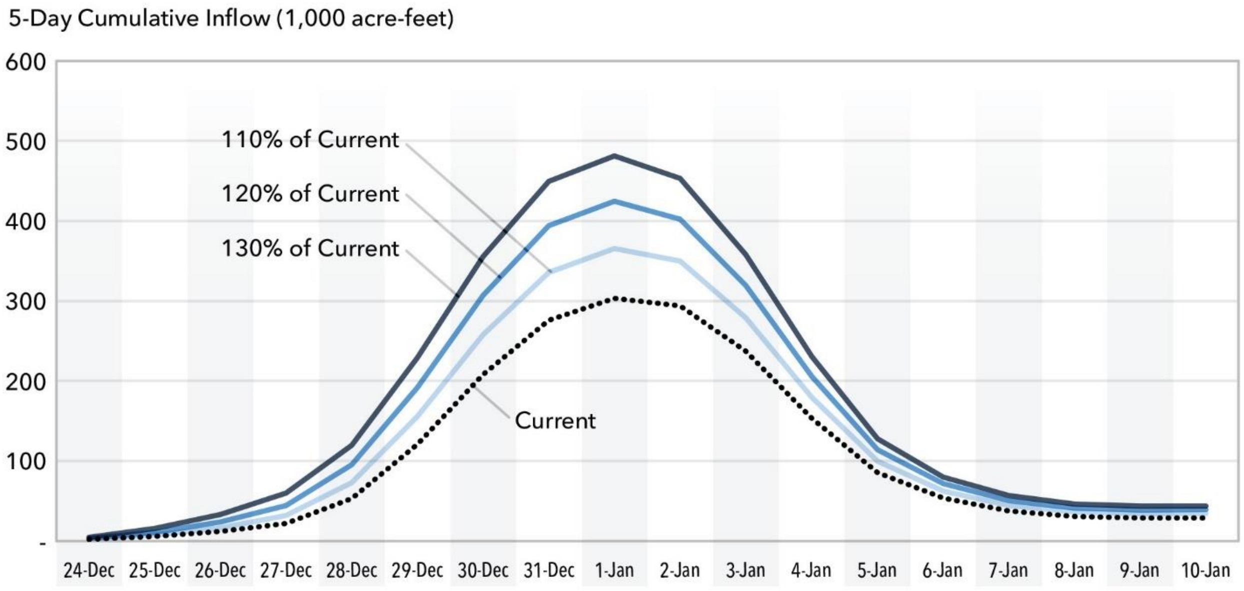
State of California
California Natural Resources Agency
Department of Water Resources

Merced River Watershed Flood-MAR Reconnaissance Study

Baseline Performance and Climate Change Vulnerability



Technical Information Record

November 2023

Acknowledgements

Integrated Watershed Management

Kristopher Tjernell, Deputy Director

Division of Planning

Kamyar Guivetchi, Chief

Statewide Infrastructure Investigations Branch

Ajay Goyal, Principal Engineer

Prepared under the direction of:

Jim Wieking, Project Manager

Prepared by:

Karandev Singh, Senior Engineer

Wyatt Arnold, Senior Engineer

Lee Bergfeld, Principal Engineer

Based on content developed by:

California Department of Water Resources
David Arrate **Shem Stygar** **Aleksander Vdovichenko**
Francisco Flores-López **Clark Churchill** **Alejandro Perez**
Romain Maendly **Iman Mallakpour**

Document Support

Robert Stoltz, Editorial Review

Scott Olling, Graphic Services

MBK Consulting

Lee Bergfeld   Wes Walker

Woodard & Curran

Ali Taghavi   Liz DaBramo   Sercan Ceyhan

Sustainable Conservation

Daniel Mountjoy   Taylor Broadhead   Roshni Katrak-Adefowora

Earth Genome

Glen Low   Devon Lake   Daniel Segall

Special thanks to the Merced Irrigation District

Hicham ElTal   Brian Kelly   Marco Bell

Stephen Ho   Matthew Beaman

Contents

List of Figures

List of Tables

Acronyms and Abbreviations

cfs	cubic feet per second
CHDD	Crocker Huffman Diversion Dam
DAC	disadvantaged community
DWR	California Department of Water Resources
Flood-MAR	floodwater used for managed aquifer recharge
FM2SIM	Flood-MAR Groundwater-Surface Water Simulation Model
GCM	global climate model
GDE	groundwater-dependent ecosystem
GSP	groundwater sustainability plan
Merced River watershed	Merced watershed
MID	Merced Irrigation District
study	Merced River Reconnaissance Study
TIR	technical information record
SGMA	Sustainable Groundwater Management Act
taf	thousand acre-feet
WUA	weighted usable area
°C	degrees Celsius

Executive Summary

The California Department of Water Resources (DWR), in partnership with the Merced Irrigation District (MID), is conducting a reconnaissance study to assess (1) water management vulnerability resulting from the effects of climate change, and (2) use of high flows for managed aquifer recharge (Flood-MAR) to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed.

Flood-MAR is an integrated and voluntary resource management strategy that can be used to address the risks of changing climatic conditions to three primary water management sectors of flood risk, water supply, and ecosystems. This technical information record (TIR), the third in a series of four, describes an analysis of climate change vulnerabilities across these three sectors for the Merced River watershed (Merced watershed) by introducing the decision scaling approach to climate change analysis, describing metrics and indicators used to measure the system response, and quantifying potential changes under climate change conditions.

ES.1 Climate Change Analysis Approach

This Merced River Watershed Flood-MAR Reconnaissance Study incorporates climate change through decision scaling, a method from the “bottom-up” family of approaches that DWR first piloted in its *Climate Action Plan* to analyze long-term risks to the State Water Project (California Department of Water Resources 2019). Decision scaling analyzes the full range of projected changes in temperature and precipitation from all available global climate models as a starting point to evaluate a wider sampling of climate conditions that the watershed may be exposed to over the 21st century.

Decision scaling incorporates the relative likelihood of future climate conditions, a feature that enables interpretation of risk levels and increases the value of study results to facilitate decision-making. The study reports results based on expected values, calculated as outcomes multiplied by their probabilities, for the 2040 and 2070 planning horizons.

ES.2 Metrics

Quantitative metrics are central to communicating current system performance and the effects of future climate conditions on water management. Metrics were developed and selected to measure aspects of system performance that are considered key indicators for flood risk, surface and groundwater resources, and ecosystems. Additionally, metrics were developed to describe the current and future hydrologic conditions of the watershed to provide insight into how climate change may influence runoff volume and timing and demands for water.

ES.3 Key Results

The study finds that all sectors are sensitive to warming temperatures and changes in precipitation. Although some of the plausible future climate conditions are shown to be beneficial, the cumulative climate risk that accounts for the range of uncertainty and relative likelihood of climate changes informed by global climate models indicates that all three water management sectors – water supply, flood risk, and ecosystems – are vulnerable to climate change. While warming temperatures negatively impact all sectors, changes in precipitation have mixed impacts on water supply and flood risk (e.g., less precipitation worsens supply conditions but reduces flood risk).

Table ES-1 shows expected values of performance under current and future climate conditions. Results for the 2040 and 2070 planning horizons show that watershed conditions will see a significant change in runoff timing, flood risk will increase in the maximum 100-year flow, groundwater storage conditions will continue to decline at faster rates, surface water shortages will increase, and in-stream spawning habitat for salmonids will decline. Because the range of warming and changes in precipitation expands from the 2040 to the 2070 planning horizons, the expected performance and possibility of extremely severe outcomes for all water management sectors significantly worsens by 2070.

Table ES-1 **Expected Performance Under Current and Future Climate Conditions for Merced Watershed Water Management Sectors**

Sector	Metric (Indicator)	Current	2040	2070	Units
Watershed Conditions	Average seasonal runoff into Merced watershed during Flood-MAR months (November – March).	434	528	619	taf/year
	Average seasonal runoff into Merced watershed outside Flood-MAR months (April – October).	689	610	542	taf/year
Flood Risk	Merced River 100-year maximum simulated flow[1] (November – June 30).	6,004	15,677	29,327	cfs
Water Supply (Groundwater)	Basinwide average annual change in groundwater storage.[2]	-50	-79	-101	taf/year
Water Supply (Surface water)	Number of years MID's surface water availability at or below 80 percent.	7	10	12	years
Ecosystems	Proportion of months depth to groundwater less than 30 feet.	77	57	50	percent
	Merced River in-stream salmonid spawning habitat (September – April).	531	509	492	thousand acre-days
	Potential Merced River off-channel juvenile rearing habitat (December – May).	212	367	501	thousand acre-days

Notes: 1. Simulated outflow downstream of Lake McClure reservoir at Crocker Huffman Diversion Dam. 2. Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act.

cfs = cubic feet per second; Flood-MAR = floodwater used for managed aquifer recharge; MID = Merced Irrigation District; taf/year = thousand acre-feet per year.

ES.4 Conclusions

The study shows that without any strategies or actions to minimize the effects of climate change on the system, the baseline condition of the Merced watershed is likely to degrade over time. However, the expected changes in the hydrology of the Merced watershed resulting from climate change also increase the potential for Flood-MAR opportunities.

Chapter 1. Introduction

The California Department of Water Resources (DWR), in partnership with the Merced Irrigation District (MID), is conducting a reconnaissance study to: (1) assess water management vulnerability resulting from the effects of climate change, and (2) use high flows for managed aquifer recharge (Flood-MAR) to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed (Merced watershed).

Flood-MAR is an integrated and voluntary resource management strategy that uses floodwaters resulting from, or in anticipation of, rainfall or snowmelt events for groundwater recharge on agricultural lands, working landscapes, and managed natural lands. The Merced River Watershed Flood-MAR Reconnaissance Study (study) explores the effectiveness of Flood-MAR concepts and assesses strategies to overcome barriers to project planning and implementation. This pilot study is responsive to the 2020 California Water Resilience Portfolio that highlighted daunting challenges, including changing climate and the need to harness the best in science, engineering, and innovation to prepare for the immediate and long-term future and ensure long-term water resilience and ecosystem health. One of 32 broad portfolio actions includes, “support regional decision-making with watershed-scale climate vulnerability and adaptation assessments.”

DWR has a role and responsibility to improve understanding of the quantitative effects of climate change to water management. To that end, this technical information record (TIR), the third in a series of four, addresses the study’s first objective of assessing watershed-scale climate vulnerability and covers the following topics:

- Definition of metrics to quantify vulnerability and performance of Flood-MAR strategies.
- The baseline condition of the Merced River watershed.
- Climate change vulnerability of the Merced River watershed.

The subsequent and fourth TIR of this study, *Adaptation Strategy Performance*, utilizes metrics defined within this report to illustrate the benefits of Flood-MAR strategies.

1.1 Merced River Watershed

The Merced River originates in the Sierra Nevada Mountain range and flows into the San Joaquin Valley where it joins the San Joaquin River in California’s Central Valley. The watershed is more than 1,700 square miles in area and largely undeveloped upstream of the largest reservoir on the river, Lake McClure. The average annual runoff of the Merced River is approximately one million acre-feet. The watershed above Lake McClure is relatively high in altitude and the runoff is dominated by melting snowpack in the spring.

MID owns and operates several dams and reservoirs on the river including Lake McClure, which has a capacity of approximately one million acre-feet. These reservoirs manage the river flows for flood control, water supply, ecosystems management, hydropower generation, and recreation. Lake McClure is operated to provide 350 thousand acre-feet (taf) of flood reservation space in the winter and provides surface water for irrigation during the summer. MID is a conjunctive management district, utilizing surface water in years when it is available and relying on groundwater during drought periods. Annual Merced River historical diversions in years with ample water are approximately 500 taf but can be nearly zero during drier years. Diversions from the Merced River are used for irrigation within MID, Stevinson Water District, and at the Merced National Wildlife Refuge.

MID is located within the Merced groundwater subbasin, an area of more than 500,000 acres. MID brings surface water into the subbasin from the Merced River and other local streams. The Merced subbasin is designated as critically overdrafted by DWR, and the *Merced Subbasin Groundwater Sustainability Plan* (GSP) estimates the average annual Current Condition Baseline change in storage is approximately 52,000 acre-feet (Woodard & Curran 2023), although recent annual overdraft has been as high as 192 taf (Water Year 2006-2015).

The Merced River watershed’s climate, like much of California, is warm-to-hot summer Mediterranean. Most precipitation falls during three months (December through February), and most of it is stored as snowpack that melts in the spring through early summer from the higher-elevation southern Sierra Nevada watersheds. These characteristics make watersheds in the Sierra Nevada, such as the Merced River watershed, particularly sensitive to a warming climate, with more precipitation falling as rain, a decreased snowpack, and an earlier seasonal snowmelt and runoff as compared to that of the 20th century. These changes are anticipated to exacerbate flood risk and decrease water supply reliability absent any adaptive measures.

1.2 Baseline Condition and Study Period

The baseline condition of the Merced River watershed and groundwater subbasin for the study reflects the level of development for agricultural land use and cropping patterns documented in 2014 and that for urban land use and demands based on 2015 urban water management plans. Land use remains constant throughout all modeling simulations, and for that reason long-term growth or reduction in demand resulting from future land use change is not represented; but, agricultural demands do fluctuate in response to varying temperature and precipitation conditions and changes in climate. Therefore, the study isolates the impacts of changes in climate from other drivers of demand, such as the conversion of agricultural lands to urban areas or other changes in land use.

The study also assumes that applied water demand is always met through a combination of surface water and groundwater over the entire simulation period. So, any reduction in surface water delivery is complemented by additional groundwater pumping.

The baseline condition includes existing reservoir and conveyance infrastructure with a validated model of current reservoir operations. The baseline condition does not incorporate any potential projects and management actions under consideration by local groundwater sustainability agencies to meet requirements of the Sustainable Groundwater Management Act (SGMA). In addition, neighboring groundwater subbasins are managed under pre-SGMA conditions.

The study covers a 100-year period of analysis, beginning in the historical water year 1900, with a historical climate dataset of precipitation and temperature. Because the historical climate dataset is used without any temperature detrending, the simulation may show transient effects of warming temperatures that have occurred during the latter half of the 20th century.

Chapter 2. Climate Change

2.1 Historical and Projected Changes

There is unequivocal evidence that California’s climate is changing as a consequence of global warming. California’s mean air temperature has increased up to 1.1 degrees Celsius (°C) since 1900 (California Department of Water Resources 2015), and temperature change is accelerating (LaDochy et al. 2011), with the greatest rate of change occurring in temperature minimums (California Department of Water Resources 2015). There is high scientific confidence that air temperatures will continue to rise until the globe can reach “net zero” carbon emissions (Intergovernmental Panel on Climate Change 2021). The effects of warmer temperatures are generally well understood. Rising air and water temperatures are intensifying droughts, increasing heavy downpours, reducing snowpack, melting glaciers, causing declines in surface water quality, and raising sea levels. These changes threaten ecosystems with increasing wildfire frequency, changes in insect and disease outbreaks, migration of native species, and spread of invasive species; agriculture with decreasing yields and water availability and increased disease and pest outbreaks; built-infrastructure with increasing extreme events, causing more frequent and longer-lasting service disruptions and cascading impacts to multiple sectors (U.S. Global Research Program 2018).

