyzed at four locations of interest along the Russian River: Lake Mendocino Outflow, Russian River at Cloverdale USGS Gage location, Lake Sonoma outflow, and the Russian River at Hacienda Bridge Gage location. Dissolved oxygen was analyzed at two locations: the Russian River at Cloverdale USGS Gage location, and the Russian River at Hacienda Bridge Gage location. These locations represent areas of concern for salmonid and steelhead habitat in the both the Upper Russian River (from Lake Mendocino to Cloverdale) and Lower Russian River (at Hacienda Bridge).

The results for the three future climate scenarios show similar increasing trends in average water temperature at all four analysis locations. Table 8-5 demonstrates these trends with annual average temperature calculated for three climate scenarios over three time periods: historical, Mid-Century, and Late-Century. Also included in the table are values for average temperature values of the Russian River watershed. The Mid-Century and Late-Century temperature values include the change in temperature for the period relative to the historical period in paratheses. The hottest and driest scenario, EC-Earth3-Veg SSP5-8.5, shows the highest increase in water temperature over the period for all locations. For this scenario, increases in river temperature are due to the larger increase in air temperature as well as drier conditions that lead to lower average flows in the Russian River (lower flows allow for more atmospheric heat transfer to the river due to lower velocities). The coldest and wettest scenario of the three, MRI-ESM2-0 SSP3-7.0, shows the lowest increase in water temperature, which corresponds to higher average flows in the Russian River and a smaller increase in average air temperature. The values in the table represent a summary of overall water temperature trends in the Russian River, the daily and seasonal trends are described in more detail below.

Table 8-5. Daily Average Temperature Results for Lake Mendocino Outflow, Cloverdale, Lake Sonoma Outflow, and Hacienda Bridge Model Locations

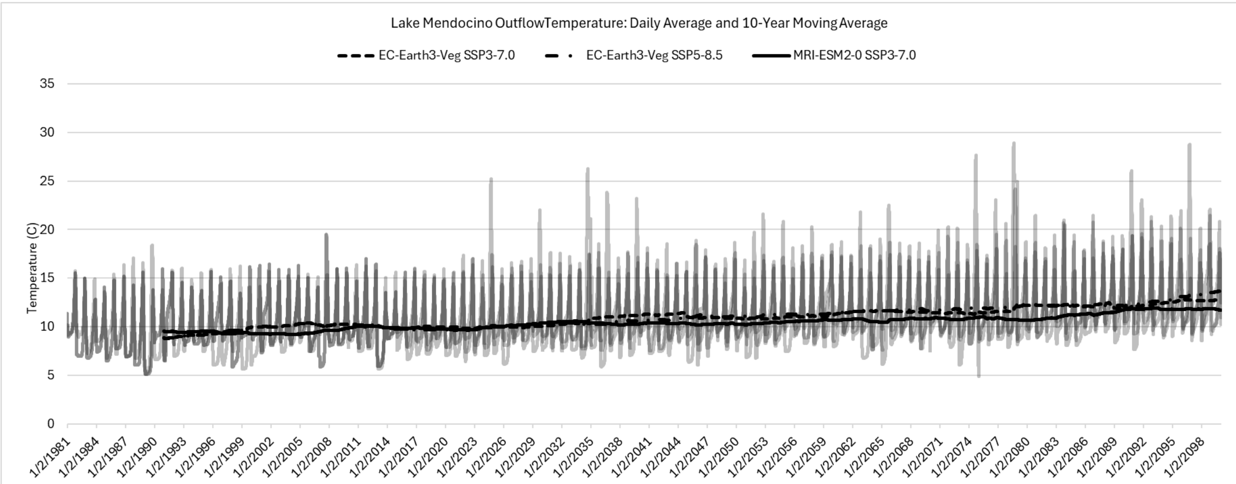
Average Annual Temperature and Change from Historical Period (degrees C)

Constituent	Historical			Mid-Century			Late Century		
	1981-2010			2030-2070			2071-2100		
	Median	Hot/Dry	Warm/Wet	Median	Hot/Dry	Warm/Wet	Median	Hot/Dry	Warm/Wet
Russian River Air Temperature	14.7	14.7	14.6	16.3 (1.6)	16.7 (2.0)	15.8 (1.2)	17.8 (3.1)	18.7 (4.0)	16.6 (2.0)
Lake Mendocino Outflow Water Temperature	9.7	9.7	9.6	11.2 (1.5)	11.2 (1.6)	10.5 (0.9)	12.3 (2.6)	12.7 (3.0)	11.4 (1.8)
Cloverdale Water Temperature	14.2	14.2	14.1	15.3 (1.1)	15.7 (1.4)	15.0 (0.9)	16.5 (2.3)	17.2 (2.9)	15.6 (1.5)
Lake Sonoma Outflow Water Temperature	9.3	9.3	9.1	10.6 (1.3)	10.7 (1.4)	10.1 (0.9)	11.7 (2.4)	12.3 (3.0)	10.9 (1.7)
Hacienda Bridge Water Temperature	14.5	14.5	14.4	15.6 (1.1)	15.9 (1.4)	15.3 (0.9)	16.6 (2.1)	17.4 (2.9)	15.9 (1.5)

8.3.1 Lake Mendocino Outflow Temperature

Lake Mendocino releases water from an outlet located at the bottom of Coyote Valley Dam, where water temperature is a function of reservoir storage, inflow temperature, and atmospheric temperature. The reservoir stratifies over the summer, with warmer water in the epilimnion layer floating above a colder hypolimnion pool. Since the Lake Mendocino release outlet is at the bottom of the dam, water is released from this cold-water pool until the reservoir turns over and mixes in the fall season. The timing of the turnover is affected by the volume of storage in Lake Mendocino, with a lower storage typically corresponding to an earlier mixing event due to the cold-water pool being depleted earlier. The Surface Water Vulnerability Assessment describes a decreasing trend in Lake Mendocino fall storage in the future, primarily caused by a major operation change in Eel River diversions starting in 2035 due to the assumed decommissioning of the PVP and the construction of the NERF. In addition to the change in Eel River diversion operations, more extreme droughts result in more years with lower fall storage. The reduced storage in the future can lead to earlier depletion of the cold-water pool resulting in a greater frequency of fall water temperature spikes out of Lake Mendocino. These can be seen in Figure 8-2, which shows the daily average temperatures for all three scenarios in the light gray lines and the 10-year moving average temperature in the darker lines. The frequency of extreme temperatures (above 20C) increases starting in 2035 compared to the historical period and becomes more frequent and extreme by later century (post-2070).

Figure 8-2. Lake Mendocino Outflow Daily Average Temperature



The impact of lower reservoir storage and higher atmospheric temperature becomes more apparent when looking at seasonal trends. Figure 8-3 and Figure 8-4 represent the average daily water temperature and average reservoir storage over a specified periods for two different future climate scenarios, with Figure 8-3 representing the hot/dry scenario and Figure 8-4 representing the warm/wet scenario. The figures show a steady increase in water temperature at Lake Mendocino over the whole year for the future climate periods. The increase in spring and winter water temperatures is caused by warmer inflows into the reservoir, and due to higher winter air temperature during these seasons. Higher winter temperatures result in warmer reservoir release temperatures overall, as well as a warmer cold-water pool increases release temperature throughout the whole year. For the hot/dry scenario, the fall peak water temperature shows a greater increase in water temperature compared to the rest of season, as well as shift in timing for the late-century period (Figure 8-3). This is a result of the cold-water pool being depleted earlier due to lower reservoir storage. The warm/wet scenario doesn't show as extreme a shift in the fall water temperature because the reservoir storages don't decline to the same extent due to wetter hydrology (Figure 8-4).

Figure 8-3. Average Seasonal Lake Mendocino Outflow Temperature and Storage EC-Earth3-Veg SSP5-8.5

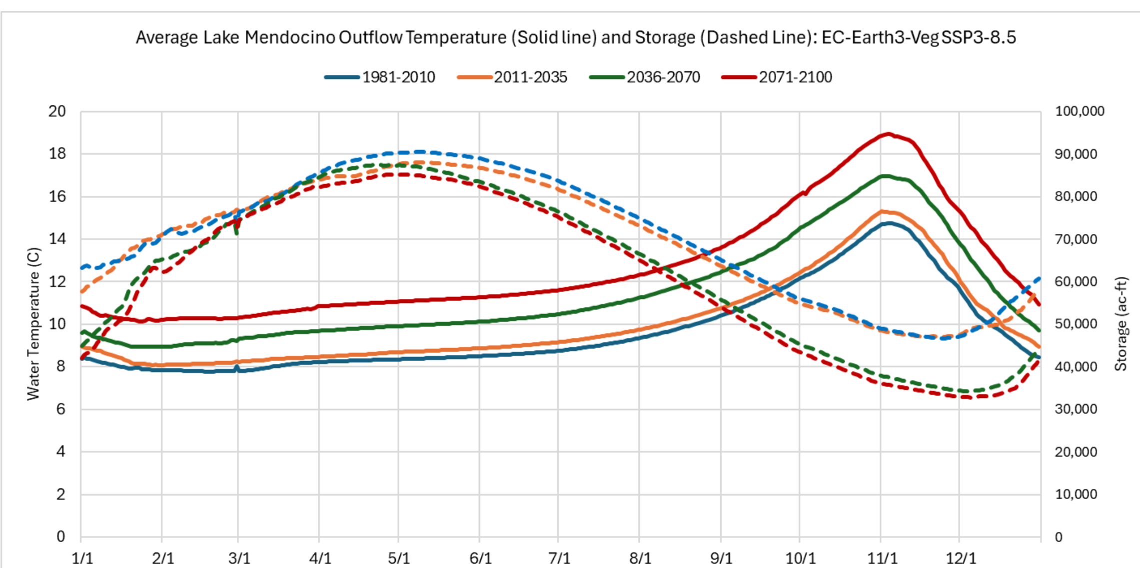
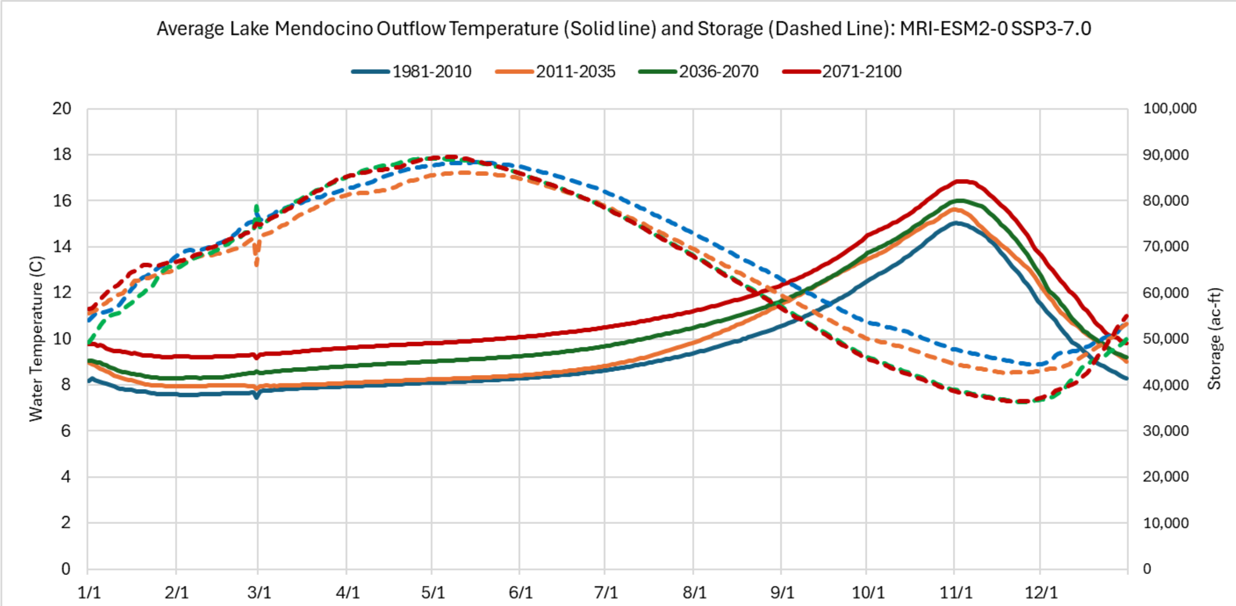


Figure 8-4. Average Seasonal Lake Mendocino Outflow Temperature and Storage MRI-ESM2-0 SSP3-7.0



8.3.2 Russian River at Cloverdale Temperature

The Cloverdale site is located approximately 30 miles downstream of Lake Mendocino on the mainstem of the Russian River. The water temperature at this site is important to analyze for fisheries impacts on the Upper Russian River because it represents the historical downstream extent of the Lake Mendocino cold-water pool influence that benefits steelhead rearing. Downstream of Cloverdale, the longer travel times result in greater air temperature heat exchange that creates water temperatures too high for steelhead habitat.

Flows at Cloverdale are influenced by Lake Mendocino releases as well as local natural flows from the watershed. During the winter and spring seasons, local flows make up the largest proportion of flows at the site and total flows remain relatively high. When local flows recede in the summer and fall seasons, Lake Mendocino releases contribute most of the flow volume and flows remain lower and relatively static due to reservoir operations.

Results for water temperature at Cloverdale show a similar overall trend to Lake Mendocino outflow with increasing average water temperatures in the future climate periods (Figure 8-5). Comparing the different future climate scenarios, the hot/dry scenario (EC-Earth3-Veg SSP5-8.5) shows the largest increase in water temperature while the warm/wet (MRI-ESM2-0 SSP3-7.0) shows the smallest change. Like Lake Mendocino outflow, Cloverdale water temperatures are affected by changes to hydrology as well as air temperature. In the winter and spring months, when natural local flow contributions are high, the increase in water temperature over the future period is correlated with the increase in air temperature (Figure 8-6). Starting in the early summer, the local flow recedes and Lake Mendocino releases become a greater fraction of the flow at Cloverdale through summer and fall seasons. Since Lake Mendocino releases water from the cold-water pool, it will buffer the effects of the warmer air temperature on water temperature, resulting in lower water temperatures relative to air temperature. However, the water temperature during the whole season increases through the future climate period, due to increasing cold-water pool temperature and warmer air temperature.

Figure 8-5. Cloverdale Daily Average Temperature

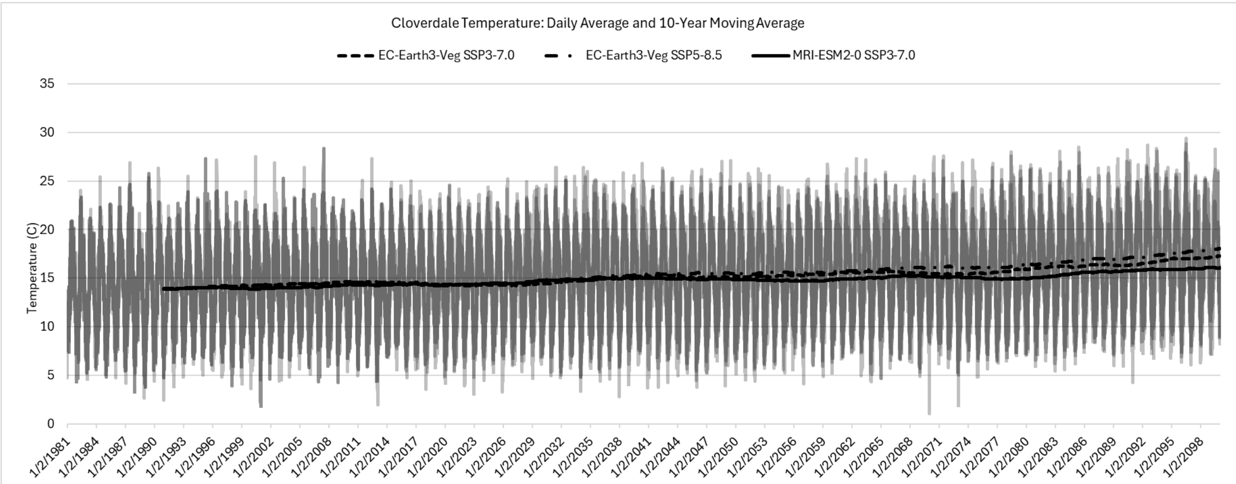
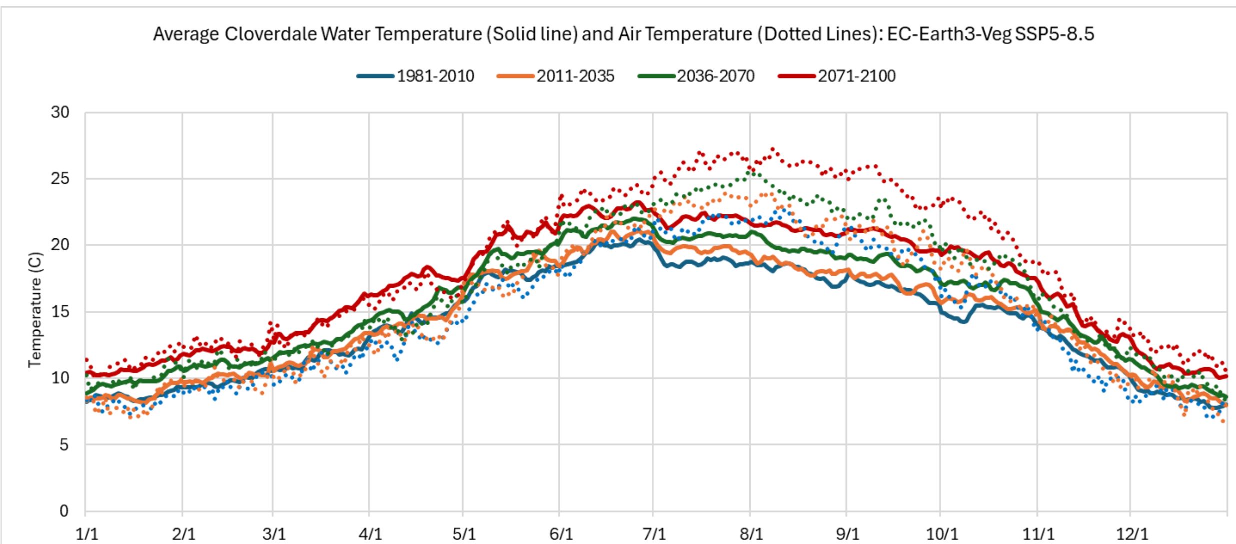


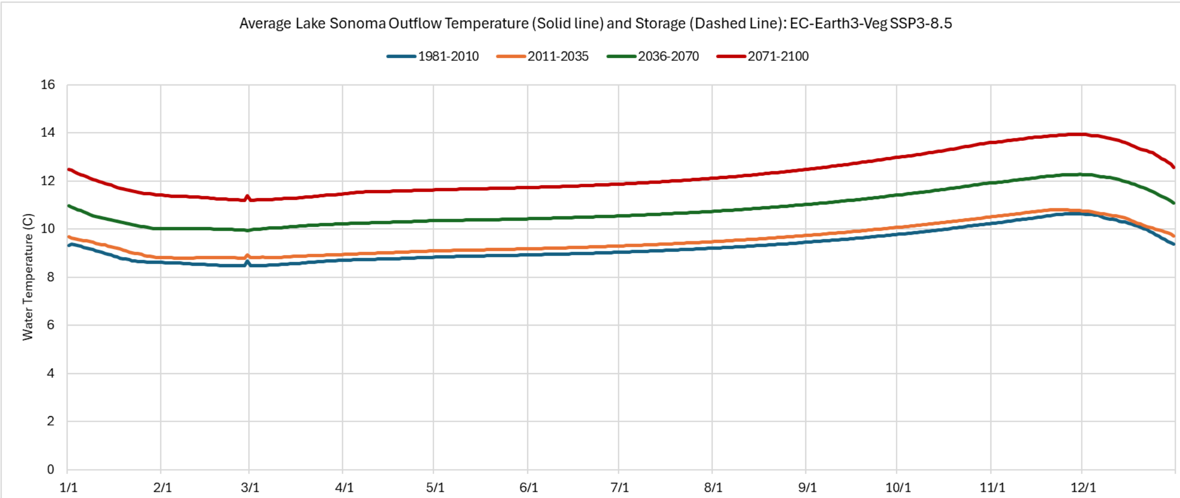
Figure 8-6. Average Seasonal Cloverdale Water Temperature and Air Temperature EC-Earth3-Veg SSP5-8.5



8.3.3 Lake Sonoma Outflow Temperature

Lake Sonoma is a much deeper and larger reservoir than Lake Mendocino and contains a more prominent cold-water pool. This cold-water pool is only depleted in extreme multi-year droughts, therefore, water temperature of Lake Sonoma releases is primarily a function of inflow water temperature and air temperature. Figure 8-7 shows the increasing water temperature trend over the future climate projections due to the warmer inflows into the reservoir that leads to an increasing cold-water pool temperature that releases are drawn from.

Figure 8-7. Average Seasonal Lake Sonoma Outflow Temperature EC-Earth3-Veg SSP5-8.5



8.3.4 Russian River at Hacienda Bridge Temperature

The Hacienda Bridge site is located in the Lower Russian River downstream of the Russian River-Dry Creek confluence as well as downstream of Sonoma Water's river diversion facilities. It is approximately 80 miles downstream of Lake Mendocino and 30 miles downstream of Lake Sonoma. The flows at this location are comprised of Lake Sonoma and Lake Mendocino releases, and local natural flows of the Russian River watershed. Like Cloverdale, large local flows in the winter and spring make up most of the flow at Hacienda Bridge until the summer and fall, when local flows recede and releases from the reservoirs make a greater contribution.

The results for Hacienda Bridge show a similar trend to Lake Mendocino outflow and Cloverdale, with water temperatures increasing steadily during the future climate period (Figure 8-8). The increase in water temperature is a result of increases in air temperature and increases in Lake Sonoma release temperatures. Since the site is a long distance downstream of Lake Mendocino, water temperatures are minimally affected by those reservoir releases because the water in the river has more time to be heated by air temperatures as it flows through the Upper and Middle reaches of the Russian River. However, the water temperature is affected by Lake Sonoma releases in the summer and fall since the reservoir is much closer. Since Lake Sonoma typically releases water out of the cold-water pool, the releases tend to bring down the water temperature compared to upstream (Figure 8-9). However, because both the cold-water pool temperature and the air temperature are increasing, results show steadily increasing water temperature at Hacienda Bridge during the future climate period during the entire year.

Figure 8-8. Hacienda Bridge Daily Average Temperature

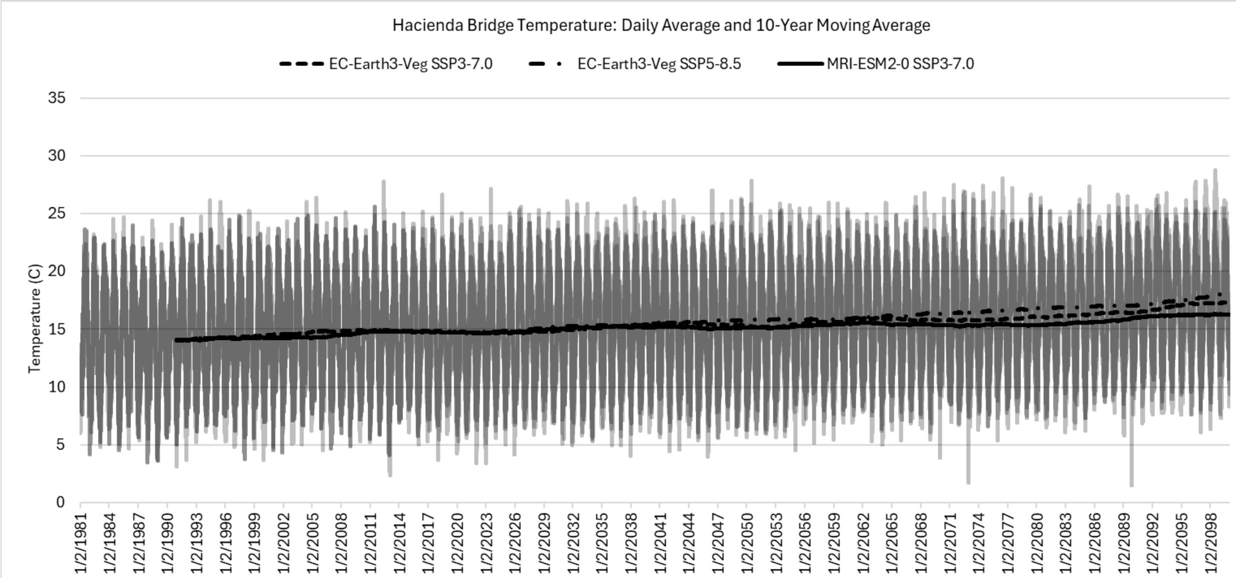
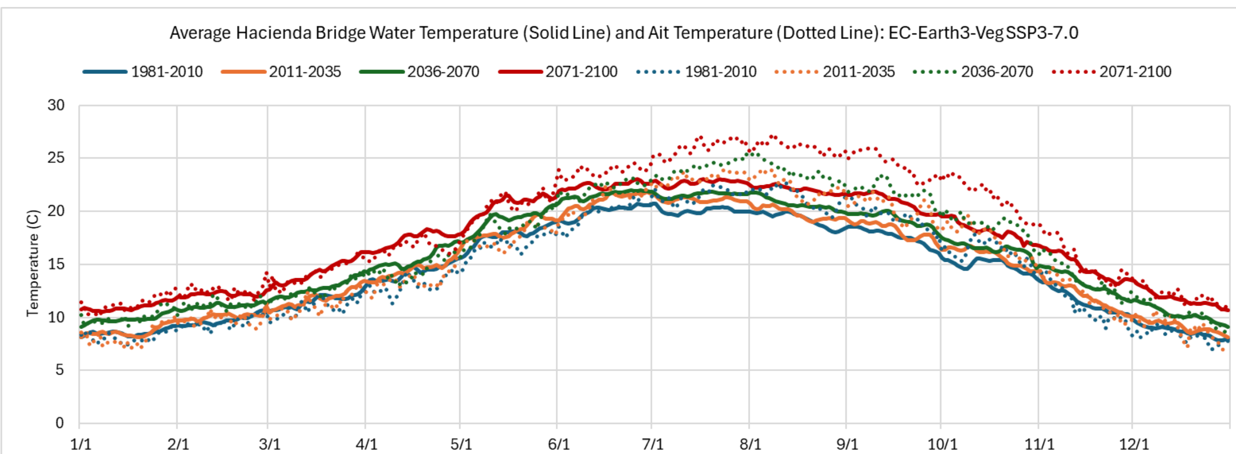


Figure 8-9. Average Seasonal Hacienda Water Temperature and Air Temperature EC-Earth3-Veg SSP5-8.5



8.3.5 Russian River at Cloverdale and Hacienda Bridge Dissolved Oxygen

Dissolved oxygen is also analyzed in this assessment. Since the future climate modeling does not assume any changes to the nutrient inputs in the Russian River for the future climate period, the changes in dissolved oxygen will be correlated to changes in meteorology. In general, higher water temperatures correlate to lower average dissolved oxygen at a given site due to temperature's effect on the saturation of oxygen in water, while diurnal variability is often driven by biological processes.

The results for the three future climate scenarios all show similar decreasing trends in average daily dissolved oxygen for the Cloverdale and Hacienda Bridge locations. Table 8-6, Figure 8-10, and Figure 8-11 show daily average dissolved oxygen plots for the two locations. The hottest and driest scenario, EC-Earth3-Veg SSP5-8.5, shows the largest decrease in dissolved oxygen over the simulation period, which is to be expected due to having lower overall flows in the Russian River, which will result in higher water temperatures and low velocities that reduce oxygen saturation and restricts air entrainment from mixing. The coldest and wettest scenario of the three, MRI-ESM2-0 SSP3-7.0, shows the smallest decrease in dissolved oxygen.

Table 8-6. Daily Average Dissolved Oxygen Results for Cloverdale and Hacienda Bridge Model Locations

Average Annual Dissolved Oxygen (mg/L) and Percent Change from Historical Period

Constituent	Historical			Mid-Century			Late Century		
	1981-2010			2030-2070			2071-2100		
	Median	Hot/Dry	Warm/Wet	Median	Hot/Dry	Warm/Wet	Median	Hot/Dry	Warm/Wet
Cloverdale Water Temperature	9.8	9.8	9.8	9.5 (-0.3)	9.4 (-0.4)	9.6 (-0.2)	9.2 (-0.6)	9.1 (-0.7)	9.5 (-0.4)
Hacienda Bridge Water Temperature	10.3	10.3	10.4	10.1 (-0.3)	10.0 (-0.3)	10.2 (-0.2)	9.8 (-0.5)	9.6 (-0.7)	10.0 (-0.3)

Figure 8-10. Daily Average Dissolved Oxygen Results for Cloverdale Model Location

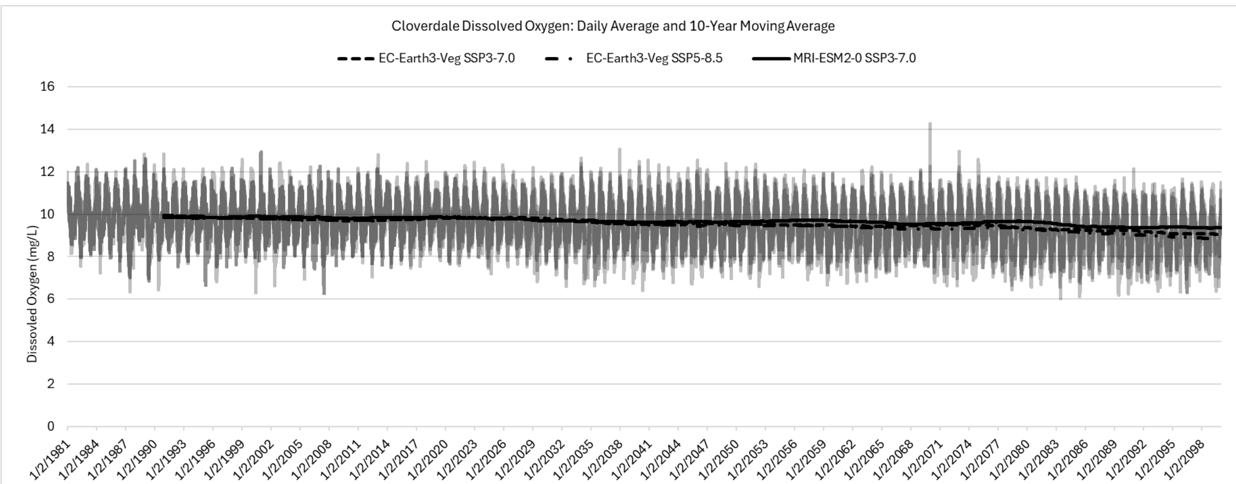
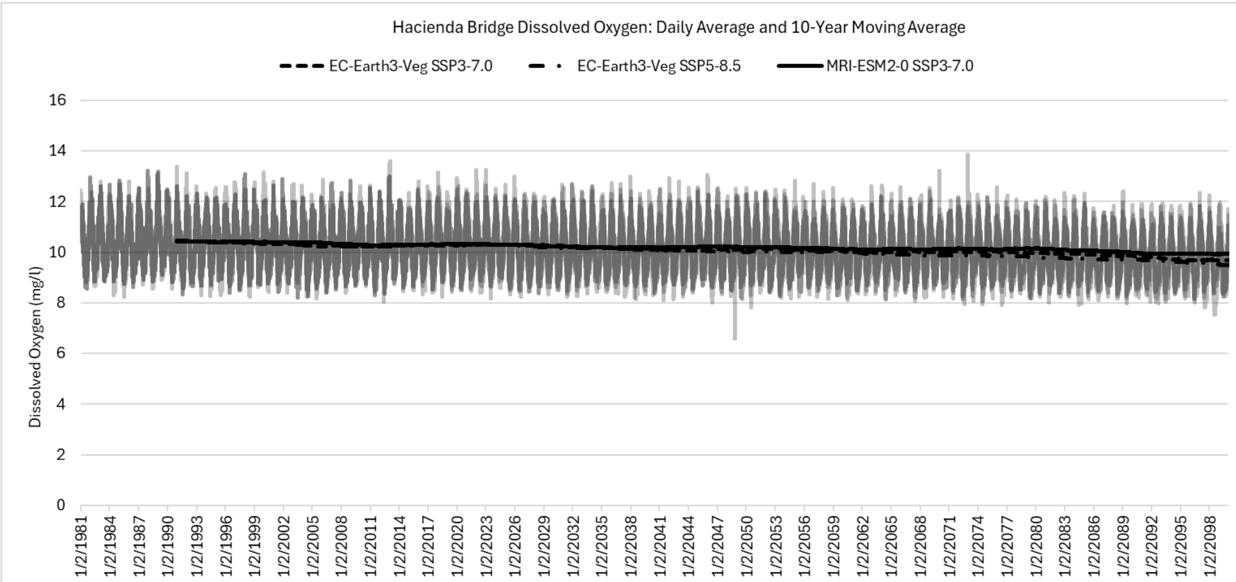


Figure 8-11. Daily Average Dissolved Oxygen Results for Hacienda Model Location



8.4 Summary

This assessment evaluates projected changes in water quality under three future climate scenarios, representing a subset of the full suite of 41 climate projections: hot/dry, warm/wet, and a middle ground scenario. To estimate these changes, the Russian River HEC-ReSim Water Model (RRWQM) was utilized to simulate different water quality parameters under varying hydrologic and meteorological inputs. For this assessment water temperature and dissolved oxygen model outputs were analyzed at Lake Mendocino and Lake Sonoma reservoirs and along the mainstem of the Russian River to determine the general vulnerabilities of Russian River watershed.

The results show that under all evaluated future climate scenarios the water temperature being released from Lake Mendocino and Lake Sonoma is expected to increase due to warmer inflows from increased in air temperature. Specifically for releases from Lake Mendocino, there is a projected increase in the frequency of fall water temperature spikes due to the depletion of cold-water pool earlier in the season from lower reservoir storage. These increases in water temperature from reservoir releases may have an impact on Coyote Valley Dam hatchery operations as well as salmon and steelhead lifecycle stages downstream.

For the Russian River, both Cloverdale in the Upper Russian River and Hacienda Bridge in the Lower Russian River are projected to see an increase in water temperature through the whole year due to warmer local natural flow from increasing air temperatures, warmer reservoir releases, and greater heat absorption while flowing downstream from increasing air temperatures during the low-flow periods in the summer. Both locations are also expected to experience decreasing dissolved oxygen in the river due to higher water temperatures and lower river flows. These changes also have the potential to impact salmon and steelhead rearing and spawning in the Russian River by decreasing the availability of suitable habitat.

This analysis does not look at specific vulnerabilities to fisheries in the Russian River but instead provides general trends in water quality and an interpretation of the causes based on the RRWQM. Specific vulnerability analyses are provided in the Ecosystem Vulnerability Assessment.

9. Ecosystem Vulnerability Assessment

9.1 Background

The Russian River watershed encompasses approximately 1,485 square miles across Mendocino and Sonoma counties and flows roughly 110 miles from its headwaters near Redwood and Potter valleys to the Pacific Ocean at Jenner (RRWA 2023; NOAA 2023). The basin drains a diverse network of tributaries—including the East Fork Russian River, Big Sulphur Creek, Maacama Creek, Mark West Creek, Austin Creek, and Dry Creek—that collectively support a complex mosaic of aquatic and riparian habitats (NOAA 2023; CDFW 2022). The Russian River watershed terminates in the Russian River estuary (referred to throughout this document as the 'estuary').

Collectively, these habitats within the Russian River watershed are critical for federally listed salmonids, which have been identified as species of management interest for purposes of this assessment because they collectively represent diverse life histories and environmental/habitat requirements, and they are among the most sensitive to environmental perturbation; therefore, findings from assessments of these species can be effectively used to make inferences about other species in the watershed.

These species include Central California Coast (CCC) coho salmon (*Oncorhynchus kisutch*) (endangered), CCC steelhead (*Oncorhynchus mykiss*) (threatened), and California Coastal Chinook salmon (*Oncorhynchus tschawytscha*) (threatened) (NMFS 2016; NOAA 2023). Coho salmon are also listed as endangered under the California *Endangered Species Act*.

The watershed is defined by a Mediterranean climate that drives strong seasonal hydrologic variability (Dettinger 2011). Historically, this regime produced the following (CDFW 2022):

- High winter flows from October–May storms
- Very low or intermittent summer conditions in many tributaries
- Seasonal contraction of salmonid rearing habitat during late summer

Flow regulation, while limited to a relatively small area of the total watershed, influences current flow regimes in the mainstem and Dry Creek. Operation of Coyote Valley Dam (Lake Mendocino) and Warm Springs Dam (Lake Sonoma) attenuates winter peaks and augments summer baseflows (NMFS 2008; NMFS 2025). Although regulation sustains perennial flow in reaches that formerly dried prior to reservoir construction, it has also altered sediment transport, temperature regimes, and channel hydraulics, with implications for salmonid habitat.

Dry Creek illustrates these tradeoffs most clearly. Draining approximately 217 square miles, with roughly 60% of the Dry Creek watershed regulated by Warm Springs Dam (NMFS 2008; Sonoma Water 2023), Dry Creek historically became intermittent in late summer. Warm Springs Dam operations currently sustain summer flow but have contributed to the following:

- Channel incision
- Reduced instream structural complexity
- Unsuitable rearing habitat conditions due to high water velocity

These impacts prompted large-scale habitat enhancement projects on Dry Creek designed to create low-velocity summer juvenile-rearing habitat (NMFS 2008; NMFS 2025; Sonoma Water 2023).

Outside Dry Creek, tributaries such as Maacama, Mark West, and Austin creeks continue to provide key spawning and rearing habitat, particularly where groundwater inputs maintain cool-water refugia (CDFW 2022; NMFS 2025). However, many smaller tributaries now experience the following:

- Seasonal drying and fragmentation
- Elevated summer temperatures
- Reduced habitat connectivity

More than a century of land conversion, gravel extraction, and flood control reshaped the geomorphic structure of the river system. Documented channel incision in portions of the Russian River and Dry Creek reduced floodplain connectivity and eliminated off-channel habitats historically important for juvenile rearing (Florsheim et al. 2008; NMFS 2008). These changes simplified channel structure and constrained access to low-velocity, complex habitats (NMFS 2008; NMFS 2025).