Nevertheless, the full extent of climate change unfolding over the 21st century remains deeply uncertain because of complexities in modeling the Earth’s land, ocean, cryosphere, and atmospheric processes and the unknowable uncertainty in global greenhouse gas emissions over the next several decades. Although a further rise in temperature is expected, the magnitude and timing of warming at a given time horizon is uncertain. Changes in other climatic parameters, such as precipitation for certain regions of the globe, are even less clear. Although studies have indicated that in the last half century California has become wetter in the north and drier in the south (Killam et al. 2014), the large variability in precipitation seen in California makes it difficult to separate trends from natural variability. Likewise, in terms of water management, the timing and intensity of precipitation can be just as important as the total volume of precipitation. A few very large winter events have significantly different outcomes for flood risk, water supply, and ecosystems than the same volume of precipitation spread out over multiple months. Altogether, the uncertainties in projecting future climate are many and complex, and, accordingly, careful selection of the climate change analysis approach is crucial for ensuring that these uncertainties do not become an impediment to developing a fuller understanding of watershed sensitivity to climate change and targeting specific courses of action.

2.2 Climate Change Analysis Approach for this Study

In general, there are two ways to incorporate climate change projections into water management and infrastructure planning. The first method can be viewed as a “top-down” approach as it starts with global climate models (GCMs) and downscales to higher spatial resolutions for input to local watershed and system operation models. Top-down analysis can provide useful information; but, results are conditioned on a pre-determined filtering and selection of GCMs, which can limit understanding of system exposure and sensitivity to a wider range of plausible climate change conditions. Additionally, top-down studies rarely summarize and communicate results in terms of risk (a combination of consequence and likelihood). Instead, top-down studies typically use “extreme” GCM scenarios to bracket (or “bookend”) the potential range of climate change exposure and guide decision-making towards planning and investment in climate change adaptation or maintaining the status quo.

Alternatively, this study incorporates climate change through “Decision Scaling”, a method from the “bottom-up” family of approaches that DWR first piloted in its *Climate Action Plan* to analyze long-term risks to the State Water Project (California Department of Water Resources 2019). Decision scaling deviates from the top-down approach in two respects.

First, decision scaling analysis does not pre-select downscaled GCMs as a direct input to water system models. Instead, the full range of projected changes in temperature and precipitation by all available GCMs is used as a starting point to evaluate a wider sampling of climates that the system of interest (in this case, watersheds and water system operations) may be exposed to over the 21st century. The changes in temperature and precipitation are imprinted on a historical climate record, thus preserving many of the finer scale characteristics of weather and climate while incorporating large-scale signals of climatic change. Climate changes are incrementally applied and modeled to conduct a "stress test" of the water system.

Secondly, decision scaling allows assigning probabilities to the sampled range of future climate conditions. The incorporation of probabilities enables interpretation of risk, thus significantly increasing the value of study results to facilitate decision-making (i.e., "scaling" the information to the "decisions"). Using this approach, the study first seeks to provide a quantitative understanding of vulnerability to climate change to water management and then will assess the performance of Flood-MAR adaptations with the effects of climate change.

2.3 Quantifying Climate Vulnerability

The common framework of determining vulnerability to climate change has been well-described and widely used in literature and practice (Intergovernmental Panel on Climate Change 2007). In general, vulnerability is a function of exposure, sensitivity, and adaptive capacity. Exposure captures the extent to which climate change conditions overlap with the resource or system that is being analyzed. Sensitivity represents the susceptibility of a facility, operations, or group of people when exposed to climate change. Adaptive capacity is the ability to endure the consequences or the flexibility to take adaptive measures to mitigate or avoid the impacts of exposure.

In this study, performance of multiple water management sectors in the Merced watershed is estimated for a current climate condition and then compared to performance estimated under a range of plausible exposures to climate change. This estimated change in performance is quantified in terms of sensitivity and vulnerability of the system. Flood-MAR strategies that change the baseline watershed condition are then simulated under climate change conditions to quantify the adaptive capacity of the system. The Flood-MAR strategies and results are described in the fourth TIR in this series, *Adaptation Strategy Performance*.

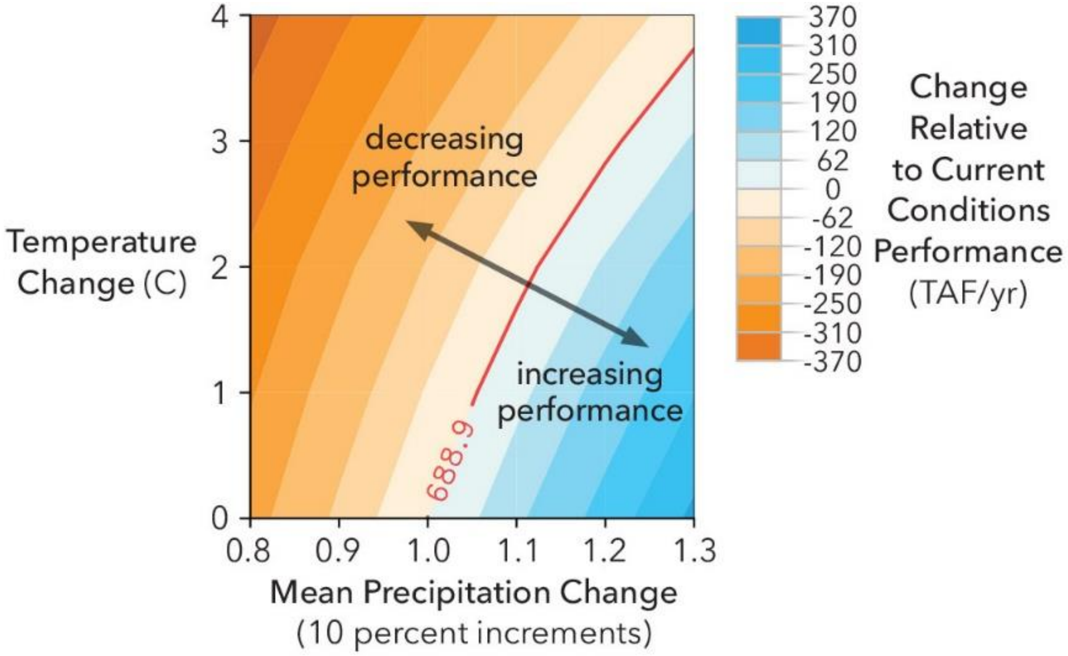
2.3.1 Risk-based Level of Performance

The study employs decision scaling to develop probabilistic information about the expected change in system performance with climate change. This is done by combining probabilistic estimates of climate change exposure based on projections by GCMs at the regional scale together with the results of system performance under each simulated climate change condition (i.e., likelihood combined with consequence). Two descriptions of risk-based level of performance are provided in the study: (1) the "expected value" provides the future performance weighted by the likelihood of future conditions (i.e., the average change performance weighted by the relative likelihood of occurrence); and (2) the cumulative probability of being equal to or worse than a performance level of concern. By default, the performance level of concern is set at the level of current performance but may be set higher or lower for certain metrics to represent a threshold at which the system is considered to have failed.

2.3.2 Response Surfaces

Response surfaces provide a visual representation of how a system performs over a range of changes, indicating trends and characteristics of system sensitivity. An example response surface is shown in Figure 2-1. Contour lines of equivalent system performance create visual cues of trends and characteristics of system sensitivity for a specific metric and indicator. The bold red contour line represents a specific performance threshold, typically set equal to performance under current climate conditions but can also be set to a threshold of performance beyond or below which the system is considered to have failed. In this study, the range of changes explored are combinations of two variables of climate conditions — changes in mean precipitation and temperature. Accordingly, contours of performance that are more vertical indicate that the system is more sensitive to changes in precipitation (x-axis), and contours that are more horizontal indicate more sensitivity to changes in temperature (y-axis). Blue colors represent performance superior to the performance threshold, and orange-red colors represent performance inferior to the performance threshold. Importantly, the response surface does not describe performance at any given time in the future; it simply illustrates how the system performs across the range of precipitation and temperature climate conditions.

Figure 2-1 **Example Response Surface**



2.4 Probability of Climate Change Exposure by Planning Horizon

This study evaluates plausible conditions of climate change over the 21st century including changes in temperature from 0 °C (current climate) to +4 °C (in one-degree increments) and precipitation from -20 percent to +30 percent (in 10-percent increments). So, together with the current climate condition (no change in temperature or precipitation), the total number of individual climate conditions simulated in the study is 30. Conditional probabilities for each climate condition are inferred by using the projected changes in average precipitation and temperature over a 30-year period in the future relative to the historical 1981–2010 average by an archive of available GCM models at their native output scale (i.e., "GCM-informed" probabilities). At the time of this study, more than 50 GCMs were included from the Coupled Model Intercomparison Project Phase 5.

The following two tables show the conditional probability of each climate change condition at the 2040 and 2070 planning horizons. The 2040 planning horizon in Table 2-1 indicates seven scenarios with a probability of occurrence greater than 1 percent, with most of the cumulative probability (approximately 58 percent) on climate change conditions of two degrees warming with 0 or +10 percent increase in precipitation. The 2070 planning horizon in Table 2-2 shows 15 scenarios with a probability greater than 1 percent, with a third of the cumulative GCM-informed probability on 3 °C warming with 0 or +10 percent increase in precipitation. As shown in these tables, climate change conditions are increasingly uncertain as the planning horizon moves further into the future.

Table 2-1 GCM-Informed Conditional Probabilities of Future Climate Conditions at a 2040 Planning Horizon

2040 Planning Horizon						
	Change in Precipitation					
Change in Temperature	-20%	-10%	0%	+10%	+20%	+30%
0°C	0%	0%	0%	0%	0%	0%
+1°C	0%	5%	15%	8%	1%	0%
+2°C	0%	9%	36%	22%	2%	0%
+3°C	0%	0%	1%	0%	0%	0%
+4°C	0%	0%	0%	0%	0%	0%

Table 2-2 GCM-Informed Conditional Probabilities of Future Climate Conditions at a 2070 Planning Horizon

2070 Planning Horizon						
	Change in Precipitation					
Change in Temperature	-20%	-10%	0%	+10%	+20%	+30%
0°C	0%	0%	0%	0%	0%	0%
+1°C	0%	0%	0%	0%	0%	0%
+2°C	1%	3%	7%	7%	3%	1%
+3°C	2%	10%	19%	17%	8%	2%
+4°C	1%	4%	7%	6%	3%	1%

Chapter 3. Metrics of System Performance

A multi-sector understanding of flood risk, water supply, and ecosystems was developed by identifying 12 metrics and 18 indicators specifically for the Merced River watershed and groundwater subbasin. Each sector has multiple metrics, with one or more indicators per metric to quantify the different aspects of performance under a single metric and within a single sector. These indicators were selected based on relevance to the respective water managers for the respective sectors, broad understanding among the water management community, and evaluated at an appropriate resolution that can be reasonably supported using the integrated modeling toolset. Please refer to Appendix A for a complete list of metrics and indicators considered in the study.

3.1 Watershed Condition Metrics

Changes in the volume and timing of runoff and demand for applied water are key drivers for many of the changes seen in the three sectors in response to climate change. Therefore, the following watershed condition metrics and indicators in Table 3-1 were developed to contextualize the effects of climate change on the watershed and aid discussion in changes seen across the three sectors.

Table 3-1 Watershed Condition Metrics

Metric	Indicator	Location	Period	Model
Merced River Runoff	Average annual	New Exchequer Dam	October – September	SAC-SMA
	Flood-MAR season		November – March	
	Irrigation season		April[1] – October	
Agricultural Demand for Applied Water	Average annual	Basinwide	October – September	FM2Sim

Notes: 1. In practice, the Merced Irrigation District’s irrigation season does begin in March in some years depending on watershed conditions; however, modeling for this study assumes that all years begin in April.

SAC-SMA = Sacramento Soil Moisture Accounting; FM2Sim = Flood-MAR Groundwater-Surface Water Simulation.

Average annual Merced River runoff defines the available surface water supply for irrigation and ecosystems; dividing the runoff into the winter Flood-MAR season and the summer irrigation season will illustrate shifts in the timing of runoff, and the average annual runoff will quantify changes in the overall volume.

The study will also evaluate how changes in temperature and precipitation affect the agricultural demands for applied water. Increased temperature is expected to increase crop evapotranspiration and demands, but changes in precipitation may increase or decrease the demand for applied water to meet the evapotranspiration.

3.2 Flood Risk Sector Metrics

Lake McClure is operated for flood protection of areas located downstream of the reservoir along the Merced and lower San Joaquin rivers. Additionally, small reservoirs located on ephemeral streams in the foothills east of Merced attenuate flows on streams, such as Bear Creek, to prevent flooding of areas in the valley floor. Table 3-2 shows the flood risk sector metrics selected for the study.

Table 3-2 Flood Risk Sector Metrics

Metric	Indicator	Location	Period	Model
Merced River Flow	Number of years above 7,300 cfs[1]	Crocker Huffman Diversion Dam (CHDD)	October – June	HEC-ResSim
Merced River Flow	100-year maximum simulated flow	CHDD	October – June	HEC-ResSim
Local Creeks	100-year maximum simulated flow	Bear Creek (Eastside Bypass)	October – September	HEC-RAS
Reservoir Flood Space	Maximum encroachment	Lake McClure	November 1 – March 15	HEC-ResSim

Notes: 1. Significant flooding is assumed to occur at flows higher than 7,300 cfs.

HEC-RAS = Hydrologic Engineering Center River Analysis System; HEC-ResSim = Hydrologic Engineering Center Reservoir System Simulation.

Flood risk sector metrics in Table 3-2 represent key performance parameters. The maximum simulated flow at two locations is used to understand flows on both the Merced River, where the upstream watershed runoff is a combination of snowmelt and rainfall, and Bear Creek as one of several local creeks with flood risks from rainfall events.

The New Exchequer Dam and Reservoir Water Control Manual identifies the maximum design channel capacity of the Merced River as 6,000 cubic feet per second (cfs) near the mouth of the Merced River where it joins the San Joaquin River (United States Army Corps of Engineers 1981). However, USACE has directed MID to release higher flows in the past due to the volume of snow moisture content in the watershed and high inflows to Lake McClure. According to MID, with incremental flow increases backed by field surveys and observations, it was determined that up to 7,100 cfs (or more critically, Elevation 71.9 feet at the Stevenson Gage) could be maintained with minimal flooding. Therefore, a threshold of 7,300 cfs was used at the Crocker Huffman Diversion Dam (CHDD) with the understanding that any higher flows would have significant downstream flood impacts.