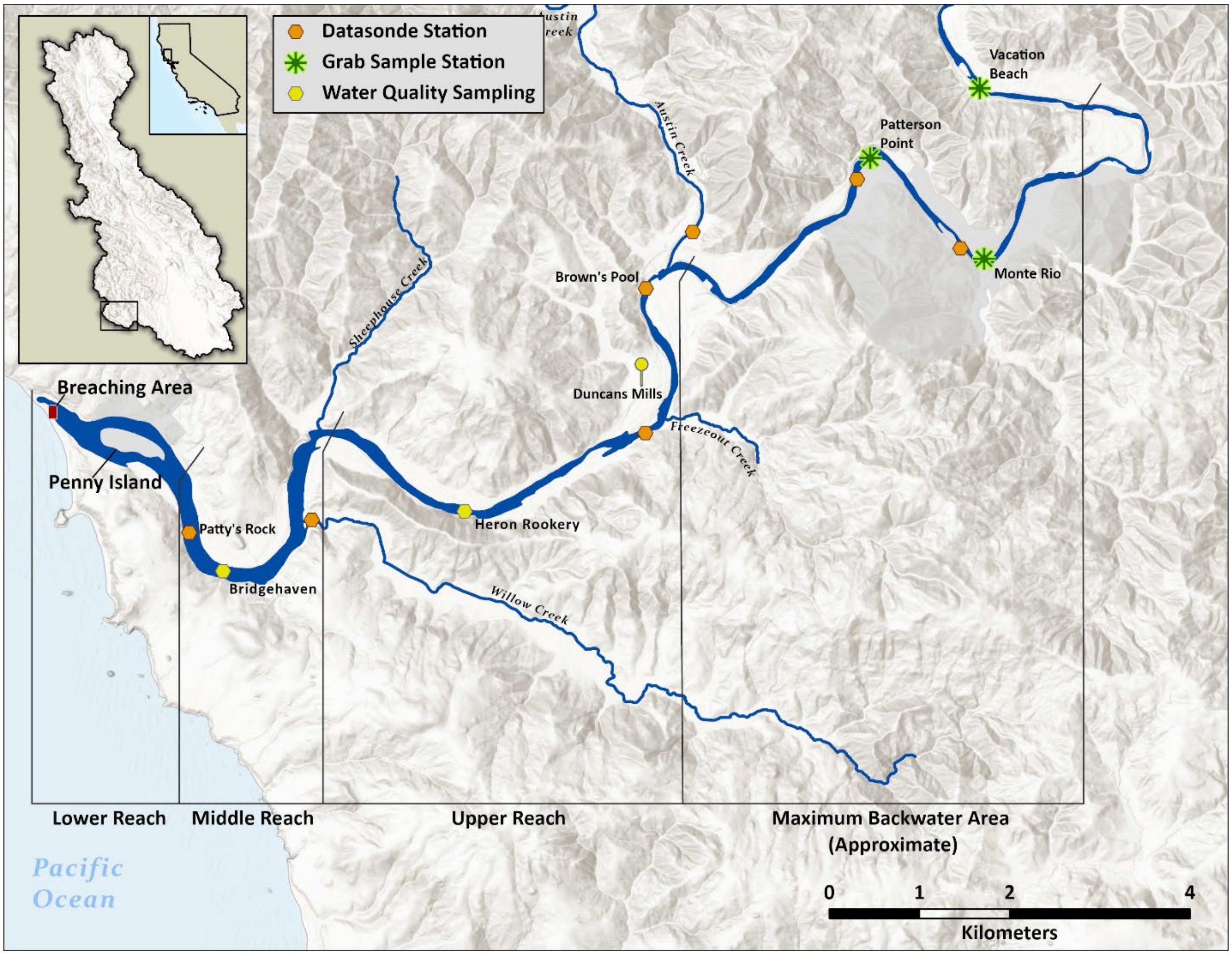
Water quality further constrains habitat suitability. Summer water temperature is a primary limiting factor for listed salmonids; exceedances of preferred thermal thresholds are common during low-flow periods in both the mainstem and tributaries (NMFS 2016; NMFS 2025). Elevated water temperatures reduce dissolved oxygen (DO) concentrations and increase physiological stress (EPA 2003). These conditions are also a limiting factor in the estuary (Largier and Koohafkan 2019, Largier 2021, ESA 2021), where salmonids congregate in periods of closed-mouth conditions.

Groundwater-surface water interactions remain critical to ecological resilience. Springs, hyporheic exchange zones, and riparian wetlands function as groundwater-dependent ecosystems that provide thermal buffering during dry periods (Boulton 2000; CDFW 2022). However, channel incision and groundwater extraction have lowered water tables in some areas, reducing hydrologic connectivity and limiting the persistence of cool-water refugia (Florsheim et al. 2008; NMFS 2025).

The estuary (Figure 9-1) provides unique habitat for a broad range of freshwater, brackish water, and marine adapted species because of its highly variable hydrology and salinity. It undergoes major changes throughout the year as it transitions from river-dominated conditions in the winter to coastal-dominated conditions in the spring, summer, and fall. In the latter, ocean waves carry enough sand into the river mouth (also called a 'tidal inlet' or 'inlet'), resulting in formation of a barrier beach that partially or fully block tidal exchange (NMFS 2025). This is a natural process that occurs at most estuaries in the state of California (e.g., Heady et al. 2015), but leads to flooding challenges for low-lying properties along the estuary. When a barrier beach closes the river mouth, the resulting lagoon water surface elevation rises with continued river flows and ocean waves continuing to add water to the lagoon, increasing potential flood risk. Importantly, many native species have evolved to take advantage of the variable conditions in the estuary, including salmonid species listed under the federal Endangered Species Act.

Figure 9-1. Site Map Showing the Location of the Russian River Estuary Within the Russian River Watershed

This map also shows locations where Sonoma Water routinely collects continuous measurements of water quality parameters from fixed sensors. Parameters typically include temperature, dissolved oxygen, salinity, and fluorescence. From National Marine Fisheries Service (2025).



Another important factor is the behavior of the river mouth, which is closed by wave action for about 10 to 30% of the days in most years (NMFS 2025). While this is a natural process, it has implications for both water quality and habitats in the estuary, where it typically leads to temporarily higher water levels that inundate shallow areas adjacent to the mainstem of the river. This creates additional summer and early-fall rearing habitat for juvenile salmonids in the estuary (Largier 2021). At the same time, the beach is managed to minimize flood risk to low-lying properties along the estuary. In practice, this means that if lagoon water surface elevations may reach flood stage, the barrier breach may be artificially breached to open the river mouth and reduce the water surface elevations (NMFS 2025).

9.2 Purpose

This Ecosystem Climate Vulnerability Assessment evaluates how projected changes in hydrology and water quality may affect habitat conditions for listed salmonids in the Russian River watershed, with emphasis on the mainstem Russian River and Dry Creek. The primary objective of the assessment is to compare physical habitat conditions, water quality, and fish passage across three modeled epochs

(Historical [1981–2010], Mid-Future [2041–2070], and Late-Future [2071–2100]), to identify how the suitability of these systems for migration, rearing, and survival may change through time.

The following assessment focuses on three principal drivers of habitat suitability within the mainstem Russian River and Dry Creek:

- **Physical habitat conditions –** Evaluated through relative changes in discharge and the expected direction (trends) of habitat response (e.g., depth, velocity, wetted area, and availability of hydraulic refuge). Habitat suitability is interpreted using literature-supported relationships between flow magnitude and salmonid habitat attributes.
- **Water quality –** Evaluated through projected changes in water temperature and DO, with emphasis on the magnitude and seasonal timing of conditions that are likely to impair habitat use or increase physiological stress for salmonids.
- **Fish passage –** Evaluated by examining changes in flow conditions at three locations where critical riffles are known to function as migration obstacles for adult upstream migrating salmonids.

To complement these analyses, the assessment includes a focused literature and data review of stream drying and connectivity patterns in Russian River tributaries. The purpose of the tributary assessment is to provide ecological and seasonal context for interpreting mainstem results, to characterize the spatial and temporal sensitivity of smaller tributary habitats, and to identify data gaps relevant to future monitoring and management.

Additionally, this Ecosystem Climate Vulnerability Assessment evaluates how projected changes in hydrology and water quality may affect habitat conditions for listed salmonids in the Russian River Estuary (the lowest portion of the Russian River). The primary objective of the assessment is to compare habitat suitability across three modeled epochs (Historical [1981–2010], Mid-Future [2041–2070], and Late-Future [2071–2100]), to identify potential changes through time.

The following assessment focuses on two principal drivers of habitat suitability within the estuary:

- **Frequency of river mouth closure events –** Evaluated using a hydrologic model of the estuary that accounts for sand deposition in the mouth. The timing of closure events and their duration is predicted for different hydrologic scenarios.
- **Water quality and resulting habitat availability –** Evaluated using statistical relationships derived from a large database of water quality data collected in the estuary for Sonoma Water by University of California at Davis Bodega Marine Laboratory. This database includes hundreds of snapshots of instantaneous water quality conditions during times when the river mouth was historically open or closed. When paired with habitat suitability thresholds from Boughton et al. (2017), this produces a way of estimating a volume of suitable habitat available in the estuary related to river mouth closure duration.

9.3 Methodology

Discussion of the methodology for the ecosystem climate vulnerability assessment is organized according to approaches conducted for the mainstem Russian River and its tributaries as well as the Russian River Estuary.

9.3.1 Mainstem Russian River and Tributaries

9.3.1.1 Physical Habitat and Passage

The physical habitat and passage analyses in this assessment rely on daily flow outputs from the HEC-ResSim simulation platform described in Attachment C-1. HEC-ResSim simulates reservoir operations and river flows for the mainstem Russian River and Dry Creek on a daily timestep through continuous simulations from water years 1950–2100, using consistent operating rules for flood control, water supply, and environmental flow requirements (see model inputs and logic described in Attachment C-1). Modeled periods are summarized for comparison across three analysis epochs: Historical (1981–2010), Mid-Future (2041–2070), and Late-Future (2071–2100).

The assessment focuses on the following four key model nodes in the river network:

- Russian River at Cloverdale.
- Russian River at Healdsburg.
- Dry Creek at its confluence with the Russian River.
- Russian River at Hacienda.

These model nodes were selected to represent spatial gradients in hydrology and ecosystem function from upstream to downstream in the mainstem system and Dry Creek.

Modeled daily discharges from HEC-ResSim were compiled for 41 climate model simulations across each epoch. For each climate model and epoch, discharge values were grouped by calendar day across the 30-year period. For each calendar day, the 2.5th and 97.5th percentiles of that model's within-epoch distribution were calculated and values outside this 95% interval were excluded to reduce the influence of extreme events. The remaining values were then averaged to produce a representative mean discharge for that calendar day for that climate model and epoch, yielding an average daily hydrograph for each model in each epoch. Finally, for each calendar day, the mean and standard deviation were calculated across the 41 model-specific daily means to derive the epoch-average hydrograph and inter-model variability. Excluding extreme values limited the influence of large flow events that could obscure interpretation of seasonal patterns.

Modeled daily discharges from HEC-ResSim are interpreted to evaluate relative changes in physical habitat for salmonid spawning, fry, and juvenile life stages based on established depth–velocity relationships. Because reach-specific Weighted Usable Area curves are not available for the study locations, habitat suitability is assessed qualitatively using documented conceptual models that describe how discharge influences hydraulic conditions relevant to salmonids.

Within the Russian River watershed, channel incision, confinement, and floodplain disconnection limit the availability of suitable habitats. As a result, optimal conditions generally occur at low to moderate flows. Habitat suitability for all life stages generally decline at higher discharges due to increased velocities and loss of low-velocity margin habitat, and at very low discharges due to reduced depth and wetted area (NMFS 2008; NMFS 2025; ENTRIX, Inc. 2003). Modeled flows are interpreted in the context of this response, with intermediate discharges assumed to provide the most favorable hydraulic conditions.

Adult passage is constrained by critical riffles at three locations that become obstacles or impassable below defined flow thresholds. In the mainstem Russian River, these occur at Healdsburg (105 cubic feet per second [cfs]) and Hacienda (110 cfs), with a third located in Dry Creek (90 cfs). Given inherent model uncertainty, passage effects are evaluated based on relative changes in flow during the adult migration period for each species, rather than treating threshold values as absolute cutoffs.

9.3.1.2 Russian River and Dry Creek Tributary Watershed Flows

To supplement mainstem analyses, 41 simulations from the BCM were utilized to assess changes in total watershed-averaged flows for smaller tributary watersheds along the Russian River and Dry Creek. Various flow-related metrics at both seasonal and annual scales were evaluated under historical (1981–2010), Mid-Future (2041–2070), and Late-Future (2071–2100) climate conditions to qualitatively determine how changes in the timing and distribution of flows may impact ecosystems. Tributaries were evaluated based on various hydrologic unit code (HUC) 12 boundaries within the planning area. In some cases, HUC-12 boundaries were consolidated to simplify tributaries with forks or upper and lower reaches. Tributaries evaluated include: Forsythe Creek, Ackerman Creek, Robinson Creek, Feliz Creek, Pieta Creek, Alder Creek-Big Sulphur Creek (Alder Creek-Big Sulphur Creek + Little Sulphur Creek), Maacama Creek, Franz Creek, Porter Creek-Mark West Creek, Windsor Creek, Santa Rosa Creek (Upper + Lower Santa Rosa Creek), Laguna de Santa Rosa (Upper + Lower Laguna de Santa Rosa), Green Valley Creek, Peja Creek, Mill Creek, Ward Creek-Austin Creek (Ward Creek-Austin Creek + East Austin Creek), Dutch Bill Creek-Russian River, Dry Creek, and East Fork Russian River. Total watershed-averaged flows were assessed to determine projected changes in annual total flow volumes, 99th percentile 1-day and 3-day maximum annual flows, and seasonal total flow volumes for fall, winter, and spring. Changes in summer flow were not evaluated due to the prevalence of BCM-generated flow values of zero. Given the 270-meter spatial resolution of the BCM, additional uncertainties exist for smaller tributary areas where model performance is not as calibrated.

9.3.1.3 Water Quality

Water quality metrics were derived from the climate modeling described in Attachment C-1. Temperature and DO model output data were provided at 2-hour intervals for three of the four focal nodes (Cloverdale, Hacienda, and Dry Creek) under three climate models: ec-earth3-veg_ssp370, ec-earth3-veg_ssp585, and mri-esm2-0_ssp370.

For temperature, daily maximum values were calculated for each water year within each climate model and epoch, and then averaged across water years to generate a model-specific mean daily maximum time series. These model time series were subsequently averaged across all models within each epoch to produce epoch-level mean daily maximum temperatures. Results were evaluated against upper thermal tolerance thresholds for each species and life stage, with the exception of coho salmon at Cloverdale as they are unlikely to spawn or rear in this reach of the river (Table 9-1).

Table 9-1. Water Temperature Upper Tolerance Threshold for Russian River Salmonids by Life Stage

Scenario	Adult Migration	Spawning and Egg Incubation	Juvenile Rearing	Smolt Emigration
Chinook salmon	*(Oct 1–Dec 31)* 67.0°F	*(Nov 16–Mar 31)* 60°F	*(Apr 1–Jun 30)* 68.0°F	*(Apr 1–Jun 30)* 68.0°F
Coho salmon	*(Nov 1–Feb 28)* 70.0°F	*(Dec 1–Mar 31)* 54.5°F	*(Apr 1–Nov 30)* 64.0°F	*(Mar 1–May 31)* 62.5
Steelhead	*(Dec 1–Mar 31)* 70.0°F	*(Dec 1–Apr 30)* 54.5°F	*(Apr 1–Nov 30)* 64.0°F	*(Mar 1–May 31)* 62.5°F

Source: Sonoma Water (2016).

For DO, an analogous approach was used, except daily minimum values were calculated for each water year prior to averaging. These results were compared to the 6 milligram per liter (mg/L) threshold identified in Barnhart (1986), Hassler (1987), and Bjornn and Reiser (1991) for the onset of distress symptoms in salmonids.

9.3.1.4 Tributary Drying Sensitivity Assessment

The tributary drying sensitivity assessment was conducted through a literature review of gray literature reports, presentations, streamflow enhancement plans, and white literature articles specifically focused on the Russian River tributaries. Each document was reviewed systematically for the following types of information:

- Drying Metrics (e.g., percent wetted reach, wetted classifications, days of disconnections).
- Spatial Patterns (e.g., consistently drying segments, reach types, and proximity to mainstems [Dry Creek or Russian River]).
- Temporal Patterns (e.g., seasonal timing, drought sensitivity, interannual variability).
- Salmonid Implications (e.g., life stages impacted, survival/migration constraints, connectivity thresholds).
- Proposed Management Actions.

After the literature review, the complete wet–dry mapping database from 2012–2025 was summarized to determine whether any additional trends or patterns could be identified that could help contextualize the analysis.

9.3.2 Russian River Estuary

9.3.2.1 Evaluating Changes in River mouth Behavior

We apply the Russian River Quantified Conceptual Model (QCM) to understand how river mouth closure events could change in the future. The QCM is a process-based finite difference model designed to simulate the hydrologic and morphologic behavior of bar-built coastal lagoons (Behrens et al. 2015; Behrens and Battalio 2025). It is a relatively simple water balance of lagoons connected with a sediment balance for the lagoon mouth area. It predicts lagoon mouth closure, breaching, and water level dynamics using simplified representations of water and sediment fluxes. While not explicitly focused on biological habitat, the model's outputs, particularly lagoon water levels and mouth states, can be used to understand changes in habitat conditions for aquatic species, since water quality and hydrologic conditions are strongly controlled by mouth conditions (ESA 2021). During closed-mouth conditions, the estuary has no tidal connection to the ocean, and the estuary is composed of a freshwater layer (trapped river flows behind the beach) sitting atop a salty layer at the bottom and a transitional layer where salinity increases with depth. During open-mouth conditions, tidal exchange with the ocean maintains salty, cool, and well-mixed conditions in most of the estuary.

The QCM has been calibrated against more than 20 years of historical water level data at the Russian River estuary (Behrens and Battalio 2025) and is applied here to understand changes in mouth closure timing across the time period from 1950 to 2100. This is achieved by creating boundary conditions that reflect future river discharges into the estuary, future sea levels, future waves, and future atmospheric conditions over the estuary. Each of these boundary conditions are described below.

9.3.2.2 Evaluating Changes in Habitat Suitability in the Estuary

To quantify the effects of beach management on habitat suitability, the change in availability of steelhead rearing habitat was compared between open and closed river mouth conditions. This is termed here as the ‘suitable habitat acre-days’ or SHAD model. In this analysis, steelhead rearing habitat was characterized as the availability of the littoral (shallow/shoal), surface limnetic, and epibenthic habitats with suitable water quality characteristics. These conceptual habitat zones were based on observed habitats occupied, foraging behavior, and productivity/prey availability: Shallow/shoal littoral (< 1 m total depth), high prey availability; surface limnetic (top 1 m where total depth > 1 m), low prey availability; subsurface epibenthic (total depth 1 - 5 m), high prey availability; subsurface limnetic (from 1 – 5 m where total depth > 5 m), low prey availability; and profundal (> 5 m to bottom), low prey availability.

Boat-based vertical water quality profiles of the estuary (Figure 9-2) provide additional empirical detail on the relationship between habitat zones and inlet conditions (e.g. open or closed). UC Davis has an extensive database of water quality profiles in the estuary that span open and closed conditions (ESA & Bodega Marine Laboratory 2024). By applying thresholds for water quality suitability for salmonids (e.g., Boughton et al. 2017), and accounting for depths in different segments of the estuary, these water quality fields can be related to a total amount of acres of habitat available, and comparison in time can provide a way of quantifying variance of this acreage. ESA tracked changes in the availability of these habitats using a ‘suitable habitat acre-days’ metric to reflect both the spatial (acres) and temporal (days) dynamics of inundation. ESA applied the acre-days metric to quantify optimal habitat for juvenile salmonids under the proposed beach management scenarios.

National Marine Fisheries Service (NMFS) and the California Department of Fish and Wildlife (CDFW) have recently used the acre-day metric as means for quantifying changes in salmonid habitat within other dynamic systems including floodplains in the California Central Valley[7][8][9] relative to historical conditions, levees, dikes, and altered drainage reduced wetted-acre-days and overflow frequency in the Central Valley floodplains. NMFS and CDFW uses the acre-days metric because the baseline floodplain habitats analyzed approach zero inundation in many areas and thus percent-change metrics provide little analytical value. They therefore opt to track floodplain access and hydrological connectivity with acre-days and have defined significant benefits as an achievement of 10% change in frequency, with validation of professional judgement. NMFS and CDFW have evaluated floodplains with consideration to spatial and temporal extent to optimize juvenile salmonid rearing and adult passage by maximizing continuous downstream connectivity, targeting 14 day or longer inundation windows, and coordinating drainage activities with migration timing. As part of this assessment, we apply this metric to the Russian River Estuary, since inundation of shallow areas adjacent to the estuary is known to provide access to food sources and valuable habitat (Boughton et al. 2017).

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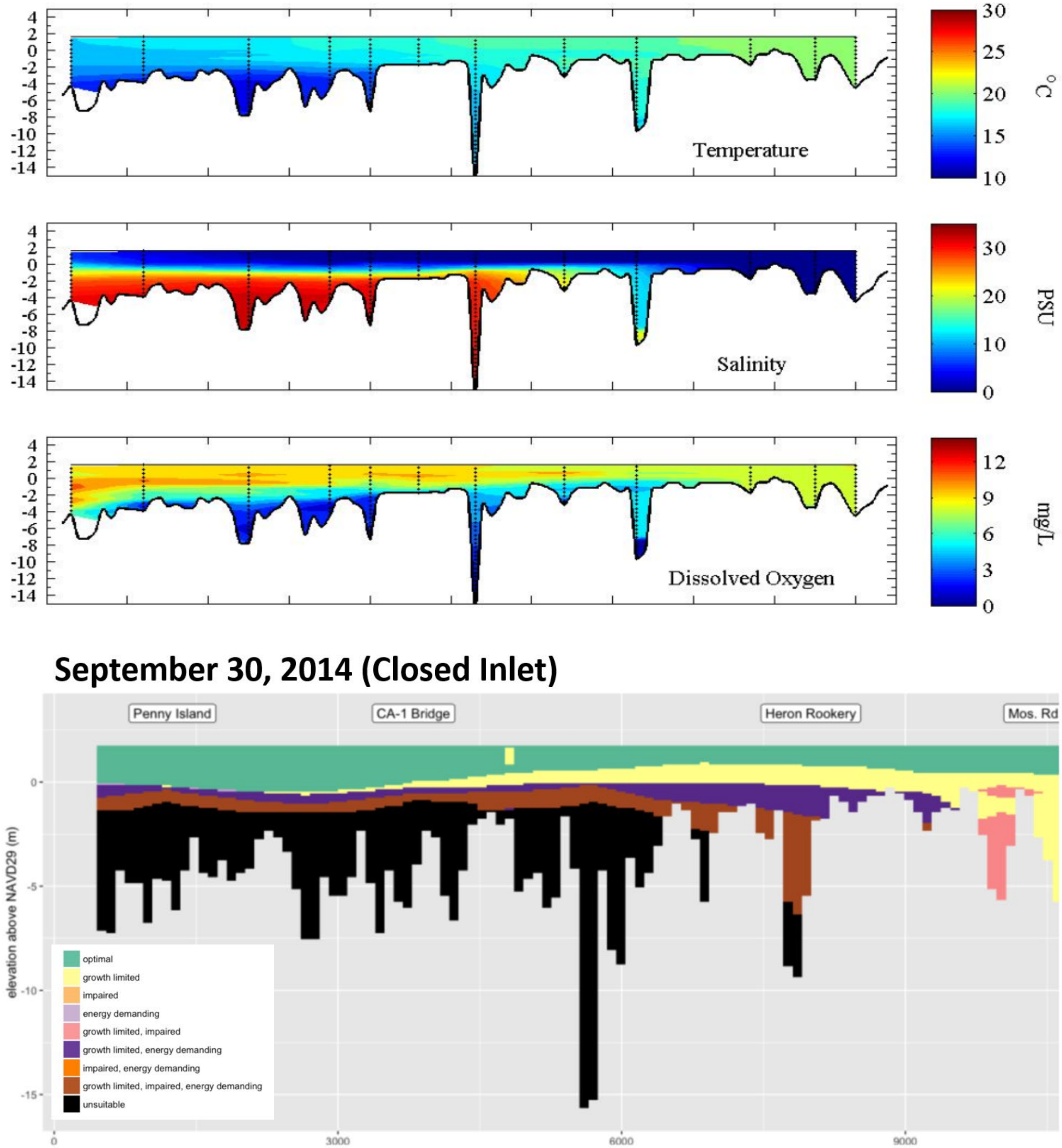
[7] CDFW, 2020. Managed Floodplain Design Criteria and Considerations.

[8] NMFS, 2021. White Paper on Central Valley Floodplain Management for Salmon: Considerations for Balancing Food Web Productivity and Fish Viability.

[9] CDFW, CDWR, and State Water Resources Control Board. 2023. *Draft Scientific Basis Report Supplement in Support of Proposed Voluntary Agreements for the Sacramento River, Delta, and Tributaries Update to the San Francisco Bay/Sacramento-San Joaquin Delta Water Quality Control Plan.*

Figure 9-2. Longitudinal Maps of the Russian River Estuary Showing Interpolated Temperature, Salinity, and Dissolved Oxygen Fields, Based on Boat-based Profiles Collected by UC Davis for a Specific Closed River Mouth (inlet) Condition on September 30, 2014

Lowest plot shows a map of habitat suitability within the estuary based on mapping the water quality parameters and applying the suitability thresholds identified by Boughton et al. (2017), funded by National Oceanic and Atmospheric Administration's (NOAA's) Habitat Blueprint initiative.



9.3.2.3 Changes to River Inflow

The estimates of future habitat conditions in this assessment (from the QCM model) rely on daily flow outputs from the HEC-ResSim simulation platform described in Attachment C-1. HEC-ResSim simulates reservoir operations and river flows for the mainstem Russian River and Dry Creek on a daily timestep through continuous simulations from water years 1950–2100, using consistent operating rules for flood control, water supply, and environmental flow requirements (see model inputs and logic described in Attachment C-1). Modeled periods are summarized for comparison across three analysis epochs: Historical (1981–2010), Mid-Future (2041–2070), and Late-Future (2071–2100).

Modeled daily discharges from HEC-ResSim were compiled for 41 climate model simulations across each epoch. For each climate model and epoch, discharge values were grouped by calendar day across the 30-year period. For each calendar day, the 2.5th and 97.5th percentiles of that model's within-epoch distribution were calculated and values outside this 95% interval were excluded to reduce the influence of extreme events. The remaining values were then averaged to produce a representative mean discharge for that calendar day for that climate model and epoch, yielding an average daily hydrograph for each model in each epoch. Finally, for each calendar day, the mean and standard deviation were calculated across the 41 model-specific daily means to derive the epoch-average hydrograph and inter-model variability. Excluding extreme values limited the influence of large flow events that could obscure interpretation of seasonal patterns.

As noted in other appendices, Russian River inflows are significantly different for future conditions:

- Early season (October – December): Modeled flows, which are increasingly (over time) driven by watershed runoff from early storms, in the Mid-Future and Late-Future epochs are lower than Historical flows from early October through late December.
- December – February: Shift toward more powerful peak flows dominated by precipitation-generated watershed runoff. Late-Future peak flows are notably higher than both Historical and Mid-Future flows. These increases are consistent with projected shifts toward more intense and concentrated precipitation events under future climate scenarios.
- March – May: Flows decrease progressively in the early dry season (associated with decreasing watershed runoff) for the two future scenarios relative to the historical flows. This pattern is consistent with projections of warmer and drier late-spring conditions.
- From early June through September, flows are largely governed by minimum instream flow requirements; however, both Mid-Future and Late-Future flows remain slightly lower than Historical flows throughout much of the regulated summer period, when natural watershed flows contribute less to river flows.

9.3.2.4 Changes to Oceanic Tides

Sea level rise is a long-term process that has been occurring for thousands of years, and is expected to accelerate in the near future as a result of global warming (OPC 2024). It will mainly alter the estuary habitat by raising local ocean tides, and thus changing the hydrology of the estuary as more areas are inundated daily. It is included as a boundary condition to the QCM model here using the most recent State of California's Sea Level Rise Guidance (OPC 2024) and the CCC's Sea Level Rise Policy Guidance (2024). The OPC recently finalized the State of California Sea Level Rise Guidance: 2024 Science and Policy Update (2024 Update), which provides projections for SLR at various locations along the coast of California through 2150 (OPC 2024). The 2024 Update presents five SLR scenarios and values that incorporate: (1) SLR observations, estimated and modeled projections, and uncertainties, and (2) a range of global greenhouse gas emissions scenarios, which rely on SSPs[10]. The OPC's 2024 Update recommends using a range of SLR amounts between the Intermediate and High Scenarios to inform appropriate SLR planning and project decisions. Additionally, it is recommended to utilize data from 1 of 12 NOAA tide gauges that are located along the coast of California. Using the data from the tide gauge closest to the project site can capture local variations due to tectonic activity, including uplift or subsidence. The nearest NOAA tide gauge to the Russian River estuary is the Point Reyes tide gauge. Table 9-2 presents the SLR projections for Point Reyes for these scenarios. For this study, intermediate scenario values are used.

Table 9-2. Projected Sea Level Rise Scenarios for Point Reyes (feet)

Year	Intermediate Scenario	Intermediate-High Scenario	High Scenario
2030	0.4	0.4	0.5
2040	0.6	0.7	0.8
2050	0.8	1	1.3
2060	1.1	1.6	2
2070	1.4	2.2	3
2080	1.9	3	4.1
2090	2.5	3.9	5.4
2100	3.1	4.8	6.6
2110	3.8	5.7	7.9
2120	4.4	6.4	9
2130	4.9	7	9.9
2140	5.5	7.6	10.9
2150	6	8.2	11.8

Source: CCC 2024, OPC 2024

9.3.2.5 Changes to Oceanic Waves

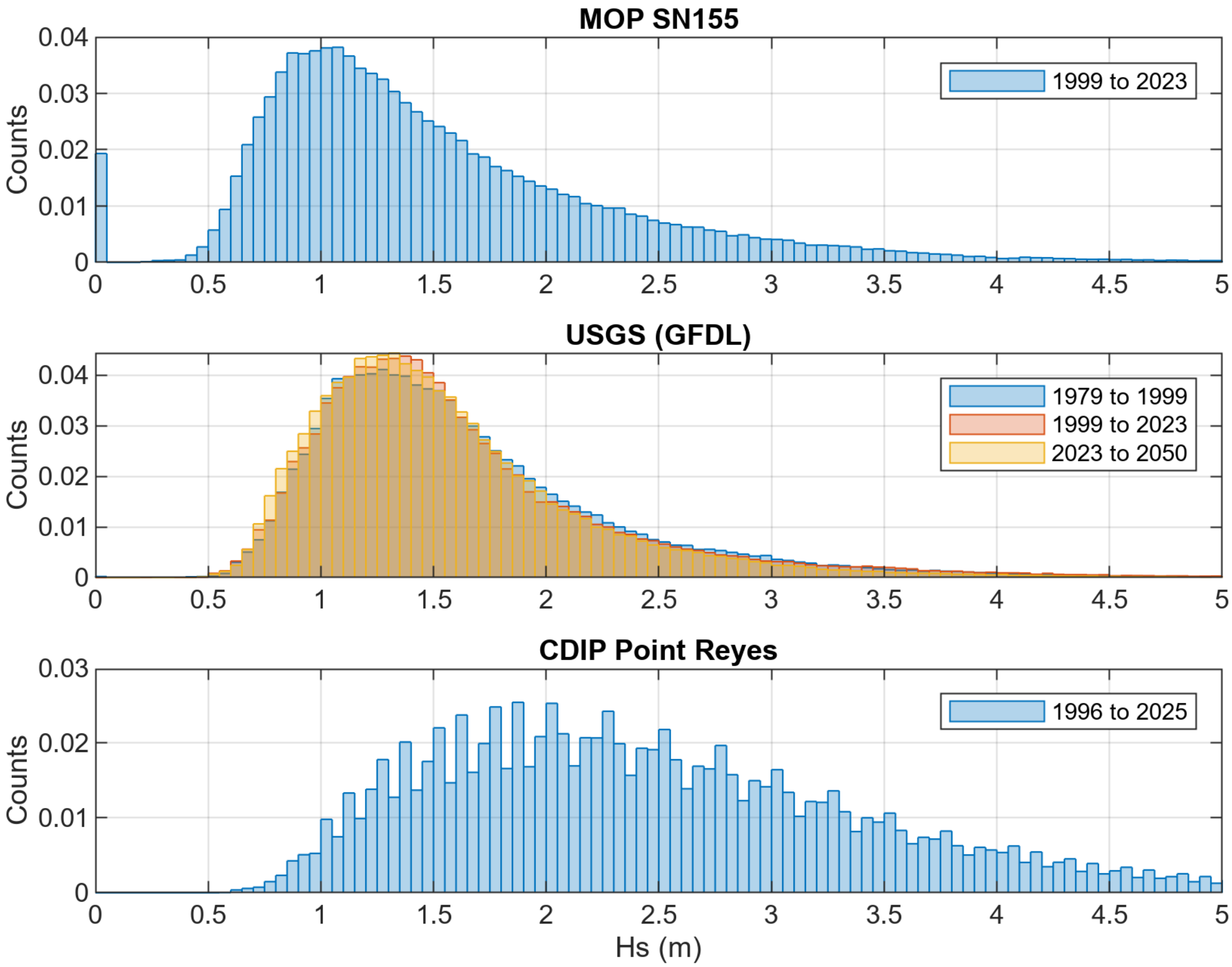
There is limited data available for future wave conditions. Erikson et al. (2016) released historical and wave projections for United States mainland coasts using GCMs from the Coupled Model Intercomparison Project, Phase 5 (CMIP5) and the WaveWatchIII numerical wave model. The historical time period spans the years 1976 through 2005, whereas the two future time periods encompass the mid (years 2026 through 2045) and end of the 21st century (years 2081 through 2099/2100). More recently, Erikson et al. (2022) released ver. 2.0 of future wave projections using similar approach but with CMIP6 wind and sea ice fields for seven GCMs, where historical period covers 1979 to 2014 but the projections only cover 2020 to 2050. ESA reviewed the USGS CMIP6 future wave data and found no obvious trend at an output station nearby

[10] SSP background from OPC 2024 guidance: Developed more recently, the SSPs are a collection of narrative descriptions of alternative futures of socio-economic development in the absence of climate policy intervention. Five SSPs describe five different pathways that the world could take, drawing on data including population, economic growth, education, urbanization, and the rate of technological development. The SSPs are important inputs into the IPCC sixth assessment and are used to explore how societal choices will affect greenhouse gas emissions. Pathways 5-85 (SSP 585) assumes heavy fossil-fueled development with high percentage of coal and energy-intensive lifestyles worldwide and assumes a radiative forcing of 8.5 W/ m^2.

(Figure 9-3). Therefore, we developed a record for 1950–2100 by repeating a historical period of measured wave conditions (2000 to 2025).

Figure 9-3. Example Wave Frequency Distribution Change from USGS CMIP6 Future Wave Dataset

X-values represent significant wave height values (Hs) at different locations. Coastal Data Information Program Point Reyes is the nearest offshore deepwater wave buoy. MOP SN155 is a station at 10 m depth near the mouth of the Russian River where the Scripps Institute of Oceanography provides predictions of nearshore wave conditions (transformed from the Point Reyes buoy). Y-values represent the percent of time that each Hs value was recorded at each location.



9.4 Results

Presentation of results for the ecosystem climate vulnerability assessment is separated into findings for the mainstem Russian River and its tributaries as well as the Russian River Estuary.

9.4.1 Mainstem Russian River and Tributaries

9.4.1.1 Physical Habitat and Passage

The physical habitat assessment evaluates flows averaged across the 41 BCM simulations and subsequently averaged within each epoch. As a result, the reported hydrographs necessarily smooth the magnitude of hydrologic variability and attenuate the apparent scale of change. For instance, in Dry Creek, average flow from January through February is 900 cfs during the Historical epoch and 992 cfs during the Late-Future epoch, representing an increase of approximately 10%. In contrast, peak simulated flow over the same period increases from 7,963 cfs to 12,668 cfs, or roughly 60%. Accordingly, interpretation of the averaged hydrographs should account for the fact that relatively small changes in mean flow may correspond to much larger changes in the magnitude of individual hydrologic events, with important ecological implications.

For all Russian River nodes, modeled flows in the Mid-Future and Late-Future epochs are lower than Historical flows from early October through late December (Figure 9-4). Reduced early season flows during this period may decrease habitat suitability for Chinook salmon spawning in the upper river (represented by the Cloverdale model node) by limiting adequate depth and appropriate velocity conditions. Lower flows may also delay upstream migration, particularly in the Late-Future epoch, where several climate model traces indicate that passage thresholds at Healdsburg and Hacienda may not be met until mid-December.

From late December through early February, average flows across all three epochs are generally similar before diverging in February and early March. During this period, Late-Future peak flows are notably higher than both Historical and Mid-Future flows. These increases are consistent with projected shifts toward more intense and concentrated precipitation events under future climate scenarios. Elevated flows during this window may increase the likelihood of streambed scour affecting Chinook salmon and steelhead redds (spawning) and could displace rearing Chinook salmon downstream.

Flows across the three epochs reconverge from mid-March through mid-April before diverging again from mid-April through early July. During this spring period, Mid-Future flows are lower than Historical flows, and Late-Future flows decline further. This pattern is consistent with projections of warmer and drier late -spring conditions. Because this period overlaps with juvenile outmigration, reduced flows may constrain available habitat, migration conditions, and associated survival for outmigrating salmonids.

From early June through September, flows are largely governed by minimum instream flow requirements; however, both Mid-Future and Late-Future flows remain slightly lower than Historical flows throughout much of the regulated summer period, which could have implications both for habitat availability and water quality (addressed below).

Results for Dry Creek show patterns that differ from the mainstem, particularly during the fall and summer periods when Lake Sonoma operations strongly influence discharge (Figure 9-5). From early October through early November, Historical flows are substantially lower than those under the Mid-Future and Late-Future epochs. Higher flows during this early-fall period may improve depth conditions for Chinook salmon spawning and increase the likelihood that adequate hydraulic conditions are available for upstream movement at critical riffles.

Figure 9-4. Modeled Average Daily Discharge at Russian River HEC-ResSim Nodes

Thin lines represent the mean daily hydrograph for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041 -2070], Late-Future [2071 -2100]), calculated by averaging daily flows across the 30-year epoch after excluding values outside the 2.5th to 97.5th percentile range for each calendar day. Thick lines represent the ensemble mean daily hydrograph for each epoch, computed by averaging the model-specific daily means across all 41 climate models.