The New Exchequer Dam and Reservoir Water Control Manual describes the required flood reservation space in Lake McClure that is used to regulate peak inflows and control downstream flows (United States Army Corps of Engineers 1981). Encroachment into the flood reservation space occurs when peak inflows are temporarily regulated in Lake McClure to control flows in the downstream reach. The maximum encroachment in Lake McClure is a flood risk sector metric that defines the remaining capacity of the reservoir to regulate large peak inflow events. The remaining capacity is a “buffer” against larger inflows than analyzed. The Manual requires that a 350,000 acre-feet flood reservation space be maintained between November 1 and March 15. The flood reservation space gradually decreases to zero by June 15.

3.3 Water Supply Sector Metrics

The water supply available from the Merced River works in concert with the regional groundwater basin to provide water for irrigation, wildlife, and communities. For this study, water supply is defined by both the water available from the Merced River and the Merced groundwater subbasin. Tables 3-3 and 3-4 show the water supply sector metrics for groundwater and surface water domains selected for the study.

Table 3-3 Water Supply (Groundwater) Sector Metrics

Metric	Indicator	Location	Period	Model
Groundwater Storage	Average annual change in groundwater storage	Basinwide	October – September	FM2SIM
Groundwater Levels	Average annual change in groundwater levels	Subsidence prone regions	October – September	FM2SIM
Groundwater Levels	Average annual change in groundwater levels	Aquifer underlying DACs east of Corcoran Clay layer	October – September	FM2SIM
Groundwater Pumping	Average annual groundwater pumping to meet agricultural uses	Basinwide	October – September	FM2SIM

Notes: FM2Sim = Flood-MAR Groundwater-Surface Water Simulation.

Table 3-4 Water Supply (Surface Water) Sector Metrics

Metric	Indicator	Location	Period	Model
Surface Water Deliveries	Average annual total surface water deliveries to agricultural users	MID	October – September	HEC-ResSim
Surface Water Deliveries	Number of years MID’s surface water availability at or below 80%	MID	October – September	HEC-ResSim
Reservoir Storage	Average annual storage at the end of the irrigation season (October 31)	Lake McClure	October 31	HEC-ResSim

Notes: HEC-ResSim = Hydrologic Engineering Center Reservoir System Simulation; MID = Merced Irrigation District.

The metrics in Tables 3-3 and 3-4 cover the primary areas of water supply sector system performance and vulnerability to climate change. Changes in runoff timing and volume are expected to translate into changes in storage in Lake McClure, and thus surface water shortages for MID. The volume of groundwater pumped indicates the change in stress on the Merced groundwater subbasin. The average change in groundwater storage reflects the combined effects of changes in surface water supply, groundwater pumping, recharge, local runoff, seepage from streams, and other components of the groundwater system water budget of the Merced subbasin and interbasin flows with the neighboring subbasins. The average annual change in groundwater levels for specific regions in the Merced groundwater subbasin indicates the vulnerability of those areas to changes in groundwater conditions.

3.4 Ecosystem Sector Metrics

The study focuses on two metrics of ecosystem sector performance: groundwater-dependent ecosystems (GDEs) and salmonid habitat (Table 3-5).

Table 3-5 Ecosystem Sector Metrics

Metric	Indicator	Location	Period	Model
Groundwater-dependent ecosystems	Portion of months with depth to groundwater less than 30 feet	Merced groundwater basin GDEs	October – September	FM2Sim
Salmonid habitat	Merced River in-stream salmonid spawning habitat	Merced River (CHDD to Shaffer Bridge)	September – April	HEC-RAS
Salmonid habitat	Potential Merced River off-channel juvenile rearing habitat during qualified events	Merced River (CHDD to Shaffer Bridge)	December – May	HEC-RAS

Notes: CHDD = Crocker Huffman Diversion Dam; HEC-RAS = Hydrologic Engineering Center River Analysis System; FM2Sim = Flood-MAR Groundwater-Surface Water Simulation; GDE = groundwater-dependent ecosystems; GW = groundwater.

3.4.1 Groundwater Dependent Ecosystems

The GDE metric tracks the frequency of habitat accessibility to riparian trees. Valley oak was chosen as the indicator species to evaluate the effects of Merced River Flood-MAR on GDEs. Information from the GSP is used to select the extent of GDEs and the benchmark depth-to-groundwater threshold of 30 feet for measuring groundwater availability to GDEs (Woodard & Curran 2019). The indicator chosen for the GDE habitat relies on data from 136 Merced Flood-MAR Groundwater-Surface Water Simulation Model (FM2Sim) nodes, grouped into five reaches along the Merced and San Joaquin rivers. The indicator is defined as the percent of months over the 100-year simulation period the spatially averaged monthly groundwater level across the 136 nodes is within the benchmark threshold of 30 feet.

3.4.2 Salmonid Habitat

Salmonid habitat is evaluated separately for in-stream and off-channel habitat. The current off-channel habitat on the Merced River has limited suitability for salmonid rearing given the lack of structure, cover, and vegetation, which are important for rearing success. Because the quality of inundated habitat was not determined for this study, this habitat is assumed to be potential habitat. Moreover, modeled water temperature data were not available to inform this analysis. The inclusion of water temperature data would be expected to show greater vulnerability of salmonids to climate change than modeled by habitat quantity alone. So, the results presented for salmonids should be assumed to represent the minimum vulnerability that salmonids are expected to face from climate change.

Flow-habitat relationships were used to evaluate regulated stream discharges and their impacts on salmonid habitat quality and quantity. The spawning habitat metric is derived from weighted usable area (WUA) curves developed for spawning life-stage and two sub-reaches in the Merced River between Crocker-Huffman and Shaffer Bridge (Merced Irrigation District 2013). Each WUA curve creates an index for habitat in acres that satisfies the physical habitats of a given species and life stage (e.g., depth, velocity, substrate). The in-stream spawning habitat metric is generated daily using flow and flow-WUA relationship and presented as total acre-days of spawning habitat available between September and April over the entire 100-year simulation period.

The potential off-channel rearing habitat metric is developed for five reference reaches in the Merced River using flow-inundation area relationship indexed to the Crocker-Huffman flow meeting the following criteria:

- More than 1 foot deep to allow adequate depths for rearing.
- Outside of the main channel as defined during the summer base flow period.
- Connected by surface water to the main channel.
- Outside of captured mining pits to avoid predator hotspots.

Qualified, off-channel events were defined as 14-day or longer periods where the flow threshold (1,800 cfs) was met on each day during the period. Potential off-channel rearing habitat is calculated as the total acres-days of accessible potential rearing habitat during the qualified events within the primary rearing period (December through May) over the 100-year simulation period.

MID is currently engaged in projects to improve and restore in-stream and off-channel habitat critical for salmon spawning and rearing. The recently completed Merced River Instream and Off Channel Habitat Restoration Project improved 7-acres of riparian and upland habitat, 3.9 acres of seasonally inundated juvenile rearing habitat, and 13 acres along the Merced River channel. Just over 2 miles of river section will have been restored with the completion of the Above Henderson Park project.

Chapter 4. Climate Change Vulnerability Results

This section describes the results of the climate change vulnerability analysis, beginning with a high-level summary and followed by additional details regarding each sector’s sensitivity to climate change.

4.1 Expected Value of Performance

The expected value of watershed condition metrics and system performance for the three sectors of flood risk, water supply, and ecosystems is presented in Table 4-1. Metrics are tabulated for the baseline current and 2040 and 2070 planning horizons. The expected value is calculated as the weighted sum of each metric’s value under a given climate condition multiplied by the probability of that climate change condition (see section 2.4, “Probability of Climate Change Exposure by Planning Horizon,” for the climate-weighted probabilities).

Table 4-1 Summary of Expected System Performance for the Baseline Watershed Condition at Current Climate and the 2040 and 2070 Planning Horizons

Sector	Indicator	Current	2040	2070	Units
Watershed Conditions	Average annual runoff into Merced watershed (October – September).	1,123	1,138	1,161	taf/year
	Average seasonal runoff into Merced watershed during Flood-MAR months (November – March).	434	528	619	taf/year
	Average seasonal runoff into Merced watershed outside Flood-MAR months (April – October).	689	610	542	taf/year
	Average annual applied agricultural demand in the Merced watershed[1].	800	835	860	taf/year
Flood Risk	Maximum encroachment at Lake McClure (November 1 – March 15).	61	79	87	percent
	Merced River 100-year maximum simulated peak flow[2] (November 1 – June 30).	6,004	15,677	29,327	cfs
	Total number of years Merced River at CHDD is above 7,300 cfs (November 1 – June 30).	0	3	5	years
	Bear Creek 100-year maximum simulated outflow.[3]	14,615	15,056	15,453	cfs
Water Supply/ Groundwater	Basinwide average annual change in groundwater storage[4].	-50	-79	-101	taf/year
	Average annual change in groundwater levels in subsidence prone region.	-0.8	-1.1	-1.3	feet/year
	Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer.	-0.6	-1.0	-1.3	feet/year
	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed.	466	494	510	taf/year

Sector	Indicator	Current	2040	2070	Units
Water Supply/ Surface Water	Average annual total surface water deliveries to agricultural users in the Merced watershed.	355	359	359	taf/year
	Number of years MID's surface water availability at or below 80 percent.	7	10	12	years
	Average annual Lake McClure storage at the end of the irrigation season[5] (October 31).	518	479	436	taf
Ecosystem	Proportion of months with depth to groundwater less than 30 feet.	77	57	50	percent
	Merced River in-stream salmonid spawning habitat (September – April).	531	509	492	thousand acre-days
	Potential Merced River off-channel juvenile rearing habitat during qualified events (December – May).	212	367	501	thousand acre-days

Notes: 1. Applied water demand changes in response to increased temperatures or changes in precipitation. 2. Simulated outflow downstream of Lake McClure Reservoir. 3. Bear Creek outflow into Eastside Bypass. 4. Groundwater conditions assume that no actions or projects are implemented in Merced or neighboring subbasins to comply with the Sustainable Groundwater Management Act. 5. Maximum Lake McClure carryover storage capacity is 675,000 taf.

cfs = cubic feet per second; DAC = disadvantaged community; Flood-MAR = floodwater used for managed aquifer recharge; MID = Merced Irrigation District; taf/year = thousand acre-feet.

The expected value of watershed conditions shows a slight increase in annual runoff from the Merced River and local streams, as well as in agricultural demand for applied water. The most significant change is in the seasonal partition of runoff, with an increasing portion of annual runoff occurring November through March and less runoff occurring April through October. In general, the changes shown at the 2040 planning horizon are amplified at the 2070 planning horizon. This is consistent with the increasing probability of exposure to warmer temperatures further into the future and the sensitivity of many system metrics to warmer temperatures.

Results for the flood risk sector show increased flood risk at both planning horizons. The flood management space in Lake McClure is expected to be utilized more to regulate higher inflows in the winter. Current flood space and operations are not adequate to control the simulated inflows of the Merced River into Lake McClure at either planning horizon. Increased flows are also expected on the local creeks such as Bear Creek.

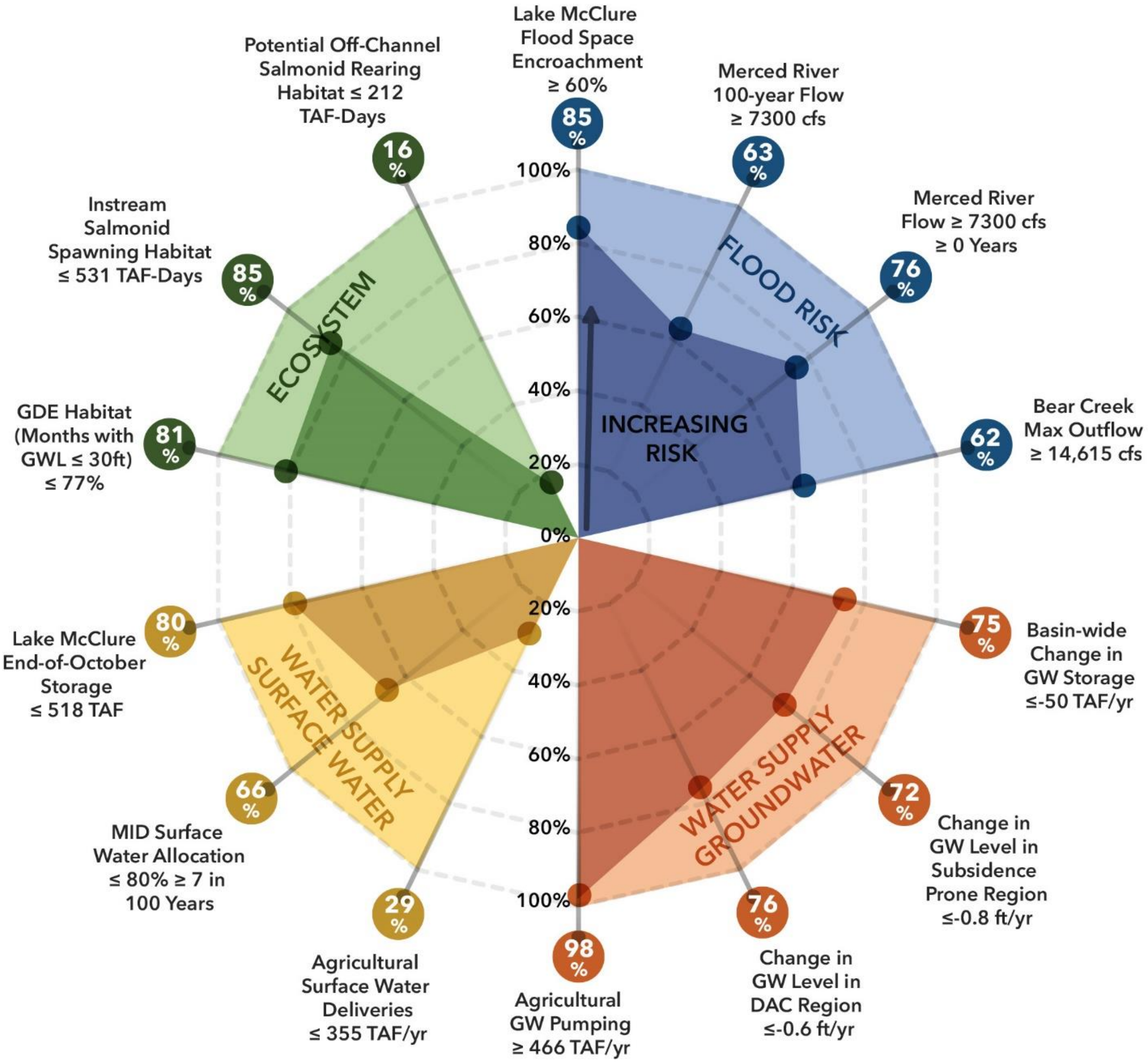
Climate change also presents a risk to the water supply sector. The small increase in the expected value of average annual surface water deliveries does not offset the increased demand for applied water for irrigation. This results in increased groundwater pumping and continued groundwater level declines, including in areas prone to subsidence and areas below disadvantaged communities (DACs). The average annual overdraft in the current baseline conditions of the study (approximately 50 taf per year) is exacerbated by the increased pumping. In addition, although average annual surface water deliveries increase slightly, surface water availability decreases in drought years due to reductions in carryover storage in Lake McClure.

The ecosystem sector tracks the effect of climate change on two indicator species: GDEs and salmonids. GDEs likely will experience a decrease in groundwater availability resulting from increased groundwater pumping and continued decline in groundwater levels under climate change, likely affecting GDE sustainability. The expected value of habitat quantity for spawning salmonids shows a slight decrease at the 2040 and 2070 planning horizons, whereas the expected value of potential off-channel habitat inundation for salmonids increases for both planning horizons. Climate change is expected to shift the runoff timing to earlier in the season which will result in higher flood releases and increased frequency and magnitude of off-channel inundation flows. Despite the expected value improvement in potential juvenile rearing habitat quantity, off-channel habitat on the Merced River has limited suitability for salmonid rearing given the lack of structure, cover, and vegetation which are important for rearing success. For this reason, increased accessibility to off-channel reaches cannot be directly equated with increase in salmonid habitat and is considered to the potential habitat. In addition, modeled water temperature data were not available to inform this analysis. The inclusion of water temperature data would be expected to show greater vulnerability of salmonids to climate change.

4.2 Cumulative Risk of Changes in Performance

The probabilistic characterization of joint changes in precipitation and temperature shown in Figure 2-2 can be transferred into distributions of changes for each sector indicator. This analysis quantifies the cumulative risk of being “worse-off” under future climate compared to a specified level of performance. Figure 4-1 shows the cumulative risk of performance worse than the indicated performance threshold at the 2040 planning horizon for all 14 multi-sector indicators. All flood risk sector and water supply (groundwater) sector indicators show a more likely than not (i.e., probability of greater than 60 percent) decline in future performance. Most of the water supply (surface water) and ecosystem indicators also show more likely than not declines in future performance. Three water supply indicators—Lake McClure end-of-October storage, MID surface water availability in drought years, and agricultural groundwater pumping—show higher probability of declines in future performance. These three water supply indicators are linked, as declines in carryover storage reduce surface water availability in subsequent drought years. Reduced surface water availability, combined with increased demand for agricultural applied water result in greater rates of groundwater pumping.

Figure 4-1 Cumulative Risk of a Loss in Performance equal to or greater than the Indicated Performance Threshold for all 14 Multi-Sector Indicators at the 2040 Planning Horizon



4.3 Sensitivity to Climate Change

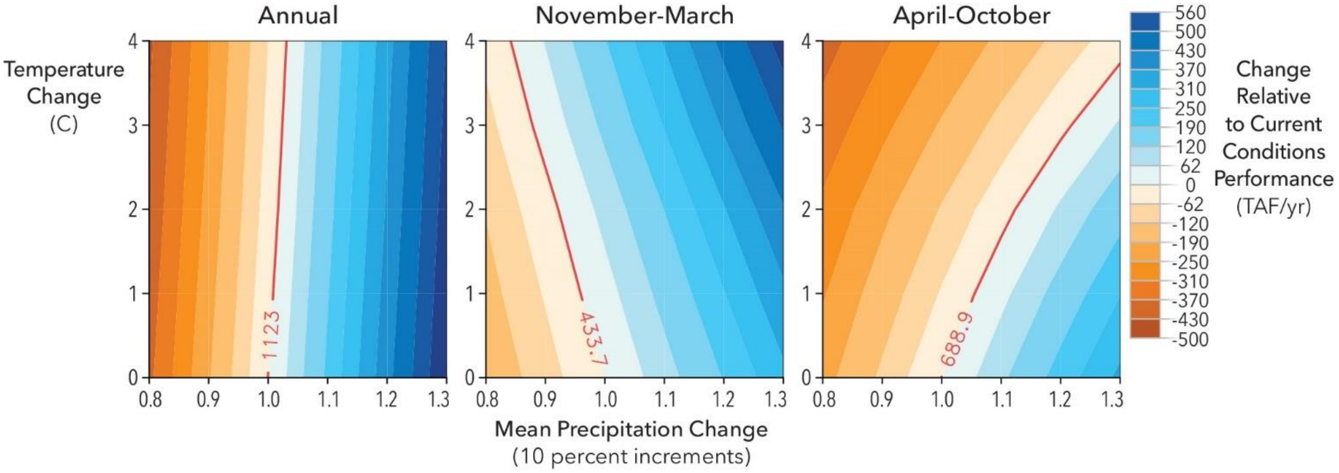
This section provides detailed results and trends for the watershed conditions and specific metrics of the three sectors to understand system sensitivity to climate change. Results are shown with a response surface plot that tracks the performance of a specific indicator across all combinations of climate change conditions.

4.3.1 Watershed Conditions

4.3.1.1 Annual and Seasonal Runoff

Figure 4-2 shows changes in the Merced watershed average annual and seasonal runoff across all simulated climate conditions. Annual runoff is highly sensitive to changes in precipitation as shown by nearly vertical lines between the different shaded regions of change, with approximately a 200 taf (approximately 20 percent) change for each ±10 percent change in precipitation. Annual runoff decreases by approximately 15 taf for each 1 °C increase in temperature. These results are generally additive such that a 10 percent reduction in precipitation plus 2 °C of warming reduces runoff by approximately 230 taf. The reduction in annual runoff with increased temperature is a result of increased evapotranspiration in the upper watershed, whereas the greater sensitivity of runoff to precipitation is driven by changes in the partition of rainfall into runoff and evapotranspiration throughout the year. As shown in the seasonal runoff response in Figure 4-2, increased temperatures increase runoff during the November-through-March period and decrease runoff during the April-through-October period. The seasonal response is a primary result of earlier snowmelt and more precipitation falling as rain than snow.

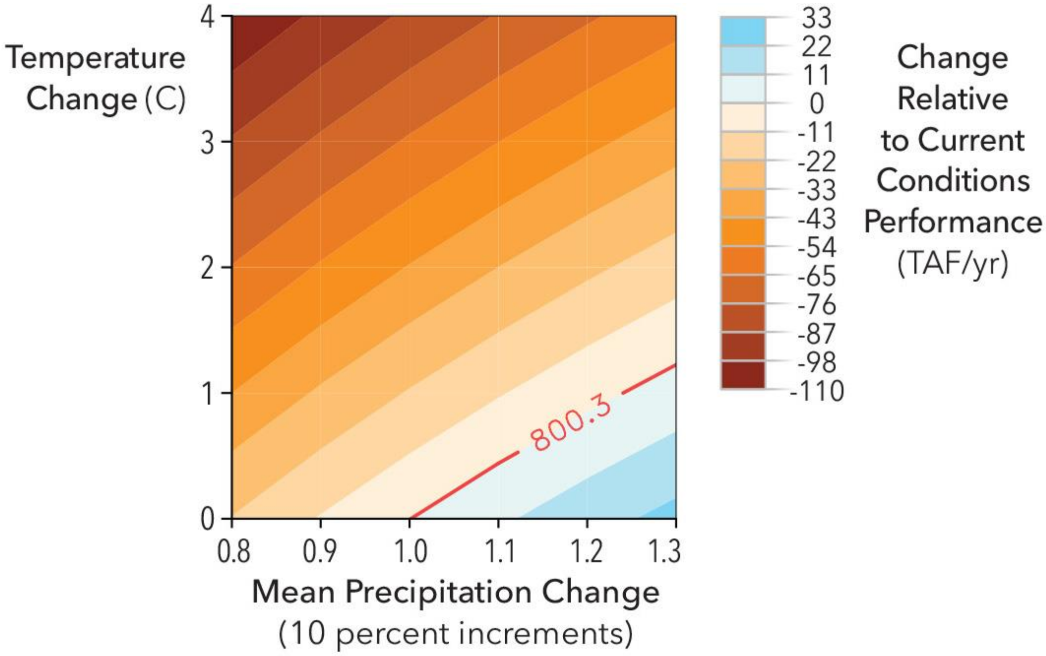
Figure 4-2 Response Surfaces for Average Annual, November through March, and April through October Runoff (measured in thousand acre-feet)



4.3.1.2 Demand for Applied Water

The response surface plot for applied water demand is shown in Figure 4-3. Demand for applied water changes by approximately 10 taf for every 10-percent change in precipitation, with demands increasing as precipitation decreases and vice versa. Changes in precipitation result in changes in effective precipitation (the precipitation contributing to soil moisture and physically available to crops) that increase or decrease crop water demand. Demands increase by approximately 20 taf annually for every 1 °C increase in temperature. Increases in temperature result in increased evapotranspiration from crops, thus raising crop water demand for applied water. The changes in applied water demand are generally additive for combinations of temperature and precipitation change. For example, increases in precipitation can offset increased demands from warming temperatures as illustrated in the response surface where the current level of demand is maintained with 1 °C warming combined with an increase in precipitation of 20 percent.

Figure 4-3 Response Surface for Average Annual Agricultural Demand for Applied Water

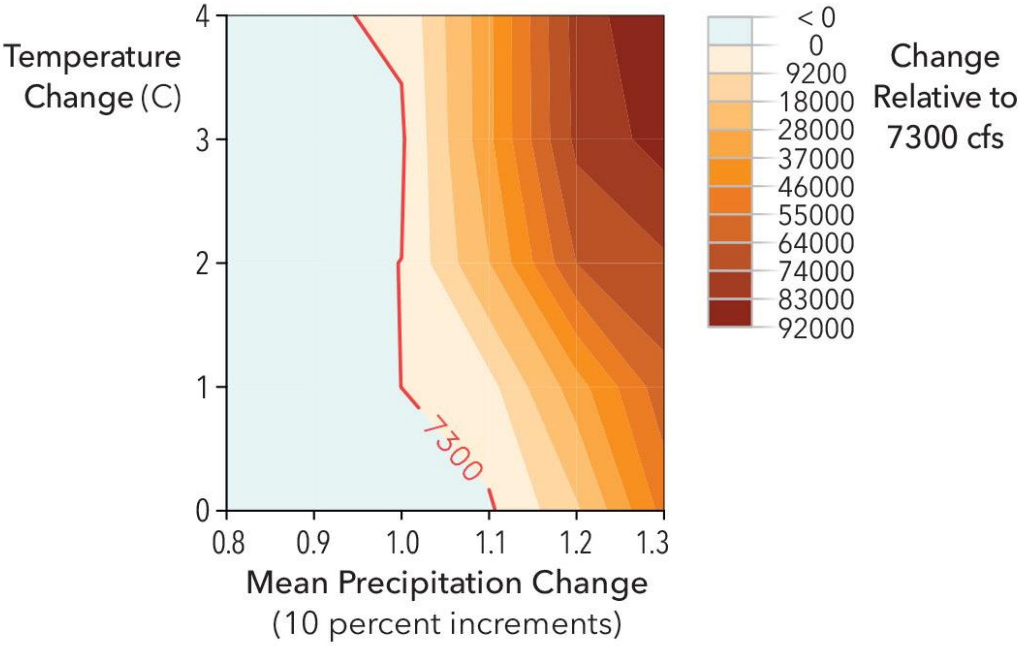


4.3.2 Flood Risk Sector

4.3.2.1 Maximum Simulated Merced River Flow

The response surface of the maximum simulated Merced River flow is shown in Figure 4-4. The red line in the response surface has been set to 7,300 cfs – a flow threshold beyond which significant damage from flooding is expected to occur – to trace out the threshold of this vulnerability to climate change conditions. Warming of at least 1 °C would cause maximum flows nearing 8,000 cfs, whereas beyond 2 °C of warming the maximum flow is mostly sensitive to increases in precipitation. Any increase in precipitation tends to translate directly into greater maximum reservoir release, with a 10-percent precipitation change corresponding to a 18,000 to 28,000 cfs increase in the maximum simulated flow.

Figure 4-4 Response Surface for Maximum Simulated Merced River Flow Downstream of CCHD

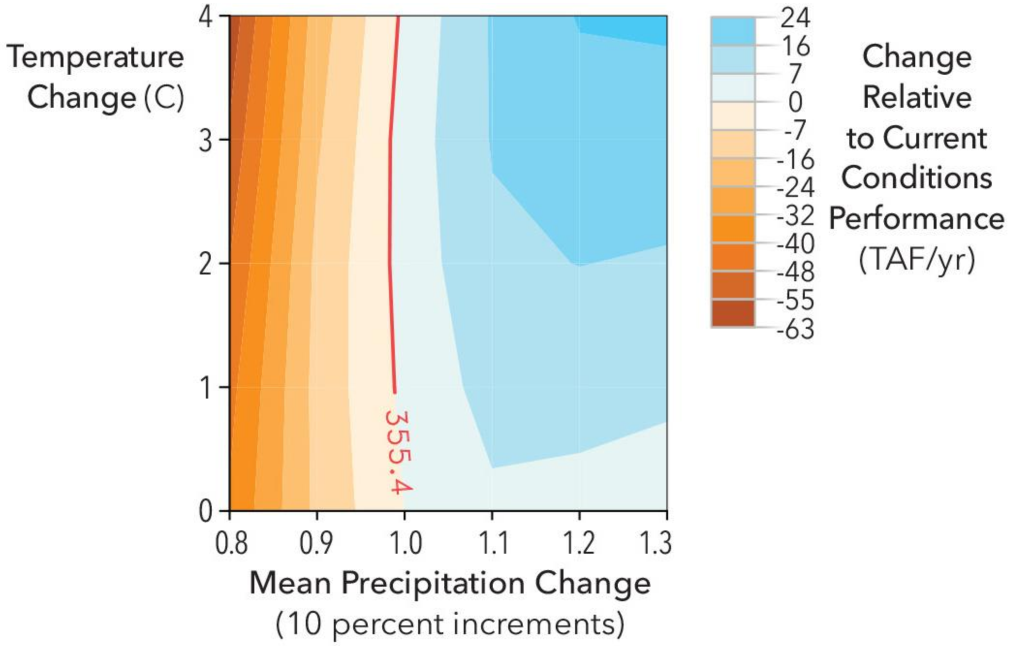


4.3.3 Water Supply Sector

4.3.3.1 Surface Water Diversion to MID

The response surface of average annual surface water diversions to MID is shown in Figure 4-5. Average annual surface water diversions increase slightly with increasing precipitation but are much more sensitive to decreases in precipitation. In general, the sensitivity to decreasing precipitation is driven by reductions in total runoff. A corresponding increase is not seen with increases in precipitation because applied water demand tends to decrease with increasing precipitation. But, under climate conditions that are at least 10 percent wetter than current climate conditions, warming tends to increase average annual surface water diversions because of (1) the higher applied water demand, and (2) the additional watershed runoff (from greater precipitation) that the reservoir can capture and deliver to meet those demands.