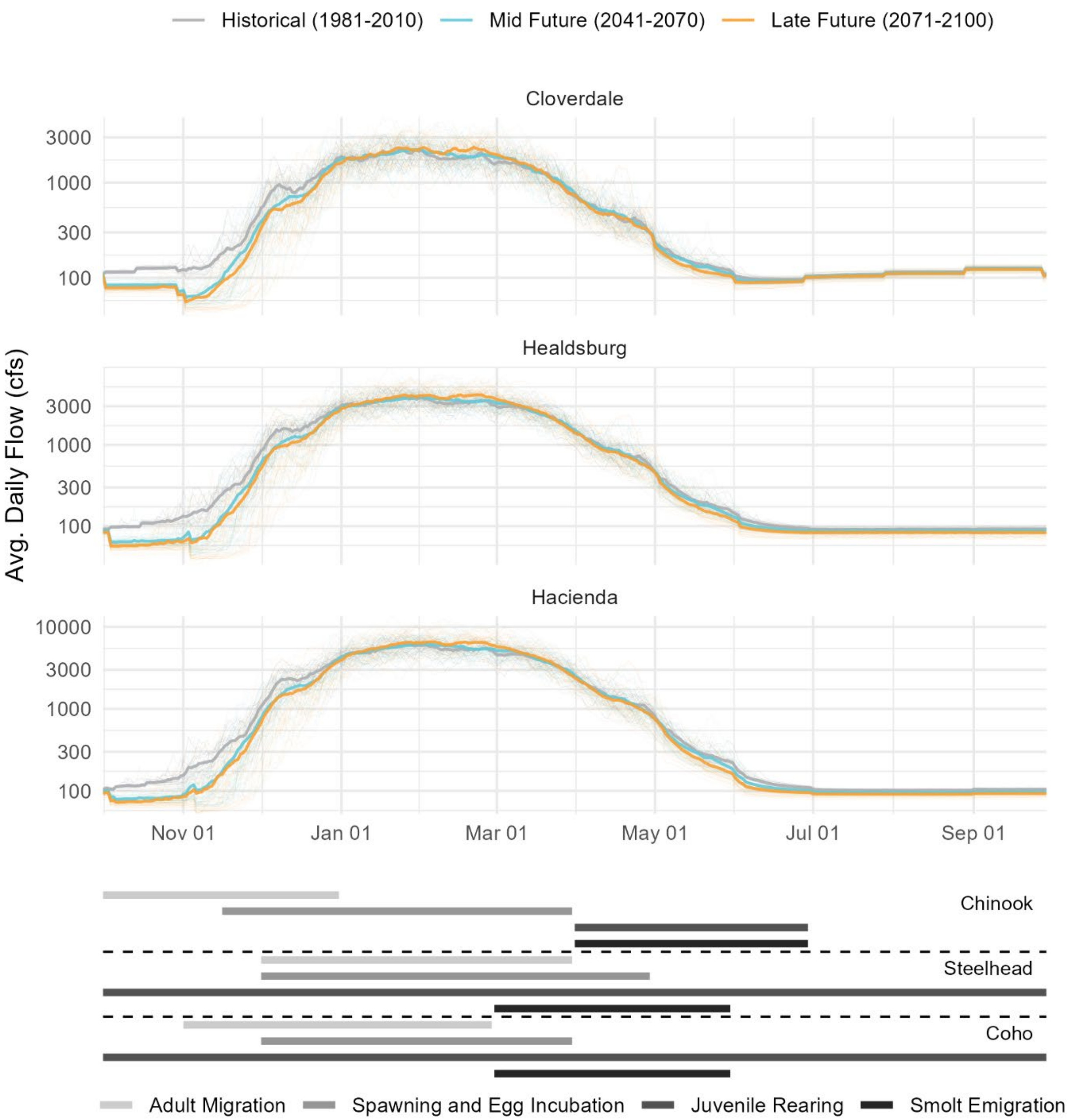
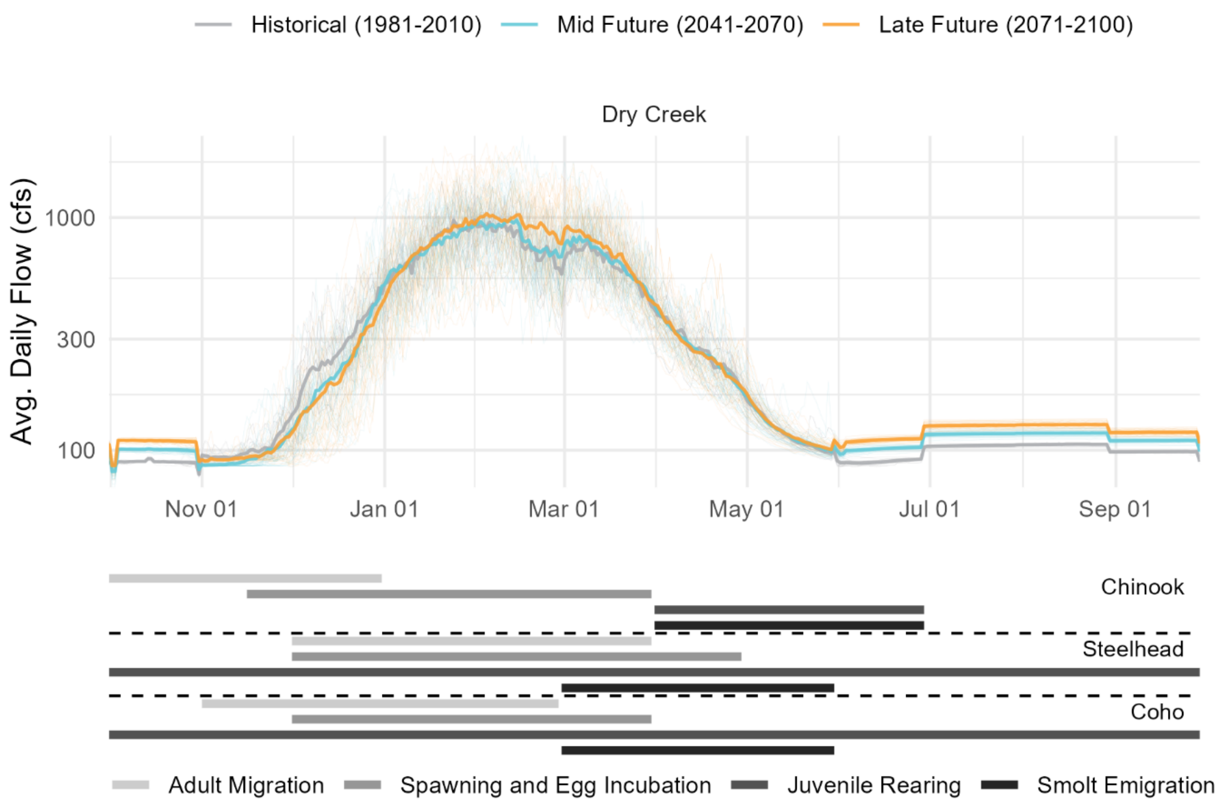


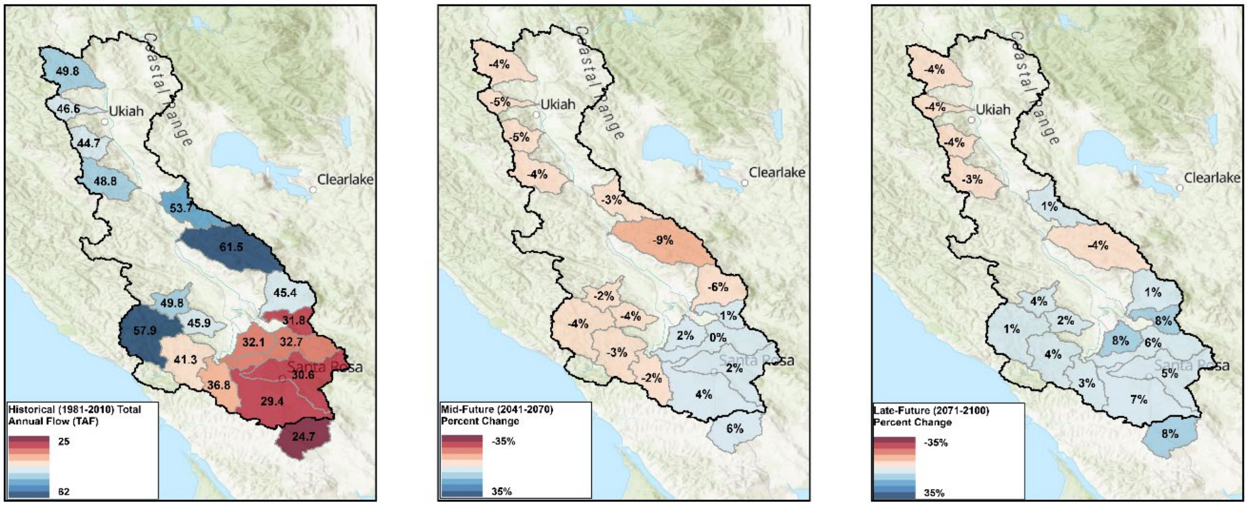
Figure 9-5. Modeled Average Daily Discharge for the Dry Creek at its Confluence with the Russian River HEC-ResSim Node

Thin lines represent the mean daily hydrograph for each individual climate model within each epoch (Historical [1981 -2010], Mid-Future [2041 -2070], Late-Future [2071 -2100]), calculated by averaging daily flows across the 30-year epoch after *excluding values outside the 2.5th -to 97.5th percentile range for each calendar day. Thick lines represent the ensemble mean daily hydrograph for each epoch, computed by averaging the model-specific daily means across all 41 climate models.*



Flows converge in early November, before diverging again from mid-November to early January. During this time Historical flows are generally higher than Mid-Future or Late-Future Flows. From early January through early February, flows across all three epochs converge once more. This pattern (higher Historical flows through much of winter), is consistent with patterns observed in the mainstem Russian River. During the following divergent period, Late-Future flows are notably higher than both Historical and Mid-Future flows. Elevated discharges in Late-Future conditions, which peaked at over 12,600 cfs in some model scenarios compared to 7,900 cfs during the Historical epoch, may increase velocities beyond preferred ranges for spawning and early rearing and could increase the potential for bed scour affecting coho salmon and steelhead redds. Higher flows may also increase downstream displacement of rearing Chinook salmon into the mainstem. Flows reconverge from March through early June before diverging again in early summer. During this latter period, both Mid-Future and Late-Future flows are higher than Historical flows. Sustained higher summer discharges may increase main-channel velocities and reduce the availability of low-velocity refuge habitat for over-summer rearing coho salmon and steelhead, consistent with established depth–velocity relationships for Dry Creek as described in the Fish Habitat Flows and Water Rights Project Draft EIR (SCWA 2016). Russian River and Dry Creek Tributary Watershed Flows Figure 9-6 displays the watershed-averaged change in total annual flow for assessed tributary watersheds under Mid-Future (2041–2070) and Late-Future (2071–2100) conditions. In general, changes in total annual flows under Mid-Future conditions range from a decrease of 9% to an increase of 6%. Increases are limited to the southeastern portion of the watershed. In Late-Future conditions, the geographic distribution of changes remains similar, with additional watersheds in the southern part of the planning area shifting from a slight decrease to a slight increase in total annual flow.

Figure 9-6. Percent Change in Total Annual Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)



Changes in 99th percentile annual 1-day (Figure 9-7) and 3-day (Figure 9-8) maximum tributary flows are far more variable across the watershed. For Mid-Future conditions, changes range from a decrease of 12% to an increase of 15% and a decrease of 3% to an increase of 11% for 1-day and 3-day maximum flows, respectively. For Late-Future conditions, changes shift toward higher peak flow conditions, with increases up to 32% (1-day) and 25% (3-day).

Figure 9-7. Percent Change in 99th Percentile Annual 1-day Maximum Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)

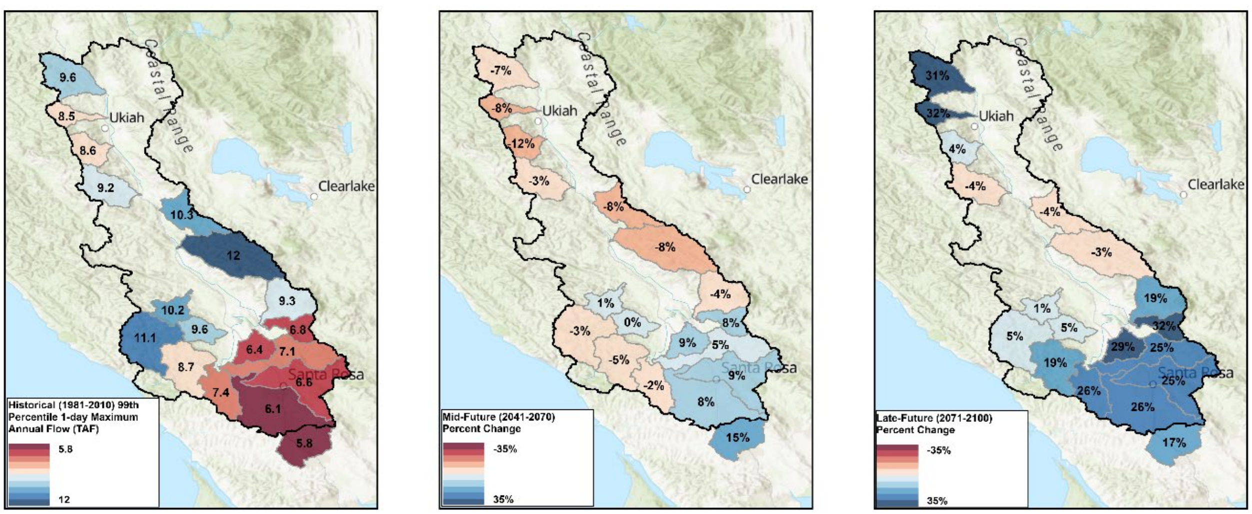
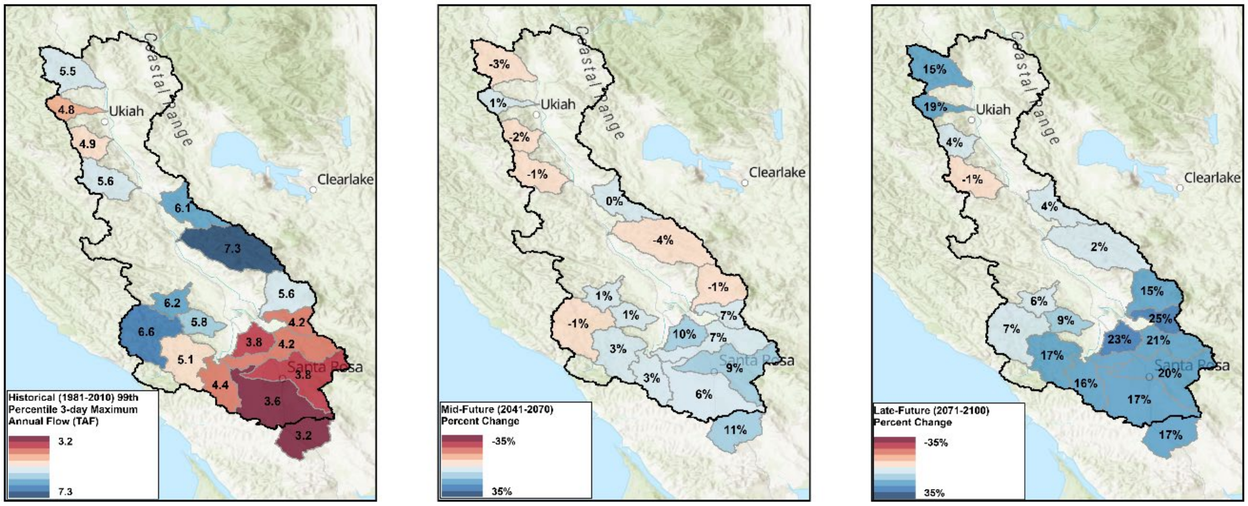


Figure 9-8. Percent Change in 99th Percentile Annual 3-day Maximum Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)



Shifts in total seasonal flows provide insight into changes in hydrograph conditions for each tributary watershed. For fall (Figure 9-9), both Mid-Future and Late-Future display declining total flow volumes, with decreases up to 15% and 23%, respectively. Seasonal totals during winter (Figure 9-10) become wetter from Mid-Future (up to 10% increase) to Late-Future (up to 15% increase) conditions.
Totals during the spring (Figure 9-11) display similar trends to conditions from the fall, with decreases of up to 12% for Mid-Future conditions and 25% for Late-Future conditions. In general, the southeastern portion of the planning area, including Porter, Windsor, Mark West, and Santa Rosa creeks, shows the lowest shift from historical conditions during fall and spring, but becomes the focal point for total flow volume increases in the winter.

Figure 9-9. Percent Change in Total Fall (October through December) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)

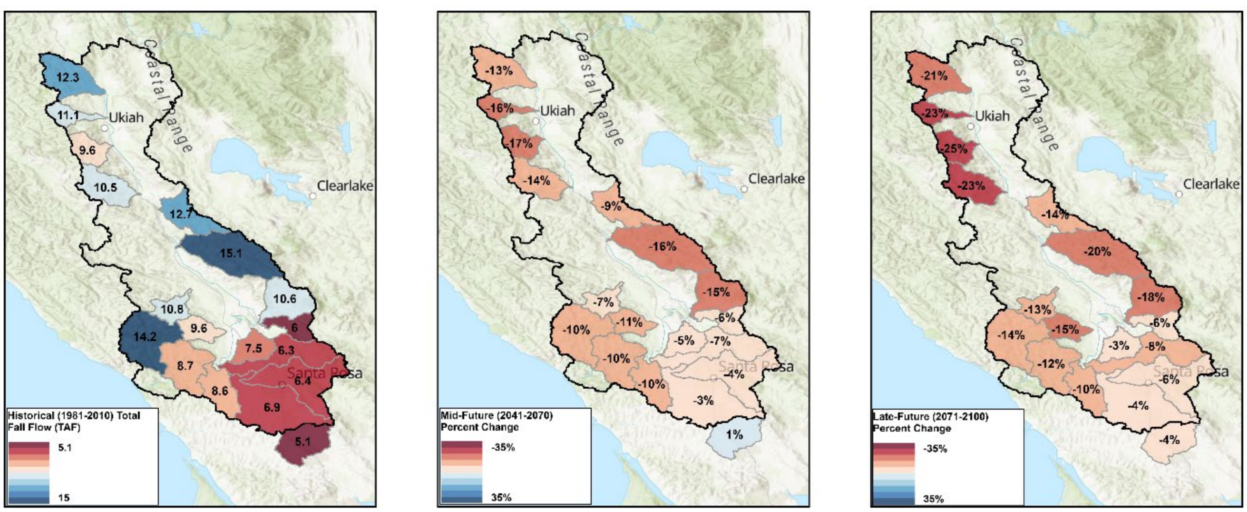


Figure 9-10. Percent Change in Total Winter (January through March) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)

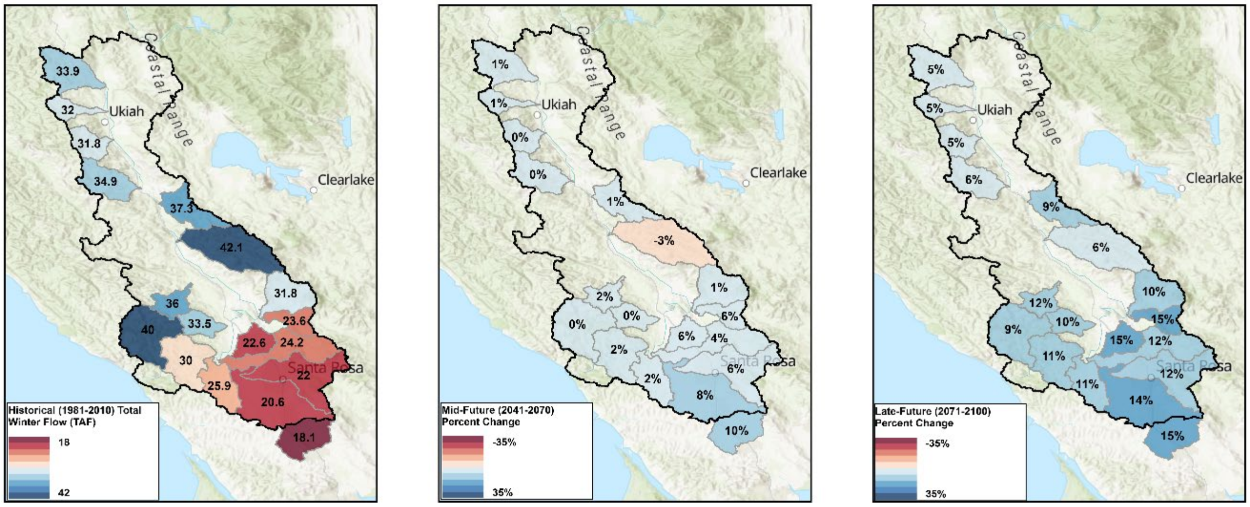
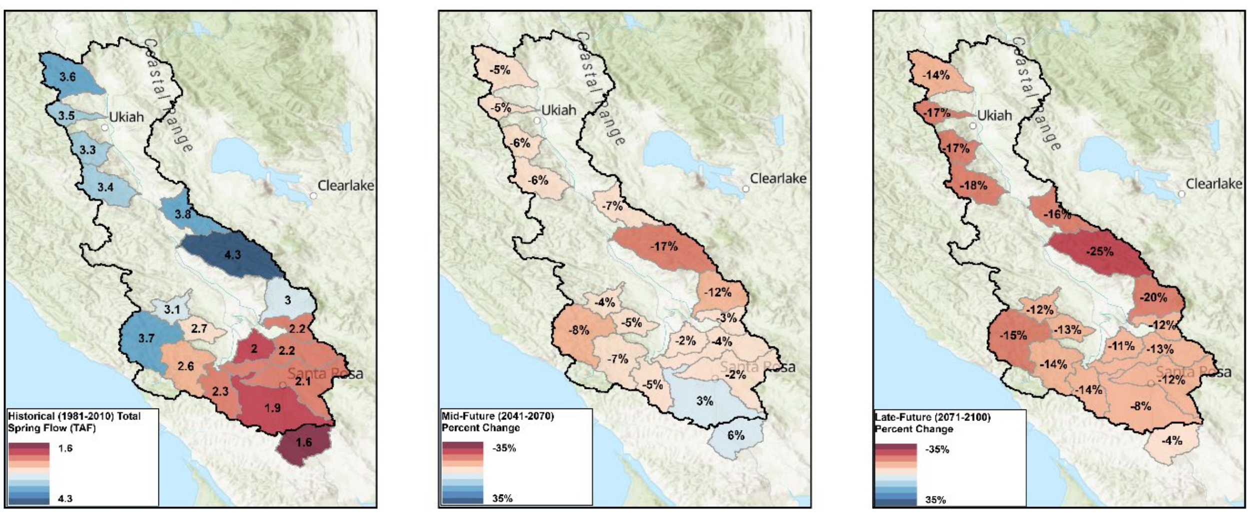


Figure 9-11. Percent Change in Total Spring (April through June) Seasonal Tributary Flow under Mid-Future (middle) and Late-Future (right) Conditions Relative to Historical Conditions (left)



In general, future conditions indicate a consolidation of flows into the winter season at the loss of total flow volumes in the fall and spring. This results in an increase in peak flows across the planning area and in some tributary watersheds, an increase in average annual total flow volumes. For ecosystems, these shifts are likely to result in increased stress for aquatic species that are dependent on flow signals in the fall and spring. For salmonids, reductions in the fall flows may delay upstream migration and decreases in flows during the spring may result in lower habitat availability, decreased survival during outmigration, and shifts in population distributions. For many of these tributary watersheds, and contrary to the main stem locations presented above, no mechanism exists to manage the sharper hydrograph peak and more closely mirror the historical timing and distribution of flows.

9.4.1.2 Water Quality

Temperature

Generally, temperatures under climate models increased over time, with temperatures in the Mid-Future model approximately 3 degrees Fahrenheit (°F) higher than Historical and temperatures in the Late-Future approximately 6°F higher (Figure 9-12 through Figure 9-14). During periods when temperatures are well below the upper tolerance thresholds (Table 9-1) (December–March), these increases will be less impactful than during the warmer months (April–November).

Adult Salmon and Steelhead Migration (October–March) (Figure 9-12)

During this period, temperatures are generally well below the maximum temperature limits for adults under all climate models at all three nodes. The one exception to this is the mainstem Russian River during October of the Late-Future epoch. At this node, the mean daily maximum temperature across all models rises above the upper tolerance threshold.

Salmon and Steelhead Spawning and Egg Incubation (November–April) (Figure 9-13)

Generally, temperatures are higher during the Mid-Future and Late-Future epochs and may have negative effects, especially at the beginning and end of the season. At Cloverdale, temperatures are generally suitable for Chinook salmon and steelhead egg incubation until the end of the season. The upper tolerance limit is reached earlier in the Late-Future epoch (late March) than in the Mid-Future (early April) or Historical (mid-April) epochs. At Dry Creek, temperatures are generally suitable throughout the period for both Chinook salmon and steelhead, however, Coho salmon may be affected during December and March, especially during the Late-Future epoch. Similar to Dry Creek, at Hacienda, temperatures are generally suitable for Chinook salmon and steelhead until late March. However, also like Dry Creek, Coho salmon may be affected during December and March, especially during the Late-Future epoch.

Juvenile Rearing (April–November) (Figure 9-14)

For all species, mainstem summer temperatures eventually exceed upper tolerance thresholds during some or most of the rearing period, even during Historical epoch. While in Dry Creek, temperatures are suitable for all species at this life stage year-round.

Figure 9-12. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During the Adult Migration Period (October–March).

Thin lines represent the mean maximum daily temperature for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]), calculated by averaging the maximum daily temperature across the 30-year epoch. Thick lines represent the ensemble mean daily hydrograph for each epoch, computed by averaging the model-specific daily mean maximums across the three climate models. Dotted and dashed horizontal lines represent the species-specific thermal limit for this life stage.

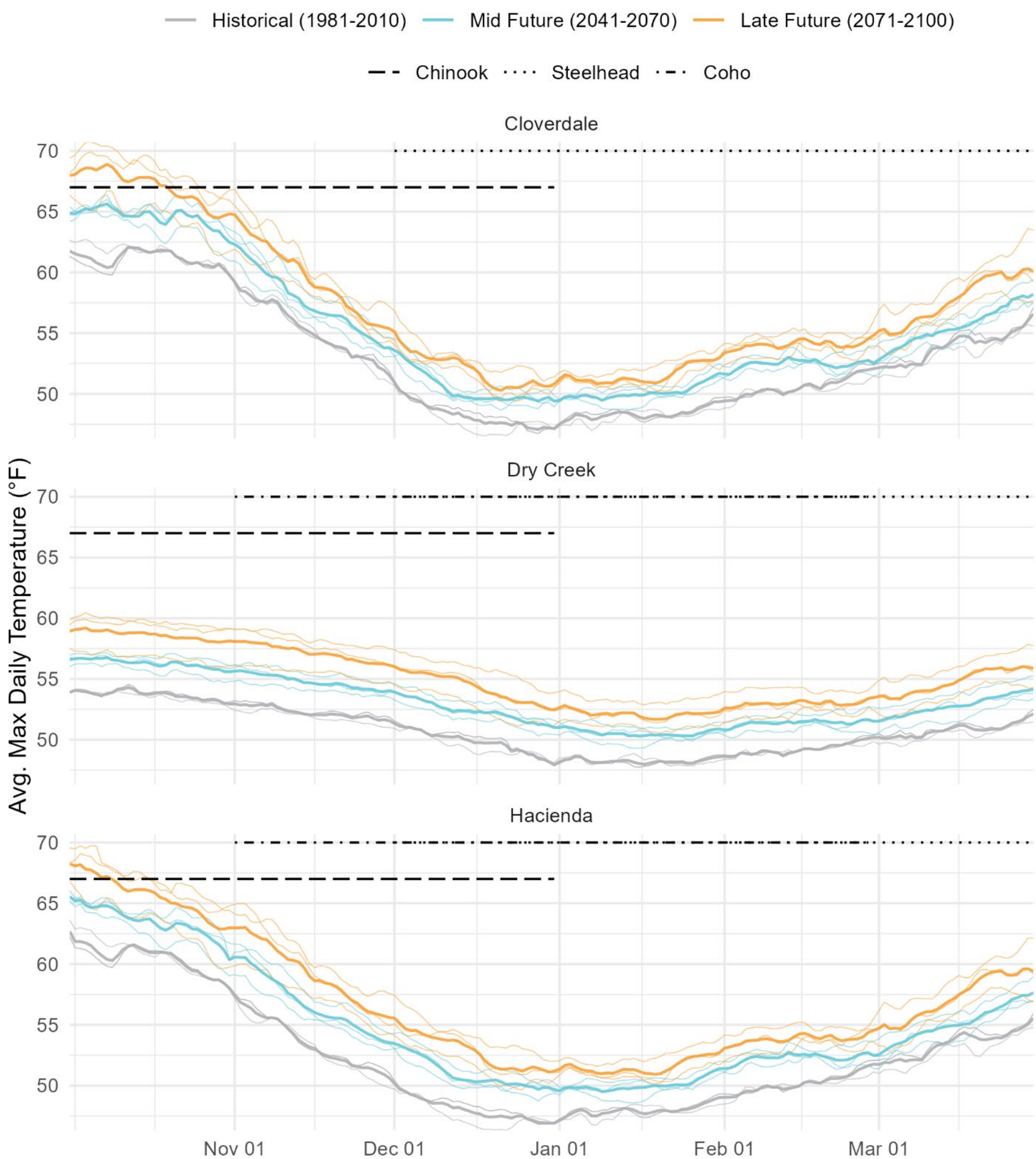


Figure 9-13. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During the Spawning and Incubation Period (November–April)

Thin lines represent the mean maximum daily temperature for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]), calculated by averaging the maximum daily temperature across the 30-year epoch. Thick lines represent the ensemble mean daily hydrograph for each epoch, computed by averaging the model-specific daily mean maximums across the three climate models. Dotted and dashed horizontal lines represent the species-specific thermal limit for this life stage.

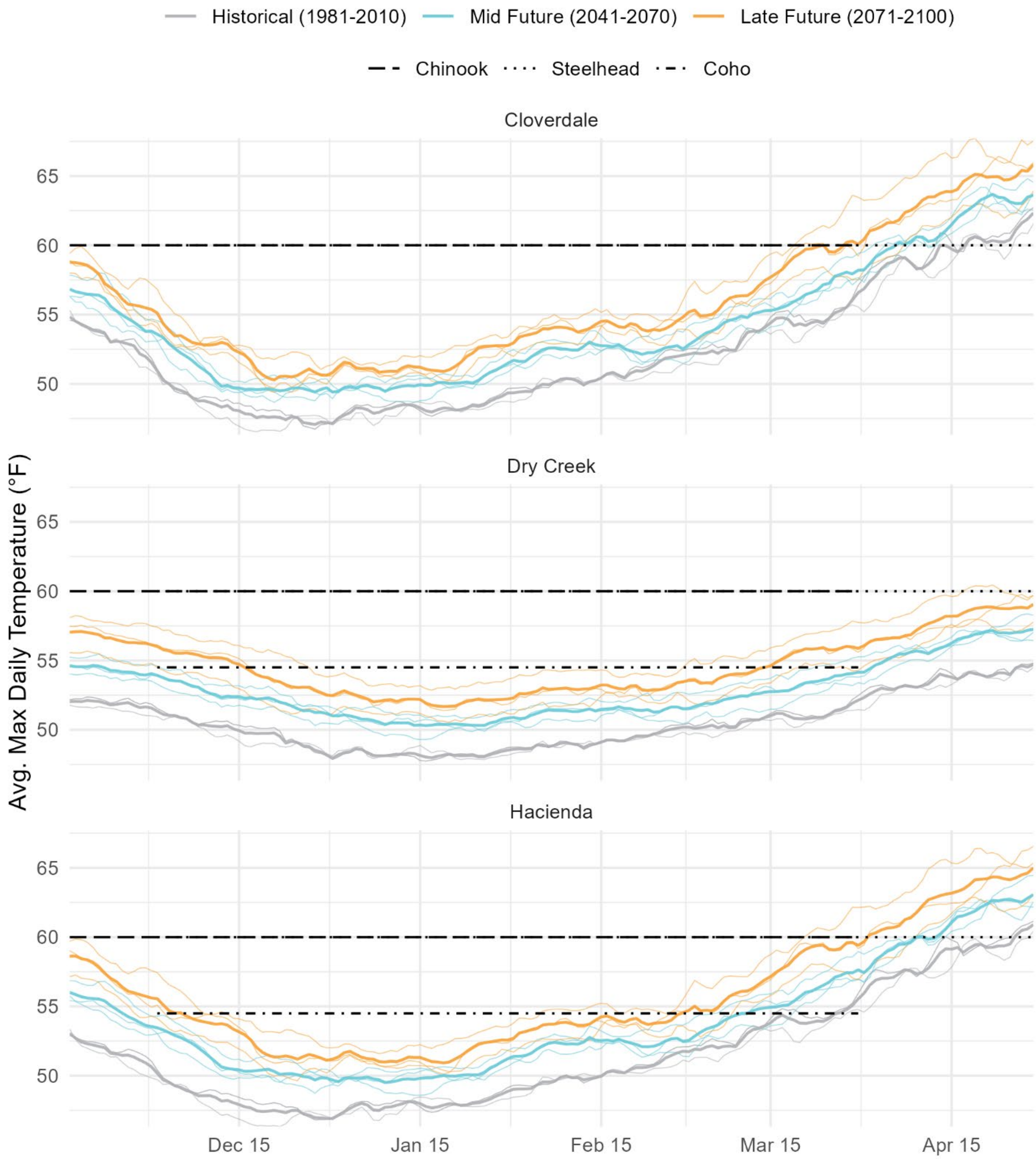
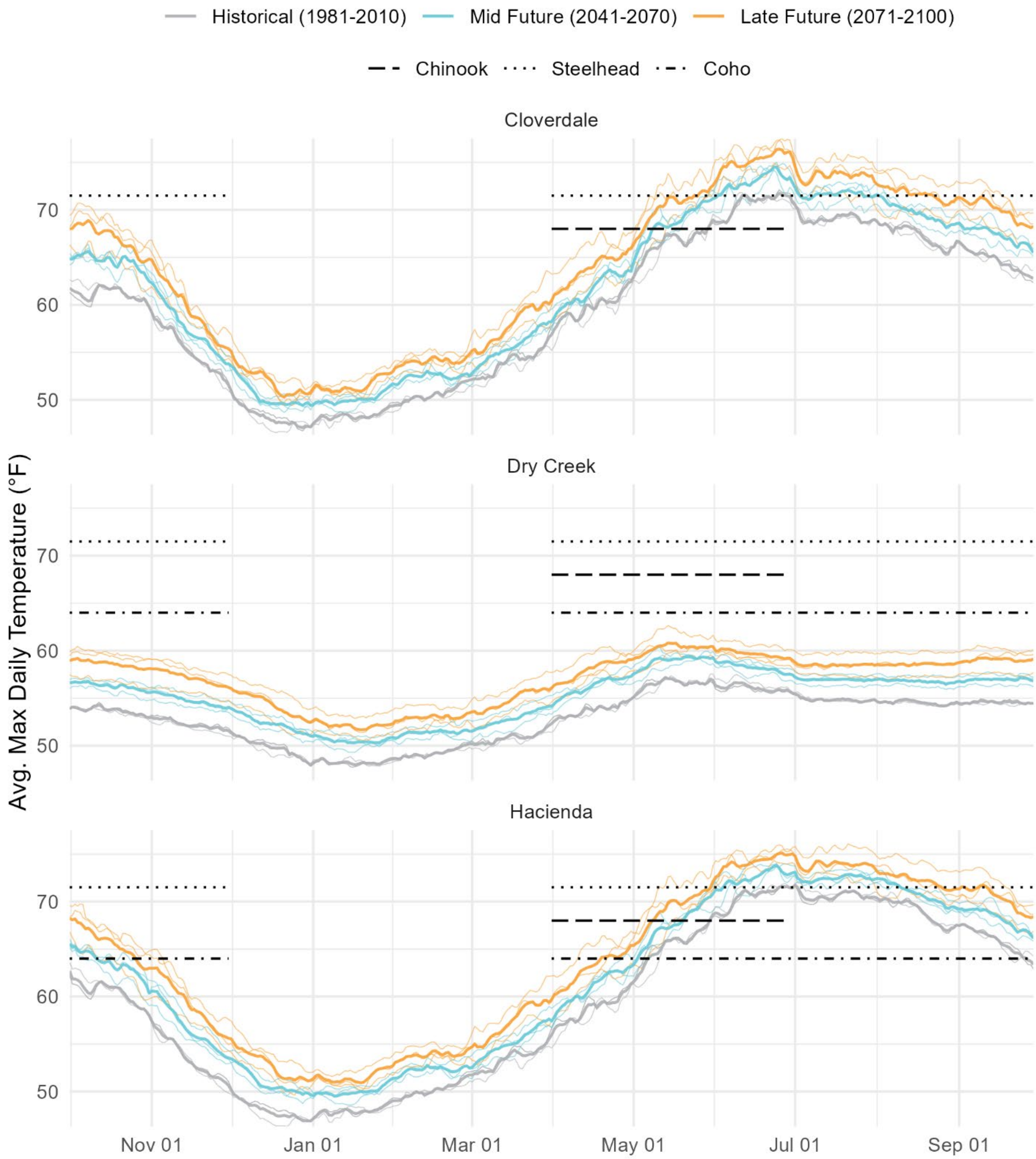


Figure 9-14. Modeled Average Maximum Daily Temperature for the Three Water Quality Nodes During Salmonid Juvenile-rearing Period (April–November)

Thin lines represent the mean maximum daily temperature for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]), calculated by averaging the maximum daily temperature across the 30-year epoch. Thick lines represent the ensemble mean daily hydrograph for each epoch, computed by averaging the model-specific daily mean maximums across the three climate models. Dotted and dashed horizontal lines represent the species-specific thermal limit for this life stage.



Dissolved Oxygen

DO concentrations were projected above the 6 mg/L limit at the Dry Creek and Hacienda nodes for all epochs under all models (Figure 9-15 and Figure 9-16). However, for the Cloverdale node, the mean minimum DO concentration falls below the threshold in early May during the Late-Future epoch and remains near or below the threshold throughout summer and early fall. DO concentrations during the Mid-Future and Historical epochs does not drop as far and remains at or just above the threshold throughout summer.

Figure 9-15. Modeled Average Daily Minimum Dissolved Oxygen at Russian River Nodes

Thin lines represent the mean minimum daily DO for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]), calculated by averaging minimum daily DO across the 30-year epoch. Thick lines represent the ensemble mean daily minimum DO for each epoch, computed by averaging the model-specific daily means across the three climate models.

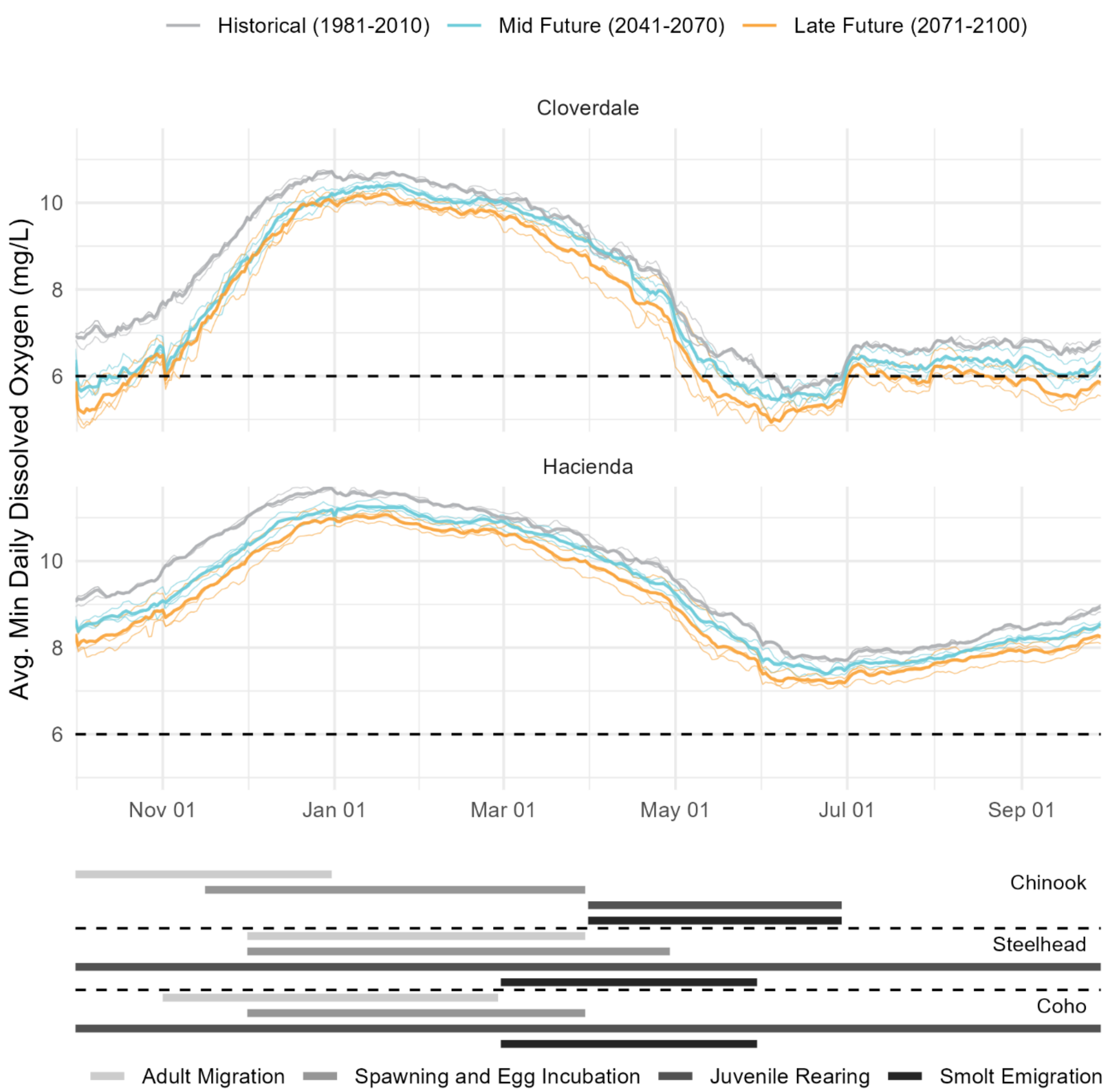
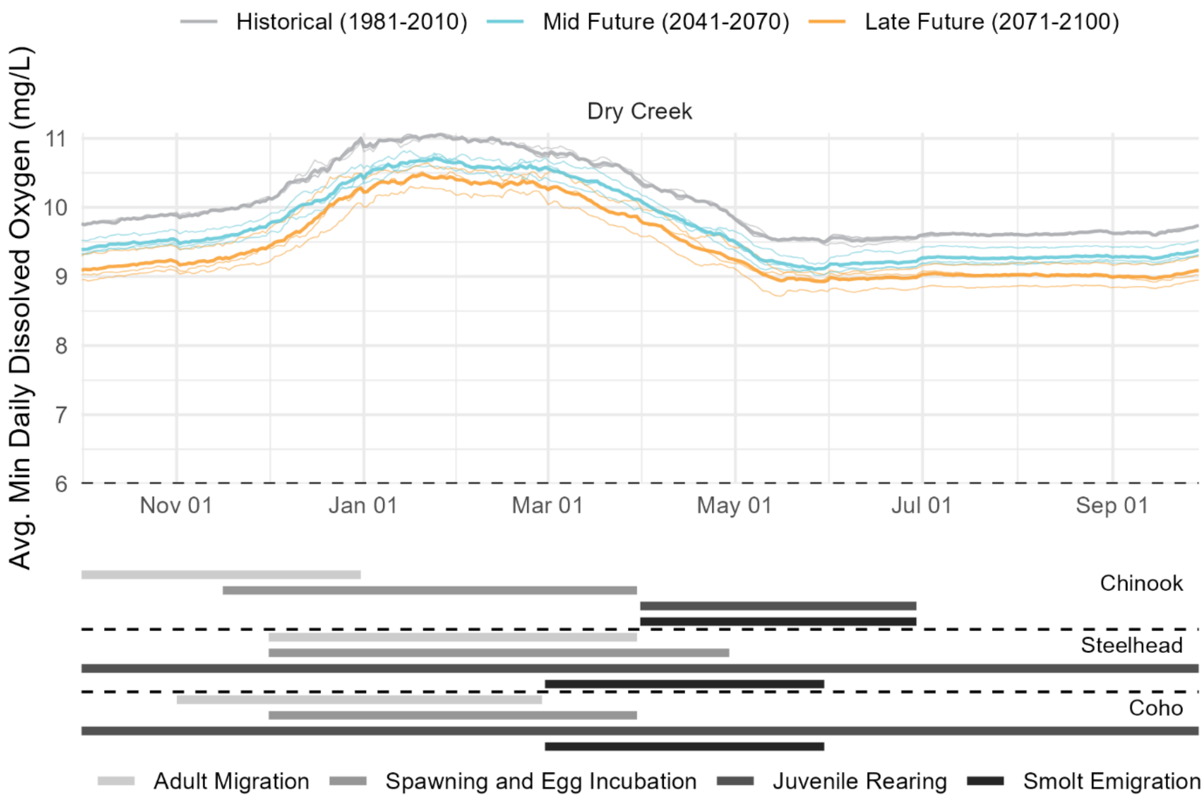


Figure 9-16. Modeled Average Daily Minimum Dissolved Oxygen at Dry Creek

Thin lines represent the mean minimum daily DO for each individual climate model within each epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100]), calculated by averaging minimum daily DO across the 30-year epoch. Thick lines represent the ensemble mean daily minimum DO for each epoch, computed by averaging the model-specific daily means across the three climate models.



9.4.1.3 Tributary Drying Sensitivity Assessment

Literature Review

Russian River tributaries provide essential spawning, rearing, and migration habitat for coho salmon and steelhead, but the extent and quality of this habitat contract predictably each year as flows recede through late spring and summer. Across several tributaries throughout the watershed, studies consistently identify the seasonal transition from continuous surface flow to disconnected pools as a critical ecological threshold that governs habitat availability and fish performance (Obedzinski et al. 2018; Vander Vorste et al. 2020; California Sea Grant 2019; California Sea Grant 2022).

Seasonal Dynamics of Drying

Drying in Russian River watershed tributaries follows a strong seasonal pattern. Flow connectivity typically begins to decline in late spring or early summer as winter runoff diminishes, with the most extensive habitat contraction occurring from July through September (California Sea Grant 2018, 2019, 2022; Trout Unlimited and California Sea Grant 2023a). Late-season surveys repeatedly show that substantial portions of tributary channels can shift from wet to intermittent or dry by the end of summer. For example, basin-wide mapping in 2018 documented that approximately 63% of surveyed tributary length remained wet in late summer, while 11% was intermittent and 27% was completely dry (California Sea Grant 2019). Similar late-season surveys in 2021, a severe drought year, found that only about 51% of the approximately 120 miles of streams surveyed across 45 tributaries remained wet and connected (Trout Unlimited and California Sea Grant 2023a).

The timing of disconnection is particularly important for salmonids because it frequently coincides with critical biological periods. Over-summering juvenile coho and steelhead must survive the summer rearing period in increasingly fragmented habitats, and smolt outmigration in spring can be constrained when tributaries lose connection to the Russian River prematurely (Nossaman-Pierce 2022a; Russian River Coho Water Resource Partnership 2017; Rossi et al. 2023; Nossaman-Pierce 2022b). Multiple tributary plans document years when adult access to spawning habitat or juvenile emigration was delayed until the first substantial fall rain re-established surface connectivity (Russian River Coho Water Resource Partnership 2017; Nossaman-Pierce 2022c).

Spatial Dynamics of Drying

Drying is highly variable across space, both among tributaries and within individual stream networks. Wet--dry mapping and predictive modeling demonstrate that end-of-season wetted extent is strongly structured by physical setting and proximity to the mainstem Russian River (Moidu et al. 2021). Analyses of 25 Russian River tributaries (primarily in the lower watershed) found that lower tributary reaches near the Russian River are disproportionately likely to become dry, whereas upper watershed reaches are more likely to remain persistently wet (Moidu et al. 2021). In that study, only a small fraction of reaches was classified as “reliably wet,” while a larger portion was categorized as “variable,” indicating sensitivity to annual precipitation and antecedent conditions (Moidu et al. 2021).

Tributary-specific monitoring further illustrates these spatial gradients. In Mill Creek, late-season surveys in 2022 showed that habitat upstream of Mill Creek Falls remained largely wet and connected, while downstream alluvial reaches were mostly dry or intermittent except for isolated patches near the mouth (Trout Unlimited and California Sea Grant 2023b). In Mark West Creek, late-season mapping in 2021 documented numerous localized disconnections concentrated near the Porter Creek confluence, while upstream segments retained higher levels of connectivity (Trout Unlimited and California Sea Grant 2023a). Conversely, in 2022—a wetter year—Mark West Creek remained largely wet and connected across most of the surveyed extent, demonstrating how the same tributary can shift between years from broadly connected to partially fragmented depending on hydrologic conditions (Trout Unlimited and California Sea Grant 2023a).

These examples highlight that climate vulnerability may not be uniform across the basin. Drying tends to be most pronounced in lower, alluvial valley-bottom segments, while headwater reaches and groundwater-influenced areas are more likely to retain persistent wetted habitat (Moidu et al. 2021; California Sea Grant 2022; Trout Unlimited and California Sea Grant 2023b).

Groundwater-Supported Refugia

Although drying is widespread, multiple sources note that some residual pools persist through summer even when surface flows approach zero, likely supported by hyporheic exchange or shallow groundwater inputs (Obedzinski et al. 2018; Vander Vorste et al. 2020; Trout Unlimited and California Sea Grant 2023b). These groundwater-influenced habitats function as localized refugia that can sustain juvenile salmonids through otherwise inhospitable periods. From a climate vulnerability perspective, such areas represent critical groundwater-dependent ecosystem features that provide disproportionate ecological value but may themselves be sensitive to declining baseflows and increasing drought intensity.

Empirical data collection in Russian River tributaries has linked over-summer survival of juvenile coho to flow-related variables, with survival positively associated with streamflow magnitude, wetted volume, and DO, and negatively associated with days of disconnected surface flow and temperature; “days of disconnection” was identified as the best overall predictor of survival across study reaches, though relationships vary by reach type and drought conditions (Obedzinski et al. 2018). Related analyses of drought impacts highlight that some pools can function as refugia even during extreme drought, but that an increasing number of pools show reduced or near-zero survival in drought years, and that longer duration of disconnection is a major driver of reduced survival during drought (Vander Vorste et al. 2020). These findings support a tributary-focused climate vulnerability framing in which longitudinal connectivity, persistence of wetted habitat (pool volume and extent), and temperature and DO conditions jointly determine the capacity of tributaries to support listed salmonids through dry-season rearing and spring migration bottlenecks.

Annual wetted habitat mapping further documents that, even in a comparatively “improved” year relative to recent drought years, substantial portions of surveyed tributary channels can become intermittent or dry by late summer. For example, in 2018, across all surveyed habitat in a set of lower Russian River tributaries, approximately 63% remained wet through the dry season, approximately 11% became intermittent, and approximately 27% went completely dry, with tributary-to-tributary differences (e.g., Mill and Felta reported reduced wetted habitat relative to 2017, and Wallace Creek showing a high proportion of dry habitat in its single 2018 survey) (California Sea Grant 2018, 2019). These spatial differences are important because climate vulnerability is unlikely to be uniform across tributaries; rather, it is expected to concentrate in reaches where disconnection occurs earlier, lasts longer, and coincides with warm temperatures and low DO.

Mark West Creek provides an example of a tributary system where local conditions can support substantial late-summer connectivity even under severe drought, but where low flow and water quality impairment still emerge seasonally at some sites. In water year 2021 (October 2020–September 2021), wetted habitat mapping documented increasing disconnections into summer, with notable drying near the Porter Creek confluence area; the same report notes that, basinwide in 2021, only approximately 51% of approximately 120 miles sampled across 45 streams remained wet and connected through the dry season (Trout Unlimited and California Sea Grant 2023a). In water year 2022, a higher proportion of basinwide wetted habitat remained connected relative to water year 2021, and within the study area Mark West Creek remained largely wet and connected, illustrating how interannual hydroclimatic variability can shift the extent of dry-season habitat contraction (Trout Unlimited and California Sea Grant 2023a). Importantly, Mark West Creek water quality monitoring indicates DO objectives were not consistently met at all sites (with large site-to-site differences in the proportion of days meeting a daily minimum objective), reinforcing that “wet” habitat is not necessarily “suitable” habitat without adequate water quality (Trout Unlimited and California Sea Grant 2023a).

Finally, while this tributary synthesis is focused on surface water connectivity and pool persistence, multiple sources emphasize that residual pools can remain occupied when surface flows approach zero, potentially sustained by hyporheic exchange and/or groundwater inputs (Obedzinski et al. 2018). From a climate vulnerability perspective, these groundwater-influenced pools and reaches function as groundwater-dependent ecosystem features that may provide disproportionate refuge value during extended dry periods.

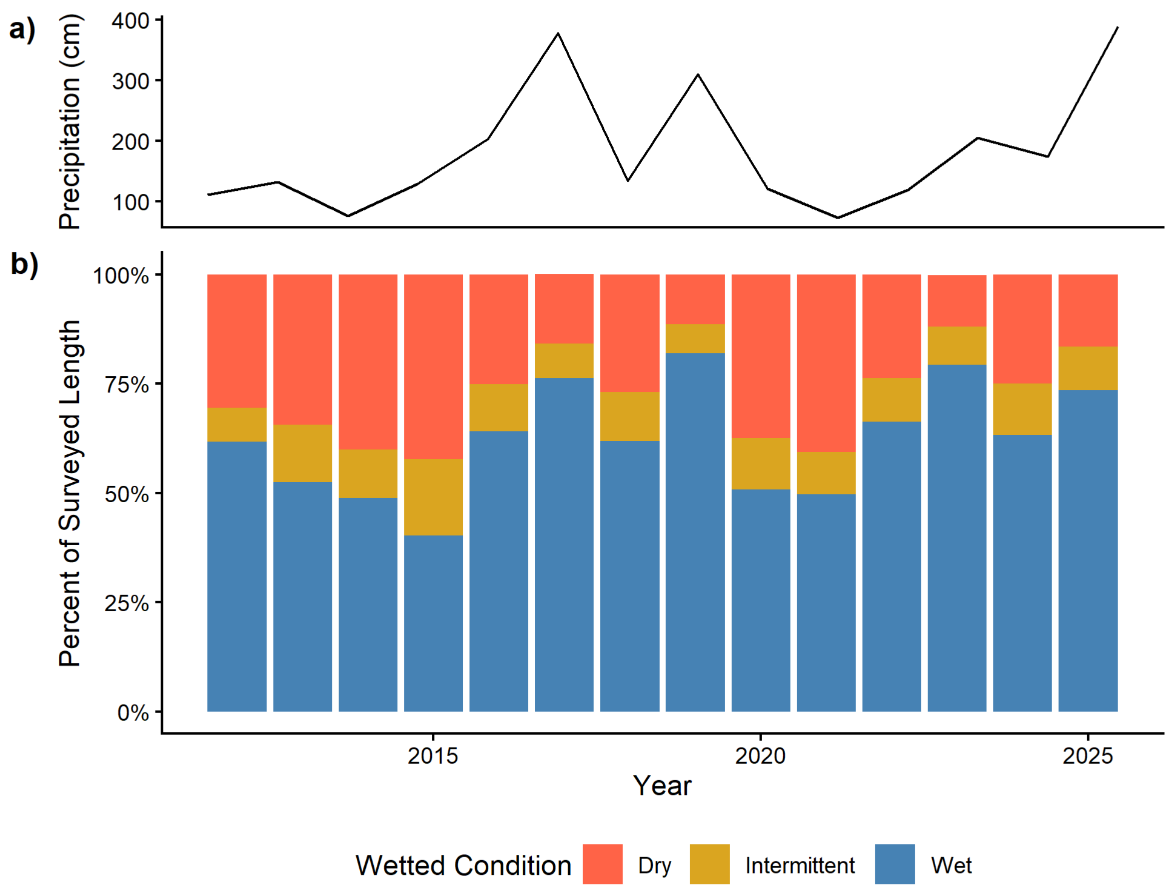
9.4.1.4 Wet/Dry Mapping Data Review

A preliminary review of the long-term wet–dry mapping dataset collected by Sea Grant and Sonoma Water demonstrates that tributary connectivity responds strongly to interannual precipitation patterns, while also exhibiting evidence of buffering by shallow groundwater systems (Figure 9-17). Even during the severe drought period of 2013–2015, a portion of surveyed habitat remained connected, indicating that some reaches retain flow persistence despite very low rainfall. The dataset shows a general decline in the proportion of wet and connected habitat from 2012 through 2015 when cumulative annual precipitation remained below approximately 150 centimeters (cm). Connectivity increased markedly in 2016 and 2017 when precipitation exceeded 200 cm and remained relatively high in 2018 despite more moderate precipitation. Subsequent dry years in 2020 and 2021 corresponded with renewed declines in connectivity.

These patterns illustrate both the sensitivity of tributaries to annual climate variability and the importance of groundwater-supported persistence in moderating complete loss of habitat. Interpretation of year-to-year trends must consider that not all streams were surveyed every year and that the total distance mapped varied among years.

Figure 9-17. (a) Cumulative Annual Precipitation (cm) by Water Year (October–September) at the Venado Weather Station near Healdsburg, California. (b) Proportion of Total Tributary Channel Length Surveyed from 2012–2025 in the Russian River and Dry Creek Watersheds Classified as Wet, Intermittent, or Dry at the Time of Late-season Surveys

Percentages reflect the combined length of all tributaries surveyed in each year; the number of tributaries and total distance surveyed varied among years.



Juvenile over-summer rearing represents the most consistently vulnerable life stage in the mainstem. Summer temperatures exceed thermal thresholds during portions of the rearing period even under Historical conditions, and projected increases of approximately 3°F (Mid-Future) and 6°F (Late-Future) substantially expand the duration and severity of exceedance. Reduced late-spring flows may further constrain outmigration and rearing habitat. Dissolved oxygen declines compound these risks at Cloverdale, where Late-Future mean minimum concentrations fall below 6 mg/L beginning in early May and remain near or below that threshold through summer. In contrast, Dry Creek maintains generally suitable temperatures and dissolved oxygen year-round under modeled conditions due to releases from Lake Sonoma, though higher summer releases may reduce low-velocity refuge habitat for over-summering coho and steelhead.

Tributaries emerge as a critical vulnerability node. Empirical mapping and survival analyses consistently identify longitudinal disconnection, pool contraction, elevated temperature, and declining dissolved oxygen as primary drivers of juvenile mortality. "Days of disconnection" is repeatedly identified as a strong predictor of survival. Climate projections indicating warmer springs, reduced late-season baseflows, and more variable precipitation are therefore likely to increase the duration and spatial extent of seasonal drying, particularly in lower alluvial reaches near the mainstem which may not allow juveniles to escape warming tributaries into the more suitable mainstem. Groundwater-supported pools function as localized refugia, but their persistence may diminish under intensified drought and declining baseflow.

Overall, the most climate-sensitive components of the system appear to be the following:

- Mainstem adult Chinook salmon passage in October at critical riffle locations.
- Mainstem juvenile coho salmon and steelhead rearing in summer due to combined thermal and dissolved oxygen stress.
- Tributary over-summering coho salmon and steelhead juveniles due to increased frequency and duration of disconnection.
- Egg incubation during late winter and early spring due to rising temperatures and episodic high-flow scour risk.

Chinook salmon adult migration shows episodic vulnerability during early-fall low-flow periods but is comparatively less temperature-limited.

9.4.1.5 Considerations

These conclusions rely on modeled discharge and water quality outputs subject to uncertainty in climate forcing, reservoir operations, and hydraulic representation. Passage thresholds were evaluated qualitatively rather than as absolute cutoffs, and reach-specific habitat flow relationships were not available. Flow, temperature and dissolved oxygen analyses reflect ensemble averages that may mask short-duration extremes, which can drive profound biological responses. For example, extreme storm events in the winter can cause increased redd scour, decreasing egg survival and reducing recruitment. Extreme temperatures (i.e. above the lethal limit for the species) or extremely low DO (i.e. below 3 mg/L) for even short periods can cause localized die-offs if refugia are inaccessible. Tributary wet–dry mapping varies in spatial coverage among years, and groundwater contributions are not explicitly modeled. As a result, the direction of impact is robust, but the magnitude and precise timing of effects may be under- or over-estimated in specific reaches or years.

9.4.2 Russian River Estuary

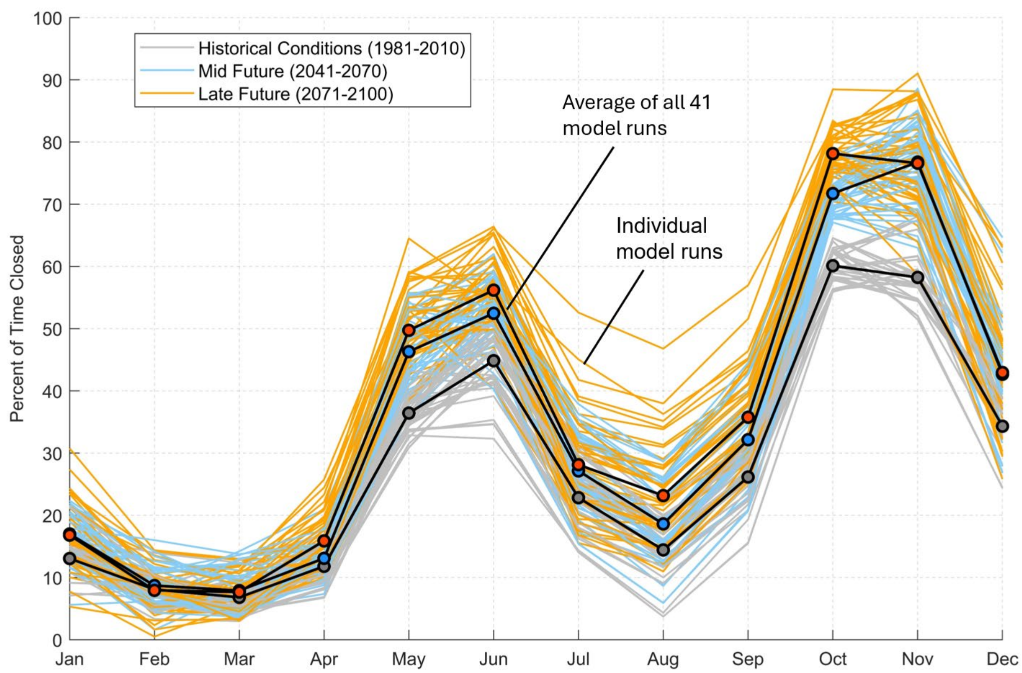
9.4.2.1 River Mouth Closure Behavior

The results of the QCM model indicate that the expected change in river discharge, particularly reduced discharge in the spring and fall seasons, is expected to lead to more frequent and longer closure events. In general, drier fall conditions lead to extension of closure events by increasing the time required for river inflows into the lagoon to raise water surface elevations to a level where a self-breach (i.e. spill over the beach at its low point and erode a new inlet or seepage through barrier beach) or be breached manually to minimize flood risk. In the spring months, future flow conditions lead to earlier onset of closure, or an increased frequency of closure events, though closure was still less prevalent in these months than in the fall. Overall, these results are expected when reviewing the historical record and observations in the Russian River, which has river flow records and inlet closure records extending back to the middle of the 20th century (Behrens et al. 2013). During the period of record, the river often shows substantially longer periods of closure during dry years, so the prediction of worsening droughts in the future, with both the Mid-Future and Late-Future horizons, should lead to a similar increase in closure events, and closure event duration.

Figure 9-18 shows the percent time closed for the river mouth by a month of the year for the historical mid-century and far-future cases. It indicates an increase in closure duration of about 5 to 10% in spring and about 5 to 20% in fall for the mid-century case. The late-future case continues this trend further. These results are relevant to habitat in the estuary because longer mouth closure conditions provide more opportunity for prolonged solar heating, reducing the suitability of salmonid rearing habitat in the estuary. This aspect of the results is explored further in the next section regarding the SHAD model.

Figure 9-18. Modeled Inlet Closure Seasonality Within Each Epoch (Historical [1981–2010], Mid-Future [2041–2070], Late-Future [2071–2100])

The thin lines in the background represent individual model runs, and show the percent of each month of the year that the Russian River inlet is predicted to be closed (e.g., 100% closed means that the river was closed for the full month). Different colors represent the different epochs. Thick lines in the foreground represent averages of all 41 model runs.



9.4.2.2 Habitat Suitability

The SHAD model considers the change in closure duration from the QCM model and also incorporates predicted estimated increases in river temperatures entering the estuary (described in other appendices). Monitoring data from Sonoma Water stationary sensors indicate that water temperatures in the estuary are highly correlated to temperature measured by the USGS at the Hacienda Bridge gauge, meaning that river inflows have a strong influence on temperatures. The correlation is strongest during periods of river mouth closure, and the same monitoring data also indicate that surface and mid-depth water temperatures tend to be warmer during closed-mouth conditions. The areas of the estuary most susceptible to warming are about 2 to 6 miles upstream of the river mouth, where the topography limits the upstream movement of coastal fog (ESA 2021).

Both the expected change in timing of river mouth closure events and the increase in river temperatures upstream create a downward pressure on acre-days of suitable habitat in the estuary for salmonids. As summarized in Figure 9-19, the SHAD model ultimately found that both Mid-Future and Late-Future conditions lead to net lower amounts of steelhead rearing habitat availability during the months of May through November. Overall, the change is relatively small (a loss of about 10 to 20% in the months of June and July). There is not a clear worsening trend from Historical through Mid-Future and Late-Future conditions. This is because longer closure events can actually increase the volume of available habitat in the spring and late fall months, when river temperatures are cooler and more suitable for rearing. The Far-Future scenario has the highest frequency of inlet closure events across all seasons, so it essentially creates more exposure to both conditions. Overall, both the Mid-Future and Late-Future scenarios are associated with less habitat than the Historical scenario. The reason for this is more clearly illustrated in Figure 9-20, which shows 5th to 95th percentile ranges of estuary temperatures for the months of May through November, and for the three time periods of interest. The temperature of the estuary is expected to rise through the end of the century during closed river mouth conditions, more frequently surpassing the suitability threshold for juvenile steelhead (indicated as a dashed line).

Figure 9-19. Suitable Steelhead Rearing Habitat Availability per Month in Acre-days for Historical (1981–2010), Mid-Future (2041–2070), Late-Future (2071–2100) Epochs

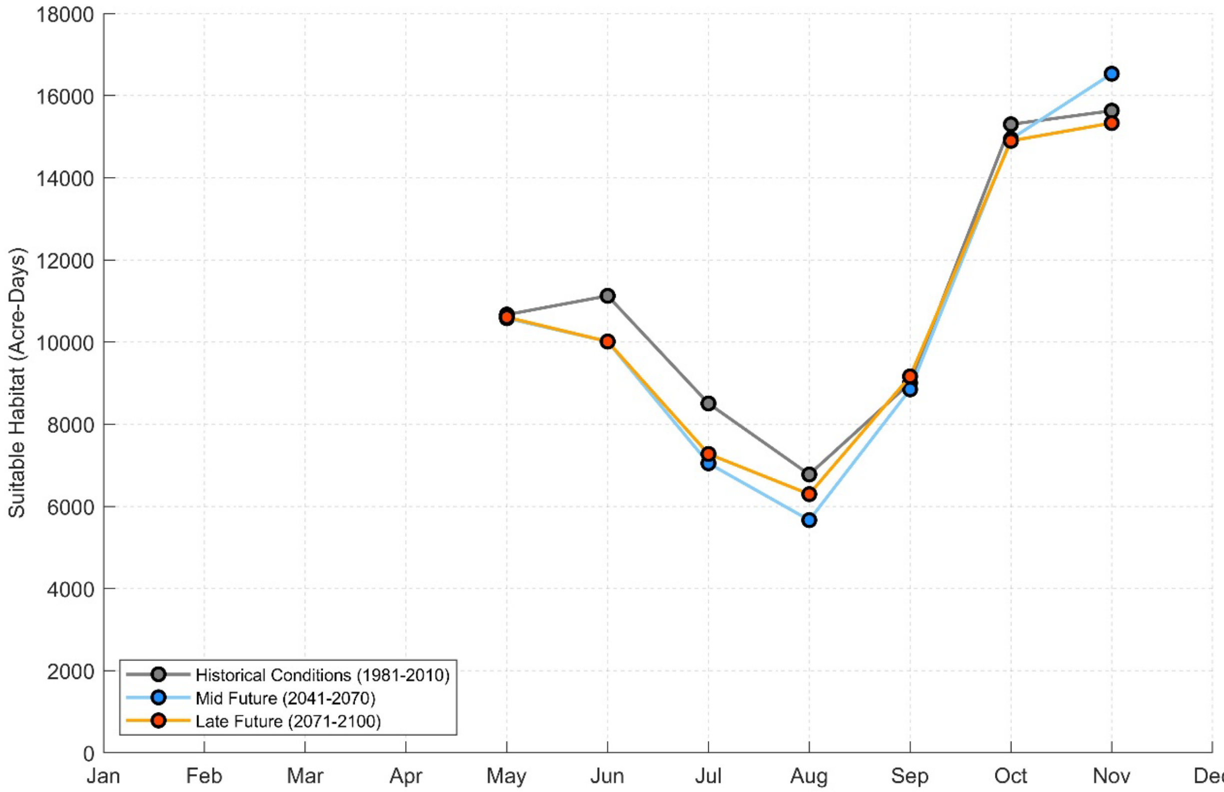
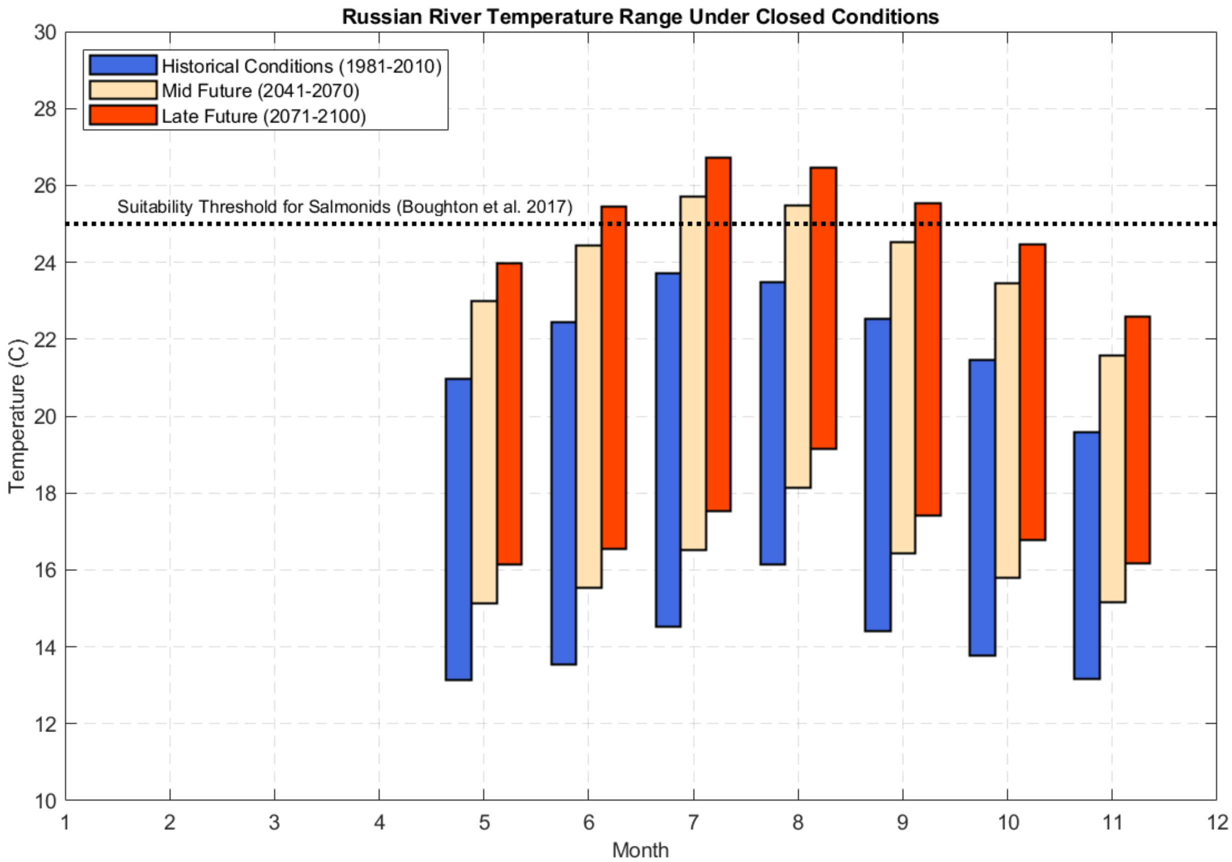


Figure 9-20. Temperature Range by Month Under Closed Conditions in the Estuary for Historical (1981–2010), Mid-Future (2041–2070), Late-Future (2071–2100) Epochs with the Suitability Threshold for Juvenile Salmonids Defined by Boughton et al. (2017)



9.5 Summary

For the mainstem Russian River and its tributaries, this assessment evaluated projected climate-driven changes in hydrology, temperature, and dissolved oxygen in the mainstem Russian River and Dry Creek; total watershed-averaged flow metrics for tributary watersheds to the Russian River and Dry Creek; and hydrologic connectivity in select tributaries of the Russian River watershed using ensemble climate simulations and literature-supported habitat relationships. Daily reservoir and river flows were modeled across Historical (1981–2010), Mid-Future (2041–2070), and Late-Future (2071–2100) epochs. Modeled discharge was interpreted qualitatively in relation to salmonid depth–velocity suitability preferences and migration thresholds at known passage critical riffles at four HEC-ResSim model nodes (Cloverdale, Healdsburg, Dry Creek at the Russian River, and Hacienda). Water temperature and dissolved oxygen projections were evaluated relative to species- and life stage-specific tolerance limits at a subset of the HEC-ResSim nodes (Cloverdale, Dry Creek, Hacienda). Total watershed-averaged flow outputs for identified tributary watersheds were generated using 41 simulations from the Russian River and Upper Eel River BCM. A complementary review of tributary wet–dry mapping and empirical survival studies was conducted to assess sensitivity to seasonal flow disconnection.

For the Russian River estuary, projected changes in hydrology and water quality were evaluated to determine how habitat conditions for federally listed salmonids in the estuary may be affected. Three epochs, Historical [1981–2010], Mid-Future [2041–2070], and Late-Future [2071–2100], were assessed to quantify changes in suitable habitat availability. Separate lagoon hydrology and habitat models were integrated to simulate future conditions, taking into account changes in boundary conditions driven by climate change, including altered river temperature, sea level rise, ocean tides, and wave conditions. The QCM simulates river mouth closure dynamics, and the SHAD analysis quantifies spatial and temporal changes in juvenile steelhead rearing habitat under varying inlet conditions. River and reservoir operations were simulated separately using HEC-ResSim, and future tidal conditions follow State of California sea level rise guidance.

For the mainstem Russian River and its tributaries, results indicate that climate change is expected to intensify seasonal habitat constraints and increase vulnerability for multiple listed salmonid life stages, particularly under Late-Future conditions. In the mainstem Russian River, projected reduced early-fall flows increase the risk of delayed adult migration at critical riffles, especially for Chinook salmon (*Oncorhynchus tshawytscha*) (Figure 9-21). Higher and more variable winter peak flows elevate the likelihood of streambed and redd (spawning nests) scour for Chinook salmon, and to a lesser degree, steelhead (*Oncorhynchus mykiss*) and coho salmon (*Oncorhynchus kisutch*). Warmer late-winter and early-spring temperatures advance incubation threshold exceedances, shortening the window of suitable egg development conditions at upstream locations, such as Cloverdale (Figure 9-22).

The most consistent and severe vulnerability is projected during juvenile rearing. Mainstem summer temperatures already approach or exceed thermal thresholds under Historical conditions and increase under Mid- and Late-Future scenarios (Figure 9-22). Reduced late-spring flows may further constrain juvenile outmigration and rearing habitat and associated survival to the Pacific Ocean (Figure 9-23).

Tributaries of the Russian River watershed represent an additional critical vulnerability nodes. Empirical evidence identifies longitudinal disconnection and reduced wetted habitat as primary drivers of juvenile mortality, with “days of disconnection” strongly associated with survival. Projected warming and declining baseflows are expected to increase the duration and spatial extent of seasonal drying, particularly in lower alluvial reaches. Although groundwater-supported pools provide localized refugia, their persistence may diminish under intensified drought conditions. BCM-generated total watershed-averaged flow results for tributary watersheds indicate a consolidation of flows into the winter season at the loss of total flow volumes in the fall and spring, signaling vulnerabilities for upstream migration in the fall and outmigration in the spring.

Figure 9-21. Average Monthly Discharge Across All Water Years Simulated by the 41 Climate Models for Each Epoch (Historical, Mid-Future, and Late-Future) at the Four Focal Nodes

Boxes denote the interquartile range (25th–75th percentiles), with the horizontal line indicating the median. Whiskers extend to the most extreme values within 1.5 times the interquartile range, and values beyond this range are shown as individual points.