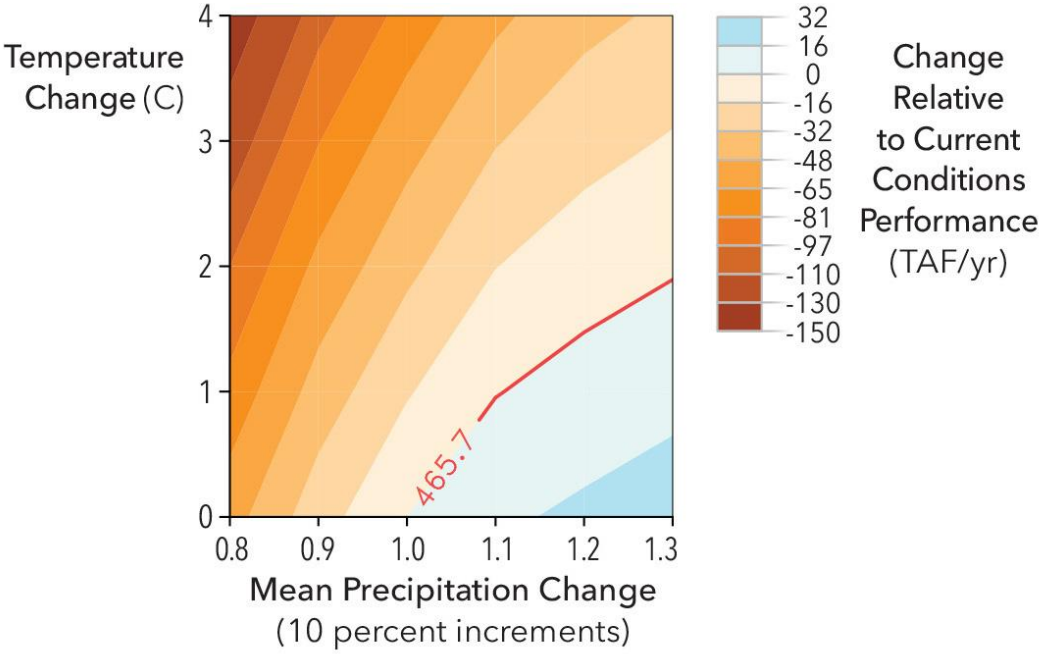
Figure 4-5 Response Surface for Average Annual Surface Water Diversion to MID



4.3.3.2 Groundwater Pumping

The response surface of average annual groundwater pumping in the Merced subbasin is shown in Figure 4-6. The response surface shows that groundwater pumping is sensitive to both changes in temperature and precipitation. Increases in precipitation do not reduce pumping as quickly as reductions in precipitation increase pumping. Also, with increasing precipitation, groundwater pumping becomes less sensitive to increases in temperature. Groundwater pumping would remain at current levels with significant increases in precipitation up to approximately 2 °C. For any increase in temperature above 2 °C, pumping is expected to exceed the current levels under both wetter and drier precipitation conditions.

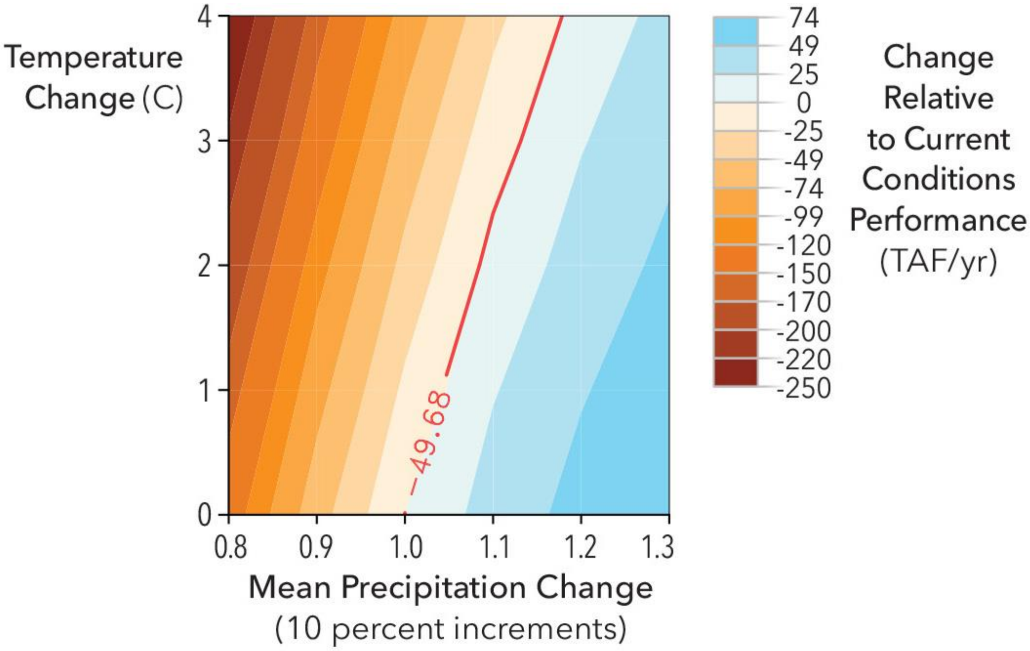
Figure 4-6 Response Surface for Average Annual Groundwater Pumping in Merced Subbasin



4.3.3.3 Change in Groundwater Storage

Temperature and precipitation in the form of rainfall directly influence the groundwater model through changes in the soil-moisture accounting at the land surface. In addition, temperature, and precipitation in the form of rain and snowfall indirectly influence the groundwater model through propagation of upper watershed runoff through the surface water reservoir and delivery system. The response surface plot of average annual change in groundwater storage is shown in Figure 4-7. The response surface indicates that average annual change in groundwater storage, which is approximately -50 taf per year under current climate conditions, increases (becomes more negative) by approximately -20 taf per year per 1 °C of warming and approximately -70 taf per year per 10-percent decrease in precipitation. With every 2 °C of warming and no change in precipitation, the -40 taf per year additional decline in groundwater storage corresponds to a roughly 8-percent decrease in precipitation without warming. Alternatively, for average annual decline in groundwater storage to remain the same as under current climate conditions (i.e., -50 taf per year) but at 2 °C of warming, precipitation would need to increase by at least 10 percent.

Figure 4-7 **Response Surface for Average Annual Change in Groundwater Storage**

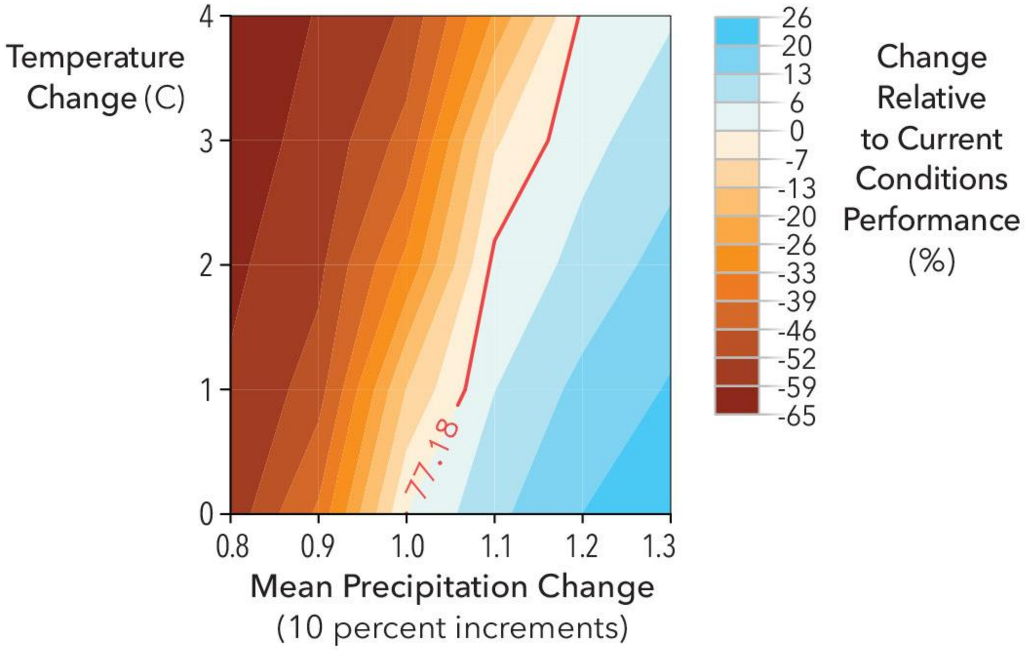


4.3.4 Ecosystem Sector

4.3.4.1 Depth to Groundwater Below GDEs

Risks to GDEs from climate change are similar to the results for average annual change in groundwater storage. Depth to groundwater is less frequently within the 30 feet under the same future conditions that result in increases in annual groundwater overdraft, as shown in Figure 4-8.

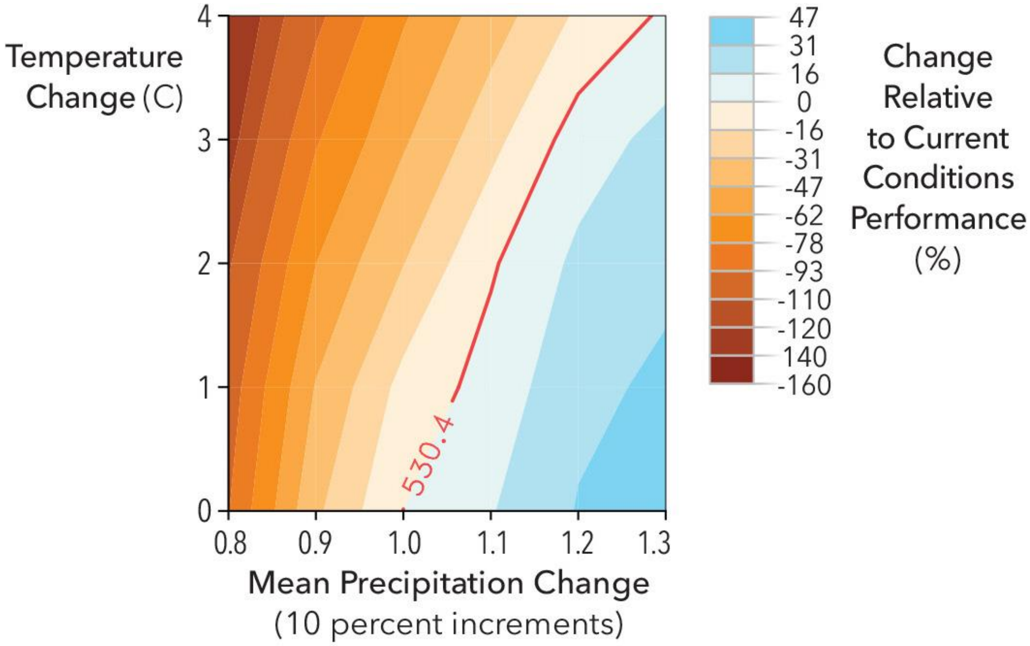
Figure 4-8 Response Surface for Proportion of Months when Depth to Groundwater below GDEs is less than 30 feet



4.3.4.2 Instream Salmonid Spawning Habitat

Spawning habitat for salmonids in the Merced River downstream of CHDD is less than under current conditions in most potential climate change scenarios. Spawning habitat increases in scenarios with increased precipitation and moderate warming. As warming increases by 2 to 3 °C, a larger increase in precipitation is necessary to maintain current condition levels of spawning habitat, as shown in Figure 4-9. Reductions in spawning habitat are generally less than 10 percent, except for more severe reductions in precipitation and some level of warming. Modeled water temperature data and other information like field surveys to determine the habitat quality of these areas or potential impacts to predatory species are beyond the scope of a reconnaissance study. The inclusion of additional information would be expected to show greater vulnerability of salmonids to climate change.

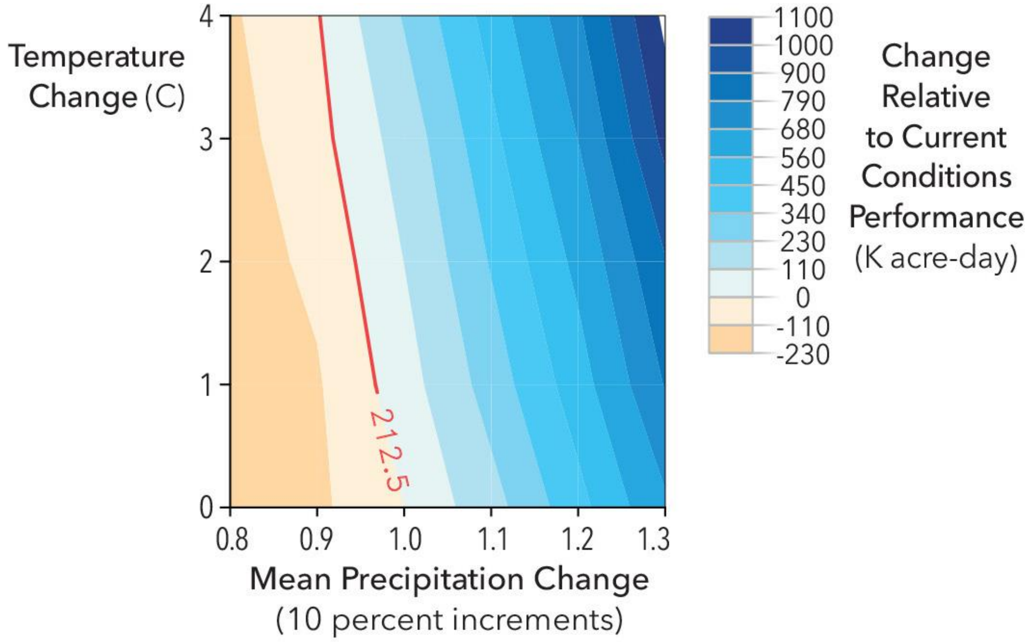
Figure 4-9 Response Surface for In-stream Salmonid Spawning Habitat



4.3.4.3 Potential Off-Channel Juvenile Salmonid Rearing Habitat

Off-channel rearing habitat for juvenile salmonids during qualified flow events is significantly more sensitive to potential climate change compared to spawning habitat, as shown in Figure 4-10. It is one of the few metrics expected to improve at both planning horizons, and many scenarios show a significant percent increase above current conditions. The off-channel rearing habitat increases when more runoff occurs during the winter and creates higher flows. Rearing habitat decreases in all scenarios with less precipitation, and the reductions can be a significant percentage of current conditions habitat for scenarios with less warming. As noted previously, off-channel reaches on the Merced River have limited suitability for salmonid rearing given the lack of structure, cover, and vegetation that are important for rearing success. For this reason, increased accessibility to off-channel reaches cannot be directly equated with increase in salmonid habitat and is considered to be potential habitat.

Figure 4-10 **Response Surface for Potential Off-channel Juvenile Salmonid Rearing Habitat during Qualified Events**



Chapter 5. Drivers of Multi-Sector Risks Under Climate Change

The expected performance, risk-based performance, and climate sensitivity results have all demonstrated that each sector shows some level of vulnerability because of climate change conditions. This section more closely reviews flood, water supply, and ecosystem results under specific climate change conditions to demonstrate the causes and mechanisms of system performance risk complicated by climate change for each sector.

5.1 Drivers of Flood Risk Under Climate Change

The primary drivers of flood risk from climate change are potential increases in precipitation and increases in temperature. Both factors increase the peak flow and the five-day cumulative volume of inflow from the largest storm event analyzed. Figure 5-1 illustrates the effect of increased precipitation on the five-day cumulative volume; Figure 5-2 illustrates the effect of increased temperature on this same metric.

For climate conditions with increased precipitation, the combination of these two factors results in five-day cumulative inflows that exceed the capacity of the existing system and operations to manage Merced River flows below 7,300 cfs, a threshold beyond which significant flood damages are expected to occur. Using this flow threshold together with 375 taf of flood control space in Lake McClure allows the reservoir to manage approximately 450 taf of inflow over a five-day period. When inflow exceeds this volume, releases will exceed the 7,300 cfs flow threshold. The example operation shown in Figure 5-3 illustrates how climate change conditions which create inflow volumes just exceeding the 450 taf flood control capacity results in a maximum release of approximately 35,000 cfs.

Figure 5-1 **Increase in Cumulative Five-Day Inflow to Lake McClure with Increased Precipitation**

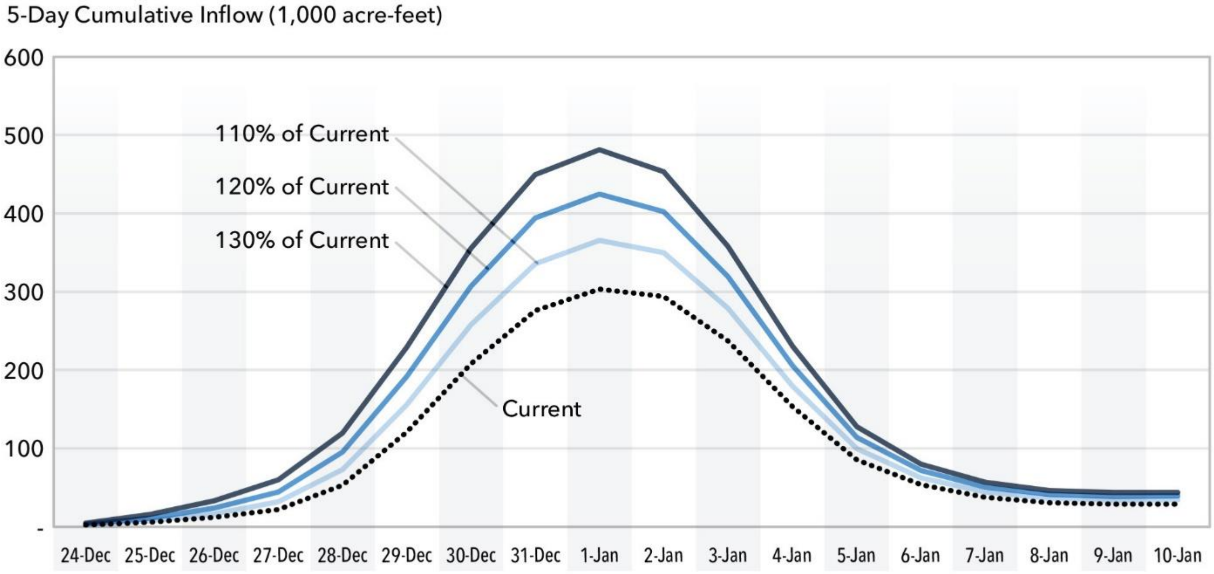


Figure 5-2 **Increase in Cumulative Five-Day Inflow to Lake McClure with Increase in Temperature**

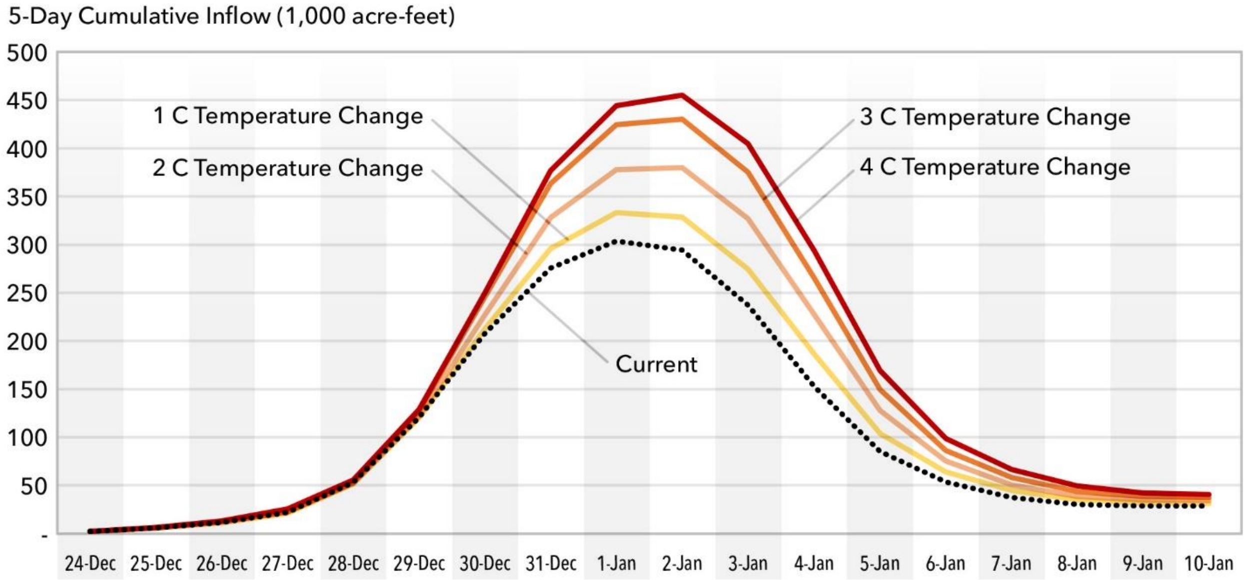
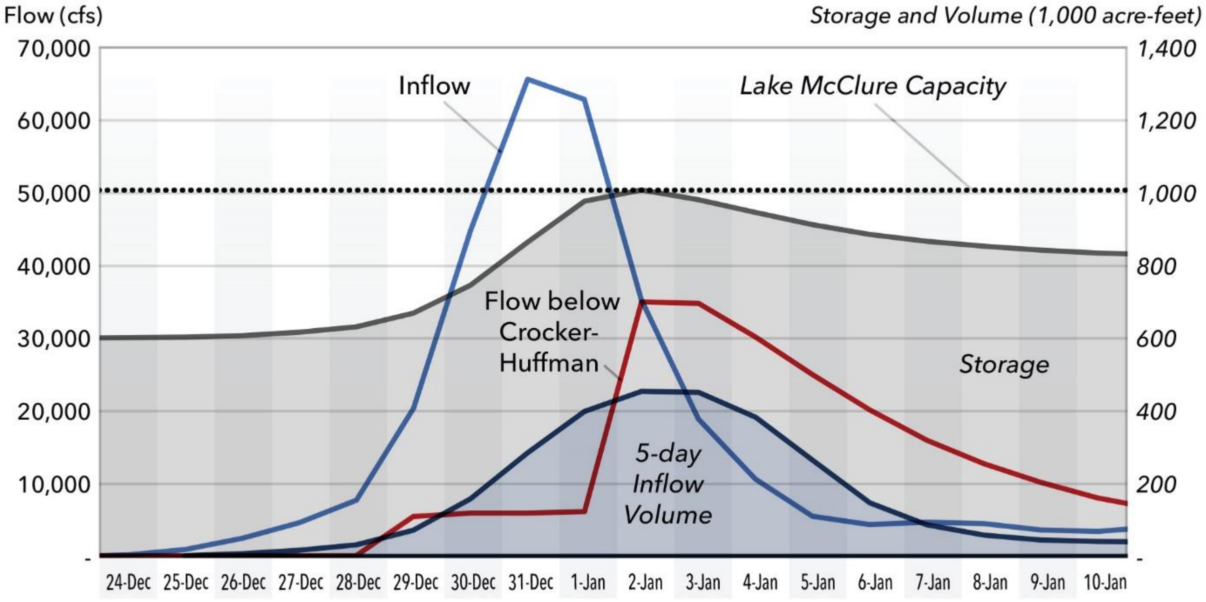


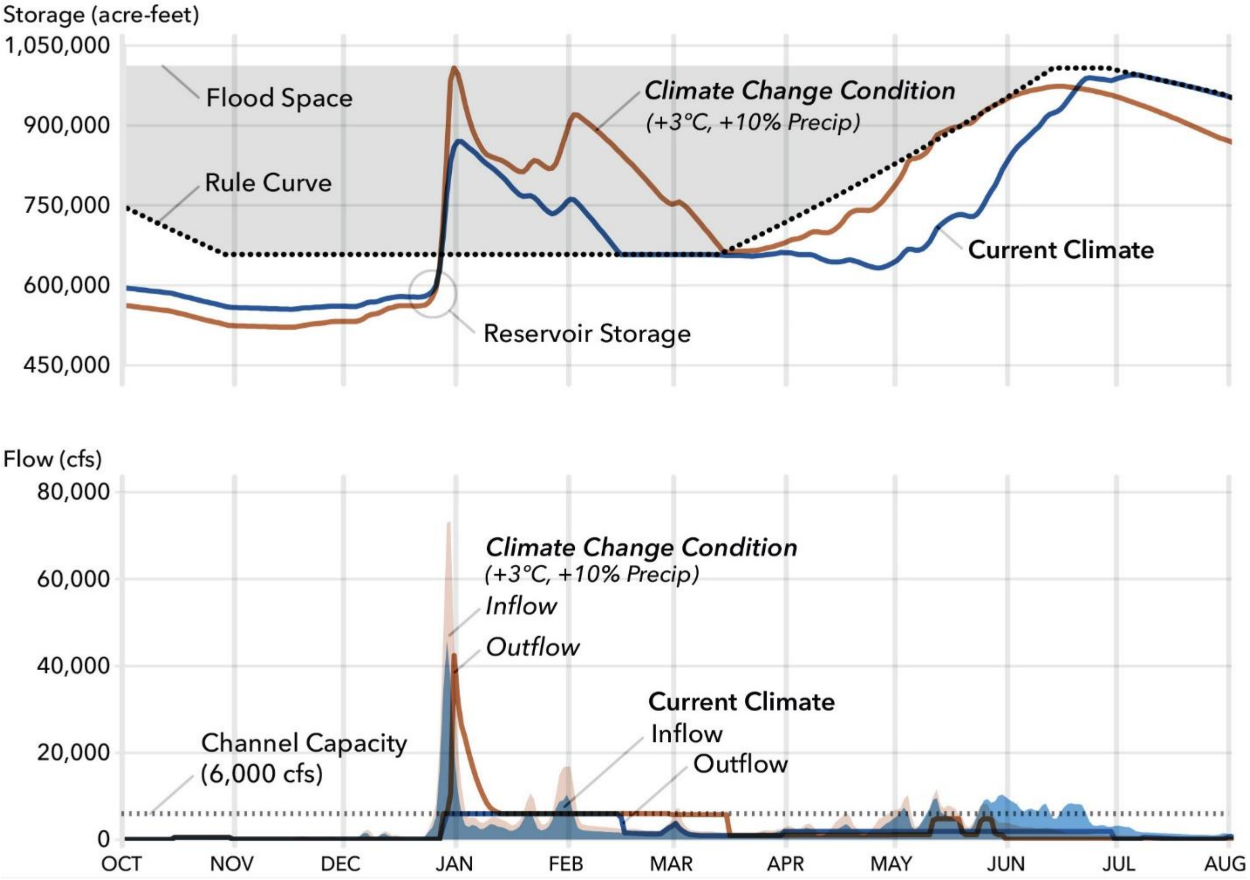
Figure 5-3 Example Flood Risk for Climate Condition with 2 °C Temperature Increase and +10 Percent Precipitation



An increase in upper watershed runoff with future climate conditions produces higher inflow peaks. The higher inflow volume during flood events pushes reservoir storage into a flood space quicker when compared to current climate conditions because of the lack of time to evacuate the flood water from the reservoir to accommodate runoff inflow. As a result, storage reaches the top of flood pool and forces the reservoir into emergency operations mode. While in emergency operations mode, the reservoir release exceeds the channel capacity in the Merced River and that produces flood conditions downstream of the reservoir. In some cases, the releases are seven times higher than channel capacity as shown in Figure 5-4.

In addition to higher peaks, the duration of the storm events increases as well. The total number of days Merced River at CHDD is above 7,300 cfs – the significant flooding threshold – during the flood control season increases from 0 days with current climate to 18 days and 80 days for the 2040 and 2070 planning horizons, respectively. It takes longer to evacuate larger inflow volumes coming with the more extreme storm events. The reservoir releases are held at downstream channel capacity for longer periods putting more stress on the levees.

Figure 5-4 **Comparison of Simulated Event under Current Climate Conditions and One of the Future Climate Conditions (+3 °C, +10% Precipitation)**

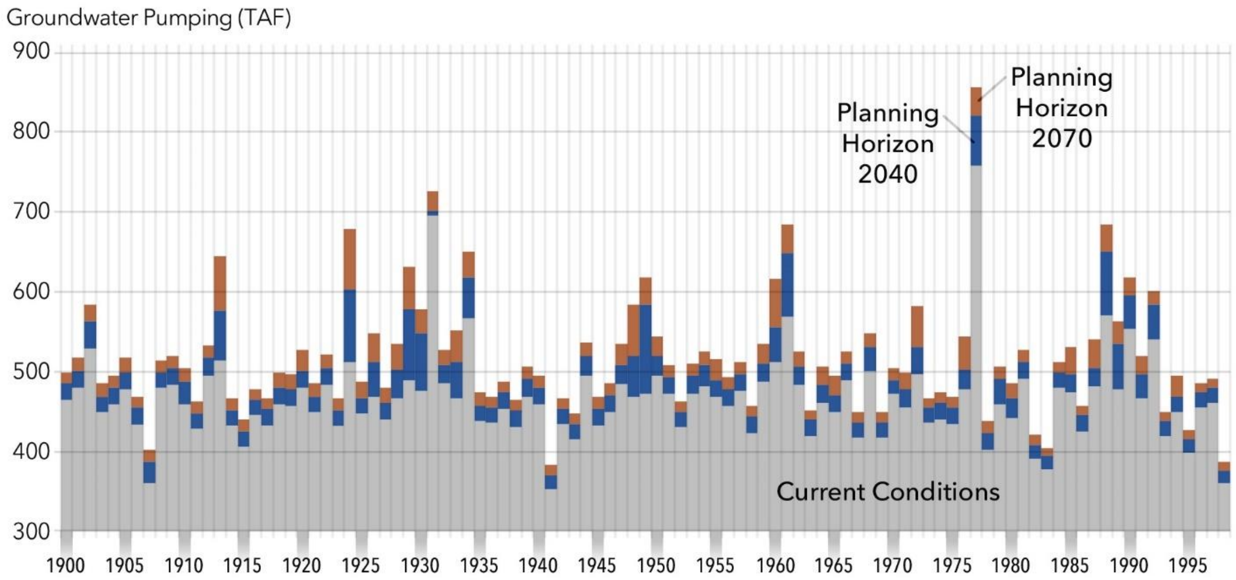


5.2 Drivers of Water Supply Risk Under Climate Change

The risks to water supply in the Merced watershed caused by climate change involve multiple factors in the watershed conditions, reservoir operations, and groundwater response. As stated in the assumptions for the baseline condition, land use remains constant under all climate change conditions. There are no demand management actions, and any demand for applied water is fully met through a combination of surface water delivery and groundwater pumping. So, although the simulated water supply is sufficient to meet all watershed demands under all climate conditions, changes in runoff, surface water supply, and applied water demand combine to have a substantial influence on groundwater conditions.