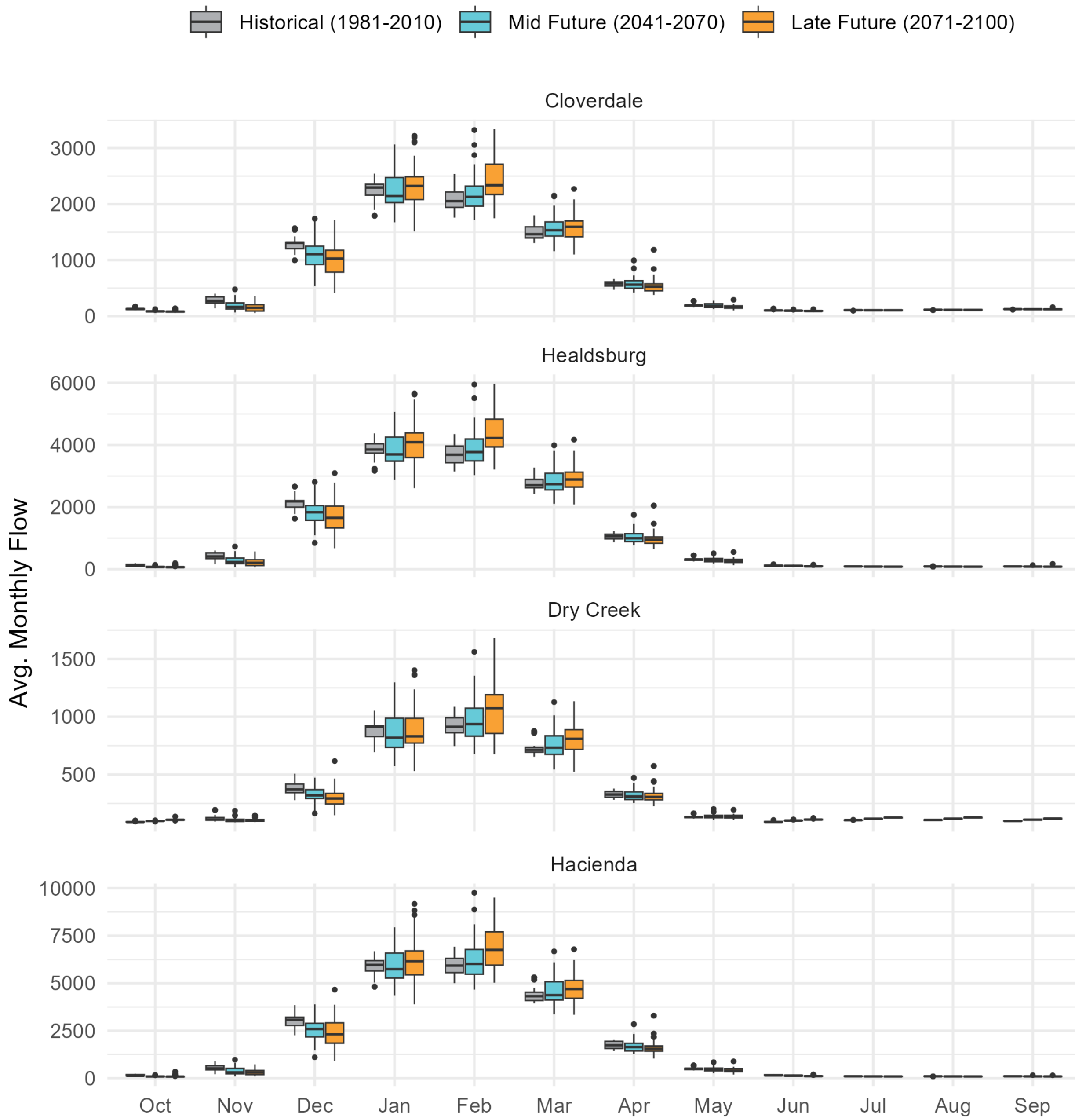


Figure 9-22. Average Maximum Daily Temperature Average by Month Across all Water Years Simulated by the Three Climate Models for Each Epoch (Historical, Mid-Future, and Late-Future) at the Three Water Quality Nodes

Boxes denote the interquartile range (25th–75th percentiles), with the horizontal line indicating the median. Whiskers extend to the most extreme values within 1.5 times the interquartile range, and values beyond this range are shown as individual points.

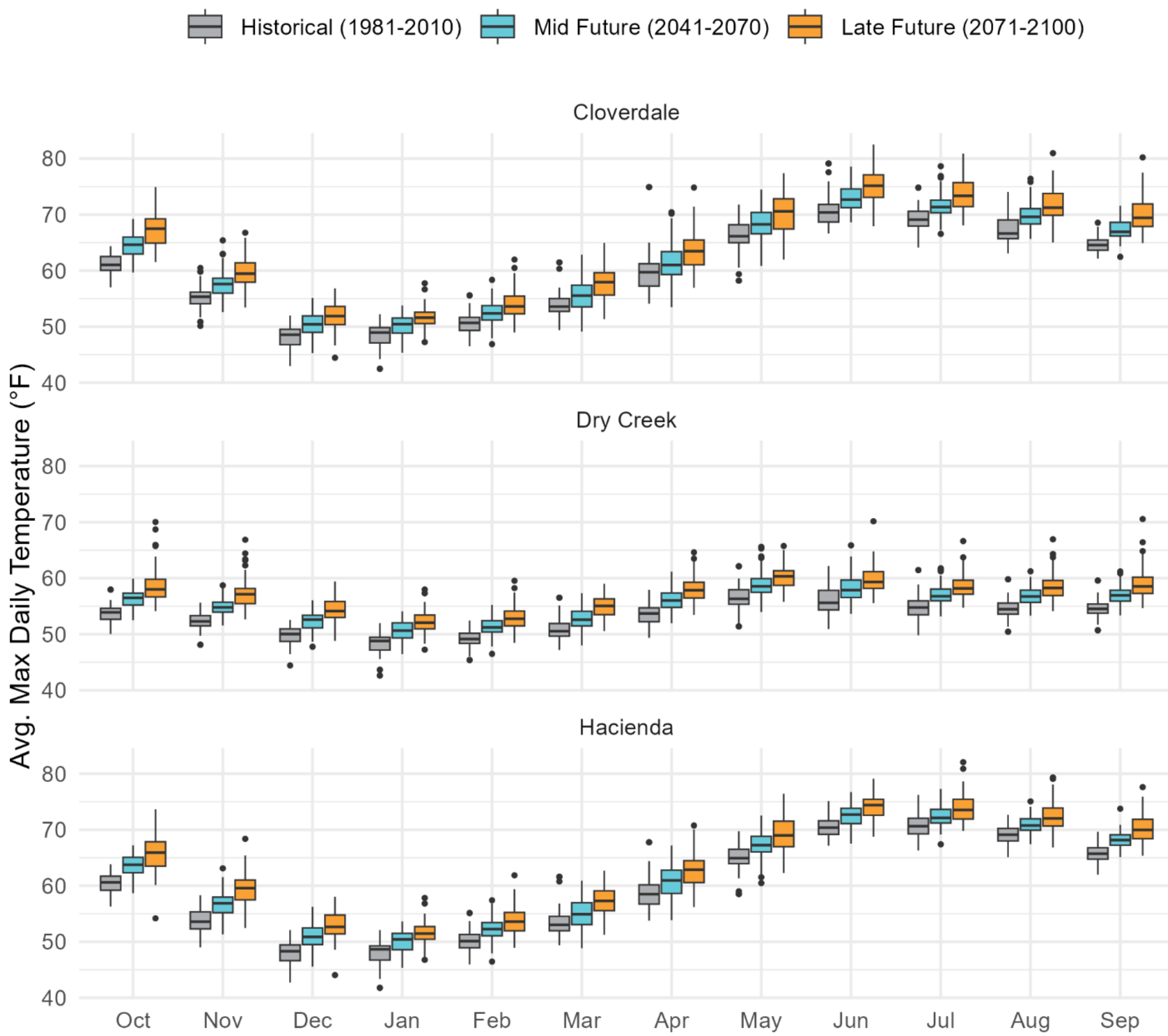
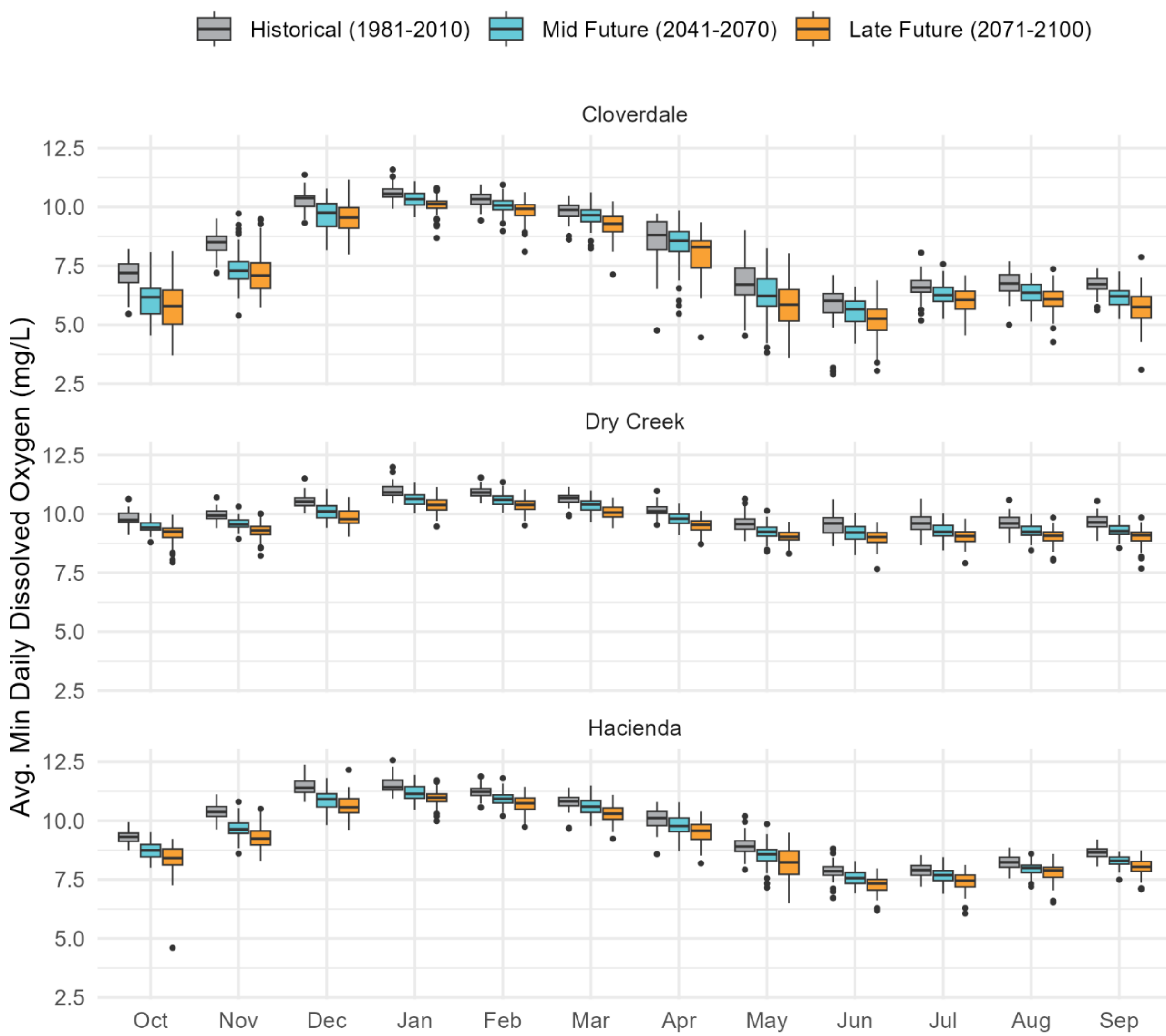


Figure 9-23. Average Minimum Daily Dissolved Oxygen Average by Month Across all Water Years Simulated by the Three Climate Models for each Epoch (Historical, Mid-Future, and Late-Future) at the Three Water Quality Nodes

Boxes denote the interquartile range (25th–75th percentiles), with the horizontal line indicating the median. Whiskers extend to the most extreme values within 1.5 times the interquartile range, and values beyond this range are shown as individual points.



Overall, the most climate-sensitive components of the system are mainstem juvenile rearing, tributary over-summer survival, and egg incubation during late winter and spring. Adult Chinook salmon migration is vulnerable primarily during low-flow fall periods but is comparatively less constrained by temperature. These findings identify seasonal thermal stress, low-flow passage constraints, and tributary connectivity loss as the dominant drivers of future climate vulnerability for listed salmonids in the watershed.

For the Russian River Estuary, results indicate that future climate conditions increase risk to multiple salmonid life stages. Both Mid- and Late-Future epochs show reduced early-fall, early-winter, and spring flows and longer or more frequent inlet closure events. Late-Future scenarios also project higher winter peak flows. Projected increases in air temperature are expected to elevate river temperatures entering the estuary, and monitoring data confirm that estuary temperatures closely track upstream river conditions, particularly during closed-mouth periods. Increased closure duration and higher river temperatures are projected to reduce suitable juvenile steelhead rearing habitat during rearing months (May–November).

Overall, the estuary is expected to retain its typical seasonal open/closed dynamics, but with intensified drought sensitivity and temperature-related stress. These findings support continued use of adaptive management strategies that protect thermal refugia to sustain salmonid rearing and migration under future conditions.

10. Recreation Vulnerability Assessment

10.1 Purpose

In addition to providing surface water supplies and habitat for aquatic species, the Russian River, Lake Mendocino, and Lake Sonoma offer opportunities for aquatic recreation within the planning area. These opportunities are dependent on annual surface water supplies, reservoir management, and downstream diversions. Under future climate conditions, shifts in the timing and magnitude of unimpaired inflows to reservoirs and decreases in the total annual surface water supplies may affect the quality and availability of recreational activities, particularly in summer months. Consequently, reductions in aquatic recreation can have impacts on the regional economy and public health within the planning area. This assessment seeks to evaluate vulnerabilities to climate change for selected recreational activities at Lake Mendocino, Lake Sonoma, and locations along the Russian River.

10.2 Methodology

Vulnerabilities to climate change were assessed for both lake and riverine recreation using outputs from the Sonoma Water DSM at Lake Sonoma, Lake Mendocino, and various locations along the Russian River. For lake recreation, thresholds from the *Fish Habitat Flows and Water Rights Project Draft EIR* (Sonoma Water 2016b; Table 10-1 and Table 10-2) were used to determine changes in the frequency of boat ramp and adjacent campground access between May 1 and September 30 (i.e., days when aquatic recreation in the region are most prevalent). Daily reservoir elevation outputs between these months for Lake Mendocino and Lake Sonoma were used to determine the exceedance probability of reservoir elevations for a Historical period (1981–2010), a Mid-Future period (2041-2070), and a Late-Future period (2071–2100) for each simulation. Once exceedance probabilities were determined, the probability of occurrence for each reservoir elevation threshold (Table 10-1 and Table 10-2) were calculated. Calculated percentages were then multiplied by the number of days within the period of interest (i.e., 153 days between May 1 and September 30) to translate results into a distribution of annual days for each simulation. For each analysis period, statistics were calculated across the full range of 41 simulations.

Table 10-1. Lake Mendocino Reservoir Elevation Thresholds

Reservoir Elevation (feet)	Description
764.8	Spillway
755	Lower Kyen Campground begins to be inundated
750	Pomo Day Use Area, Inlet Road, and South Boat Ramp parking lot beings to be inundated
748	North Boat Ramp lower parking lot begins to be inundated
Below 728	North Boat Ramp closed by USACE
Below 722	South Boat Ramp closed by USACE
644	Minimum pool

Source: Adapted from Sonoma Water 2016

Table 10-2. Lake Sonoma Reservoir Elevation Thresholds

Reservoir Elevation (feet)	Description
495	Spillway
458	Lower Campground begins to be inundated
451	Top of water supply pool
Below 416	Yorty Creek Boat Ramp becomes disconnected from Lake Sonoma
Below 360	Lake Sonoma Marina Boat Ramp access becomes limited
Below 320	Lake Sonoma public boat ramp is unusable
280	Minimum pool

Source: Adapted from Sonoma Water 2016

For riverine recreation, a similar approach to lake recreation was used, except identified thresholds are based on Russian River flows instead of reservoir water surface elevations. Again, thresholds from the *Fish Habitat Flows and Water Rights Project Draft EIR* (Sonoma Water 2016b) were used. However, thresholds were expanded to consider reaches of the Russian River upstream of Rio Lindo Academy, including the Russian River confluence to Cloverdale and from Cloverdale to Rio Lindo Academy. To expand this analysis, similar logic was used as defined in the *Fish Habitat Flows and Water Rights Project Draft EIR* (Sonoma Water 2016b). More specifically, sufficient boating depths for non-motorized crafts are defined as 0.5 feet. For the USGS gage rating curve for the Russian River near Hopland (#11462500), the flow corresponding to a depth of 0.5 feet is approximately 80 cubic feet per second (cfs). This value was set at the threshold for the Russian River confluence to Cloverdale, and the threshold for Cloverdale to Rio Lindo Academy was set as the average between the upstream and downstream reaches (i.e., 75 cfs) for this location. Flow thresholds for each Russian River reach were compared to daily flow outputs between May 1 and September 30 for the output locations noted in Table 10-3. Dry Creek was excluded from this analysis because it has no known public access points for recreation and limited aquatic recreation due to higher velocities and colder water temperatures.

Table 10-3. Russian River Flow Thresholds for Recreation Analysis

Reach	Threshold (cfs)	Output Node
Russian River Confluence to Cloverdale	80	Hopland
Cloverdale to Rio Lindo Academy	75	Cloverdale
Rio Lindo Academy to Mouth of Dry Creek	70	Healdsburg
Mouth of Dry Creek to Wohler	180	Windsor
Wohler to Mouth of Russian River / Pacific Ocean	80	Guerneville

Additionally, through Watershed Network coordination, assessment of changes to riverine public access along the Russian River was requested. Because the Sonoma Water DSM does not provide stage outputs, research was conducted to identify riverine public access points and tie each of these to the individual reaches described above (Table 10-4). For the recreation vulnerability assessment, it is assumed that if flow thresholds are exceeded, riverine access is sufficient. Furthermore, in areas of the Lower Russian River (i.e., where most public access points are located), operation of instream summer dams is a larger driver for changes in water surface elevations than changes in instream flows. Riverine boating, public access, swimming, and other recreational opportunities are more likely to change if operation of summer impoundment dams changes.

Table 10-4. Public Access Points along Assessed Reaches of the Russian River

Riverine Access Point	Associated Assessment Reach
Vichy Springs	Russian River Confluence to Cloverdale
Thousand Trails Russian River*	Russian River Confluence to Cloverdale
Cloverdale River Park	Cloverdale to Rio Lindo Academy
Alexander Valley Campground*	Cloverdale to Rio Lindo Academy
Del Rio Woods	Rio Lindo Academy to Mouth of Dry Creek
Badger Park	Rio Lindo Academy to Mouth of Dry Creek
Healdsburg Veterans Memorial Beach	Rio Lindo Academy to Mouth of Dry Creek
Riverfront Regional Park	Mouth of Dry Creek to Wohler
Wohler Bridge	Mouth of Dry Creek to Wohler
Mirabel Park Campground*	Wohler to Mouth of Russian River
Steelhead Beach River Park	Wohler to Mouth of Russian River
Forestville River Access	Wohler to Mouth of Russian River
Sunset Beach River Park	Wohler to Mouth of Russian River
Hilton Family Park Campground*	Wohler to Mouth of Russian River
Guerneville River Park	Wohler to Mouth of Russian River
Johnson's Beach*	Wohler to Mouth of Russian River
Vacation Beach	Wohler to Mouth of Russian River
Monte Rio Community Beach	Wohler to Mouth of Russian River
Dutch Bill Beach	Wohler to Mouth of Russian River
Sandy Beach	Wohler to Mouth of Russian River
Cassini Ranch Family Campground*	Wohler to Mouth of Russian River
Duncan Mills Camping Club*	Wohler to Mouth of Russian River
Willow Creek State Park	Wohler to Mouth of Russian River
Jenner Boat Ramp	Wohler to Mouth of Russian River
Goat Rock State Beach	Wohler to Mouth of Russian River

* River access is limited to campground visitors, club members, or nearby homeowners.

Finally, the recreation vulnerability assessment also considers recreational fishing between September 1 and April 30. Consistent with CDFW's 2026 regulations (CDFW 2026) for the Russian River, fishing is prohibited during this period if flows (measured at the Russian River near Guerneville) are below 300 cfs.

To characterize the change in frequency of fishing, a similar threshold-based approach was employed using daily flow outputs for the Russian River at Guerneville.

10.3 Results

Figure 10-1 displays the range of annual days under historical and future climate conditions for each reservoir elevation threshold at Lake Mendocino. The optimal range for recreational activities corresponds to elevations of 728 to 748 feet, where all recreation-related sites are functioning. Under median future climate conditions, the frequency of these conditions increases by roughly 8 days (Mid-Future) and 7 days (Late-Future) annually. Furthermore, the frequency of higher reservoir elevation conditions that result in inundation to surrounding campgrounds decreases by up to approximately 14 days, depending on threshold and analysis period. However, these beneficial shifts in aquatic recreational conditions are partially offset by a higher frequency of lower reservoir elevations that are characterized by one or more closures to boat ramps. While lightweight vessels can still be hand-launched under these conditions, motorized boating is completely inaccessible. A comparison between the median number of annual days for each reservoir elevation threshold is displayed in Figure 10-2. While optimal conditions for recreation do increase in frequency under future climate conditions, periods of boat ramp closures increase by approximately 14 days each year for the Mid-Future and 17 days for the Late-Future.

Figure 10-1. Comparison between the Number of Annual Days at Lake Mendocino Reservoir Elevation Thresholds between May 1 and September 30

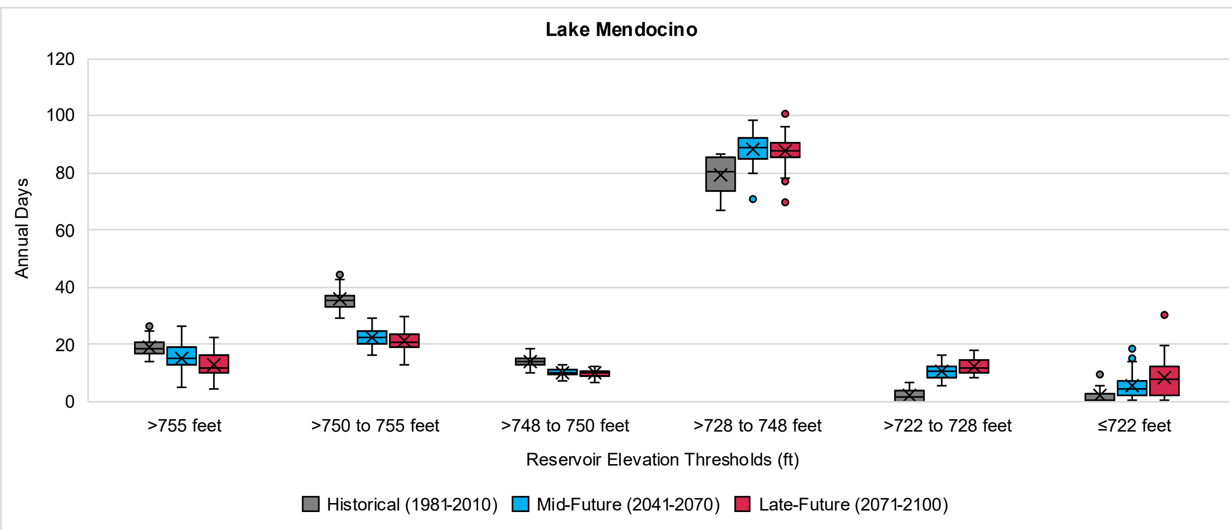


Figure 10-2. Comparison between Median Annual Days for Lake Mendocino Reservoir Elevation Thresholds between May 1 and September 30

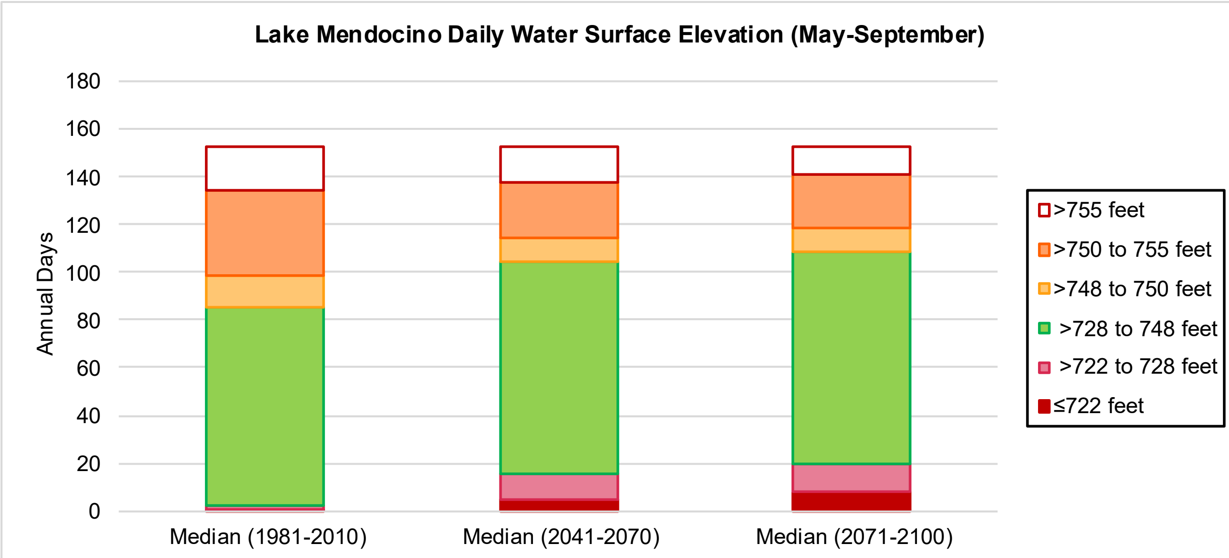


Figure 10-3 displays the range of annual days under historical and future climate conditions for each reservoir elevation threshold at Lake Sonoma. The optimal range for recreational activities corresponds to elevations of 416 to 458 feet (451.1 is the top of the water conservation pool, but has no effect on recreation activities), where all recreation-related sites are functioning. Under median future climate conditions, there is relatively no projected change (limited to a 1-day increase to a 2-day decrease for the Late-Future and Mid-Future, respectively) in the frequency of reservoir elevations between 416 and 451.1 feet, and elevations between 451.1 to 458 feet decrease by up to approximately 3 days under Late-Future conditions. This decrease is accompanied by a roughly 1- to 3-day increase, depending on analysis period, for reservoir elevations between 360 and 416 feet, resulting in access impacts to the Yorty Creek Boat Ramp. However, alternative access options for boating are still available at the Lake Sonoma Marina Boat Ramp and Lake Sonoma Public Boat Ramp. Trace increases in the frequency of days above 458 feet or below 360 feet are noted under the suite of future climate simulations, but median conditions result in no change in these occurrences. A comparison between the median number of annual days for each reservoir elevation threshold is displayed in Figure 10-4. In general, recreation at Lake Sonoma appears to be sufficiently resilient to future climate change conditions.

Figure 10-3. Comparison between the Number of Annual Days at Lake Sonoma Reservoir Elevation Thresholds between May 1 and September 30

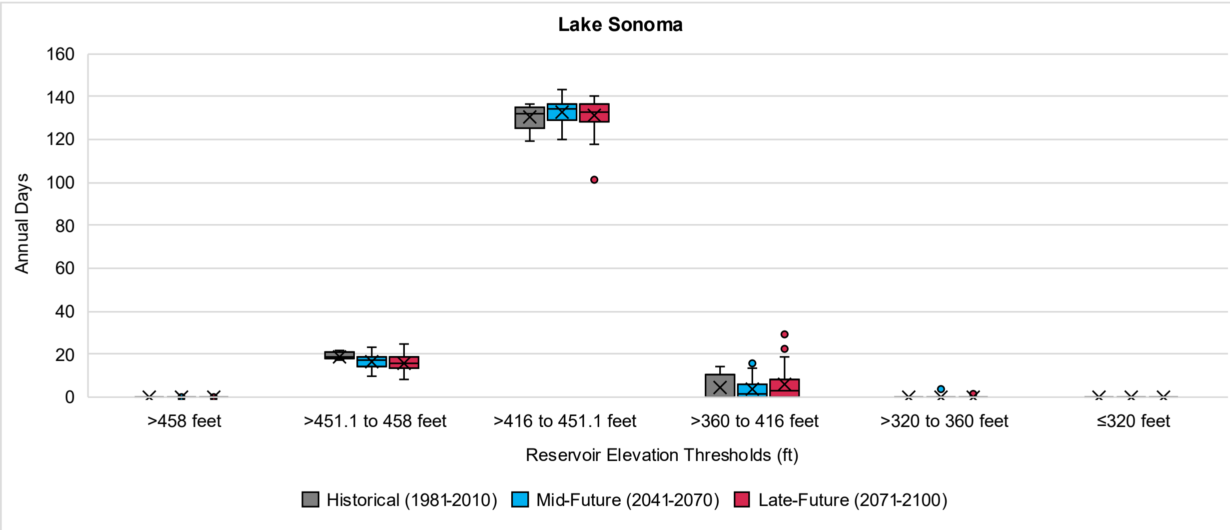


Figure 10-4. Comparison between Median Annual Days for Lake Sonoma Reservoir Elevation Thresholds between May 1 and September 30

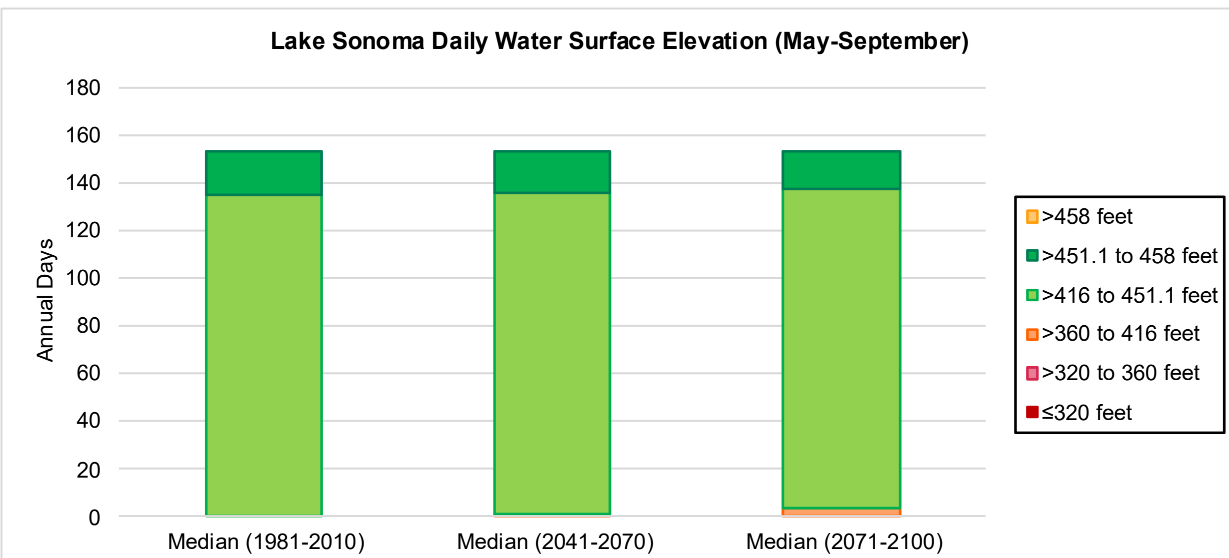
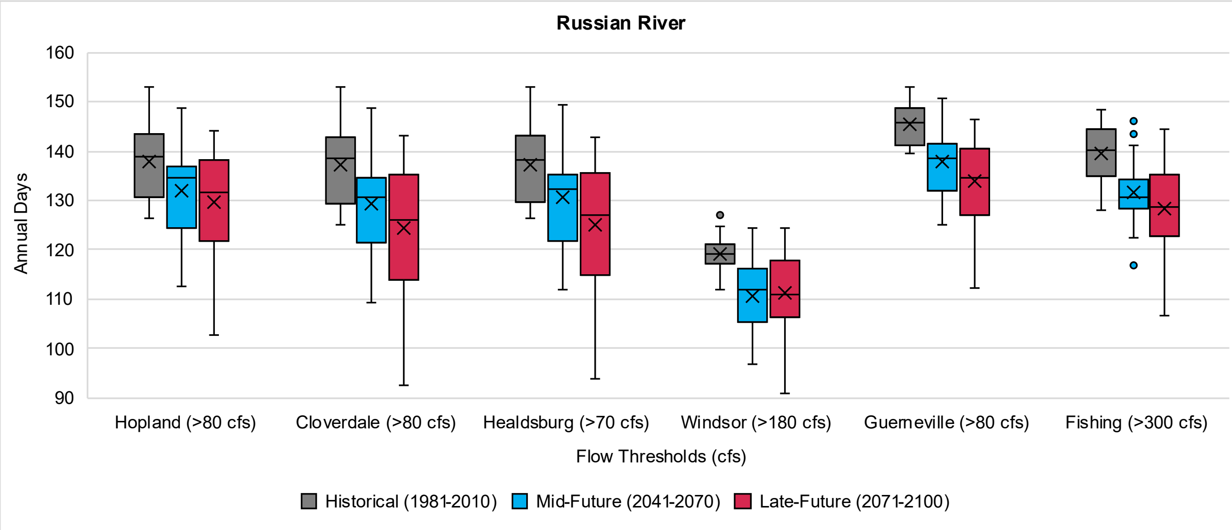


Figure 10-5 presents the range of annual days under Historical, Mid-Future, and Late-Future climate conditions for recreational activities at various locations along the Russian River. For riverine recreation (e.g., non-motorized boating) along the Russian River at Hopland, Cloverdale, Healdsburg, Windsor, and Guerneville, days between May 1 and September 1 are considered. For fishing along the Russian River, days between September 1 and April 30 are considered, in accordance with CDFW regulations. In general, the number of recreationally suitable days along the Russian River decreases from Hopland to Windsor, mirroring historical trends. However, under median future climate conditions, the number of recreational days decreases between 4 to 12 days, depending on location and analysis period. The number of recreational days at Guerneville has historically been higher than upstream locations but still demonstrates a 7- to 11-day decrease per year under median Mid-Future and Late-Future climate conditions, respectively. Fall through spring fishing along the Russian River displays similar trends, with a median 9-day decrease for Mid-Future conditions and 11-day decrease for Late-Future conditions. Late-Future conditions display a significantly larger spread across the range of projections for most locations.

Figure 10-5. Comparison between the Number of Annual Days for Recreational Activities at Various Locations along the Russian River



The decrease in flows above identified thresholds at these locations is driven by reductions in storage at Lake Mendocino. With declining storage relative to historical conditions after May, annual summer water supplies are reduced under future climate conditions. This results in lower Russian River flows during these months relative to historical conditions, particularly in May and June where reductions from historical values are highest. For fishing, reductions in recreationally suitable days are primary driven by a decrease in flows between October and December. While Lake Sonoma storage appears to be more resilient to future climate conditions, this stability does not offset the impacts to flows caused by the reduction in Lake Mendocino storage in areas below the confluence with Dry Creek.

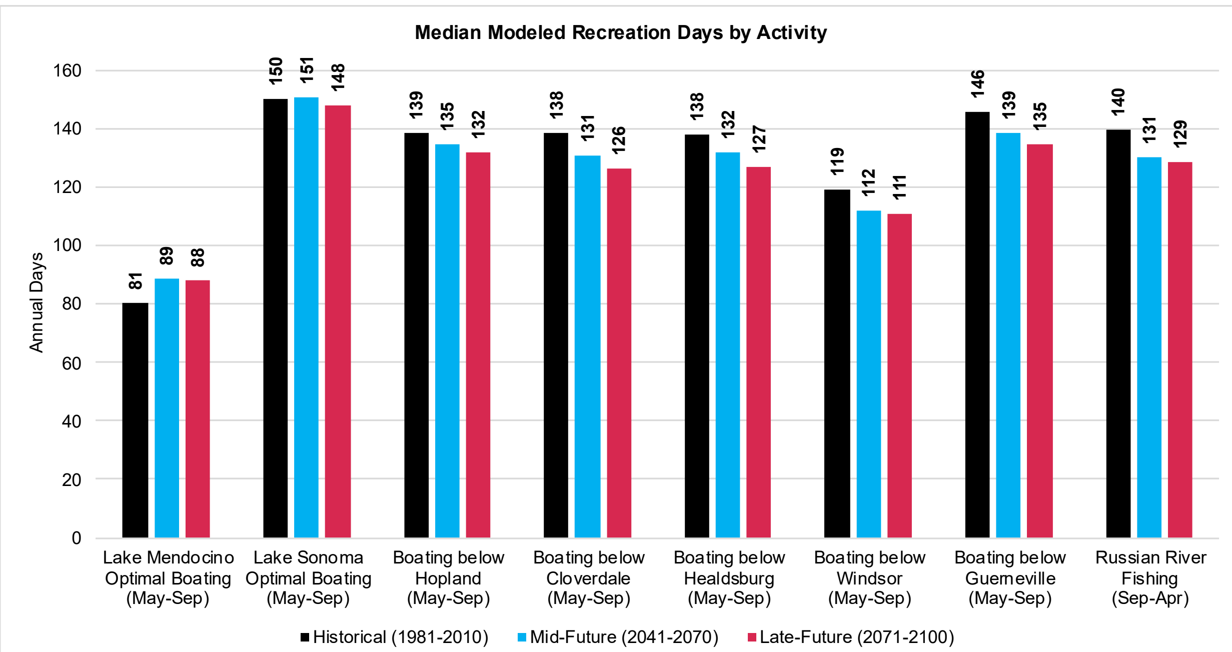
10.4 Summary

The Russian River, Lake Mendocino, and Lake Sonoma offer opportunities for aquatic recreation within the planning area. These opportunities are dependent on annual surface water supplies, reservoir management, and downstream diversions. Under future climate conditions, shifts in the timing and magnitude of unimpaired inflows to reservoirs and decreases in the total annual surface water supplies may affect the quality and availability of recreational activities, particularly in summer months.

Vulnerabilities to climate change were assessed for both lake and riverine recreation using daily outputs at Lake Sonoma, Lake Mendocino, and various locations along the Russian River. Key reservoir elevation and riverine flow thresholds identified in the *Fish Habitat Flows and Water Rights Project Draft EIR* (Sonoma Water 2016b) were utilized and supplemented with additional thresholds to expand coverage to upstream portions of the Russian River above Rio Lindo Academy. Simulated reservoir elevation and Russian River flow timeseries under Historical (1981–2010), Mid-Future (2041–2070), and Late-Future (2071–2100) conditions were compared to identified thresholds to estimate the number of annual days sufficient for the range of recreational activities considered. For Lake Sonoma and Lake Mendocino, changes in the availability of motorized boating, non-motorized boating, and camping were considered between May 1 and September 30. For the Russian River, non-motorized boating and public access were considered between the same time period. Fishing along the Russian River was also evaluated between September 1 and April 30.

Findings from the analysis are summarized for median conditions in Figure 10-6. For Lake Mendocino, the number of days with optimal (i.e., no negative impact on any recreational activities) conditions for recreation increases by approximately 8 days (Mid-Future) and 7 days (Late-Future) annually relative to historical trends. However, the annual frequency of closures that fully prohibit motorized boating increase by roughly 14 days each year for the Mid-Future and 17 days for the Late-Future due to a higher prevalence of lower reservoir storage under future conditions. For Lake Sonoma, median conditions are relatively unchanged by future climate conditions, with only a 1-day increase to 2-day reduction in optimal reservoir elevations, depending on analysis period, that result in access limitations at only one of the three boat ramps. For both Lake Mendocino and Lake Sonoma, sufficient adaptive capacity exists to maintain the availability of recreational opportunities at these locations. While Lake Mendocino is more vulnerable to future climate conditions and displays a decreasing trend in annual storage, lightweight crafts can still be hand-launched to access the lake and the reduction in storage results in a decreased frequency of events that inundate surrounding campgrounds and parking lots. For Lake Sonoma, alternative boat ramps can still be utilized during periods of lower reservoir elevations to access the lake.

Figure 10-6. Summary of Recreation Vulnerability Assessment Findings



Along the Russian River, the median frequency of recreationally suitable days decreases between 4 to 9 days for Mid-Future conditions and 7 to 12 days for Late-Future conditions, depending on location and activity. The decrease in days that flows are above identified thresholds at these locations is driven by reductions in storage at Lake Mendocino between May and February. The reduction in storage results in a decrease in surface water supplies that can be released downstream, resulting in a higher frequency of days with flows below thresholds suitable for recreation. Additionally, while Lake Sonoma storage appears to be more resilient to future climate conditions, this stability does not offset the impacts to flows caused by the reduction in Lake Mendocino storage in areas below the confluence with Dry Creek. Along the Upper Russian River, riverine recreation is particularly vulnerable to the reduction in annual water supplies at Lake Mendocino as no infrastructure currently exists to manipulate water surface elevations. For the Lower Russian River, where most of the recreation in the watershed is consolidated, operation of the instream summer dams has a greater impact on the prevalence of recreational activities in these areas. If instream dams continue to operate as normal and create sufficient water surface elevations for swimming, boating, and public access, the impacts of higher frequencies of low-flow occurrences can be partially mitigated.

11. Hydropower Vulnerability Assessment

11.1 Purpose

Releases from Coyote Valley Dam at Lake Mendocino and Warm Springs Dam at Lake Sonoma are used to generate hydropower in the Russian River watershed. The Lake Mendocino Hydroelectric Plant has a capacity of 3.5 Megawatts and supplies energy to the City of Ukiah (City of Ukiah 2023). The Warm Springs Hydroelectric Dam has a capacity of 2.79 Megawatts and generates energy for Sonoma Water and wheels the power through the Power and Water Resources Pooling Authority (Sonoma Water 2026). The power output of the hydropower facility typically runs at 1.3 MW. Changes in the magnitude and distribution of reservoir inflows and subsequent downstream releases throughout the year can influence the quantity of hydropower production and the reliability of these energy supplies for municipalities and residents within the watershed. This assessment seeks to evaluate vulnerabilities to hydropower production under projected future climate conditions.

11.2 Methodology

To determine hydropower vulnerabilities to climate change at Lake Mendocino and Lake Sonoma, a python-based tool developed by Sonoma Water was incorporated into the Sonoma Water DSM to generate hydropower-specific outputs. This python tool models turbine operations and calculates power output based on flow constraints, net head, turbine efficiency, generator capacity, and operational thresholds using daily reservoir elevation and release data. Outputs for daily power production and turbine flow are generated through the following process:

- Determine appropriate turbine flow limits and configurations based on reservoir elevation.
- Estimate flow through the turbine based on release volume and operational thresholds (e.g., bypass and capacity limits).
- Calculate net head using elevation, tailwater level, and elevation-dependent head loss coefficients.
- Estimate turbine efficiency using a lookup table based on flow and net head.
- Determine generator efficiency for Lake Sonoma and Lake Mendocino.
- Calculate daily energy production in kilowatt-hours using turbine and generator efficiency, flow, and head estimates.

Additional details on the assumptions and limitations for the python-based hydropower tool are provided in Attachment C-1. Daily power production and turbine flow outputs between 1950 and 2100 from the Sonoma Water DSM are presented in the following subsection.

11.3 Results

Hydropower generation is a function of releases through the turbines at the hydroelectric facilities at Coyote Valley and Warm Springs dams. Turbine releases are dependent on reservoir storage during periods of hydropower generation. Figure 11-1 and Figure 11-2 show the distribution of change in daily average turbine releases for Mid-Future (2041–2070) and Late-Future (2071–2100) conditions for Lake Mendocino and Lake Sonoma, respectively. For Lake Mendocino, daily average hydroelectric turbine releases decrease dramatically in October through January under both Mid-Future and Late-Future conditions, with November and December demonstrating roughly 50 to 60% of historical flows.

Hydroelectric turbine releases increase slightly between March and July, but these gains are not large enough to offset the reduction from the fall and early winter. These changes result in a median reduction in Lake Mendocino hydropower generation of roughly 17% for Mid-Future conditions and 19% for Late-Future conditions relative to historical trends (Figure 11-3).

For Lake Sonoma, daily average hydroelectric turbine releases decrease (up to roughly 8%) between July and February as well as April for Mid-Future conditions. For Late-Future conditions, these decreases (up to approximately 7%) are limited to October through February and April on average. All other months for both Mid-Future and Late-Future conditions increase (up to roughly 2% for Mid-Future and 4 percent for Late-Future) relative to historical daily average hydroelectric turbine releases. Ultimately, these changes result in a median 2% decrease in hydropower generation for Mid-Future conditions and a 1% decrease for Late-Future conditions (Figure 11-4). The Late-Future period also has outlier occurrences where annual hydropower production is reduced by over 12%.

Figure 11-1. Lake Mendocino Change in Daily Average Turbine Flow per Month

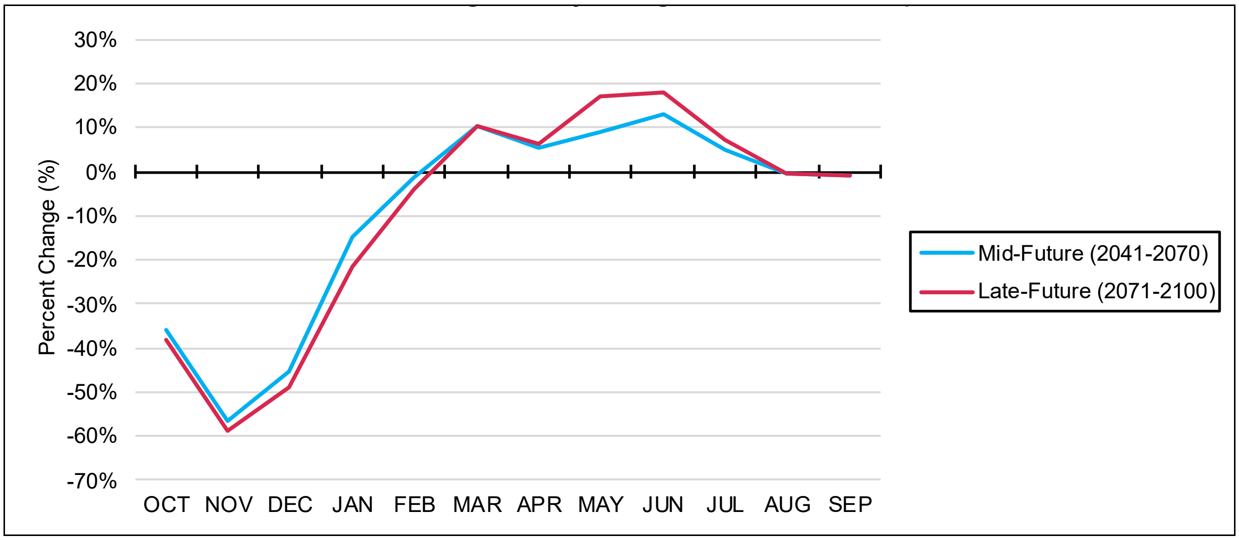


Figure 11-2. Lake Sonoma Change in Daily Average Turbine Flow per Month

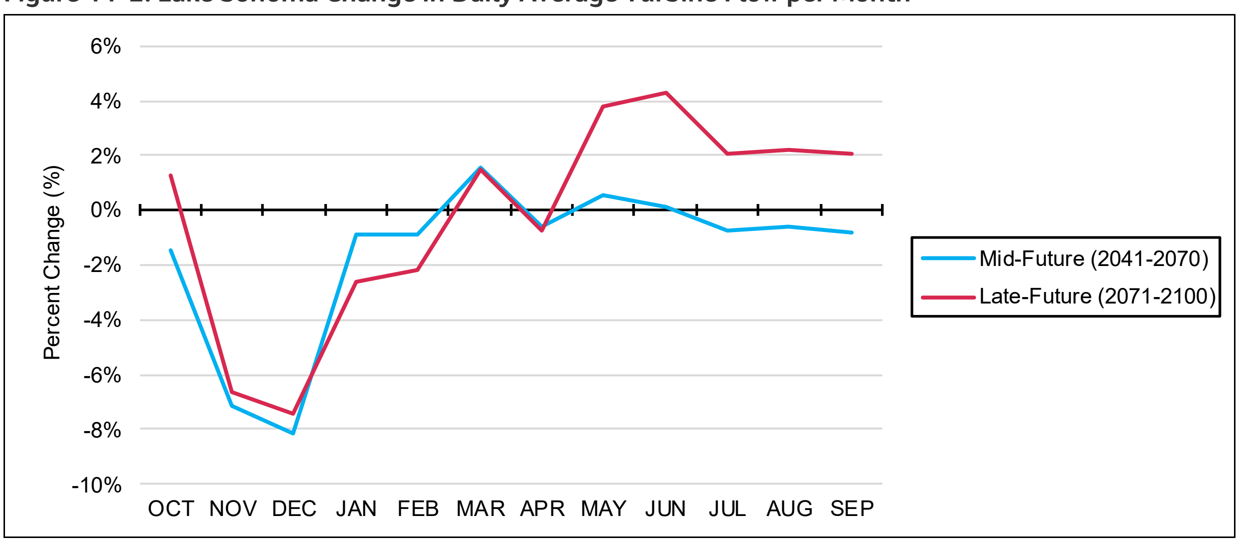


Figure 11-3. Lake Mendocino Change in Annual Total Hydropower Generation

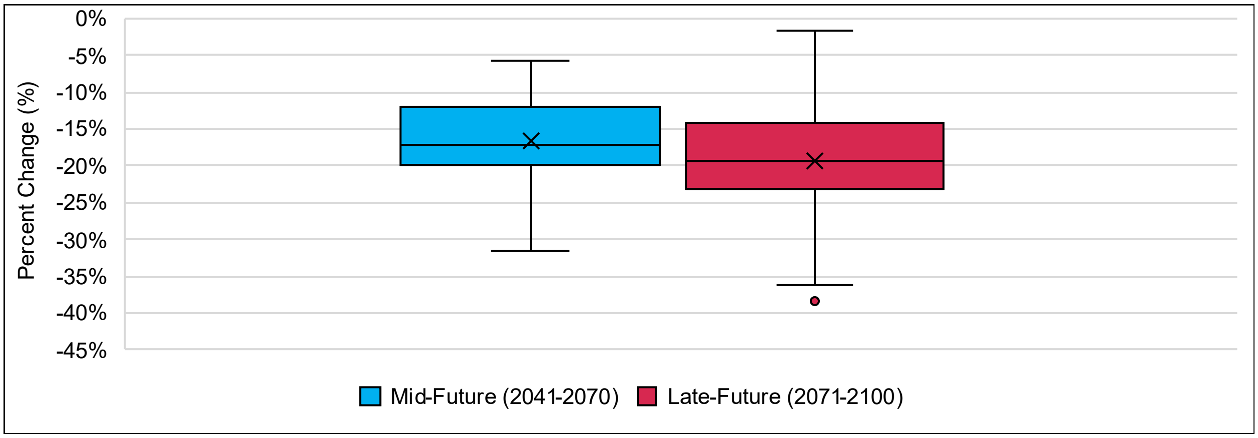
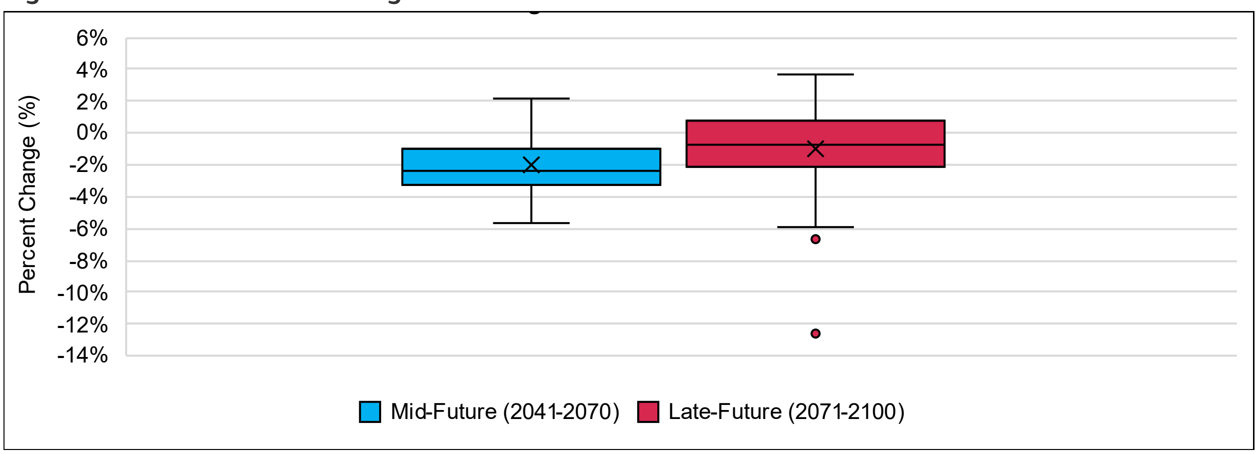


Figure 11-4. Lake Sonoma Change in Annual Total Power Generation



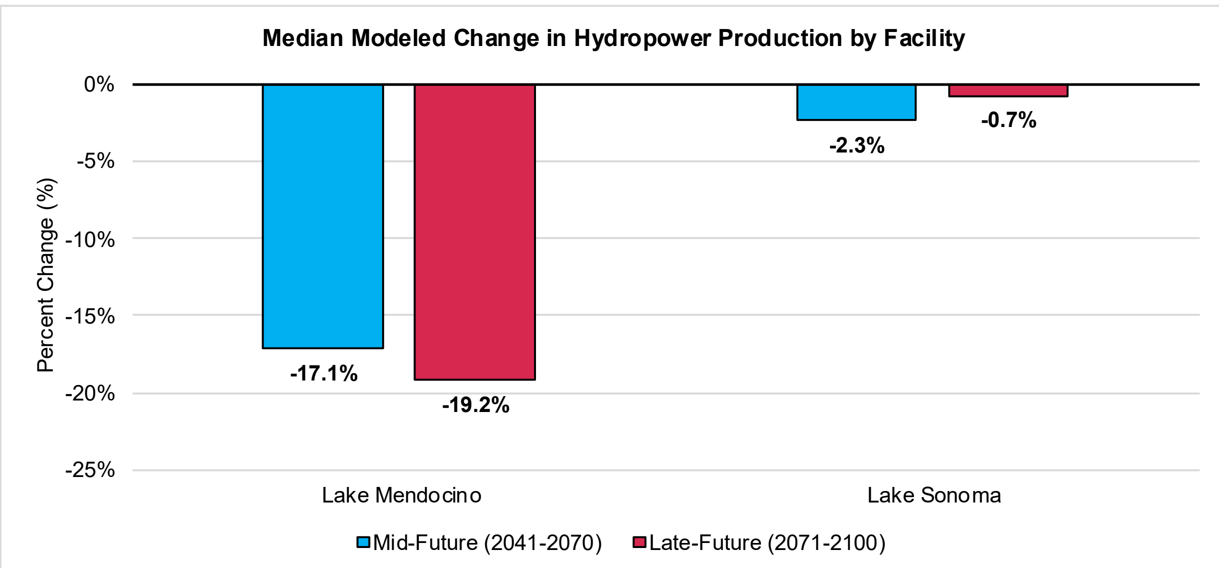
Differences in projected changes in hydropower generation at Lake Mendocino and Lake Sonoma are primarily driven by shifts in unimpaired inflows and reservoir storage at each facility as well as resulting shifts in downstream releases. Lake Mendocino is projected to experience a more significant reduction in reservoir storage, caused by a decrease in reservoir inflows in late fall and early winter, primarily due to reductions in Eel River transfers after 2034. This results in a reduction in storage in May through February and nearly no increase in March and April relative to historical conditions, causing reductions in reservoir releases in October through January. Lake Sonoma, on the other hand, appears to be far more resilient to future climate conditions, with relatively similar reservoir storage trends under both Mid-Future and Late-Future conditions. Hydropower generation increases slightly between late spring and early fall during the late-future, likely due to a minor increase in reservoir releases from Lake Sonoma to meet instream minimum flow requirements and compensate for the reduction in Lake Mendocino releases.

11.4 Summary

Releases from Coyote Valley Dam at Lake Mendocino and Warm Springs Dam at Lake Sonoma are used to generate hydropower in the Russian River watershed. Changes in the magnitude and distribution of reservoir inflows throughout the year can influence the quantity of hydropower production and the reliability of these energy supplies for municipalities and residents within the watershed. Hydropower vulnerabilities at Lake Mendocino and Lake Sonoma were evaluated using daily turbine flow and hydropower generation timeseries between 1950 and 2100. These timeseries were generated by incorporating a python-based tool developed by Sonoma Water for estimating hydropower production into the Sonoma Water DSM, a regional water supply model that simulates reservoir and diversion operations within Sonoma Water's service area. Historical trends between 1981 and 2010 were compared with Mid-Future (2041–2070) and Late-Future (2071–2100) climate conditions to evaluate vulnerabilities to hydropower generation at Lake Mendocino and Lake Sonoma.

Lake Mendocino annual total hydropower generation is projected to decrease by roughly 17% and 19% under median Mid-Future and Late-Future conditions, respectively (Figure 11-5). These changes are primarily driven by a significant reduction in reservoir releases to hydroelectric turbines in October through January. The reduction in turbine flow for these months is caused by a decrease in reservoir inflows to Lake Mendocino between spring and early winter as a result of reduced Eel River transfers. Given that Lake Mendocino hydroelectric supplies are primarily utilized by the City of Ukiah, alternative, local energy sources may need to be considered between October and January to compensate for the reduction in power production during these months.

Figure 11-5. Summary of Hydropower Vulnerability Assessment Findings



Lake Sonoma annual total hydropower generation demonstrates high resilience to future climate conditions, with a 2% and 1% decrease under median Mid-Future conditions and Late-Future conditions, respectively, relative to historical trends (Figure 11-5). Monthly trends are projected to vary slightly from month-to-month on average, but any decreases in some months are largely offset by increases in others, particularly under late-future conditions. Ultimately, shifts in reservoir inflows at Lake Sonoma have a relatively muted effect on annual reservoir storage, and reservoir operations appear to be capable of maintaining historical hydropower generation trends under future conditions. Between late spring and early fall under late-future conditions, Lake Sonoma hydropower production increases slightly relative to historical conditions, resulting in a minor overall increase in hydroelectric generation during this period. This change is driven by an increase in Lake Sonoma releases to continue to compensate for the reduction in releases from Lake Mendocino during this period and ensure that minimum instream flow requirements continue to be met.

12. Community and Equity Considerations

12.1 Purpose

Centering community and equity is foundational to the Watershed Resilience Program (WRP), and both the California Water Plan Update 2023 and WRP emphasize watershed scale planning that prioritizes inclusiveness, integrates climate vulnerability across sectors, and guides funding and implementation. Leveraging California's Vulnerable Communities Platform (VCP)—the state's first hazard-specific social vulnerability tool—the assessment evaluated potential variation in sensitivity and adaptive capacity to flooding, drought, extreme heat, and wildfire across communities. RRWRP conducted a watershed scale social vulnerability assessment to characterize who in the Russian River watershed is exposed to and most vulnerable to climate hazards. This chapter defines the community context for the Russian River watershed, identifies populations facing disproportionate environmental and climate burdens, and explains how these profiles inform both the vulnerability assessment and the adaptation strategy development steps of the pilot.

12.2 Methodology

Community vulnerability in the watershed is assessed by overlaying climate hazard datasets with social vulnerability indicators to identify where populations with higher sensitivity may be disproportionately exposed. This analysis draws on the sensitivity indicators developed by the VCP led by the Office of Land Use and Climate Innovation. The VCP aggregates multiple social and access-related indicators for each climate hazard—including wildfire, drought, extreme heat, and flooding—to characterize how different populations may experience climate impacts. To enhance relevance at the watershed scale and better support RRWRP decision needs, the analysis incorporates the following refinements:

- **Local Percentile Rescaling**: The public VCP classifies vulnerability statewide (Low/Medium/High), which can mask differences within a single watershed. To improve local relevance, VCP social sensitivity were recalculated as *watershed-relative percentiles*, enabling comparison **within** the watershed rather than statewide. Additional statistical renormalization was applied to more accurately characterize how vulnerability is distributed internally across the watershed and to increase the sensitivity of the analysis for local planning. This refinement accomplishes the following:
  - Reveal within-watershed variation in sensitivity.
  - Identify localized "hot spots" that statewide ranking would flatten.
  - Retain VCP's original 0/1/2 scoring thresholds (less than or equal to 50th; 51st to 75th; and greater than 75th percentiles).
- **More Precise Population Representation using FEMA Counts**: VCP aggregates social indicators at the census block group scale (American Community Survey population), and also provides FEMA/ORNL LandScan (approximately 90 meter resolution) nighttime population estimates. The RRWRP analysis joins social characteristics to LandScan counts at their mapped locations, yielding a clearer picture of who is affected, and where, better leveraging fine scale exposure footprints from the RRWRP's hazard analyses.
- **Integration of Planning-Grade Hazard Layers**: RRWRP modeling outputs for extreme heat, wildfire probability, flooding, and drought were incorporated in the social vulnerability assessment to better represent localized climate risk.

To maintain consistency with VCP methodological standards, the following QA/QC steps were applied:

- Verify that watershed-level normalization was effective by confirming that cumulative percentiles for each hazard-specific social score span 0 to 100% within the project area.
- Confirm that the highest discrete sensitivity score for each hazard aligns with the highest percentile bin.
- Exclude nulls (areas not applicable or not evaluated) from percentile calculations.
- Retain zeros (valid low scores) to preserve the true distribution and avoid bias.

Population counts may vary slightly across the different social vulnerability scores because each score is calculated only for population units with complete (non-null) data for all indicators. As a result, findings below may have small, expected differences in the underlying population counts.

12.2.1 Sensitivity Indicators

A core set of 15 social vulnerability indicators are used to build the social sensitivity scores for extreme heat, flooding, wildfire, and drought. These indicators represent broad social factors including basic needs insecurity (food insecurity, housing insecurity, transportation insecurity), social isolation and lack of support, demographic sensitivities (children under 5, disability, limited English proficiency, low income, and seniors living alone), and structural or access-related factors such as residence in mobile homes, lack of internet access, high renter burden, and if the community is part of a tribal community. For each hazard, an additional set of select indicators are used to represent hazard-specific sensitivities for extreme heat, wildfire, flooding and drought. Hazard-specific social indicators are listed in Table 12-1.

Table 12-1. Hazard-Specific Social Indicators

Climate Hazard	Indicators	Hazard-Specific Indicators (Brief Description)
Extreme Heat	26	Includes additional indicators related to chronic health conditions (asthma, COPD, diabetes, coronary disease, obesity, mental distress), smoking, PM2.5 exposure, outdoor workers, nighttime heat frequency, and urban heat island intensity.
Flooding	16	Adds a single flood-specific indicator capturing sensitivity to extreme precipitation intensity through the contribution of very wet days.
Drought	17	Adds two drought-specific indicators: reliance on agricultural occupations and vulnerability of drinking water systems (failing, at risk, or domestic well-dependent areas).
Wildfire	25	Supplements the core indicator set with additional exposure and health indicators plus wildfire-relevant factors such as Fair Access to Insurance Requirements (FAIR) Plan insurance burden and Public Safety Power Shutoff exposure.

This framework underpins the social vulnerability assessment, which identifies communities with the greatest combined levels of climate hazard exposure and social sensitivity for wildfire, extreme heat, flooding, and drought. Hazard-specific social scores are generated by converting each individual indicator into percentile ranks to show how conditions in each census geography compare statewide. Based on these percentile ranks, indicators are assigned 0, 1, or 2 points depending on whether they fall below the 50^{th} percentile, between the 50^{th} and 75^{th} percentiles, or above the 75^{th} percentile (with adjustments for skewed distributions as outlined in the VCP methodology). These point values are then summed to produce the composite social sensitivity score for each hazard.

12.3 Results

Table 12-2 shows metrics for selected climate hazards and their supporting reference periods. These metrics include extreme heat, flooding, wildfire, and water supply vulnerability and are used to assess social vulnerability.

Table 12-2. Overview of Climate Hazard Metrics, Definitions, and Reference Periods

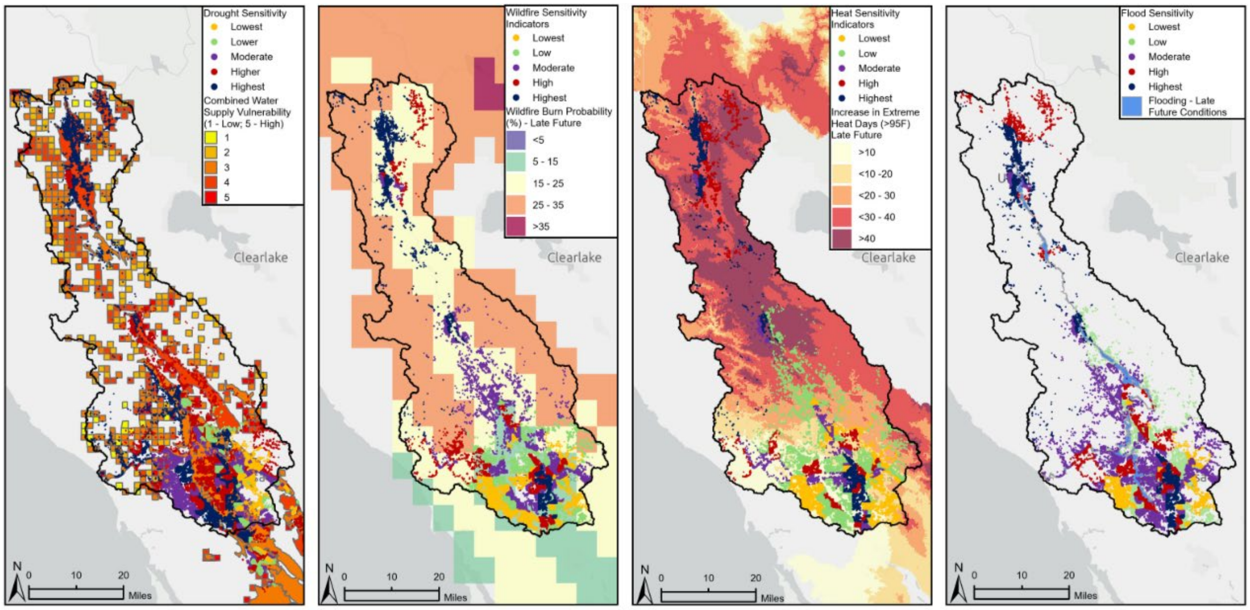
Metric	Definition	Reference Periods
Extreme Heat Days	Projected change in number of Extreme Heat Days per Year when daily maximum temperature is above 95°F Historical temperature (days/yr)	Absolute values (days/year) for Historical Period (1981–2010)
		Absolute values (days/year) for Late-Future Period (2071–2100)
Extreme Precipitation/ Flooding	Projected change in 1% annual exceedance probability precipitation (%) of a 3-day storm	Historical: Change (%) for Mid-Future Period (1981–2010)
		Annual_p50_Late_Change: Change (%) for Late-Future Period (2071–2100)
Wildfire Burn Probability	Projected changes for estimated decadal wildfire probabilities (%)	Absolute values (%) for Historical Period (1981–2010)
		Absolute values (%) for Mid-Future Period (2071–2100)
Water Supply	Projected changes are informed from qualitative and quantitative assessments of surface water supply, groundwater in alluvial basins, and groundwater in bedrock areas. In overlapping areas, surface water supply ratings take precedence over groundwater vulnerability ratings in alluvial basins and bedrock areas.	Changes are evaluated for Late-Future Period (2071–2100)

12.3.1 Flooding

The team modeled present-day and late-future conditions to assess potential impacts from flooding, wildfire, and extreme heat. For flooding, the present-day analysis also incorporated FEMA floodplain inundation to capture additional near term exposure. Drought vulnerability was evaluated using water supply modeling, but only for the late-future conditions. The four-panel Figure 12-1 maps late-future climate hazards with population vulnerability overlaid.

Figure 12-1. Late-Future Conditions Climate Impacts Mapping

(Left to Right: Vulnerable Water Supply, Wildfire, Extreme Heat, Flooding)



Flood modeling for the Russian River watershed was completed using CMIP6 climate projections to evaluate future hydrologic and hydraulic conditions. Two separate model outputs were produced—one focused on capturing flood behavior along the Russian River main stem, and another tailored specifically to Santa Rosa Creek to resolve its distinct watershed hydrology and localized flood dynamics. Two reference periods were selected—a present-day baseline and a late-century future scenario—to capture shifts in storm intensity, runoff generation, and flood behavior under evolving climate conditions. To resolve system-specific dynamics, two separate model outputs were produced: one characterizing flooding along the Russian River main stem and another tailored to Santa Rosa Creek's localized watershed hydrology and flood response.

The VCP uses 22 social indicators to assess flood vulnerability, grouped into three broad categories: (1) basic needs and socioeconomic marginalization, (2) demographic and housing-related sensitivity, and (3) environmental and occupational exposure factors.

Table 12-3 summarizes how flood sensitivity scores are distributed across the Russian River Watershed population, ranging from 0 (lowest sensitivity) to 19 (highest sensitivity). These scores reflect underlying social and demographic conditions, not physical hazard exposure, so communities may have high sensitivity even if they are not located within mapped flood-prone areas. Results show that the watershed's population is spread relatively evenly across the five bins. Nearly half of the watershed's population (45%) falls within the upper two sensitivity categories, indicating substantial baseline social vulnerability that could amplify flood impacts where exposure occurs under present or future climate scenarios. The pie chart in Figure 12-2 illustrates this distribution.

Table 12-3. Flood Sensitivity Distribution Across Russian River Watershed Population

# of Flood Sensitivity Indicators	Flood Bin	Flood Sensitive Population Count	Flood Sensitivity Distribution (%)
0 to 2	Lowest	47,787	12%
3 to 4	Low	69,681	17%
5 to 6	Moderate	109,578	27%
7 to 8	High	84,588	21%
9 to 19	Highest	96,099	24%
Total		**407,733**	**100%**

Figure 12-2. Population Sensitivity to Flooding

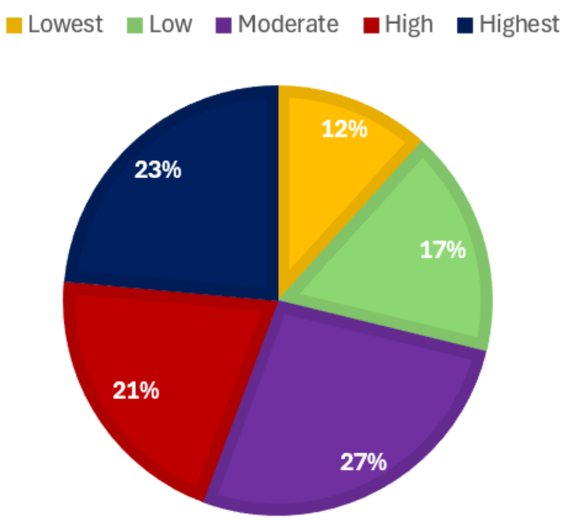
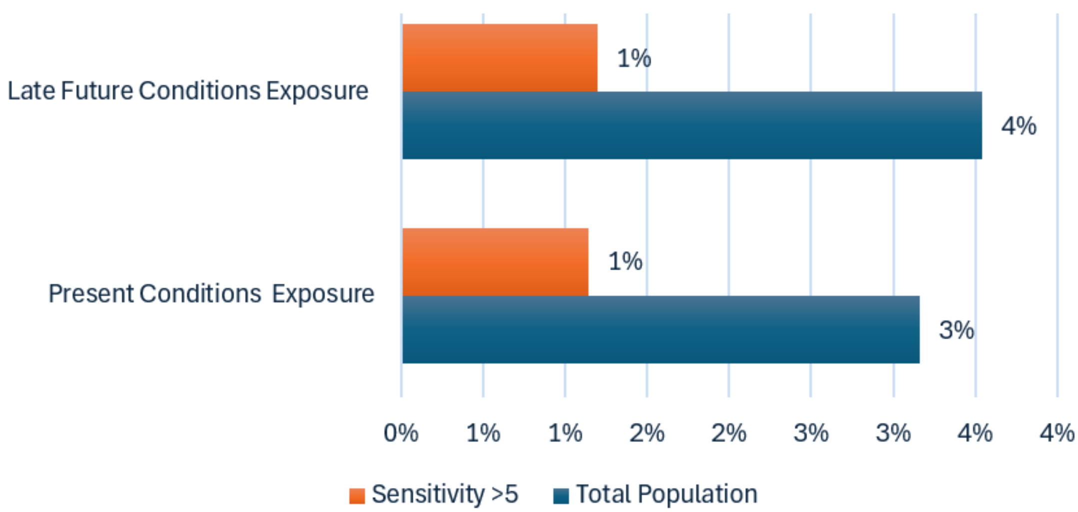


Figure 12-3. Comparison of Present and Future Exposure to Flooding



12.3.1.1 Flood Impacts – Present Conditions

Present -conditions inundation is represented by the hydraulic modeling completed by Jacobs, which defines the project's base flood extent for current climate conditions. To complement this modeled footprint, the assessment also incorporates present -day FEMA Flood Insurance Rate Map (FIRM) flood hazard zones from the National Flood Hazard Layer. The FEMA data was trimmed to include only the portions of the FEMA floodplain that extend beyond the modeled inundation area. This trimming included selective removal of inundated tributary segments where, based on hydrologic behavior, model coverage, and professional scientific judgment, FEMA-mapped flood extents were not expected to contribute additional inundation beyond what the hydraulic model already captured. The resulting FEMA layer therefore represents- the incremental regulatory floodplain to provide additional context on where socially sensitive populations may intersect with regulatory flood hazard areas outside the modeled inundation zone.

Approximately 13,000 people fall within the modeled present-day inundation zone, one-third of whom are classified in the highest social sensitivity tier with scores between 9 and 19.

The *Sonoma County Environmental Justice Technical Report* (Permit Sonoma, May 2024) identifies several Santa Rosa neighborhoods as environmental justice priority areas due to elevated pollution burdens, disproportionate exposure to environmental hazards, and socioeconomic vulnerabilities—including low income, housing cost burden, linguistic isolation, and limited transportation access—with these conditions most prevalent in central, southwest, and southeast Santa Rosa. The VCP results reinforce this pattern, with the vast majority of individuals residing in Santa Rosa classified in the highest social sensitivity tier.

12.3.1.2 Flood Impacts – Future Conditions

Over 15,000 people fall within the late-future inundation zone, including nearly 5,000 residents in the highest social sensitivity tier. In the Santa Rosa Creek watershed, late-future flooding shows a markedly expanded footprint across Santa Rosa, with floodwaters extending beyond primary creek corridors and affecting most developed areas of the city. These modeled patterns align with the known flood prone corridors mapped along Santa Rosa Creek and key tributaries in recent FEMA updates (City of Santa Rosa FEMA Flood Risk Mapping Project, 2025; FEMA 2026).

Late-future floodplain expansion extends into Southwest and central Santa Rosa, which the County identifies as core Environmental Justice communities—areas with the county's highest concentrations of nonwhite and working class residents (Sonoma County Environmental Justice Technical Report, 2024; Portrait of Sonoma County, 2021).

12.3.1.3 FEMA Floodplain Mapping

Tributary flooding was not explicitly simulated in the hydrologic–hydraulic modeling of the mainstem Russian River or Santa Rosa Creek. To approximate potential tributary flooding, FEMA floodplain mapping was incorporated as a supplemental dataset. The FEMA extents identify flooding along smaller tributaries and localized overbank areas that fall outside the baseline modeled domain—particularly in Redwood Valley, Potter Valley, Calpella, the Ukiah Valley, and neighborhoods surrounding Lake Mendocino. Because FEMA mapping reflects existing conditions, it was used only for the present-day reference period.

The FEMA-mapped floodplain extends beyond the limits of the baseline flood model and highlights additional communities and populations that may face flood risk not captured in the modeled scenarios. Approximately 7,600 additional residents fall within FEMA flood zones that are outside the present -conditions model footprint, and roughly one-third of this population is categorized in the highest sensitivity tier.

12.3.2 Wildfire

The wildfire metric captures how climate change may increase the frequency or likelihood of wildfire occurrence across the landscape. The metric highlights which communities and locations could face heightened wildfire risk over time. The following metric was selected to measure exposure to wildfire:

- **Wildfire Burn Probability**, which represents the estimated percent likelihood that a given area will burn in a typical year under historical and late-future climate conditions. **Reference periods**: 'Historical': 1981–2010; 'Mid-Future': 2071–2100

While the VCP generates a wildfire social sensitivity score, the methodology directs users to rely on CAL FIRE's Fire Hazard Severity Zones (FHSZ) when assessing wildfire vulnerability. The VCP makes this recommendation because FHSZ is the State of California's official classification of wildfire hazard for State and Local Responsibility Areas, developed using standardized factors such as fuel loading, slope, and fire weather. For the purposes of this assessment, however, we sought to maintain consistency across hazard types by applying the same VCP-developed social sensitivity indicators to all hazards. This allowed us to evaluate underlying social conditions in a comparable way across the analysis.

Table 12-4 summarizes how wildfire sensitivity scores are distributed across the population, with scores ranging from 4 to 23. The results show that population sensitivity is broadly distributed across the five bins, with mid-range sensitivity levels (scores 9–14) accounting for the largest share of the population. This reflects widespread exposure to baseline wildfire-related vulnerability factors such as housing characteristics, health conditions, and socioeconomic constraints. About 20% of the population falls within the highest wildfire sensitivity tier, indicating substantial susceptibility to wildfire impacts under both current and future conditions. Combined with the two adjacent upper-sensitivity bins, almost half of the residents are exposed to wildfire-related risks across the region. These scores reflect underlying social and demographic conditions, not physical hazard exposure, so communities may have high sensitivity even if they are not located in wildfire prone areas. The pie chart in Figure 12-4 illustrates this distribution.

Table 12-4. Distribution of Population Sensitivity to Wildfire

# of Wildfire Sensitivity Indicators	Wildfire Bin	Wildfire Sensitive Population Count	Wildfire Sensitivity Distribution (%)
4 to 6	Lowest	75,413	18%
7 to 8	Low	70,284	17%
9 to11	Moderate	90,323	22%
12 to 14	High	89,862	22%
15 to23	Highest	81,851	20%
Total		**407,733**	**100%**

Figure 12-4. Population Sensitivity and Exposure to Wildfire

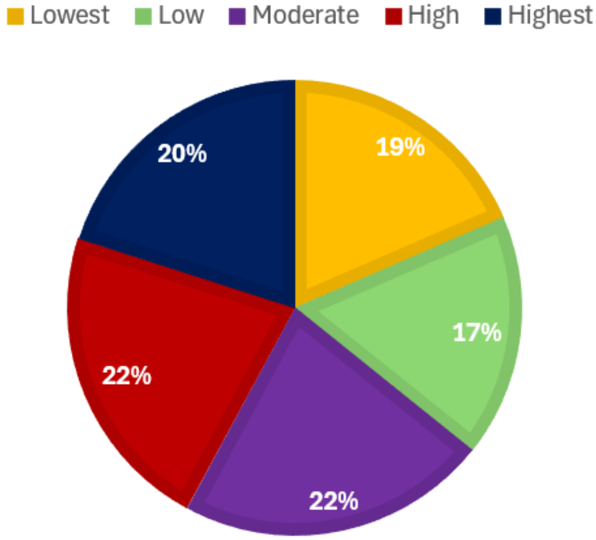
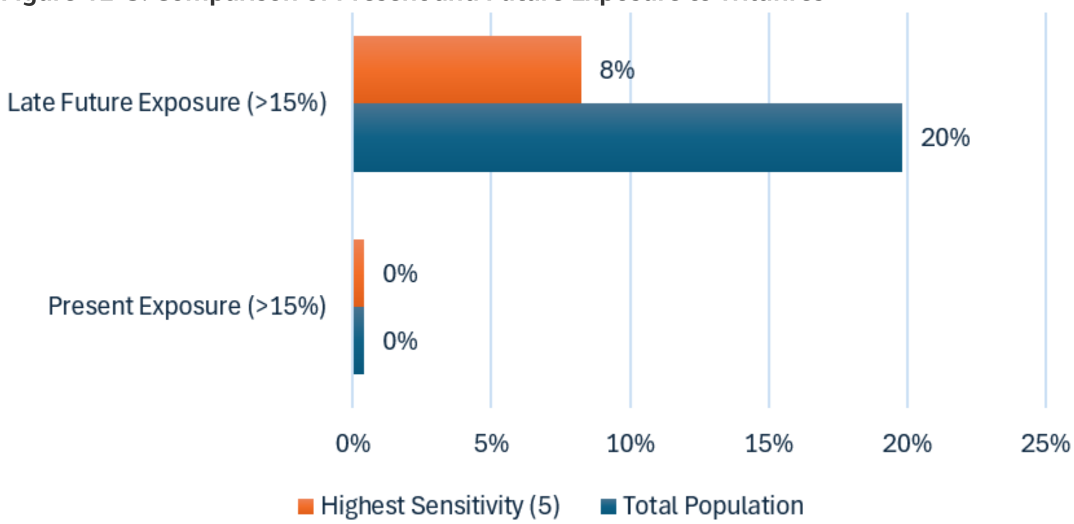


Figure 12-5. Comparison of Present and Future Exposure to Wildfires



12.3.2.1 Wildfire Impacts – Present Conditions

Overall, the present-day analysis shows that wildfire exposure is widespread across the watershed, and that the most socially vulnerable residents are disproportionately located in the areas where wildfire likelihood is already highest. Under present-day conditions, a significant portion of the watershed—particularly the forested uplands and wildland–urban interface (WUI) areas—is exposed to greater than 15% modeled wildfire burn probability, indicating that most of the watershed faces a meaningful likelihood of wildfire occurrence under current conditions. These high-hazard zones are concentrated along the Mayacamas range, in the upper watershed, and across the foothills south toward Santa Rosa. Significant wildfires in the Russian River watershed—including the 2017 Tubbs and Nuns Fires, which together burned 93,000+ acres and roughly 8% of the watershed, and the 2020 Walbridge Fire, which burned over 55,000 acres in the northwestern watershed—have repeatedly occurred along the Mayacamas range, upland forests, and wildland–urban interface areas. These same areas appear in the modeled high-probability (>15%) wildfire zones, indicating that the late-future projections are consistent with where the watershed has already experienced its most severe and recurrent wildfire activity.

12.3.2.2 Wildfire Impacts – Late-Future Conditions

Under late-future conditions, nearly the entire watershed is exposed to greater than 15% burn probability, with large inland and southern areas increasing to probabilities above 25% and 35%. This represents a significant intensification beyond present-day conditions, extending high-hazard zones into mid-valley communities and areas that historically experienced lower wildfire likelihood. High and moderate sensitivity clusters in Ukiah, Healdsburg, Windsor, and the Santa Rosa foothills fall within areas of elevated late-future burn probability, increasing the likelihood of acute evacuation challenges and disproportionate recovery impacts.

12.3.3 Extreme Heat

The following metric was selected to measure exposure to extreme heat. This metric shows how much more frequently communities are expected to experience dangerous heat conditions. By comparing historical conditions with modeled future changes, the metric provides a clear picture of how heat exposure is expected to intensify and which parts of the watershed may experience the greatest increases.

- Projected change in the **number of Extreme Heat Days per year**, defined as days when the daily maximum temperature exceeds 95°F.

Table 12-5 provides the distribution of population sensitivity to extreme heat.

Table 12-5. Distribution of Population Sensitivity to Extreme Heat

# of Heat Sensitivity Indicators	Heat Bin	Heat Sensitive Population	Heat Sensitivity
3 to 6	1	78,208	19%
7 to 9	2	86,135	21%
10 to 11	3	59183	15%
12 to 14	4	61,661	15%
15 to 22	5	122,546	30%
Total		**407,733**	**100%**

Table 12-5 summarizes how sensitivity to extreme heat is distributed across the population, with scores ranging from 3 to 22. The results show that sensitivity is spread across all five bins, but with a notable concentration in the highest tier: 30% of the population (122,546 people) fall into the most heat sensitive category. Mid-level sensitivity (scores 7–14) accounts for roughly 36% of residents, reflecting widespread socioeconomic and health-related factors that heighten vulnerability to prolonged or extreme heat events. The pie chart in Figure 12-6 illustrates this distribution.

Figure 12-6. Population Sensitivity to Extreme Heat

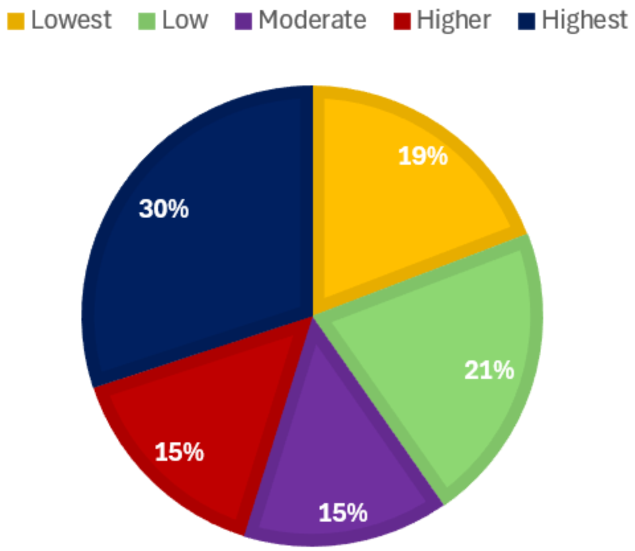
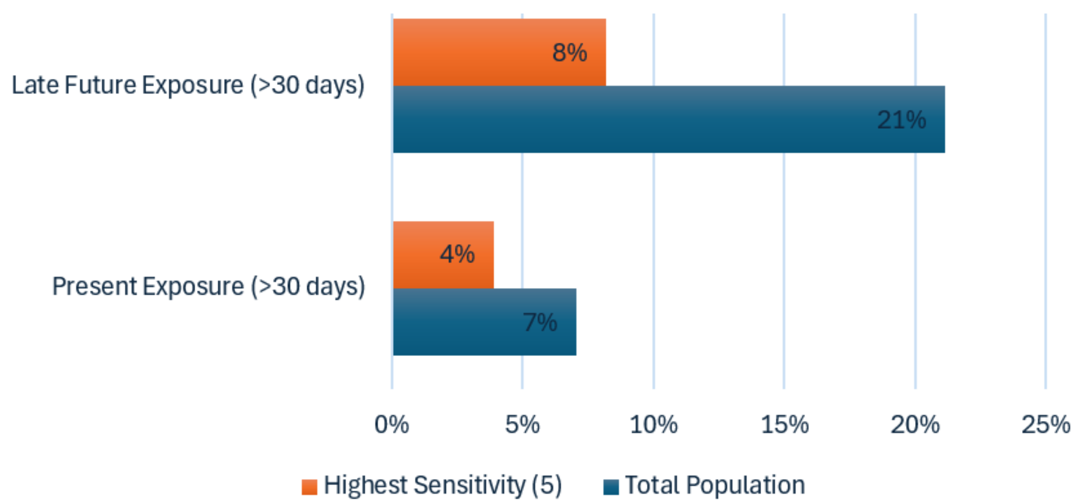


Figure 12-7. Comparison of Present and Future Exposure to Extreme Heat



Taken together, the upper two bins include nearly half of the population, underscoring substantial baseline sensitivity to extreme heat across the region. These results highlight the potential for heat-related impacts to intensify under future climate conditions, especially among communities already experiencing higher exposure, limited adaptive capacity, or underlying health stressors.

Extreme heat exposure under present conditions is highest in the inland portions of the Russian River watershed. The greatest increases in days above 95°F occur in the Ukiah Valley, Cloverdale, and the central valley corridor, with additional elevated areas south toward Santa Rosa. Sensitive populations overlap with several of these high-exposure zones, including communities in Ukiah, Cloverdale, Healdsburg, and urban neighborhoods near Santa Rosa. Residents with limited access to cooling, higher health risks, and socio-economic constraints are therefore more vulnerable to heat-related impacts in the areas where extreme heat days are already most frequent.

Late-future projections show a substantial increase in extreme heat exposure across the Russian River watershed, with most inland and mid-valley areas experiencing very large increases in days above 95°F. The highest increases—often exceeding 40 additional extreme heat days—are concentrated from Ukiah through Cloverdale and Healdsburg, and extend south toward Windsor and Santa Rosa. Populations sensitive to extreme heat overlap heavily with these areas, particularly in Ukiah, Cloverdale, Healdsburg, and the Santa Rosa urban area. This convergence indicates that the communities with underlying health, economic, or housing vulnerabilities are likely to face the greatest heat-related risks as extreme heat days become more frequent and widespread across the watershed.

12.3.4 Water Supply

Water supply vulnerability was mapped using Sonoma Water's service area boundaries, with each zone assigned a qualitative rating based on Sonoma Water DSM/ResSim modeling and the water supply vulnerability memos. In areas where surface water and groundwater service zones overlap, the surface water rating takes precedence; areas outside surface water zones receive the groundwater rating. These layers provide a unified spatial view of water supply vulnerability.

To fully capture how water supply disruptions could affect communities linked to the Russian River system, the analysis area was expanded to include the entire Sonoma Water service area. This broader scope reflects the interconnected nature of regional deliveries, storage operations, and customer demand. Under this expanded boundary, the total population evaluated increases to approximately **755,740 residents**, ensuring that all communities dependent on the Russian River system are represented in the assessment.

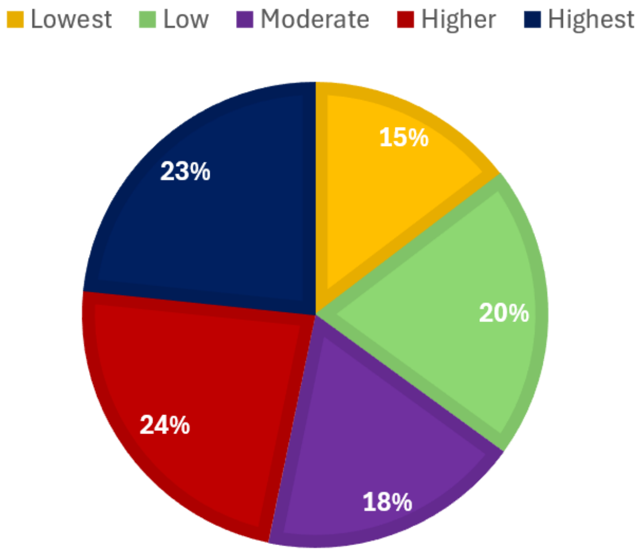
The VCP assesses social sensitivity to drought using indicators that reflect a community's ability to cope with water shortages. These include basic needs insecurity (food, housing, transportation), low income, limited English proficiency, disability, seniors living alone, renters, lack of internet access, and social isolation, all of which constrain a household's capacity to respond to or recover from drought disruptions. The VCP also incorporates drought-specific social factors such as agricultural workers, who face economic losses during drought, and water system risk, which identifies residents served by failing or at-risk systems or reliant on domestic wells.

Table 12-6 summarizes how sensitivity to vulnerable water supply is distributed across the population, with scores ranging from 1 to 18 grouped into five bins. The results indicate that sensitivity is broadly spread across all categories, with the highest tier (scores 10–18) representing 23.3% of the population, or approximately 176,380 residents. Mid-level sensitivity (scores 5–9) accounts for roughly 41% of the population, reflecting widespread factors that influence dependence on drought-sensitive water supplies. The pie chart in Figure 12-8 illustrates this distribution.

Table 12-6. Distribution of Population Sensitivity to Vulnerable Water Supply

# of Drought Sensitivity Indicators	Drought Bin	Drought-Sensitive Population	Drought Sensitivity
1 to 2	Lowest	110,682	14.7%
3 to 4	Low	153,761	20.4%
5 to 6	Moderate	137,897	18.3%
7 to 9	High	176,750	23.4%
10 to18	Highest	176,380	23.3%
Total		**755,470**	**100.0%**

Figure 12-8. Population Sensitivity to Drought



Higher combined water supply vulnerability is concentrated along the Russian River corridor and in basin-margin or foothill communities where supplies are more sensitive to drought, groundwater depletion, or curtailments. Nearly half of the population falls within the two highest sensitivity tiers, reflecting reliance on systems with limited redundancy or stronger exposure to drought year operating constraints. These patterns are consistent with past operational challenges in the watershed. During the 2021–2022 drought, the State Water Resources Control Board issued **emergency curtailment orders** that restricted surface water diversions for roughly 2,000 right holders and noted that **Lake Mendocino could have gone dry without curtailments**, highlighting system fragility during multi-year droughts. Communities dependent on fractured rock wells also experienced shallow well failures during extended dry periods, while groundwater pumping in areas such as the Alexander Valley was found to contribute to reduced river flows, prompting heightened State scrutiny and the possibility of future regulation on basin-margin wells. Fractured rock uplands and small systems tend to have highly variable yields and limited storage. Valley-margin communities relying on alluvial groundwater, such as those in the Ukiah, Healdsburg, and Sonoma–Petaluma areas, face increased drought stress when reservoir levels drop or when groundwater pumping contributes to streamflow depletion, triggering curtailments or restrictions. Together, these documented impacts reinforce that communities with limited supply diversification or strong dependence on Russian River flows are most likely to experience future disruptions under continuing drought and climate-driven hydrologic change.

12.4 Summary

Russian River Watershed communities are increasingly exposed to widespread and intensifying impacts from flooding, wildfire, extreme heat, and drought driven water supply disruptions. Climate hazard modeling and vulnerability analyses show that hazard footprints expand substantially under future conditions. Social vulnerability is already elevated across the region, with 40 to 50% of residents falling within the moderate to highest sensitivity tiers for each hazard. Many of the residents who are most socially vulnerable also live in areas facing the highest hazard levels, compounding risk and leading to disproportionate exposure now and in the future.

This assessment indicates that neighborhoods in Santa Rosa, the Ukiah Valley, the Cloverdale–Healdsburg–Windsor corridor, and the communities surrounding Lake Mendocino face the most significant and overlapping climate pressures in the Russian River Watershed. Across all hazard types, the assessment identifies a consistent set of geographic hotspots where high sensitivity and high exposure overlap most acutely. These priority areas include Santa Rosa and the Santa Rosa Plain; the Ukiah‑Redwood Valley‑Calpella corridor; the Cloverdale‑Healdsburg‑Windsor corridor; the lower Russian River communities including Guerneville, Monte Rio, and Forestville; and neighborhoods surrounding Lake Mendocino. Drought and watersupply sensitivity are especially pronounced in the upper watershed and across the Santa Rosa Plain, where -nearly half the regional population falls within the top two drought -sensitivity tiers, reflecting widespread dependence on groundwater, fractured rock wells, and climate- s-ensitive surface water allocations. Wildfire sensitivity is highest in foothill and WUI communities throughout central and southern Sonoma County, extending north toward Ukiah and Redwood Valley, driven by steep terrain, limited evacuation capacity, and older or isolated housing stock. Extreme heat vulnerability is most concentrated in major valley population centers—particularly in Santa Rosa, Rohnert Park, Cotati, Sebastopol, and the Windsor–Healdsburg–Cloverdale corridor—where inland temperatures are projected to rise sharply. Flood vulnerability is centered along the lower mainstem corridor and in the Ukiah‑Redwood Valley basin, where modeled inundation intersects neighborhoods with high baseline social sensitivity.

Together, these findings underscore that the watershed's greatest equity challenges emerge in places where structural socioeconomic vulnerability intersects directly with increasing climate hazard intensity and geographic expansion. The same communities most burdened by limited mobility, cost pressures, and rural infrastructure gaps are also those facing the steepest increases in flood extent, wildfire probability, extreme heat days, and drought driven water supply stress. These overlapping pressures create a landscape of compounding and mutually reinforcing risks, making clear that equitable adaptation must prioritize the watershed's identified hotspot regions—particularly central and southwest Santa Rosa, the Ukiah–Cloverdale–Healdsburg–Windsor corridor, the lower Russian River communities, and drought-sensitive areas around Lake Mendocino and basin-margin wells. These locations represent the watershed's clearest frontline communities, where early and sustained investment is most likely to reduce disparities and strengthen long-term climate resilience.

12.4.1 Recommendations for Implementation

This community impact assessment indicates that significant portions of the Russian River Watershed population are not only exposed to intensifying climate hazards but are predisposed to be more sensitive—and therefore disproportionately affected—by flooding, wildfire, extreme heat, and drought driven water supply disruptions. Sensitivity and exposure hotspots converge in specific locations: central, southwest, and downtown adjacent Santa Rosa for both present and late-future flooding; Ukiah Valley, Cloverdale–Healdsburg–Windsor, and Santa Rosa foothill communities for escalating wildfire probability and large increases in extreme heat days; and the Russian River corridor, basin-margin communities, and neighborhoods reliant on Lake Mendocino and fractured rock wells for drought and supply vulnerabilities. These patterns show where adaptation implementation should be prioritized based on hazard type—urban stormwater and drainage in Santa Rosa; wildfire evacuation, home hardening, and fuels reduction across mid-valley communities and the Mayacamas; heat safety and cooling access from Ukiah through Windsor and Santa Rosa; and water supply reliability, recharge, and small system support around Lake Mendocino and foothill groundwater-dependent areas.

Adaptation strategies for the Russian River Watershed should therefore be phased and implemented to put these most affected communities at the forefront, directing early investments where social sensitivity and climate hazard exposure overlap most strongly. The State of California has increasingly aligned climate resilience funding with equity mandates, creating substantial opportunities for the Russian River Watershed to advance adaptation strategies in ways that directly benefit the communities identified- in this assessment as most exposed and most sensitive to climate impacts. Most notably, Proposition 4—the State's $10 billion climate resilience bond approved by voters in November 2024—requires that at least 40% of all bond funds directly support disadvantaged and vulnerable communities as defined in statute. This requirement positions the watershed's high sensitivity, high- exposure neighborhoods—such as central and southwest Santa Rosa, the Ukiah–Cloverdale–Healdsburg corridor, and drought- -sensitive communities around Lake Mendocino—to compete strongly for major state investments in flood resilience, wildfire prevention, extreme heat mitigation, ecosystem restoration, and water- supply- reliability.

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Attachment C-1
Overview of Analytical Tools Used in the Russian River Watershed Resilience Analyses

Attachment C-1. Overview of Analytical Tools Used in the Russian River Watershed Resilience Analyses

C1.1 Introduction

This memorandum provides an overview of the analytical tools that are used to support the Russian River Watershed Resilience Pilot. For each analytical tool, a brief description is provided along with information on the inputs, outputs, spatial and temporal resolution, coverage map (if available), and references to supplemental material. Additionally, the Russian River Watershed Resilience Pilot has identified a range of water sectors that can be assessed using the analytical tools described in this memorandum. Relevant tools for each sector are displayed in Table C1-1.

Table C1-1. Analytical Tools by Water Sector

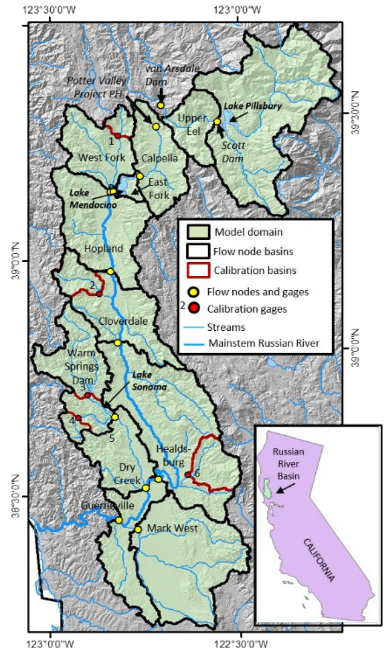
Tool	Surface Water Supply	Groundwater Supply	Flood Management	Ecosystem	Water Quality	Recreation	Hydropower
BCM	X		X	X		X	
Russian River HEC-HMS	X		X				
Santa Rosa Creek HEC-HMS	X		X				
Russian River HEC-ResSim	X					X	X
Sonoma Water Decision Support Model	X					X	X
Russian River GSFLOW Model		X					
Potter Valley Integrated Groundwater-Surface Water Model		X					
Groundwater Sustainability Plan Integrated Surface and Groundwater Computer Models		X					
Russian River Flood HEC-ResSim			X				
HEC-RAS			X				
HEC-ResSim Water Quality Model				X	X		
QCM				X	X		
Suitable Habitat Acre-day Model				X	X		
Power Tools for Hydropower							X

Notes:

BCM = Basin Characterization Model
GSFLOW = Groundwater Surface Flow
HEC = Hydrologic Engineering Center
HMS = Hydrologic Modeling System
QCM = Quantified Conceptual Model
RAS = River Analysis System
ResSim = Reservoir System Simulation
USACE = U.S. Army Corps of Engineers

C1.2 Hydrologic Models

C1.2.1 Basin Characterization Model



Description: The BCM was developed by the U.S. Geological Survey (USGS) and serves as a regional water balance model that can simulate historical and future climate watershed processes including unimpaired streamflows and evapotranspiration. BCMs have been developed for several areas across California; the initial development of the Russian River and Upper Eel River BCM was completed in 2009. Since then, the local BCM has been updated several times, with the most recent update in 2025 expanding the model domain to include south Sonoma County, part of Napa County, and Marin County. To-date, the BCM has been used in several Russian River water supply planning studies, including the Lake Mendocino Water Supply Reliability Study, Draft Fish Habitat Flow and Water Rights Project, Sonoma Water Urban Water Management Plans and Sonoma Water Climate Adaptation Plan.

Processes: With each time step, the BCM characterizes unimpaired conditions by balancing (i.e., inputs and outputs are set equal to one another) precipitation and evapotranspiration, sublimation, runoff, recharge, and change in soil storage for each grid cell. Excess water is infiltrated only when precipitation exceeds potential evapotranspiration. Recharge is represented as infiltration that percolates below the zone of evaporation. When soils are fully saturated, precipitation is ultimately represented as runoff. The distribution of recharge and runoff at each grid cell is dependent on local climate, land cover, and subsurface properties.

Inputs: Inputs are solar radiation, potential evapotranspiration, precipitation, and air temperature. Historical climate inputs rely on Parameter-elevation Regressions on Independent Slopes Model (PRISM) data, and future climate inputs utilize Localized Constructed Analogs Version 2-Hybrid (LOCA2-Hybrid) downscaled GCMs.

Outputs: Outputs are sublimation, snow accumulation, snow melt, watershed available water (excess water), local recharge, local runoff, actual evapotranspiration, climatic water deficit, basin discharge (post processing), and basin groundwater (post processing).

Spatial Resolution: 270-meter grid

Temporal Resolution: Daily

- Historical Period: Oct. 1, 1910–Jun. 30, 2024 (Russian River and Upper Eel River) and Oct. 1, 1981–June 30, 2024 (Marin Reservoirs)
- Historical GCM: Jan. 1, 1950–Dec. 31, 2014, Future Climate Period: Jan. 1, 2015–Dec. 31, 2100

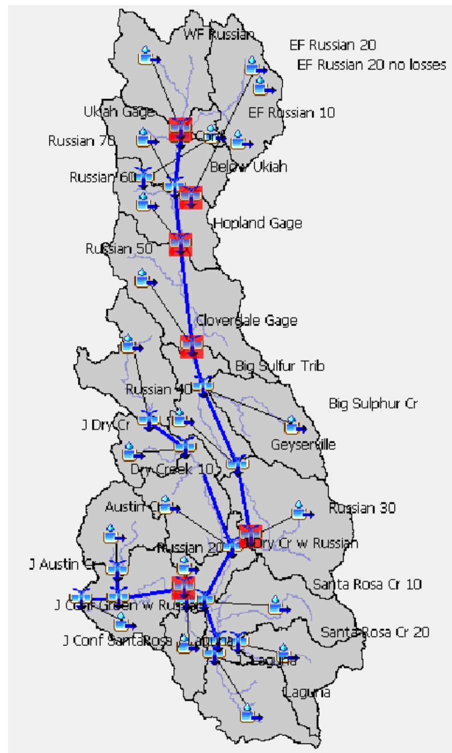
Limitations:

- Relies on regional soil maps that may be prone to errors in some locations due to difficulties with accurately determining soil depths
- Relies on PRISM meteorological data for post-1981 historical observations, which may not capture some fine-scale variability with the watershed

- May not fully characterize specific pathways in the hydrologic cycle and evapotranspiration that have been modified or influenced by human activity
- Application of hydrologic outputs should generally not be considered at scales finer than planning watersheds unless extensive calibration datasets are available.

Supplemental Material: https://pubs.usgs.gov/tm/06/h01/tm6h1.pdf

C1.2.2 Russian River HEC-HMS



Description: The HEC-HMS (Hydrologic Modeling System) model platform was developed for both the Russian River and Santa Rosa Creek watersheds and simulates precipitation-runoff processes to support flood risk and reservoir operation studies. The Russian River model was developed and calibrated for continuous simulation over a 60-year period (1950–2010) and used in both deterministic and probabilistic (FRA) simulations to evaluate FIRO at Lake Mendocino as part of the Lake Mendocino FIRO Preliminary Viability Assessment.

Processes:

- Precipitation-runoff transformation using Clark Unit Hydrograph method
- Loss modeling via Soil Moisture Accounting and Deficit & Constant method
- Baseflow simulation using linear reservoir methods
- Evapotranspiration modeled with Penman-Monteith method for Russian River model
- Routing of flows through reaches using Muskingum-Cunge methods and Modified Puls

Inputs:

- Hourly and daily precipitation from 28 gages, interpolated using GageInterp and PRISM bias grids for the Russian River model—nineteen precipitation gages using CIMIS, CDEC, and OneRain were applied in the Santa Rosa Creek model.
- Evapotranspiration data from USAF and ASOS stations (solar radiation, temperature, humidity, wind)
- Soil and land use data from SSURGO and USGS for parameter estimation
- Digital Elevation Model (DEM) and LiDAR data for basin delineation and slope calculations

Outputs:

- Hourly flow hydrographs at subbasin outlets
- Moisture deficit and soil moisture time series
- Annual peak flow frequency curves
- Runoff hydrographs for calibration and validation
- Streamflow inputs for reservoir (HEC-ResSim) and hydraulic (HEC-RAS) models

Spatial Resolution:

- Forty-two subbasins delineated across the Russian River watershed (1,485 square miles total watershed area)
- Subbasins defined by hydrologic characteristics, calibration gages, and modeling needs

Temporal Resolution:

- Hourly time step for continuous simulation

Limitations:

- No snowmelt modeling due to warm climate assumption
- Simplified channel geometry in some reaches due to lack of bathymetry
- Calibration challenges across diverse hydrologic conditions over 60 years
- Excluded subsurface flow and minor flood dynamics
- Forecast error not directly modeled in HEC-HMS but rather handled in reservoir simulations

Supplemental Material:

- U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center. 2018. *Analyzing Flood Risk for Forecast Informed Reservoir Operations in the Russian River Watershed Using HEC-WAT.* Report No. PR-100.

C1.2.3 Santa Rosa Creek HEC-HMS

Description: The HEC-HMS model platform was developed for the Santa Rosa Creek watersheds and simulates precipitation-runoff processes to support flood risk and reservoir operation studies. The Santa Rosa Creek model was developed to update flood risk assessments and support FEMA's Physical Map Revision and Natural Resources Conservation Service watershed planning.

Processes:

- Precipitation-runoff transformation using the Snyder Unit Hydrograph method
- Loss modeling via NRCS Curve Number method
- Baseflow simulation using the Snyder Unit Hydrograph method
- Routing of flows through reaches using Muskingum-Cunge method

Inputs:

- Hourly and daily precipitation from 19 precipitation gages using CIMIS and CDEC data
- Soil and land use data from the 2019 National land Cover and NRCS SSURGO soils datasets
- DEM and LiDAR data for basin delineation and slope calculations

Outputs:

- Hourly flow hydrographs at subbasin outlets
- Moisture deficit and soil moisture time series
- Annual peak flow frequency curves

- Runoff hydrographs for calibration and validation
- Streamflow inputs for hydraulic (HEC-RAS) models

Spatial Resolution:

- Seventy-eight subbasins delineated in the Santa Rosa Creek model (77.7 square miles total watershed area)
- Subbasins defined by hydrologic characteristics, calibration gages, and modeling needs

Temporal Resolution:

- Simulates 24- and 48-hour events for design storm durations
- Hourly time step

Limitations:

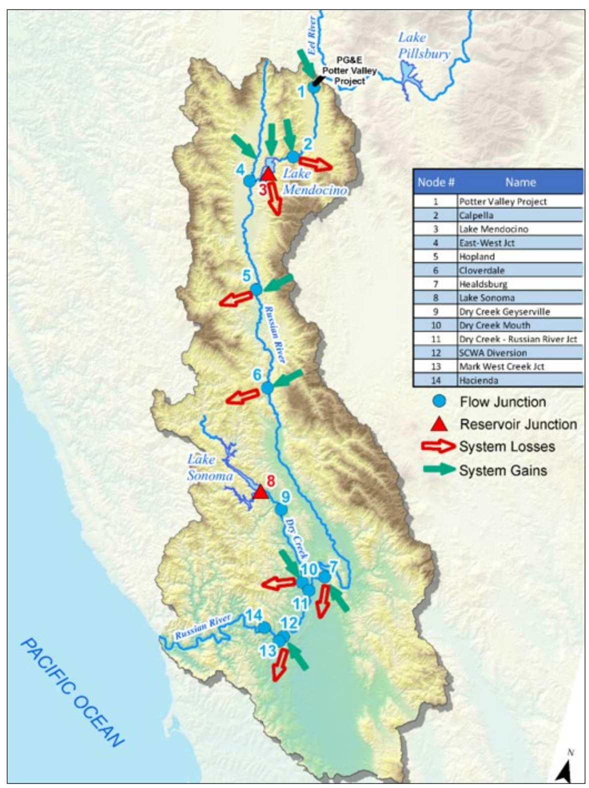
- No snowmelt modeling due to warm climate assumption
- Simplified channel geometry in some reaches due to lack of bathymetry
- Excluded subsurface flow and minor flood dynamics

Supplemental Material:

- ESA. 2022. *Central Sonoma Watershed Project Hydrologic Modeling Report*. Prepared for Sonoma Water. ESA Project No. D202100473.00. Retrieved from https://www.sonomawater.org

C1.3 Operations Models

C1.3.1 Russian River HEC-ResSim



Description: The Russian River HEC-ResSim model is a reservoir and river operations simulation tool originally developed by USACE using their HEC-ResSim software platform. It was designed to evaluate how water is stored, released, and flows through the Russian River watershed under various hydrologic and operational scenarios. The model supports planning for water supply, flood control, and environmental flow requirements, especially in relation to fish habitat and regulatory compliance.

Processes: HEC-ResSim, developed by USACE, is a reservoir system simulation tool used to model and analyze water management operations. It allows users to create detailed representations of river-reservoir networks and simulate various scenarios, including flood control, water supply, hydropower, and environmental flows. The platform supports both single-event and long-term simulations, using rule-based logic to manage reservoir operations based on priorities and system-wide goals.

The Russian River HEC-ResSim model simulates how water is stored and released from Lake Mendocino and Lake Sonoma, how it flows through the river system across various junctions and routing reaches, and how it is affected by human activities like water diversions and agricultural use. It incorporates rules for flood control, water supply operations, and environmental requirements such as minimum instream flow for fish habitat.

Inputs: Key inputs include:

- Historical and projected watershed unimpaired streamflows
- Eel River diversions into the Russian River
- Reservoir physical constraints
- Reservoir operation rules for flood control and water supply
- System water loss due to riparian evapotranspiration, reservoir evaporation, and surface water-groundwater interactions
- Water diversions for municipal and industrial and agricultural use

Outputs: The model produces:

- Daily river flow estimates at multiple locations
- Reservoir storage levels and releases
- Water temperature and dissolved oxygen levels (via a linked water quality model described in Section 11, HEC-ResSim Water Quality Model)
- Minimum instream flow requirement compliance

Spatial Resolution: The model covers the Russian River watershed from upstream of Lake Mendocino and Lake Sonoma, including the Eel River diversion into the Russian River, to the Hacienda Bridge near Guerneville. It includes 14 key locations (junctions) along the river and its tributaries.

Temporal Resolution: Simulations are run on a daily time step, covering historical conditions from 1910 to 2024 and projecting future scenarios.

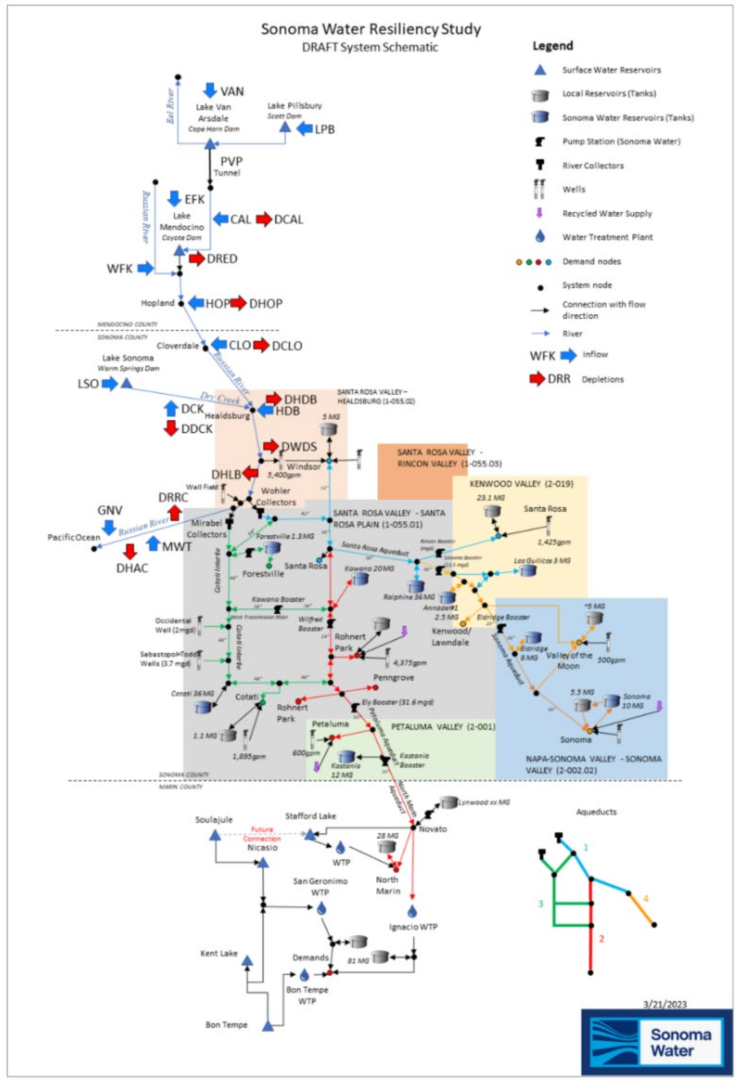
Limitations:

- Assumes simplified patterns for water losses and flow travel times
- Relies on historical data and estimated future conditions
- Does not fully capture real-time operational decisions or complex groundwater interactions

Supplemental Material:

- Sonoma County Water Agency. 2016. *Russian River Hydrologic Modeling for the Fish Habitat Flows and Water Rights Project: Draft Environmental Impact Report*. Santa Rosa, CA.

C1.3.2 Sonoma Water Decision Support Model



Description: The Sonoma Water Decision Support Model is a planning tool developed using the GoldSim simulation platform to evaluate the reliability and resilience of the regional water supply system. It helps Sonoma Water and its retail customers assess how well water demands can be met under various conditions, including droughts, floods, wildfires, and earthquakes.

Processes: The model is logic-based and simulates water movement and operations across the Russian River watershed and Sonoma Water's transmission system. It accounts for reservoir storage and releases, river diversions, aqueduct flows and capacity constraints, customer water demands, and alternative supply sources like groundwater and recycled water. It also evaluates system performance under historical and future climate scenarios.

Inputs: Key inputs include:

- Historical and projected hydrology (precipitation, streamflows)
- Reservoir storage and evaporation rates
- Operational rules and priorities
- Water demands from Sonoma Water customers
- Supply sources (groundwater, recycled water, local reservoirs)
- Infrastructure capacities (pipelines, pumps, tanks)

Outputs: The model produces:

- Annual and monthly estimates of water deliveries and shortages
- Reservoir storage levels
- Aqueduct and river flows
- Customer-specific water supply portfolios
- System-wide performance summaries under different scenarios

Spatial Resolution: The model covers the entire Sonoma Water service area and Upper Eel Watershed, including:

- Upper Eel Watershed: Lake Pillsbury

- Russian River system (Lake Mendocino, Lake Sonoma)
- Sonoma Water transmission system (collectors, aqueducts, tanks)
- Retail customer systems (e.g., Santa Rosa, Petaluma, Marin Municipal Water District)

Temporal Resolution: Simulations run on a daily time step, with results typically summarized monthly or annually. The model can simulate historical periods (1910–2022) and future scenarios through 2045 and beyond.

Limitations:

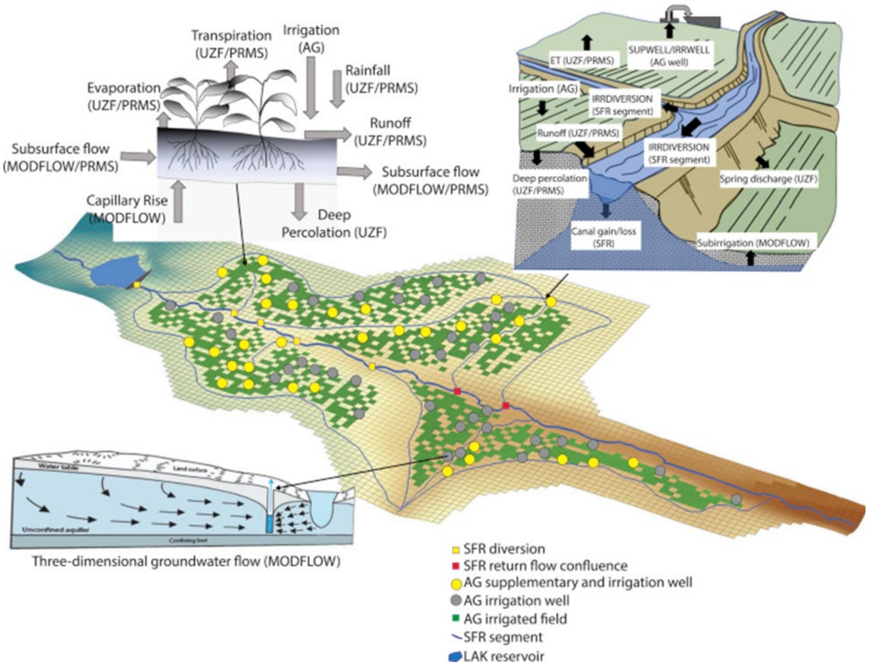
- Is not a hydraulic model; simplified representation of pipe flows and system redundancies
- Uses some estimated reservoir inflow and evaporation data due to limited records
- Assumes fixed demand patterns unless manually adjusted
- Assumes simplified patterns for water losses and travel times
- Relies on historical data and estimated future conditions
- Does not fully capture real-time operational decisions or complex groundwater interactions

Supplemental Material: The model has been applied in several studies, including:

- Jacobs Engineering Group Inc. 2021. *Sonoma Water Regional Water Supply Drought Resilience Study*. Prepared for Sonoma County Water Agency.
- Jacobs Engineering Group Inc. 2023. *Marin Municipal Water District Strategic Water Supply Assessment*. Prepared for Marin Municipal Water District.
- Jacobs Engineering Group Inc. 2024. *Potter Valley Water Supply Reliability Study*. Prepared for Sonoma County Water Agency.
- Jacobs Engineering Group Inc. 2025. *Sonoma Water Regional Water Supply Resiliency Study*. Prepared for Sonoma County Water Agency.

C1.4 Groundwater Models

C1.4.1 Russian River Groundwater Surface Water Flow Model



Description: The Russian River Integrated Hydrologic Model (RRIHM) l is a computer-based simulation tool developed by USGS in collaboration with Sonoma Water and the California State Water Resources Control Board. The RRIHM simulates stream-aquifer interactions using the coupled GSFLOW hydrologic model. The model is coupled with MODSIM to represent coupled reservoir operations and priority-based water allocations. Agricultural water demands are simulated dynamically and are passed to MODSIM for determining reservoir operations and irrigation withdrawals. It is designed to better understand how groundwater and surface water interact across the Russian River watershed, and helps scientists and water managers evaluate water availability, movement, and quality in three dimensions.

Processes: The model simulates movement and exchanges of water through the watershed, including rainfall-runoff processes, flow through the surface water system (in rivers and streams), in the groundwater system (in aquifers), and in response to human systems (agricultural and urban surface-water and groundwater diversions). Dynamic simulation of these processes and feedbacks allows for characterization of impacts of future climate change and drought, as well as changes in land use and water management decision-making.

Inputs:

- Borehole data (well locations, depth, and construction)
- Lithologic logs (descriptions of underground materials)
- Pumping test results (used to estimate how easily water moves through underground layers)
- Surface water and groundwater measurements
- Land use and climate data

Outputs:

- Simulated groundwater levels
- Streamflow estimates
- Water balance calculations (how much water enters, leaves, and is stored in the system)
- Maps and 3D visualizations of subsurface geology and hydrology

Spatial Resolution: Covers the Russian River watershed, including Sonoma and Mendocino Counties in Northern California. Horizontal grid spacing is 300 × 300 m. The model includes detailed representation of subsurface hydrostratigraphy using data from hundreds of well logs across the domain.

Temporal Resolution: The model uses historical data spanning for 1990–2015 and CMIP5 future climate forcings for 2015–2099.

Limitations:

- Daily time steps limit utility for flood simulations
- 300 × 300 m grid spacing can be too coarse to accurately simulate some localized phenomena.
- Designed primarily for scientific and planning purposes—relatively long run times are not optimized for real-time operations.

Supplemental Material:

The model and ancillary datasets are publicly available from USGS:

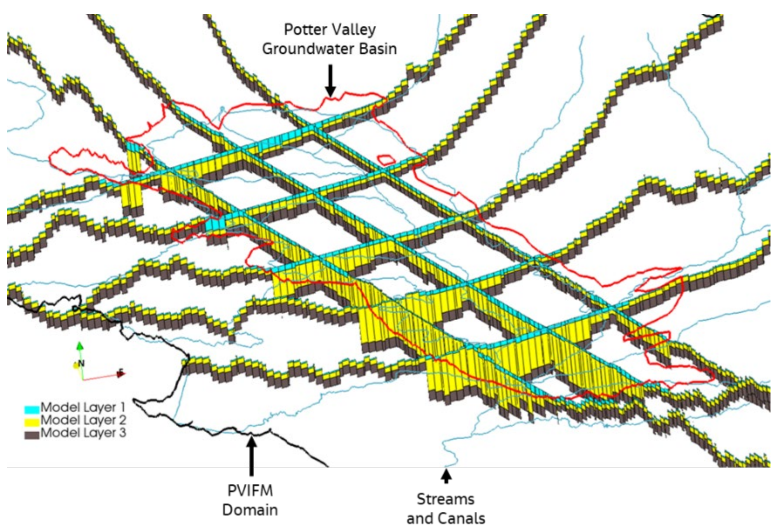
- Model Archive: [Russian River Integrated Hydrologic Model: an integrated hydrology and river operations model used to evaluate water use and climate change scenarios in the Russian River watershed - ScienceBase-Catalog]

Documentation of the model is provided in a scientific journal article:

- Adera, S., A. Alzraiee, R. Niswonger, E. Triana, D. Ryter, and J. Engott. 2026. "Assessing Future Hydrologic Extremes Using an Integrated Hydrology and River Operations Model in the Russian River Watershed". *Journal of Hydrology*. 63, 103016. https://doi.org/10.1016/j.ejrh.2025.103016.

C1.4.2 Potter Valley Integrated Groundwater-Surface Water Model

Description: The Potter Valley Integrated Flow Model (PVIFM) is a three-dimensional, integrated groundwater-surface water model developed by Jacobs Engineering for Sonoma Water. It simulates monthly hydrologic conditions in a 94-square-mile area encompassing the Potter Valley Groundwater Basin in Mendocino County, California. The model supports water supply reliability planning by evaluating hydrogeologic conditions, agricultural water use, and potential future water management strategies.



Processes: PVIFM simulates:

- Surface water flow (runoff, streamflow, canal flow)
- Groundwater flow (recharge, discharge, pumping)
- Groundwater-surface water interactions
- Evapotranspiration (ET) from shallow groundwater
- Agricultural water use and irrigation dynamics

Inputs:

- Precipitation data (scaled with orographic multipliers)
- Stream and canal inflows (from PG&E's Potter Valley Project)
- Land use and vegetation (from NLCD and PVID reports)
- Soil characteristics (from SSURGO)
- Hydraulic properties (Kh, Kv, Sy, Ss)
- ET estimates (from OpenET)
- Groundwater pumping rates
- Canal diversion data
- Topography (from LiDAR DEM)

Outputs:

- Groundwater elevations (HDS files)
- Subsurface flows (CBC files)
- Unsaturated zone flows (UZFCB2 files)
- Streamflow routing results (SFR.OUT)
- Water budgets (surface water and groundwater)
- ET estimates and comparisons with OpenET

Spatial Resolution:

- Horizontal grid: 100-meter by 100-meter cells
- Vertical layers: 3 layers representing channel alluvium, sediments, and bedrock
- Total active cells per layer: 24,404

Temporal Resolution:

- Monthly stress periods with a single time step per period
- Simulation period: October 2010–September 2022 (Water Years [WYs] 2011–2022)

Limitations:

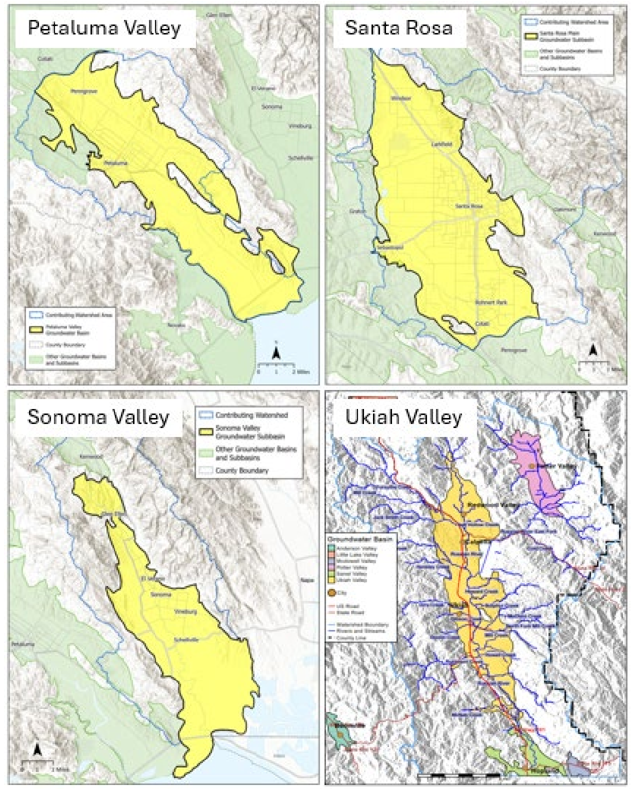
- Subsurface materials modeled as equivalent porous media
- Monthly average flows; intra-month variability not captured
- Unsaturated zone flow component disabled to resolve mass balance issues
- Limited groundwater level data for calibration
- Simplified representation of canal diversions and streambed elevations
- Model outputs are approximations and should be used as insight tools, not predictive tools.

Supplemental Material:

Jacobs Engineering. 2023. *Potter Valley Integrated Groundwater-Surface Water Model Documentation Technical Memorandum*. Prepared for Sonoma Water. Includes the following supplemental materials:

- Attachment 1: Calibration target values
- Attachment 2: Modeled eight-point stream channel cross-sections
- Attachment 3: Monthly surface water budget table
- Attachment 4: Monthly groundwater budget table
- Figures and tables detailing model domain, hydraulic properties, ET distribution, and calibration results

C1.4.3 Groundwater Sustainability Plan Integrated Surface and Groundwater Computer Models



Description: As part of California's Sustainable Groundwater Management Act, Groundwater Sustainability Agencies developed Groundwater Sustainability Plans (GSPs) for medium- and high-priority groundwater basins. A key tool used in these plans is an integrated surface and groundwater computer model, which simulates how water moves through the landscape—both above ground (in rivers and streams) and below ground (in aquifers). Four models were developed for four separate groundwater basins including Petaluma Valley, Santa Rosa, Sonoma Valley, and Ukiah Valley. These models help communities understand current water conditions and plan for long-term sustainability.

Processes: The integrated model combines data on rainfall, streamflow, land use, geology, and water use to simulate:

- How water enters the basin (e.g., rain, stream infiltration, recharge)
- How water is used (e.g., pumping for agriculture, homes, and cities)
- How water leaves the basin (e.g., evaporation, stream outflow, pumping)
- How groundwater levels and storage change over time

The model also includes climate change scenarios to test how future droughts and wet periods might affect water availability.

Inputs:

- Precipitation and climate data
- Streamflow and surface water data
- Groundwater levels and pumping rates
- Land use and crop types
- Geological and soil characteristics
- Water quality data

Outputs:

- Groundwater storage estimates
- Stream-aquifer interactions
- Water budget summaries (inflows, outflows, changes in storage)
- Projected future conditions under climate and land use changes
- Sustainable yield estimates (how much water can be pumped without causing harm)

Spatial Resolution: Four models were developed for four separate groundwater basins including Petaluma Valley, Santa Rosa, Sonoma Valley, and Ukiah Valley. Each model is tailored to a specific groundwater basin or subbasin.

- The Petaluma Valley Integrated Hydrologic Model (PVIHM) uses a finite-difference grid with 100-meter horizontal resolution.
- The Santa Rosa Plain Hydrologic Model (SRPHM) uses a 100-meter grid cell resolution.
- The Sonoma Valley Integrated Groundwater Flow Model (SVIGFM) uses a 100-meter grid resolution.
- The Ukiah Valley Integrated Water Flow Model (IWFM) uses a 200-meter grid resolution.

Temporal Resolution:

- All models typically utilize a daily time step with the exception of Ukiah Valley IWFM, which utilizes a monthly time step.
- Simulation Periods - The models simulate historical conditions and future scenarios as part of their GSPs:
  - PVIHM: Simulates historical (WY 1969–2018) and projected (WY 2021–2070)
  - SRPHM: Historical (WY 1976–2018) and projected (WY 2021–2099)
  - SVIGM: Historical period (WY 1971–2018) and projected (WY 2021–2070)
  - IWFM: Historical period (WY 1992–2018) and projected (WY 2019–2070)

Limitations:

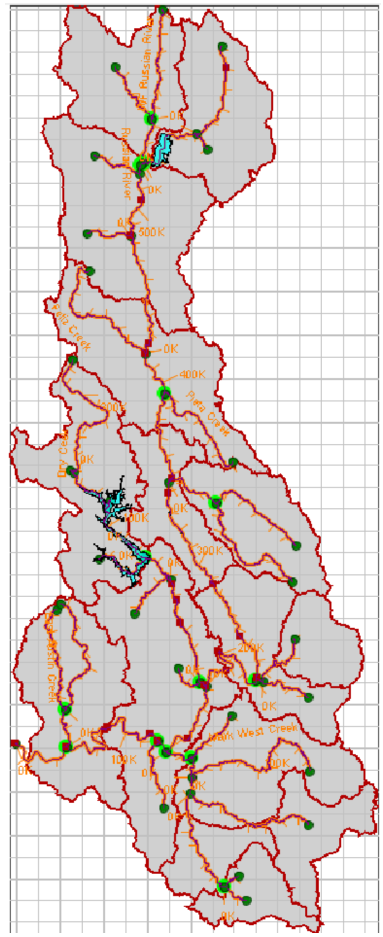
- Models rely on available data, which may have gaps or uncertainties.
- Assumptions about future land use and climate may change.
- Models are not designed for real-time operations but for long-term planning.

Supplemental Material:

- Sonoma Water and U.S. Geological Survey. 2020. *Appendix 3-C: Integrated Groundwater Flow Model (PVIHM); Modifications for Use in the Development of the Groundwater Sustainability Plan for the Petaluma Valley Groundwater Basin.* Petaluma Valley Groundwater Sustainability Agency. https://petalumavalleygroundwater.org/wp-content/uploads/3-C-PV-Integrated-Groundwater-Flow-Model-PVIHM-_ada.pdf.
- Alzraiee, A.H., A. Rich, L.R. Woolfenden, D.W. Ryter, E. Triana, and R.G. Niswonger. 2025. *Updating and Recalibrating the Integrated Santa Rosa Plain Hydrologic Model to Assess Stream Depletion and to Simulate Future Climate and Management Scenarios in Santa Rosa, Sonoma County, California.* U.S. Geological Survey Scientific Investigations Report 2024–5121. https://pubs.usgs.gov/publication/sir20245121/full.
- Sonoma Water. 2021. *Appendix 3-E: Sonoma Valley Integrated Groundwater Flow Model (SVIGFM); Modifications for Use in the Development of the Groundwater Sustainability Plan for the Sonoma Valley Groundwater Subbasin.* Sonoma Valley Groundwater Sustainability Agency. https://sonomavalleygroundwater.org/wp-content/uploads/3-E-SVGSP-SVIGFM-Appendix-3-E_08202021_ADA.pdf.
- Ukiah Valley Basin Groundwater Sustainability Agency. 2021) *Ukiah Valley Basin Groundwater Sustainability Plan*. Prepared by Larry Walker Associates and GEI Consultants. https://ukiahvalleygroundwater.org/wp-content/uploads/2023/01/ExecSummary.pdf.

C1.5 Flood Models

C1.5.1 Russian River Flood HEC-ResSim



Description: This HEC-ResSim model for the Russian River watershed was originally developed by USACE as part of the Lake Mendocino FIRO Preliminary Viability Assessment and updated by Sonoma Water to include current operating conditions. It simulates reservoir operations for Lake Mendocino and Lake Sonoma, supporting Flood Risk Management (FRM) studies and real-time decision-making and planning for flood control within the Corps Water Management System (CWMS).

Processes: See description for HEC-ResSim in previous section for general description of the software platform's processes. This ResSim model uses HEC-HMS for unimpaired flows inputs.

Inputs:

- Unimpaired flows from HEC-HMS
- Eel River diversions into the Russian River
- Reservoir physical characteristics
- Reservoir flood control and water supply operations
- Streamflow routing parameters for sub-daily travel times
- System water loss due to riparian evapotranspiration, reservoir evaporation, and surface water-groundwater interactions
- Water diversions for municipal and industrial and agricultural use

Outputs:

- Reservoir pool elevations and storage
- Reservoir releases and downstream flows
- Operational decision logs

Spatial Resolution: The model covers the Russian River watershed from upstream of Lake Mendocino and Lake Sonoma, including the Eel River diversion into the Russian River, to the mouth at the ocean. It includes 18 key locations (junctions) along the river and its tributaries.

Temporal Resolution:

- Event-based and continuous simulations
- Time steps configurable from hourly to daily
- Supports real-time forecasting and historical period-of-record analysis

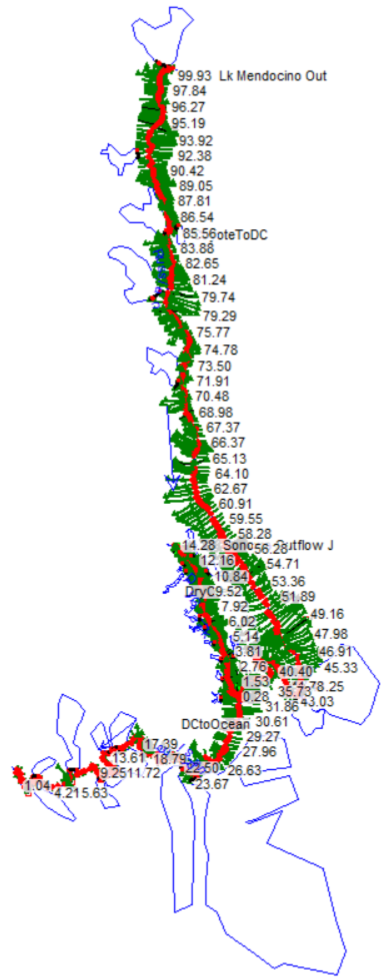
Limitations:

- Does not fully capture real-time operational decisions when used for FRM planning studies

Supplemental Material:

- https://www.hec.usace.army.mil/confluence/cwmsdocs/ctg/cwms-prospect-workshops/hec-ressim-in-cwms
- U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center. 2018. *Analyzing Flood Risk for Forecast Informed Reservoir Operations in the Russian River Watershed Using HEC-WAT*. Report No. PR-100.

C1.5.2 Russian River HEC-RAS



Description: HEC-RAS (Hydrologic Engineering Center's River Analysis System) is a standalone software application used to perform one-dimensional steady and unsteady flow simulations, as well as two-dimensional unsteady flow simulations. It includes components for water surface profile computations, sediment transport, and water quality analysis. Two HEC-RAS models exist to simulate river hydraulics in the Russian River and Santa Rosa Creek watersheds. The models support flood risk analysis, FEMA map revisions, and climate change impact assessments.

Processes: HEC-RAS computes:

- River stages and water surface profiles
- Flow routing through river channels and floodplains
- Levee breach information
- Evaluates flood extents for design storms and future climate scenarios

Inputs:

- River channel and floodplain geometry
- Reach lengths, bridge and culvert dimensions
- Ineffective flow areas
- Flow hydrographs from HEC-HMS and reservoir releases from HEC-ResSim for the Russian River model

Outputs:

- Time series of river stages and flows
- Gridded maps of depth, depth × velocity, and arrival time
- Inundation extents for flood events

Spatial Resolution:

- Full Russian River watersheds including tributaries and floodplain areas
- Geometric data from a 10-meter DEM
- Point elevations for 1D river cross-sections

Temporal Resolution:

- Simulations were conducted using hourly and six-hourly time steps depending on the model linkage and event duration for the Russian River model.

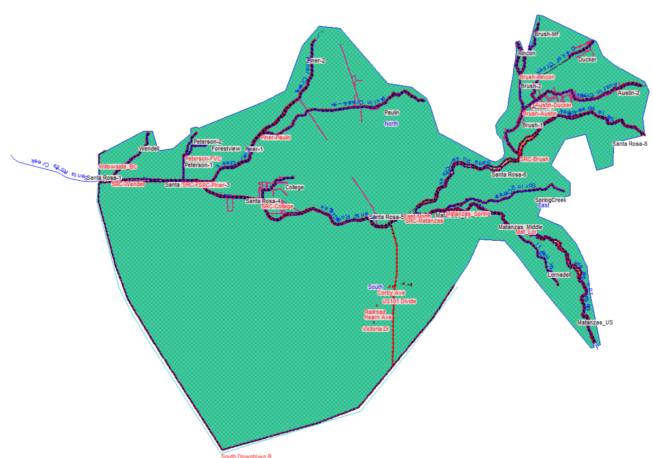
Limitations:

- DEM-derived cross-sections lacked bathymetric data below the water surface, requiring manual modification using the Channel Design/Modification tool.
- Accuracy may be reduced for smaller events due to limited channel geometry.
- Agricultural and infrastructure damage were not modeled in detail, though HEC-RAS outputs could support such analyses.
- Calibration was focused on stage due to uncertainty in USGS rating curves for high flows.
- There was limited gage data for some tributaries.
- Uniform roughness assumptions in some areas may oversimplify complex vegetation effects.
- Future climate scenarios are based on downscaled rainfall projections, not direct measurements.

Supplemental Material:

- U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center. 2018. *Analyzing Flood Risk for Forecast Informed Reservoir Operations in the Russian River Watershed Using HEC-WAT.* Report No. PR-100.

C1.5.3 Santa Rosa Creek HEC-RAS



Description: HEC-RAS (Hydrologic Engineering Center's River Analysis System) is a standalone software application used to perform one-dimensional steady and unsteady flow simulations, as well as two-dimensional unsteady flow simulations. It includes components for water surface profile computations, sediment transport, and water quality analysis. The model supports flood risk analysis, FEMA map revisions, and climate change impact assessments.

Processes: HEC-RAS computes:

- River stages and water surface profiles
- Flow routing through river channels and floodplains
- Levee breach information
- Evaluates flood extents for design storms and future climate scenarios

Inputs:

- River channel and floodplain geometry
- Reach lengths, bridge and culvert dimensions
- Ineffective flow areas
- Flow hydrographs from HEC-HMS for both models and reservoir releases from HEC-ResSim for the Russian River model

Outputs:

- Time series of river stages and flows
- Gridded maps of depth, depth × velocity, and arrival time

- Inundation extents for flood events
- Data for consequence modeling in HEC-FIA

Spatial Resolution:

- Full Santa Rosa Creek watersheds including tributaries and floodplain areas
- 2D floodplain geometric data applied 2013 LiDAR
- Point elevations for 1D river cross-sections from 2006 field surveys for the Santa Rosa Creek model

Temporal Resolution:

- Simulations are event-based, using hourly or sub-hourly time steps.
- Santa Rosa Creek model was calibrated for three historical events: NYE 2005, January 2010, and February 2019.

Limitations:

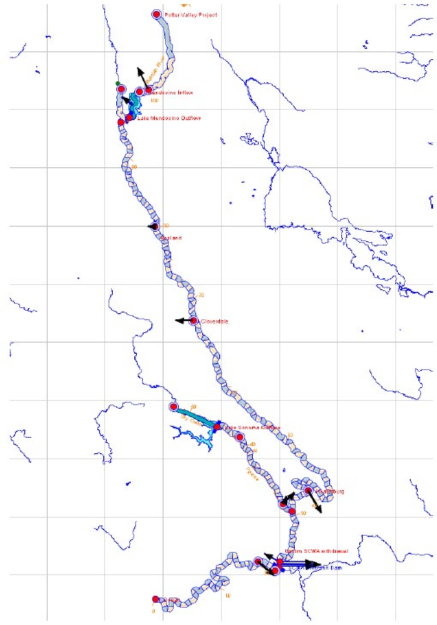
- DEM-derived cross-sections lacked bathymetric data below the water surface, requiring manual modification using the Channel Design/Modification tool.
- Accuracy may be reduced for smaller events due to limited channel geometry.
- Agricultural and infrastructure damage were not modeled in detail, though HEC-RAS outputs could support such analyses.
- Calibration focused on stage due to uncertainty in USGS rating curves for high flows.
- There was limited gage data for some tributaries.
- Uniform roughness assumptions in some areas may oversimplify complex vegetation effects.
- Future climate scenarios are based on downscaled rainfall projections, not direct measurements.

Supplemental Material:

- ESA & AECOM. 2024. *Hydraulic Modeling Report: Central Sonoma Watershed Project.* Prepared for Sonoma County Water Agency in cooperation with the Natural Resources Conservation Service. Revised January 2024.

C1.6 Ecosystem and Water Quality Models

C1.6.1 HEC-ResSim Water Quality Model



Description: The HEC-ResSim Water Quality Model (RRWQM) was developed by RMA in 2021 and recently updated in 2024; it is derived from the Russian River HEC-ResSim model. As a result, these models share the same spatial extent. The RRWQM includes multiple spatially varying parameters that are calibrated for each reach of the model to simulate water quality constituents with the main steam of the Russian River.

Processes: The RRWQM simulates water quality conditions throughout the Russian River watershed using flow, water quality constituent, and meteorological inputs. Water quality outputs are generated for the main stem Russian River, Lake Sonoma, and Lake Mendocino.

Inputs:

- Historical and projected watershed unimpaired streamflows
- Eel River diversions into the Russian River
- Reservoir physical constraints
- Reservoir operation rules for flood control and water supply
- System water loss due to riparian evapotranspiration, reservoir evaporation, and surface water-groundwater interactions
- Water diversions for municipal and industrial and agricultural use
- Russian River channel geometry
- Meteorological conditions
- Water quality parameters

Outputs: Key outputs include, but are not limited to:

- Daily river flow estimates at multiple locations
- Reservoir storage levels and releases
- Water and sediment temperature
- Dissolved oxygen
- Ammonium, nitrate, organic nitrogen
- Inorganic and organic phosphorous
- Phytoplankton, benthic algae, suspended particulate organic matter
- Particulate organic carbon and dissolved organic and inorganic carbon

Spatial Resolution: The model covers the Russian River watershed from upstream of Lake Mendocino and Lake Sonoma, including the Eel River diversion into the Russian River, to the Hacienda Bridge near Guerneville. It includes 14 key locations (junctions) along the river and its tributaries.

Temporal Resolution: Two-hour time steps, covering historical conditions from 1910 to 2023

Limitations:

- Known flow and routing issues downstream of the Sonoma Water diversion dam and above Hacienda Bridge can result in stagnant water conditions at this location.
- Some modeled river reaches are long and do not capture the full variability in riparian and shaded conditions along their extent.
- Accuracy is dependent on calibration data.

Supplemental Material:

- RMA. 2024. HEC-ResSim Simulation of Water Quality in the Russian River Basin: 2024 Update.

C1.6.2 Quantified Conceptual Model

Description: The QCM is a process-based finite-difference model designed to simulate the hydrologic and morphologic behavior of bar-built coastal lagoons. It is a relatively simple water balance of lagoons connected with a sediment balance for the lagoon mouth area. It predicts lagoon mouth closure, breaching, and water level dynamics using simplified representations of water and sediment fluxes. While not explicitly focused on biological habitat, the model's outputs—particularly lagoon water levels and mouth states—can be used to understand changes in habitat conditions for aquatic species, since water quality and hydrologic conditions are strongly controlled by mouth conditions.

Processes:

- Lagoon water balance: integrates inflows (river, wave overtopping, groundwater) and outflows (mouth discharge, seepage, evapotranspiration)
- Lagoon mouth sediment balance: models erosion and deposition in the mouth channel using wave and flow dynamics
- Transition modeling between open, perched, and closed mouth states
- Time-stepped simulation using Euler forward-stepping method
- Model calibrated at Russian River using 22 years of observation data at the site

Inputs:

- Lagoon bathymetry and beach topography (DEM and LiDAR data)
- Typical beach geometry (width, length, sediment size)
- Ocean tides (1-hour or 6-minute interval)
- Stream flow information
- Nearshore waves (significant height, peak period, peak direction)
- For model calibration: management records (e.g., artificial breaching dates), mouth closure and breaching time series, and water level data in the lagoon

Outputs: Lagoon water level time series, lagoon mouth state time series (open, perched, closed), and lagoon mouth geometry evolution (thalweg elevation, inlet width, inlet slope)

Spatial Resolution:

- Output water levels are one-dimensional and are representative of average lagoon conditions.
- Mouth geometry outputs are bulk parameters, with one value per output time step.

Temporal Resolution: Simulations run at 430-second time steps (1/200 day).

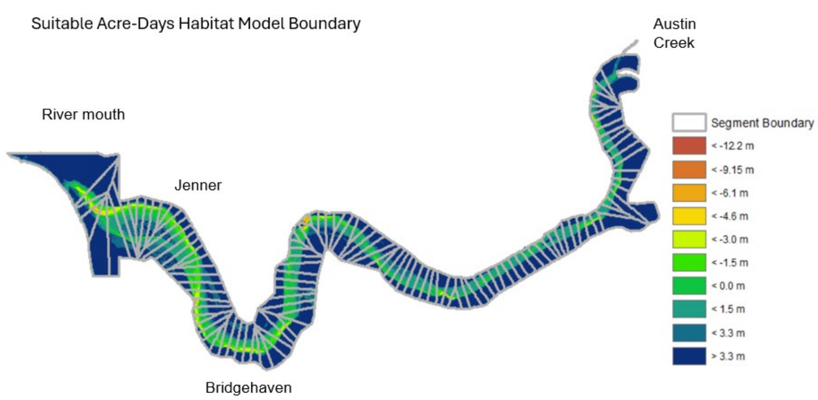
Limitations:

- QCM does not directly model biological habitat or species-specific responses.
- Accuracy depends on quality and availability of input data and calibration. Twenty-two years of data applied at Russian River allow for relatively high confidence in predictions.
- Model is a simplified representation of complex morphodynamic processes (lagoon mouth closure and breaching).
- Model is less accurate for high-flow conditions in the lagoon (e.g., river floods), when flows generate a surface slope across the site.

Supplemental Material:

- Behrens, D.K., M. Brennan, and B. Battalio. 2015. A "Quantified Conceptual Model of Inlet Morphology and Associated Lagoon Hydrology." *Shore & Beach.* Vol. 83 No. 3. pp: 33-42. June.
- Behrens, Dane and Battalio, Robert. 2025. "Progress in Modeling Coastal Lagoon Mouth Morphology and Hydrology Using a Quantified Conceptual Approach and Long-term Data Across Multiple Sites." *Geomorphology*. Vol. 487. October. DOI: 10.1016/j.geomorph.2025.109915
- ESA PWA. 2017. Feasibility of Alternatives to the Goat Rock State Beach Jetty for Managing Lagoon Water Surface Elevations. Prepared for Sonoma County Water Agency. Available online: https://evogov.s3.amazonaws.com/185/media/182347.pdf. Accessed: October 14, 2025.

C1.6.3 Suitable Habitat Acre-day Model



Description: The Suitable Habitat Acre-day Model is a tool designed to quantify impacts of management actions and future climate change on estuarine habitat in the Russian River. Management actions include beach management (i.e., opening or "breaching" the lagoon mouth to drain water and limit flooding of adjacent properties) and restoration actions such as expanding floodplain habitat. Climate change impacts include changes in water temperature, and changes in the future duration of mouth closure events. The tool estimates the amount of juvenile salmonid habitat available within the water column at different locations with the estuary. It evaluates changes in habitat availability under different inlet conditions (open vs. closed) and for different water levels and atmospheric conditions, by reviewing statistics of a large database of measured lagoon water quality conditions. These were collected by the UC Davis Bodega Marine Lab, which conducts boat-based surveys of the estuary to develop two-dimensional maps of water quality conditions, which are then translated into habitat suitability maps based on guidance from a recent NOAA NMFS study (Boughton et al. 2017). This results in a spatially-resolved dataset that can be used to generate rolled-up sums of acre-days of suitable habitat for juvenile steelhead in the estuary.

Processes:

- Characterization of juvenile steelhead habitat zones (e.g., “optimal,” “suitable,” “lethal”) based on depth and water quality data (temperature, salinity, dissolved oxygen) collected in the estuary during historical conditions when the lagoon mouth was open or closed to the ocean, and during climatic conditions
- Integration of location-based habitat suitability into rolled-up estimates of total “optimal" habitat over a period of time in the estuary in the form of acre-days of habitat
- Evaluation of habitat changes resulting from increased or decreased durations of mouth closure (e.g., resulting from changes in management, or changes in future flows into the estuary), from changes in water temperature, and from habitat enhancement (e.g., creation of new habitat areas in a specific location with the estuary)

Inputs:

- Estuary mouth condition (either “open” or “closed” to the ocean)—if “closed,” user also specifies the duration of closure.
- Estuary water level
- Location of interest within the estuary
- For temperature sensitivity, user-defined increase in atmospheric temperature or temperature of river inflows
- For habitat enhancement, user-defined volume and acreage of enhancement, and location in the estuary

Outputs: Acre-days of suitable habitat, by depth class (littoral, epibenthic, limnetic)

Spatial Resolution:

- The model discretizes two-dimensional maps of habitat in the estuary into 100-meter along-stream bins, spanning from the area closest to the estuary mouth to about 10 kilometers upstream. The model assumes uniform conditions across the channel width at each location.
- Depths are binned at 10 centimeters.

Temporal Resolution: The model typically estimates changes in habitat by month of the year, or as an average across all months.

Limitations:

- Habitat suitability ratings (e.g., “optimal” or “suitable”) are based a literature review by Boughton et al. (2017), which relied on the best possible information at the time. This is an area of ongoing research and may be updated in the future.
- Model assumes consistent juvenile steelhead behavior and salinity tolerance across years.

Supplemental Material:

- Largier, J., and M. Koohafkan. 2019. *RRE Habitat Viewer: Summary Memo*. Sonoma County Water Agency.

- Boughton, D.A., J.A. Fuller, G. Horton, E.R. Larson, W. Matsubu, and C.A. Simenstad. 2017. *Spatial Structure of Water-quality Impacts and Foraging Opportunities for Steelhead in the Russian River Estuary: An Energetics Perspective.* NOAA-TM-NMFS-SWFSC; 569. DOI: 10.7289/V5/TM-SWFSC-569.
- ESA. 2023. *Russian River Biological Assessment and Essential Fish Habitat Assessment*. Prepared for Sonoma County Water Agency. August. Available online: https://www.sonomawater.org/media/PDF/Environment/BiologicalOpinion/RRBA_Final_20230823_rev1_ADA%20V2%20kt%20OCR%20and%20Scanned.pdf. Accessed: October 14, 2025.
- Largier, J., and M. Koohafkan. 2019. *Calculation of Volume of Juvenile Steelhead Habitat in Russian River Estuary during Closure Events and Development of Habitat Browser.* University of California Davis; Sonoma County Water Agency (SCWA); NOAA Habitat Blueprint Program.

C1.7 Hydropower Models

C1.7.1 Power Tools for Hydropower

Description: This Python-based tool was developed to estimate hydroelectric power generation at Lake Mendocino and Lake Sonoma using daily reservoir storage elevation and release data as inputs. It models turbine operations and calculates power output based on flow constraints, net head, turbine efficiency, and generator capacity, and operational thresholds.

Processes:

1. **Determine Turbine Flow Constraints (Lake Mendocino only) –** Based on reservoir elevation, the tool selects appropriate turbine flow limits and configurations.
2. **Estimate Turbine Flows –** Tool determines flow through the turbine based on release volume and operational thresholds (e.g., bypass and capacity limits).
3. **Calculate Net Head –** Tool uses elevation, tailwater level, and head loss (elevation-dependent head loss coefficients at Lake Sonoma) to compute net head.
4. **Estimate Turbine Efficiency –** Lake Sonoma uses interpolation from a lookup table based on flow and net head. Turbine efficiency at Lake Mendocino uses interpolation from a lookup table based on net head only.
5. **Estimate Generator Efficiency –** The Lake Sonoma tool applies an iterative method to solve for generator efficiency using a nonlinear formula. The Lake Mendocino tool applies a fixed turbine-specific efficiency assumption.
6. **Estimate Power Capacity (Lake Mendocino only) –** Tool uses interpolation of flow and net head values to determine generator capacity for each turbine.
7. **Calculate Final Power Output –** Tool combines turbine and generator efficiency with flow and net head to estimate daily energy production in kilowatt-hours.

Inputs:

- Reservoir Elevation (feet)
- Reservoir Release (cfs)
- Efficiency Curve Table:
  - Turbine efficiency vs. flow and net head (from wsd.xlsx)
  - Turbine efficiency vs. net head (from cvd.xlsx)
- Power Capacity Table (Lake Mendocino only): power capacity vs. flow and net head for both turbines

Outputs:

- Estimated Power Production (MW-h/day)
- Turbine Flow (cfs)

Spatial Resolution: Two locations: Lake Mendocino and Lake Sonoma hydropower facilities

Temporal Resolution: Inputs and outputs are based on daily values.

Limitations:

- Model assumes fixed tailwater elevations and head loss coefficients (Lake Mendocino only).
- Head loss coefficients vary with elevation but are static within defined elevation bands (Lake Sonoma only).
- Generator efficiency is estimated via an iterative method, which may introduce minor computational uncertainty.
- Tool does not model external grid constraints or turbine maintenance.

Supplemental Material:

- Sonoma County Water Agency. 2016. *Russian River Hydrologic Modeling for the Fish Habitat Flows and Water Rights Project*. August. Retrieved from: https://evogov.s3.amazonaws.com/185/media/165217.pdf