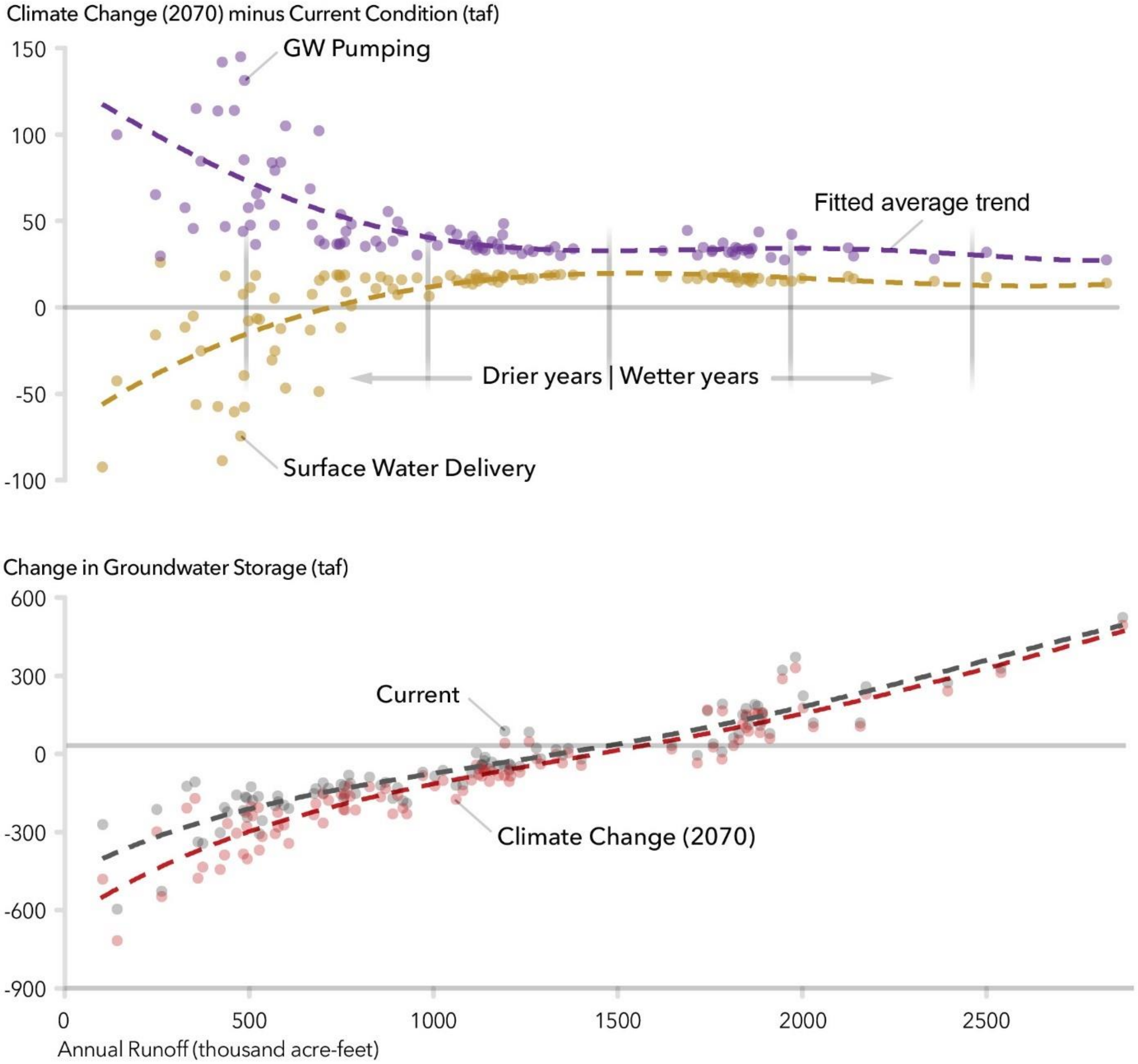
As shown in the response surfaces, average annual demand for applied water increases (or decreases) by approximately 10 taf for every 10 percent decrease (or increase) in precipitation and increases by approximately 20 taf for every 1 °C increase in temperature. Average annual surface water diversions increase slightly with increasing precipitation but decline substantially with decreases in precipitation. The combined effect is a corresponding increase or decrease in groundwater pumping to meet the change in applied water demand and surface water deliveries. Figure 5-5 displays the annual basinwide groundwater pumping, plus the additional pumping in 2040 and 2070 planning horizon conditions. Groundwater pumping increases by approximately 6 percent in the 2040 planning horizon and 11 percent in the 2070 planning horizon compared to the baseline (Table 4-1). And, over the period of record, the increased (or decreased) withdrawal from the aquifer leads to a long-term change in groundwater storage, tempered by any other groundwater flow components such as inter-basin flows and groundwater-surface water interactions.

Figure 5-5 **Baseline Merced Subbasin Annual Pumping for Current Conditions, Planning Horizon 2040, and Planning horizon 2070**



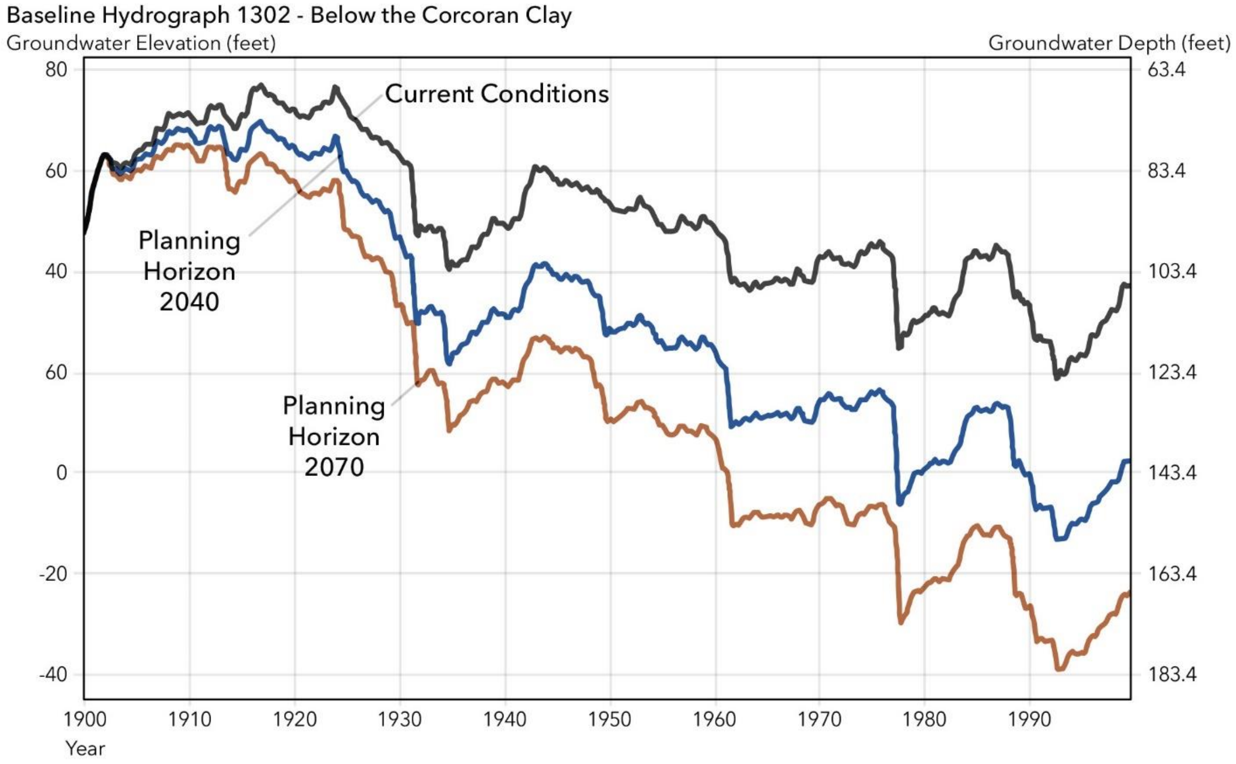
Using expected system performance under climate change for the 2070 planning horizon, Figure 5-6 shows the combined effect of changes in surface water delivery and groundwater pumping on the change in groundwater storage across a range of hydrologic conditions—indexed as annual runoff—occurring in the watershed over the 100-year period of record. In average to wetter years, both surface water deliveries and groundwater pumping increase by a roughly constant amount (approximately 20 to 25 taf from surface water deliveries and 35 to 40 taf from groundwater pumping) to meet the increased applied water demand because of higher temperature and resulting evapotranspiration. The greater increase in groundwater pumping, compared to surface water deliveries in average to wetter years, is because a significant portion of irrigation demand within the Merced groundwater subbasin is outside the MID’s service area and users have access only to groundwater supply. In drier years, surface water deliveries are more severely affected by the seasonal change in runoff (from April through September to October through March) and lower carryover storage from prior years. The lack of surface supply is met with a corresponding increase in groundwater pumping, which is reflected in the greater decline of groundwater storage during dry years.

Figure 5-6 **Expected Change in Surface Water Delivery, Groundwater Pumping, and Groundwater Storage Conditions at the 2070 Planning Horizon as a Function of Annual Surface Water Availability**



The averaged basinwide groundwater levels decrease with the decreasing groundwater storage under forecasted climate conditions. Groundwater levels drop to lower levels than current conditions under planning horizon 2040 climate conditions and to even lower levels under planning horizon 2070 climate conditions throughout the Merced subbasin. Although the expected value of long-term average annual change in groundwater levels is seemingly small (approximately 1 foot per year), groundwater decline in dry years is much more significant and total decline over many years represents a significant risk. The difference in groundwater levels is greatest in areas with more intense pumping, including groundwater levels below the Corcoran clay layer (see Figure 5-7) and directly east of the Corcoran clay extent.

Figure 5-7 Current Condition, 2040 Planning Horizon, and 2070 Planning Horizon Groundwater Elevations for Hydrograph 1302 (below the Corcoran Clay Layer)



5.3 Drivers of Ecosystem Risk Under Climate Change

GDE habitat availability closely tracks the groundwater conditions. As a result, GDEs likely will experience a decrease in groundwater availability under climate change, which in turn likely will affect GDE sustainability. As indicated in Table 5-1, depth to groundwater along the San Joaquin River and the lower Merced River is less than 30 feet under current conditions approximately 75 percent of the time. This may be reduced to approximately 50 percent and 30 percent of the time at the 2040 and 2070 planning horizons, respectively.

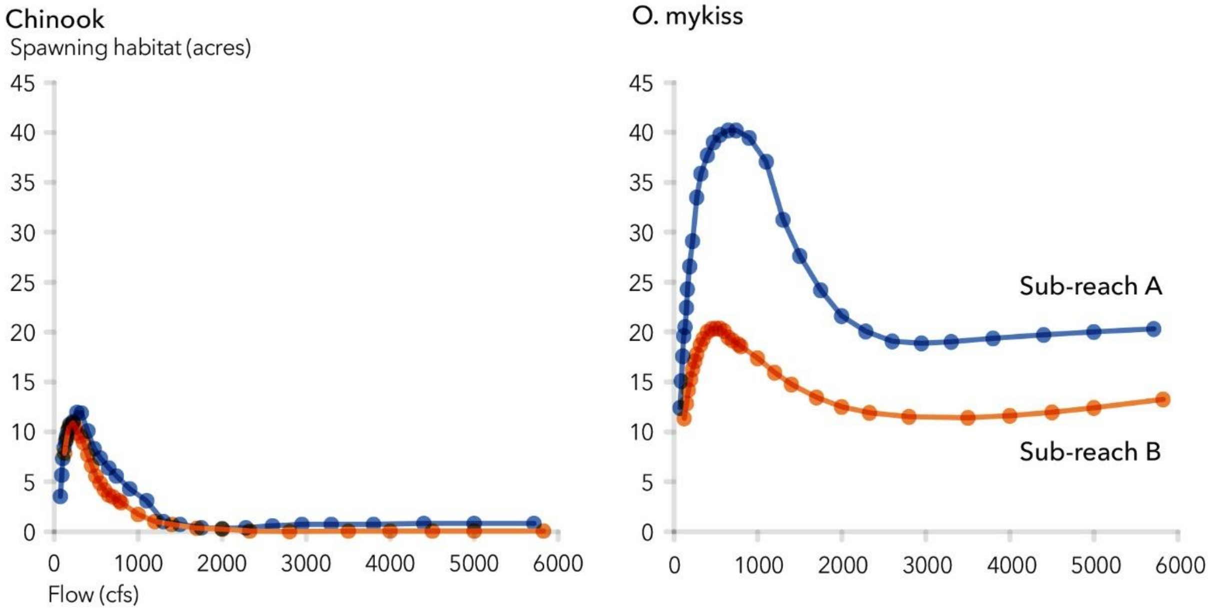
Table 5-1 **Percentage of Months with Groundwater Depth less than 30 Feet for the Baseline Watershed Condition at Current Climate and the 2040 and 2070 Planning Horizons**

Reach	Current	2040	2070	Change (2040)	Change (2070)
Merced 1	9%	4%	2%	-5%	-7%
Merced 2	93%	53%	34%	-40%	-59%
San Joaquin 1	84%	39%	30%	-45%	-54%
San Joaquin 2	100%	55%	34%	-45%	-66%
San Joaquin 3	100%	93%	58%	-7%	-42%
Overall	77%	49%	31%	-28%	-46%

Note: Data compiled by Environmental Science Associates in 2022.

Overall, in-stream habitat quantity for spawning salmonids is predicted to decrease between current conditions and climate change conditions (Table 4-1). The Merced River is a highly channelized river system and increased flow results in deeper and higher velocity flows, contrary to the shallower depths and low to moderate velocities preferred for spawning. For the two locations for which WUA curves were available, the preferred spawning flow is approximately 200 to 800 cfs (Figure 5-8).

Figure 5-8 **Weighted Usable Area Curves for the Merced River**



Source: Merced Irrigation District 2013

Table 5-2 shows the percent of time Merced River flow is within the preferred flow range at CHDD which is located downstream of Lake McClure and below all major diversions. Flows under the current climate condition are outside the preferred range most of the time for all months. With climate change, the greatest reduction in frequency of preferred conditions occurs in September under both the 2040 and 2070 planning horizons.

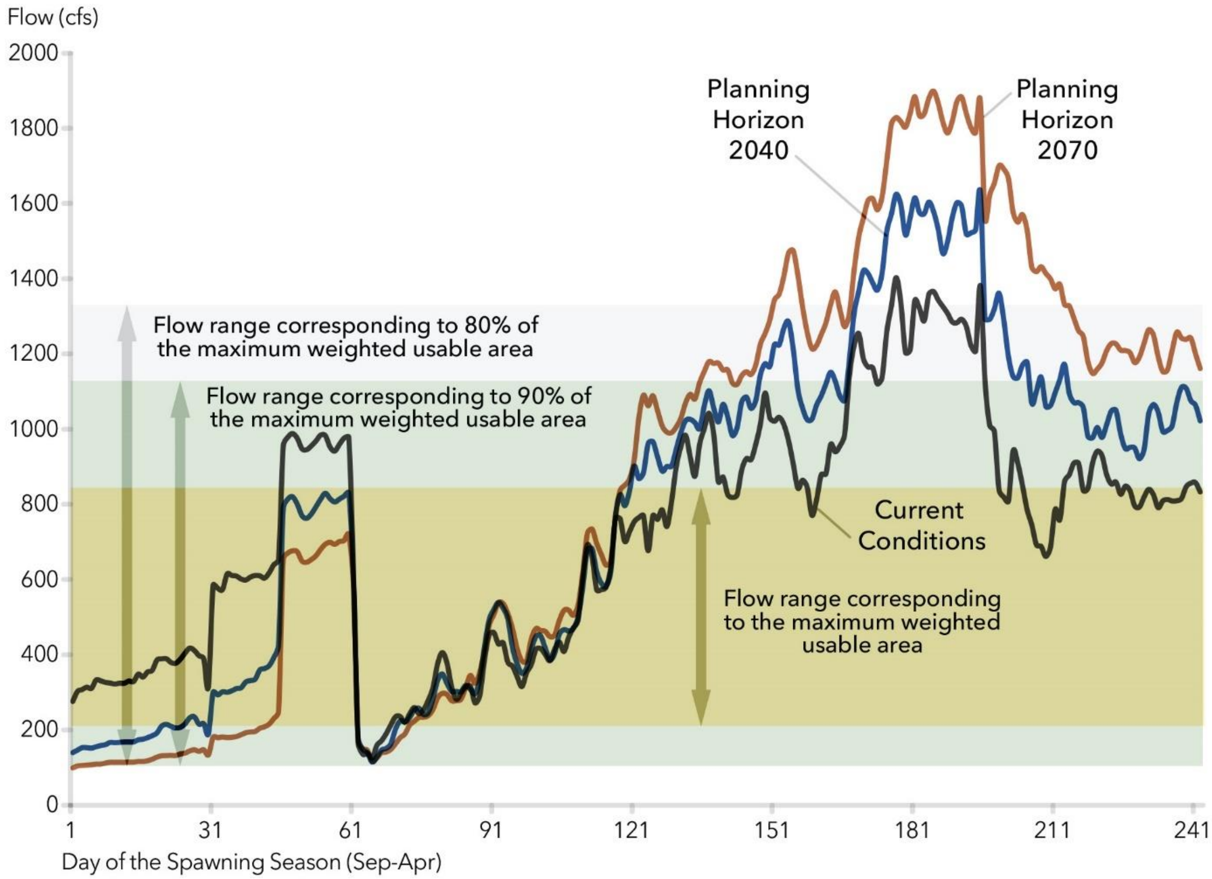
Table 5-2 **Percent of Days Merced River Flow at CHDD is within the Preferred Flow Range for Salmonid Spawning (September through April)**

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Current	22%	0%	1%	5%	4%	8%	11%	7%
PH 2040	2%	3%	2%	4%	4%	9%	8%	6%
PH 2070	2%	2%	2%	4%	5%	7%	7%	7%

Notes: PH 2040 = 2040 planning horizon; PH 2070 = 2070 planning horizon.

Figure 5-9 shows the average daily flow at CHDD for the three climate conditions (current, 2040 planning horizon, and 2070 planning horizon) overlaid by the preferred spawning flow range. The shift in runoff timing, along with the increased peak irrigation season demands under future climate conditions, are expected to reduce flows during the fall months and increase flow during the late winter and early spring months. Reduced runoff during the late spring months limits the ability to fill reservoir storage as reservoir operations transition out of flood control mode. This results in less spill and lower downstream flow during the fall months as the reservoir operations transition back to flood control mode. The opposite happens during the early spring months when high inflow occurs and flood space requirements force the water to be spilled. Reservoirs spill more frequently, with increased downstream flow under future climate conditions. The net effect of the reduced early fall and increased winter and spring flows is expected to reduce the frequency of time that flows are in the preferred flow range for salmonid spawning.

Figure 5-9 **Preferred Flow Range for Spawning and Average Daily Merced River Flow at CHDD**



Potential off-channel habitat inundation for salmonids is predicted to increase for both 2040 and 2070 planning horizons (Table 4-1). The primary driver behind the potential off-channel habitat is the frequency of the Merced

River flow at CHDD above the 1,800 cfs over-bank inundation threshold between December and May. Climate change is expected to shift the runoff timing to earlier in the spring. This results in increased magnitude and frequency of off-channel inundation flows (Table 5-3). Even though the off-channel inundation increases under future climate conditions, the current off-channel habitat on the Merced River has limited suitability for salmonid rearing because of the lack of structure, cover, and vegetation, all of which are important for rearing success. For this study, the inundated areas are considered potential habitat, although field surveys to determine the habitat quality of these areas are beyond the scope of a reconnaissance study.

Table 5-3 Total Number of Days Merced River Flow at Crocker Huffman exceeds the 1,800 cfs Threshold during the Rearing Season (December through May)

	Current	PH 2040	PH 2070
December	225	269	278
January	437	586	629
February	486	689	832
March	468	746	999
April	497	678	803
May	557	678	629

Notes: PH 2040 = 2040 planning horizon; PH 2070 = 2070 planning horizon.

Chapter 6. Conclusions

This TIR has presented a multi-sector understanding of climate change vulnerability for the Merced watershed. In recognition of the significant uncertainties in how climate will change over the 21st century, the study has adopted a risk-based, decision-scaling approach to quantify climate change exposure, sensitivity, and vulnerability. The range of temperature and precipitation changes explored show that climate change is altering the fundamental hydrology of the watershed system, driving up extremes that result in increased flood, water supply, and ecosystem risks. The expected changes in 14 indicators of system performance across three sectors show that each sector is vulnerable and sector vulnerabilities are often connected. Provided the full range of uncertainty in future climate change—and the relative likelihood of those changes informed by global climate models—it is more likely than not that future performance will worsen by 2040. In addition, the likelihood of extreme changes in degraded future performance is significantly higher by 2070.

The primary drivers of flood risk from climate change are potential increases in precipitation and increases in temperature. The risks to water supply from climate change involve multiple factors in the watershed conditions, reservoir operations, and groundwater response. Increased groundwater extraction to meet rising agricultural demands and a lack of carryover surface storage under warmer and drier conditions leads to an increase in the rate of long-term, basin-wide groundwater overdraft. For ecosystems, GDE habitat availability closely tracks the groundwater conditions and are likely to experience a decrease in groundwater availability under climate change, likely affecting GDE sustainability. Finally, both in-stream and potential off-stream salmonid habitat are highly sensitive to shifts in the magnitude and timing of Merced River flow. There is a reduction of in-stream salmonid spawning habitat under future climate conditions, while the potential off-stream salmonid habitat generally benefits from increased spring runoff seen under warming conditions.

The study shows that without strategies and actions to minimize the effects of climate change on the system, the baseline condition of the Merced watershed is likely to deteriorate from the current expected performance, but the expected changes in the hydrology of the Merced watershed resulting from climate change also increase the potential for Flood-MAR opportunities. TIR #4, *Adaptation Strategy Performance*, assesses the effectiveness of Flood-MAR and reservoir reoperations to reduce flood risk, increase water supply reliability, and enhance ecosystems in the Merced River watershed.

Chapter 7. References

California Department of Water Resources. 2015. *California Climate Science and Data for Water Resources Management*. California Climate Science and Data. June. pp 1–28.

California Department of Water Resources. 2019. Decision Scaling Evaluation of Climate Change Driven Hydrologic Risk to the State Water Project Final Report.

Intergovernmental Panel on Climate Change. 2021. "Summary for Policymakers." In: Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou, editors. *The Physical Science Basis*. (Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.) Cambridge, United Kingdom, and New York, NY, U.S: Cambridge University Press. Pages 3−32.

Killam D, Bui A, LaDochy S, Ramirez P, Willis J, Patzert WC. 2014. "California Getting Wetter to the North, Drier to the South: Natural Variability or Climate Change?" Climate. (Volume 2, Issue 3.) Pages 168–180. [Journal.]

LaDochy S, Ramirez P, Killam D, Bui A, Patzert WC, Willis J. 2011. California temperature and precipitation trends: climate variability or global warming. 91st Meeting of the American Meteorology Society. Seattle, WA, Jan. 22-27, 2011.

Merced Irrigation District. 2013*. Technical Memorandum 3-5: Instream Flow Below Crocker-Huffman. Federal Energy Regulatory Commission Project 2179. Merced, CA*.

United States Army Corps of Engineers. 1981. *New Exchequer Dam and Reservoir Water Control Manual.* Sacramento, CA.

U.S. Global Change Research Program. 2018. “Overview.” In: Reidmiller, DR, Avery CW, Easterling DR, Kunkel KE, Lewis KLM, Maycock TK, Stewart BC, editors. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II.* Washington (DC). Pages 33–71. doi: 10.7930/NCA4.2018.CH1

Woodard & Curran. 2019. *Merced Groundwater Subbasin Ground Water Sustainability Plan*. Sacramento (CA). Viewed online at: http://mercedsgma.org/resources#documents. Accessed: Apr 28, 2023.

Appendix A

Complete List of Metrics and Indicators included in the Merced Study

Sector	Metric	Indicator	Units	Model
Watershed Conditions	Upper Watershed Runoff	Average annual runoff into Merced watershed (October–September)	taf/year	SAC-SMA
		Average seasonal runoff into Merced watershed during Flood-MAR months (November – March)	taf/year	
		Average seasonal runoff into Merced watershed outside Flood-MAR months (April – October)	taf/year	
	Demand	Average annual applied agricultural demand in the Merced watershed	taf/year	FM2SIM
Flood Risk	Lake McClure	Max Encroachment at Lake McClure (November 1 – March 15)	percent	HEC-ResSim
		Max Encroachment at Lake McClure (November 1 – March 15)	taf	
	Merced River	Merced River 100-year maximum simulated flow (November 1 – June 30)	cfs	
		Total number of years Merced River at Crocker Huffman is above 7300 cfs (November 1 – June 30)	years	
		Total number of days Merced River at Crocker Huffman is above 7300 cfs (November 1 – June 30)	days	
	Local Creeks	Bear Creek 100-year maximum simulated outflow	cfs	HEC-HMS
		Mariposa Creek 100-year maximum simulated outflow	cfs	
		Owens Creek 100-year maximum simulated outflow	cfs	

Sector	Metric	Indicator	Units	Model
	Bear Creek near McKee Road	Bear Creek near McKee Road 100-year maximum simulated flow	cfs	HEC-HMS
		Total number of days Bear Creek near McKee Road is above 3,000 cfs	Days	
Water Supply/ Groundwater	Groundwater Storage	Basinwide average annual change in groundwater storage	taf/year	FM2SIM
	Groundwater Levels	Basinwide average annual change in groundwater levels in the aquifer east of the Corcoran Clay layer	feet/year	
		Basinwide average annual change in groundwater levels below the Corcoran Clay layer	feet/year	
		Basinwide average annual change in groundwater levels above the Corcoran Clay layer	feet/year	
		Average annual change in groundwater levels in subsidence prone region	feet/year	
		Average annual change in groundwater levels in aquifer underlying DACs east of Corcoran Clay layer	feet/year	
		Average annual change in groundwater level above the Corcoran Clay layer underlying DACs	feet/year	
	Groundwater Pumping	Average annual total groundwater pumping to meet agricultural uses in the Merced watershed	taf/year	

Sector	Metric	Indicator	Units	Model
Water Supply/ Surface Water	Surface Water Deliveries	Average annual total surface water deliveries to agricultural users in the Merced watershed	taf/year	HEC-ResSim
		Number of years MID's surface water availability at or below 80 percent	years	
		Average March 1 MID surface water availability	percent	
	Lake McClure	Average annual Lake McClure storage at the beginning of the irrigation season (March 1)	taf/year	
		Average annual Lake McClure storage at the end of the snowmelt runoff season (June 30)	taf/year	
		Average annual Lake McClure storage at the end of the irrigation season (October 31)	taf/year	
		Total number of days Lake McClure storage is below the operational deadpool level	days	
Ecosystem	GDE Habitat	Proportion of months with depth to groundwater less than 30 feet	percent	FM2SIM
	Salmonid Habitat	Merced River in-stream salmonid spawning habitat (September – April)	thousand acre-days	HEC-ResSim and PHABSIM --> Flow-WUA relationships

Sector	Metric	Indicator	Units	Model
		Potential Merced River off-channel juvenile rearing habitat during qualified events (December – May)	thousand acre-days	HEC-ResSim and HEC-RAS --> Flow-Inundation relationship
Ecosystem	Salmonid Habitat	Total number of qualified Merced River potential off-channel juvenile rearing habitat event years (December – May)	years	HEC-ResSim and HEC-RAS --> Flow-Inundation relationship
		Total number of qualified Merced River potential off-channel juvenile rearing habitat events (December – May)	events	
		Average duration of qualified Merced River potential off-channel juvenile rearing habitat events (December – May)	days/event	
		Proportion of months above the AFRP flow threshold (December – May)	percent	FM2SIM
	Shorebird Habitat	Acres of shorebird habitat (March)	thousand acre-days	HEC-ResSim
	Frequency of Managed Eco-Actions	Total number of shorebird habitat events (March)	events	
		Total number of managed off-channel inundation events (April)	events	
		Total number of outmigration pulse release events (April – May)	events	

Notes: AFRP = Anadromous Fish Restoration Plan; cfs = cubic feet per second; DAC = disadvantaged community;

FM2SIM = Flood-MAR Groundwater-Surface Water Simulation Model; GDE = groundwater-dependent ecosystem; HEC-HMS = Hydrologic Engineering Center Hydrologic Modeling System; HEC-RAS = Hydrologic Engineering Center River Analysis System; HEC-ResSim = Hydrologic Engineering Center Reservoir System Simulation; MID = Merced Irrigation District; PHABSIM = Physical Habitat Simulation Model; SAC-SMA = Sacramento Soil Moisture Accounting; taf = thousand acre-feet; WUA = weighted usable area.


DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA