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Natural Resources Agency
Department of Water Resources

From Climate Traces to Climate Insights: Future Scenarios Analysis for the California Central Valley

California Water Plan Update 2023
Supporting Document

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Acronyms and Abbreviations

ANN	artificial neural network
CalSim	California Water Resources Simulation Model
CDF	cumulative distribution function
cfs	cubic feet per second
COA	Coordinated Operations Agreement
CMIP5	Coupled Model Intercomparison Project 5
CVP	Central Valley Project
C2VSIM-FG	California Central Valley Groundwater-Surface Water Simulation Model–Fine Grid
DoF	California Department of Finance
DWR	California Department of Water Resources
Flood-MAR	flood-managed aquifer recharge
GCM	global climate model
GSP	groundwater sustainability plan
HR	hydrologic region
IFR	instream flow requirement
NLCD	National Land Cover Database
OMR	Old and Middle River
PA	planning area
RCP	Representative Concentration Pathway
Reclamation	U.S. Bureau of Reclamation
RPA	reasonable and prudent alternative
SacWAM	Sacramento Water Allocation Model
SEI	Stockholm Environment Institute
SGMA	Sustainable Groundwater Management Act
SWP	State Water Project
taf	thousand acre-feet

Update 2018	California Water Plan Update 2018
Update 2023	California Water Plan Update 2023
Update 2028	California Water Plan Update 2028
USFWS	U.S. Fish and Wildlife Services
Water Plan	California Water Plan
WEAP	Water Evaluation And Planning
WEAP-CVPA	Water Evaluation And Planning – Central Valley Planning Area
WY	Water Year
°C	degrees Celsius

Executive Summary

ES.1 Introduction

California Water Code Section 10004.6 requires the California Department of Water Resources (DWR) to quantify current and future water conditions in the state. This information is published in the *California Water Plan* (Water Plan), which is updated every five years. Water managers and planners constantly face the challenges of planning for an uncertain future where the only constant is change. To address the potential future changes and mitigate the probable risks, water managers must consider and quantify uncertainties and their impacts on water system vulnerability. Although it is not possible to know for certain how population growth, land use decisions, climate, and other factors change over time, water planners must consider these system stressors in long-term planning to evaluate future risks and uncertainty. The Water Plan evaluates many alternative future scenarios as an integral part of its analytical approach to quantify system vulnerability under a range of population and urban growth scenarios, land use, and climate uncertainties.

The climate change vulnerability assessments for prior updates of the Water Plan used a “top-down” approach based on a series of plausible future climate scenarios starting with Global Climate Models (GCM) (the top), which are downscaled (the bottom), to provide information about possible future water supply and demand conditions, including unmet demands (supply shortfalls). But, the limited number of GCM projections used in this approach may not capture the range or frequency of climate change conditions that California could experience in the future.

To provide a more robust assessment of future vulnerabilities to climate change, DWR applied the risk-based “bottom-up” approach called decision-scaling for Water Plan Update 2023 (Update 2023) to quantify potential vulnerability at the regional and statewide scales and identify areas for more in-depth analysis. Decision-scaling provides a “stress test” of a water system in response to a wide range of future climate variations. The resulting responses provide new insights into system performance and vulnerabilities to extreme climatic conditions. This information then could be used to make better investment decisions on climate adaptation strategy projects at regional or local scales.

To prepare the climate change vulnerability assessment for Update 2023, DWR conducted a pilot study in the Merced River watershed to test if and how the Water Evaluation And Planning Central Valley Planning Area (WEAP-CVPA) model could be applied using the decision-scaling approach. The pilot study results closely followed long-term trends and average system responses to climate change impacts from the more detailed Merced River Flood-MAR Watershed Study. Based on the findings from the pilot study, DWR applied the decision-scaling approach to the entire WEAP-CVPA model of California's Central Valley to study systemwide performance and vulnerabilities in support of Update 2023.

ES.2 Model Modifications for Update 2023

For the Update 2023 future scenarios analysis, the decision-scaling approach was applied by stress testing the system across changes in temperature from 0 to +5 degrees Celsius in increments of 1 degree Celsius and changes in precipitation from -30 percent to +30 percent in increments of 10 percent. Subsequently, GCM projections in the Coupled Model Intercomparison Project 5 (CMIP5) with Representative Concentration Pathways 4.5 and 8.5 were used to identify this range of temperature and precipitation changes and the relative likelihood of these changes.

Many of the features of the WEAP-CVPA model were modified for Update 2023 to improve the water system representation in the model with updated information. These include, along with climate change methodology, Delta biological opinions, Coordinated Operations Agreement, sea-level-rise simulation, expansion of urban lands into native vegetation, and flexible time horizon simulation. Many of the underlying datasets of the WEAP-CVPA model were modified for Update 2023 to improve the representation of the observed trends and updated information since Water Plan Update 2018 (California Department of Water Resources 2018). These include modifications to land use, population, water use, and instream flow requirements (IFRs) data.

ES.3 Vulnerability Metrics Used in Update 2023 Analysis

Future scenarios analysis for Update 2023 includes a suite of metrics designed to identify future water vulnerabilities in specific water sectors. The metrics are grouped into six categories to illustrate the vulnerabilities of the water sectors: surface water; groundwater; agricultural water supply; urban water supply; environmental water; and flood risk. Generally, these metrics are developed by comparing the average 2070 conditions to the average 2020 conditions, and the vulnerability is identified as the increase in adverse conditions in 2070 relative to 2020. The metrics include:

- **Surface Water**. The reservoir storage level metric at the end of the irrigation season is used as the surface water metric. End-of-September reservoir storage levels are the most susceptible to climate change impacts.
- **Groundwater**. The groundwater metric measures the percentage of the supply provided by groundwater compared to total water supply. This metric is intended to identify when a region is becoming increasingly dependent on groundwater, indicating a vulnerability to overdraft conditions.
- **Urban Water Supply**. The urban water supply metric used is the percent of urban demand met.
- **Agricultural Water Supply**. The agricultural water supply metric is similar to the urban water supply metric except that it is based on the percent of agricultural demand met.
- **Environmental Water**. The environmental water metric does not look at average values; instead, it counts the percentage of time IFRs are met during the driest months (April through September) at IFR control points throughout the Central Valley.
- **Flood Risk**. Flood risk metric is based on the 90th-percentile flow (10-percent exceedance flow) during the December through March period across the entire 1,100-year period at specific flood control points throughout the Central Valley. The 90th-percentile flows were chosen to represent a significant flood event within the 50-year planning horizon. December-through-March flows were selected as those represent high flow conditions in a year.

The metrics calculated using WEAP model outputs were used to generate response surfaces for each combination of temperature and precipitation changes. Response surfaces and cumulative distribution functions (CDFs) were generated for all planning areas and hydrologic points of interest in the WEAP-CVPA model area.

ES.4 Aggregated Results at the Hydrologic Region Scale

In addition to the response surfaces and CDFs, a synthesized radar plot (spider plot) was developed. The spider plot illustrated in Figure ES-1 shows the probability of the six metrics being more vulnerable in 2070 than current conditions for the Sacramento River, San Joaquin River, and Tulare Lake hydrologic regions (HRs). The spider plot shows a greater than 65 percent likelihood that a water system, represented by the six metrics, will be more vulnerable in the future across the Central Valley.

The bar plot in Figure ES-2 illustrates each metric's most probable magnitude of vulnerabilities. It provides a range of possible vulnerabilities resulting from climatic uncertainties as informed by CMIP5 GCM projections. Each HR has unique vulnerabilities and challenges, exacerbated by future climatic conditions. Using the Sacramento River HR as an example, in approximately 74 percent of future climate projections, there is reduced carryover storage in the region's reservoirs at the end of the water year. The most likely reduced average carryover storage is approximately 7 percent (probable value), which could be as large as 26 percent (possible value) because of climatic uncertainty.

Figure ES-1 Central Valley likely to be Increasingly Vulnerable in 2070 based on Six Water Metrics

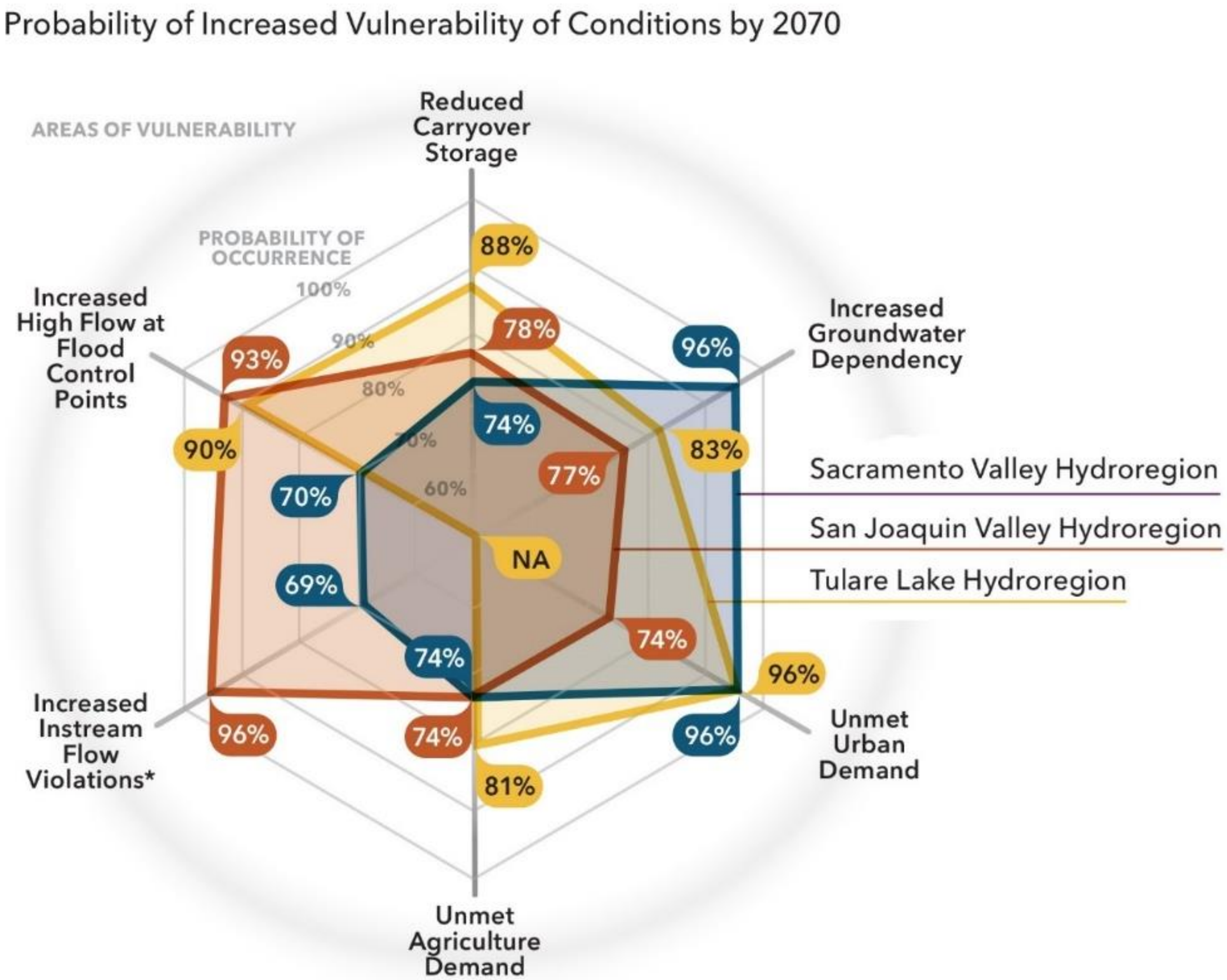
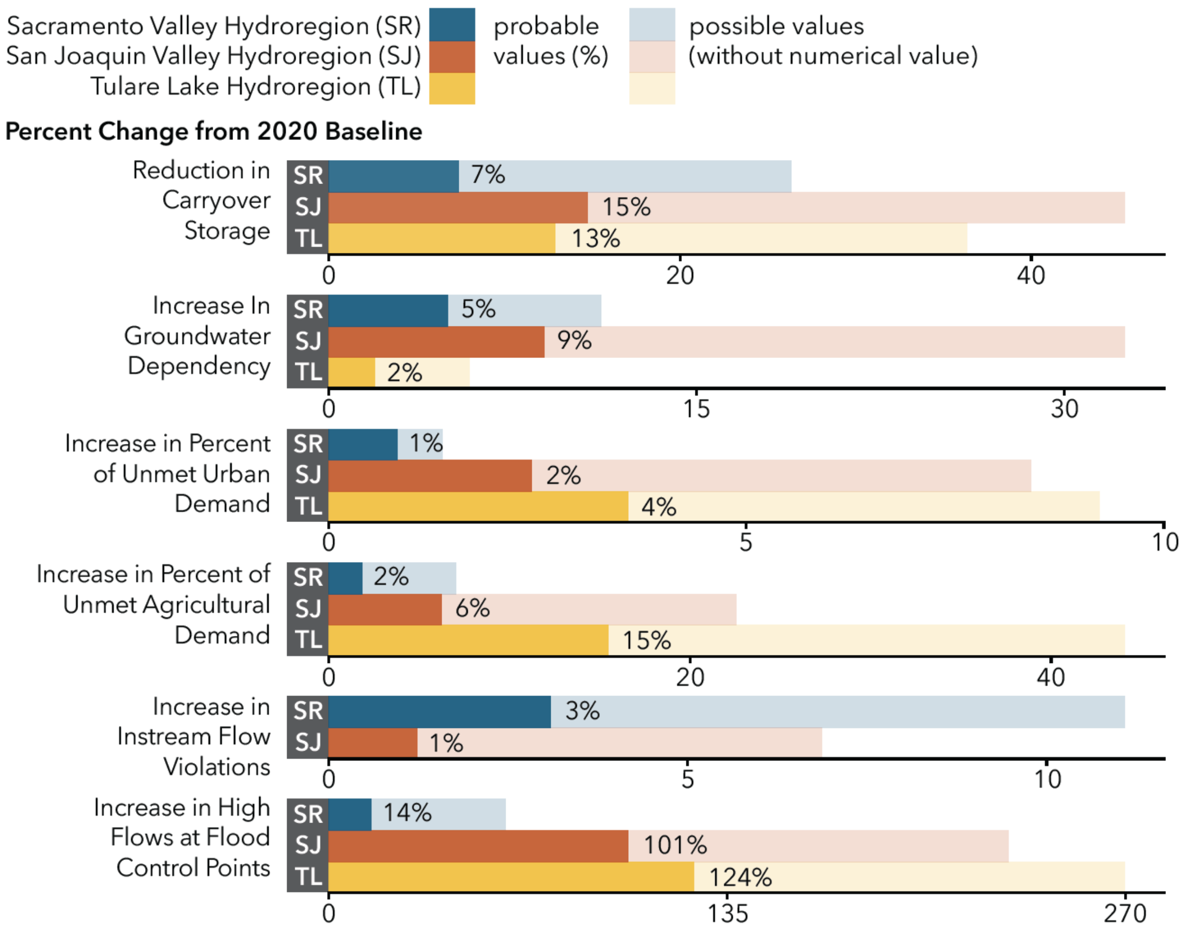


Figure ES-2 Bar Plot Shows Large Magnitude Changes for Six Water Metrics by 2070



ES.5 Findings and Future Work

The most significant finding of the future scenarios analysis for Update 2023 is that every metric representing an aspect of the water system health in the future showed a high probability (average 83 percent) of worsening conditions by 2070 compared to current conditions. The analysis reveals that without implementing adaptation actions to improve the water system performance for addressing the effects of changing climate, Californians are likely to experience more frequent water shortages based on current climatic projections.

Although the probabilities of worsening conditions are very high, some of the expected magnitude of impact appear manageable. But, considering California's already water-stressed situation, any reductions in supply can be significant.

Another important finding is that vulnerability to a changing climate is not uniform at the HR scale or within a region. Climate change will not uniformly impact regions and areas within a region. For that reason, more detailed analyses, such as the Merced River Flood-MAR Watershed Study, are required to assess areas with high predicted future vulnerabilities.

Overall, the current analysis shows increasing vulnerability for all tracked indicators related to water supply in the Central Valley. There will be moderately significant reductions in carryover storage from year to year, increasing vulnerability to droughts. Increasing groundwater dependency for the future indicates that without the implementation of Sustainable Groundwater Management Act, the existing groundwater system will be depleted even further. Unmet urban demand, on average, shows mild increases, with some areas revealing a regionally disproportionate rise in unmet urban demand because of the existing priority system and water rights structure. A more significant increase in unmet agricultural demand in the future likely would lead to a need to fallow additional land. Mild increases in instream flow violations are predicted. However, the IFR control points experiencing these violations are significant as IFRs in the model have the highest priority; so if IFRs are not met, few other demands will be met. Finally, for the flood risk metric, the San Joaquin River and Tulare Lake HRs show significant increases in high flows during the winter months, indicating a high probability of worsening flood conditions in the future. These impacts indicated by Update 2023 future scenarios analysis may be able to be mitigated by adaptive actions, including flood-managed aquifer recharge (Flood-MAR).

Transitioning into Water Plan Update 2028 (Update 2028), much work is planned to further refine the analysis conducted in Update 2023, as presented in this report. The refinements for Update 2028 will include the following:

- Update the current WEAP-CVPA model.
- Expand San Francisco Bay HR.
- Expand South Coast HR.
- Update vulnerability metrics and conduct adaptation strategy analyses.
- Develop interactive future scenarios dashboard.

Chapter 1. Introduction

1.1 California Water Code Requirements

California Water Code Section 10004.6 requires the California Department of Water Resources (DWR) to quantify current and future water conditions in the state. This information is published in the *California Water Plan* (Water Plan), which is updated every five years. The Water Plan mandates that water managers and planners prepare plans to quantify and manage potential shortfalls in the future. Water managers and planners constantly face the challenges of planning for an uncertain future where the only constant is change. To address the potential future changes and mitigate the probable risks, water managers must consider and quantify uncertainties and their impacts on water system vulnerability. Although it is not possible to know for certain how population growth, land use decisions, climate, and other factors change over time, water planners must consider these system stressors in long-term planning to evaluate future risks and uncertainty. The Water Plan evaluates many alternative future scenarios as an integral part of its analytical approach to quantify system vulnerability under a range of population and urban growth scenarios, land use, and climate uncertainties.

1.2 Chronicle of Future Scenario Analyses

Water Plan Updates 2005, 2009, 2013, and 2018 have progressively and proactively used the best available information and state-of-the-art analytical tools and techniques for assessing the impacts of climate change on California water resources and infrastructure, as well as the adaptation strategies needed and available to improve regional water resilience. For example, the analytical tool Water Evaluation And Planning (WEAP) model was used in Water Plan Updates 2005 and 2009 (California Department of Water Resources 2019) to focus on the projection and quantification of future water demand in the 10 hydrologic regions (HRs) of California through mid-century (2050). The analyses also included evaluating selected demand management strategies at the regional level. In Water Plan Update 2013 (California Department of Water Resources 2013), in addition to regional quantification of future water demands, an effort was made using the WEAP model to include the supply side of the water balance on a finer planning area (PA) scale in the three HRs of the Central Valley. This effort resulted in a Valley-wide WEAP Central Valley Planning Area (WEAP-CVPA) model that furnished a more comprehensive picture of the future water conditions, including demand, supply deliveries, and quantities of unmet demand (supply shortfalls). Water Plan Update 2018 (Update 2018) applied the same integrated water supply-demand approach used in Water Plan Update 2013 and extended the projections further into the future through the end of the century (2100) under an updated set of climate scenarios based on Representative Concentration Pathway (RCP) of greenhouse gas emissions.

The climate change vulnerability assessments for prior updates of the Water Plan used a "top-down" approach based on a series of plausible future climate scenarios downscaled starting with from global climate models (GCM) (the top), which are downscaled (the bottom), to provide information about possible future water supply and demand conditions, including unmet demands (supply shortfalls). But, the limited and discrete number of GCM scenarios used in this approach might not capture the range or frequency of climate change conditions that California may experience in the future.

To provide a more robust assessment of future vulnerabilities to climate change, DWR applied an emerging cutting-edge, risk-based, "bottom-up" approach called decision-scaling (Brown et al., 2012; California Department of Water Resources 2019) for Water Plan Update 2023 (Update 2023) to quantify potential vulnerability at the regional and statewide scales and identify areas for more in-depth analysis. Decision-scaling provides a "stress test" of a water system in response to a wide range of future climate variations. The resulting responses provide insights into system performance and vulnerabilities to extreme climatic conditions. This information then can be used to make better investment decisions on climate adaptation strategy projects at regional or local scales.

1.3 Merced River Watershed Pilot Study

To prepare the climate change vulnerability assessment for Update 2023, DWR conducted a pilot study in the Merced River watershed to test if and how the WEAP-CVPA model could be applied using the decision-scaling approach (California Department of Water Resources 2022). A small portion of the WEAP-CVPA model covering the Merced River watershed was selected for the pilot study. The study used an 1,100-year-long (Water Year [WY] 901–WY 2000) Paleo-based historical temperature and precipitation record to represent the historical range of natural variability. This data was also perturbed by shifting the temperature at 0.5 degrees Celsius (°C) increments from 0 to +4.0 °C and shifting the precipitation at 10 percent, ranging from -30 percent to +30 percent from the historical baseline. The resulting data provided 63 temperature and precipitation time series combinations representing 63 distinct climate scenarios, including the baseline historical climate. The reconstructed dataset was then used in the model to evaluate system performance in the Merced River watershed in response to extreme climates. Several modifications were made to the WEAP model to prepare it for extensive simulations used in the pilot study using the decision-scaling approach. These modifications included software revision to run long simulation periods (1,100 years) using the 1,100-year-long historical climate, keeping the urban and land use level of development at a fixed level (2020), and synchronizing the timelines to allow the model to access past historical climate data while maintaining the specified level of urban and land-use development during the simulation.

The major findings of the pilot study were that the WEAP model can be used to apply the decision-scaling approach to numerous paleo-climate scenarios. The model was able to predict risk-based system performance under a wide range of climate change conditions for system metrics such as surface water storage, groundwater contributions to urban and agricultural sectors, water demand and supply delivery capabilities to urban and agricultural sectors, and change in groundwater storage in the basin. A high-level comparison of the pilot study results was conducted with the more comprehensive Merced River Flood-MAR Watershed Study that used a complex ensemble of system models with detailed information from headwater to groundwater. The pilot study results closely followed long-term trends and average system responses to climate change impacts from the more detailed Merced River Flood-MAR Watershed Study (California Department of Water Resources 2020, 2022).

Based on the findings from the pilot study, DWR applied the decision-scaling approach to the entire WEAP-CVPA model of California's Central Valley to study systemwide performance and vulnerabilities in support of Update 2023.

1.4 Update 2023 Study Limitations and Quality Control

The future scenarios analysis for Update 2023 is a high-level screening study to quantify potential vulnerability at the HR scale and identify highly vulnerable areas for more detailed analysis. As a result of the coarse spatial resolution and simplification of operations used in the analysis, results may not represent conditions at a local scale. The future scenarios analysis is not intended to serve as a feasibility study for specific projects or adaptation actions.

The WEAP-CVPA model was not recalibrated in Update 2023 because of insufficient funding and a determination that changes to the updated model would not significantly compromise the original model calibration. Additionally, the GCM data used in this analysis is from the Coupled Model Intercomparison Project 5 (CMIP5), as that was the most current information at the time of the study. New data from CMIP6 could change the probability characteristics of the vulnerability analysis, although response spectrums likely would remain valid. Finally, sea-level-rise analysis included in Update 2023 includes only the hydrologic effects and does not incorporate physical impacts, such as overtopping of levees or submersion of the land surface.

For Update 2023, the previous model calibration was not revisited. Updated model components were assessed to ensure that they generally retained the original calibration; corrections were made as needed.

The quality control process included the examination of WEAP model inputs and outputs and the post-processing of the results into the six system metrics. Population and associated demographic data, land use, and Paleo-based climate time series data read by the model were spot-checked to ensure they matched with data in input files. At least one set of outputs from each climate combination generated by the WEAP model automation code over the model simulation period was checked against the corresponding model output files to verify they were identical. And, at least one set of outputs for each metric from the post-processing was checked to confirm that the results were the same as manually processing the outputs directly from the WEAP model. Finally, a logical consistency check was conducted for the results to examine and assess unexpected results or outliers that could not be explained.

Several outliers were identified and investigated. In most cases, the errors were related to the modeling processes. The issues related to the outliers were systematically resolved, and the model was rerun. Outputs were regenerated and verified to ensure resolution of the outlier issues.

All synthesized graphics were confirmed with manual calculations at least once for each metric. The synthesized outputs and graphics were verified a second time when assembling data for to add to the Tableau-based Future Scenarios Data Explorer website.

1.5 Summary of WEAP-CVPA Model Description

1.5.1 Geographic Coverage

The WEAP-CVPA model is a comprehensive, fully integrated river basin analysis tool of California's Central Valley at the PA scale. The model covers three Central Valley HRs: Sacramento River, San Joaquin River, and Tulare Lake. The detailed water supply and demand computations are performed and reported at the PA scale for each HR, which can be aggregated to the HR scale. The names and the corresponding identification numbers associated with each PA within the three HRs are listed below.

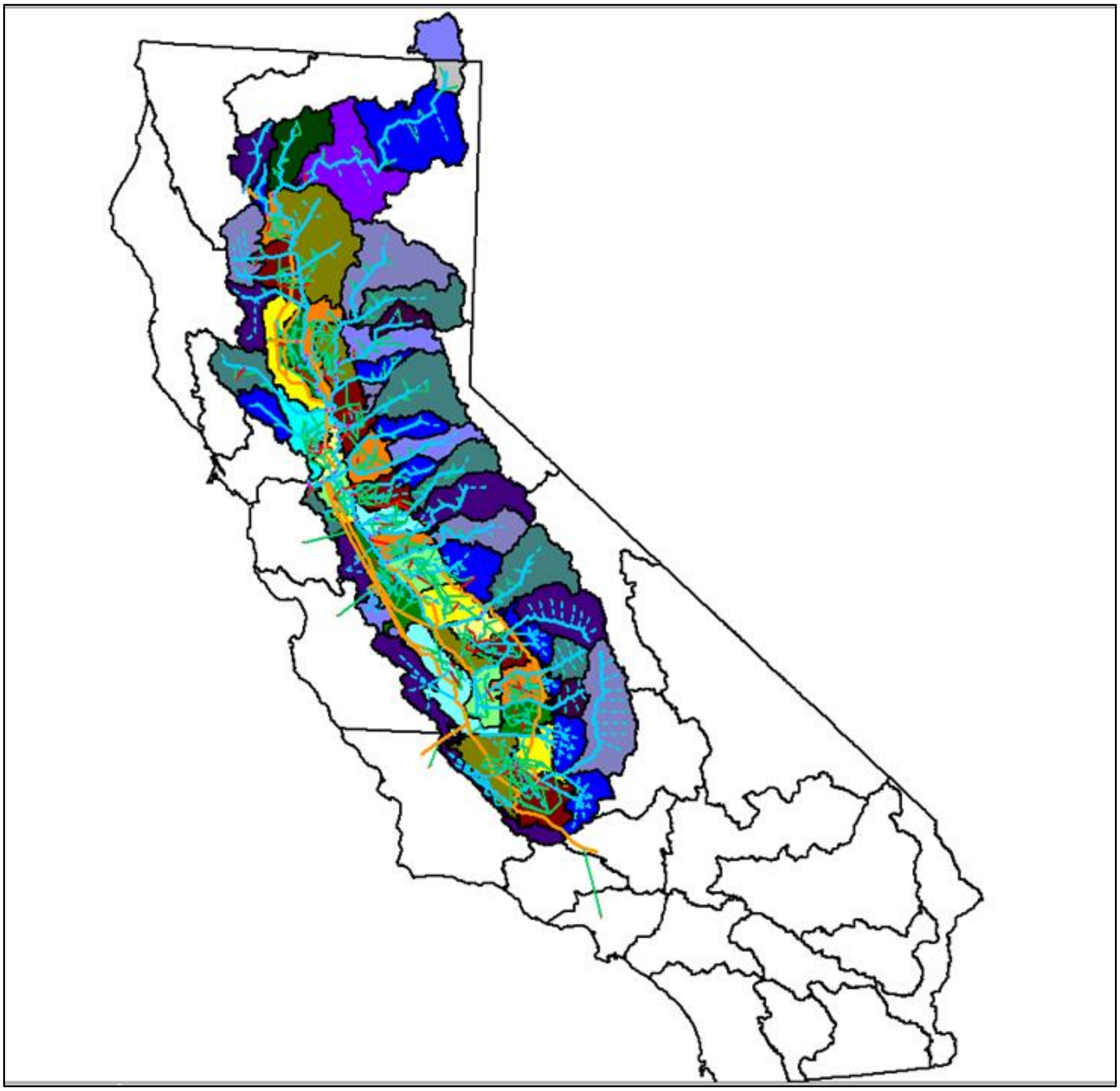
Sacramento River HR PAs. The Sacramento River HR consists of 11 planning areas: PA 501 (Shasta-Pit), PA 502 (Upper Northwest Valley), PA 503 (Lower Northwest Valley), PA 504 (Northeast Valley), PA 505 (Southwest), PA 506 (Colusa Basin), PA 507 (Butte-Sutter-Yuba), PA 508 (Southeast), PA 509 (Central Basin-West), PA 510 (Sacramento-San Joaquin Delta), and PA 511 (Central Basin-East).

San Joaquin River HR PAs. The San Joaquin River HR consists of 10 planning areas: PA 601 (Central Basin-East), PA 602 (Sacramento-San Joaquin Delta), PA 603 (Eastern Valley Floor), PA 604 (Sierra Foothills), PA 605 (West Side Uplands), PA 606 (Valley West Side), PA 607 (Upper Valley East Side), PA 608 (Middle Valley East Side), PA 609 (Lower Valley East Side), and PA 610 (East Side Uplands).

Tulare Lake HR PAs. The Tulare Lake HR consists of 10 planning areas: PA 701 (Western Uplands), PA 702 (San Luis Side), PA 703 (Lower Kings-Tulare), PA 704 (Fresno Academy), PA 705 (Alta-Orange Cove), PA 706 (Kaweah Delta), PA 707 (Uplands), PA 708 (Semitropic), PA 709 (Kern Valley Floor), and PA 710 (Kern Delta).

A schematic, geographic representation of the WEAP-CVPA model with its associated PAs is shown in Figure 1-1.

Figure 1-1 Schematic, Geographic Representation of the WEAP-CVPA Model



1.5.2 Overview of Basic Model Calculations

WEAP-CVPA model is a demand-driven water supply allocation model. The calculations start at demand sites. The demand sites receive supply deliveries based on computed demands and a system of user-defined "demand priorities." The highest priority demand sites will receive their supply deliveries first. Any water left in the system will be delivered to the next demand site(s) on the priority list. If insufficient water is left in the system, the demands in lower priority sites will not receive their full demands, resulting in unmet demands. On the supply side, the requested supplies are delivered to demand sites based on "supply preferences" imposed by water users on their supply options. This combination of demand priorities and supply preferences forms a hierarchical supply allocation "order" matrix for supply deliveries. WEAP model uses a linear programming optimization solver to determine the matrix of allocation order in the objective function. The objective function is to maximize the percentage of demand met (i.e., demand coverage) at each demand site, subject to system constraints, including storage and conveyance capacity limitations as well as contractual, environmental, institutional, and legal constraints. The primary demand sectors in the current WEAP-CVPA model are agricultural, urban indoor, urban outdoor, and environmental flows. The primary supply sources to meet the demands are stream diversions, surface reservoirs, groundwater aquifers, and return flows.

1.5.3 Elevation Bands

The WEAP model can simulate the rainfall-runoff process, including snowpack accumulation and snowmelt runoff from its uppermost elevations in a watershed. It allows subdividing the watershed into different elevation bands to more accurately model the snowpack and snowmelt processes, as climatic conditions in some watersheds could vary rapidly with elevation. The model has a robust and flexible representation of water demands from different sectors in a watershed and the ability to include operating rules for infrastructure elements, such as reservoirs, canals, and hydropower projects. These model features allow the analyses of how specific configurations of infrastructure, operating rules, and operational priorities could affect water uses as diverse as instream flows, irrigated agriculture, and municipal water supply under hydrological input data and physical watershed conditions. When integrated with its rainfall-runoff capabilities, the model's water-systems planning features make the WEAP-CVPA model ideally suited to simulate the potential effects of climate change in the Central Valley.

1.5.4 Model Adaptations for Implementing the Decision-Scaling Approach

The Merced River watershed pilot study showed that the WEAP-CVPA model can apply the decision-scaling approach in water system simulation. For example, the WEAP model was equipped to run only up to 500 years of simulation. Even so, the applicable model feature was readily updated to simulate the 1,100-year-long simulation period required for the Paleo climate time series used in the pilot study and current Update 2023 future scenarios analysis. The model was also updated to access different timelines for key input variables during simulations. For example, climate data have timelines in past historical times, whereas urban and land use have future time stamps. The model can now "look back" or "look ahead" when accessing time-series data with different timelines. In the current decision-scaling application, the urban and land use development is required to remain fixed at a given level of development (e.g., 2020 or 2070 level in current studies) over the simulation period. The model was modified, accommodated by its object-oriented formulations, to introduce a new single parameter to denote any year of development (e.g., 2030, 2050, or 2100) accessed by all demand objects in the study area.

Chapter 2. Model Updates for 2023

Many features of the WEAP-CVPA model were modified for Update 2023 to improve the water system representation in the model with updated information. These include, along with climate change methodology, delta biological opinions, coordinated operations agreement, sea-level-rise simulation, expansion of urban lands into native vegetation, and flexible time horizon simulation.

2.1 Changes in Climate Change Methodology

Update 2018 used downscaled GCMs to assess trends of water resources vulnerability over time, allowing water managers and planners to examine many possible realizations of future years up to 2100. The strength of this approach is that climate slowly shifts from year to year while land use, water use, and population growth are changed, allowing water planners and managers to examine evolving vulnerability trends under different potential climate realizations. The limitation of this approach is that there is no probability framework for decision-making; one has to select a GCM and examine the impacts and then select another GCM and examine those impacts. This methodology offers high-level insights but could not provide a probabilistic risk-informed decision-making framework.

Since 2018, DWR has explored novel ways of representing future vulnerabilities, including a decision-scaling approach to create risk-based information that can advise future decision-making on most likely future vulnerabilities based on the full range of GCMs. The decision-scaling approach works by examining how the system reacts to incremental changes in precipitation and climate. Then, it uses GCMs to create a probability envelope that can be overlaid with those system responses to identify how likely the system is to meet a given performance threshold. For the Update 2023 future scenarios analysis, the decision-scaling approach was applied by evaluating the effects of changes in temperature from 0 to 5 °C in increments of 1 °C and changes in precipitation from -30 percent to +30 percent in increments of 10 percent. The GCMs identified in the CMIP5 with RCPs 4.5 and 8.5 were used to identify a probability envelope. The 2020 baseline conditions were used as the performance threshold to identify likely changes relative to current conditions.

The decision-scaling approach used in Update 2023 assigns urban growth and agricultural land use at the 2020 level representing the existing level of development and at the 2070 level representing the future level of development. But climate factors, such as precipitation and temperature, based on the Paleo-climate time series, can vary over time to capture seasonal and annual variabilities and extreme conditions. This approach contrasts with the more conventional scenario-based approach used in previous Water Plan Updates, where land use, urban growth, and climate varied concurrently over time to track their combined effects on future system vulnerabilities under a select number of GCM climate scenarios.

2.2 Delta Biological Opinion

A 2008 U.S. Fish and Wildlife Services (USFWS) biological opinion determined that the continued operation of the Central Valley Project (CVP) and State Water Project (SWP) likely would adversely impact Delta smelt's critical habitat, jeopardizing the species' existence within the Delta. This jeopardy determination led to the development of a reasonable and prudent alternative (RPA) that was designed to avoid the likelihood of these threats. RPA includes actions intended to reduce Delta exports, as indexed by the combined Old and Middle River (OMR) flows, when the entrainment risk of Delta smelt increases. These actions are implemented in the WEAP-CVPA model as follows:

- **USFWS Action 1**. This action provides adult Delta smelt entrainment protection during the initial winter flow pulse that may occur from December through March and limits Delta exports so that OMR flows are no more negative than -2,000 cubic feet per second (cfs) for a total duration of 14 days, with a 5-day running average of -2,500 cfs.
- **USFWS Action 2**. This action provides an adaptive mechanism following Action 1 and is intended to protect pre-spawning adult Delta smelt from entrainment after the winter pulse. Action 2 limits Delta exports so that OMR flows are no less negative than -5,000 cfs to -3,500 cfs depending on existing conditions within the Delta, with a 5-day running average within 25 percent of the monthly criteria. The WEAP-CVPA model uses the previous month's X2 location as an indicator of Delta conditions. Action 2 continues until the onset of Action 3.

- **USFWS Action 3.** This action is also an adaptive approach intended to protect larval and juvenile Delta smelt from entrainment. Action 3 limits Delta exports so that OMR flows are no more negative than -5,000 to -1,250 cfs based on conditions within the Delta. Similar to Action 2, the WEAP-CVPA model uses the previous month's X2 location as an indicator of these Delta conditions.

  "X2" is the "mixing zone" in the Delta where saltwater intrusion from the San Francisco Bay meets freshwater from the Sacramento and San Joaquin rivers. The X2 location fluctuates within the Delta based on ocean tide. High tide pushes the X2 location farther into the Delta. Low tide pulls the X2 location seaward.

For more detailed information on actions and implementation process, refer to the Stockholm Environment Institute (SEI) Technical Memorandum, provided as Appendix A.

2.3 Coordinated Operations Agreement

In 1986, the DWR and the U.S. Bureau of Reclamation (Reclamation) signed the Coordinated Operations Agreement (COA) that established a framework under which the projects operate to ensure that the CVP and SWP receive an equitable share of the Central Valley's available water. The agreement also holds the parties jointly responsible for meeting water quality standards and providing water for other (senior) legal uses within the Sacramento Valley in-basin uses. The COA defines formulae for sharing joint CVP-SWP responsibilities for meeting Delta standards per State Water Resources Control Board Water Right Decisions 1485 and 1641(D-1485, 1978 and D-1641, 2000) and other in-basin legal water uses. The COA also identifies how unstored flow will be shared between the two projects. The implementation of COA in the WEAP-CVPA model requires the model to determine whether there is unstored water for export that the CVP and SWP may share or whether there is in-basin use within the Sacramento Valley and Delta that must be met by storage withdrawals from project reservoirs or import of Trinity River water through the Clear Creek Tunnel. Computer Code related to COA is implemented in the WEAP-CVPA model as user-defined linear programming constraints. It is organized as a set of seven subbranches, including Delta exports, Delta outflow, in-basin use, sharing formula, storage release, unused water, and wheeling. For more detailed information on COA implementation, refer to the SEI Technical Memorandum, provided as Appendix A.

2.4 Sea Level Rise Simulation

The previous versions of the WEAP-CVPA model included a routine for estimating the Delta outflow requirements needed to satisfy Delta salinity standards. The routine was based on the Contra Costa Water District salinity-outflow model, known as the “G-model” (Denton and Sullivan, 1993). The G-model uses a set of empirical equations developed from the one-dimensional advection-dispersion equation. The model predicts salinity caused by seawater intrusion at several key locations in Suisun Bay and the western Delta as a function of current and antecedent Delta outflow. The antecedent Delta outflow incorporates the combined effects of all previous Delta outflows affecting salinity distribution within the Delta. The G-model equations, however, were developed under current sea-level conditions. Although it would be possible to update these relationships to account for projected sea level rise, it would be more convenient to incorporate an artificial neural network (ANN) model developed for the California Water Resources Simulation Model (CalSim) into the WEAP-CVPA model tailored for several scenarios of sea level rise.

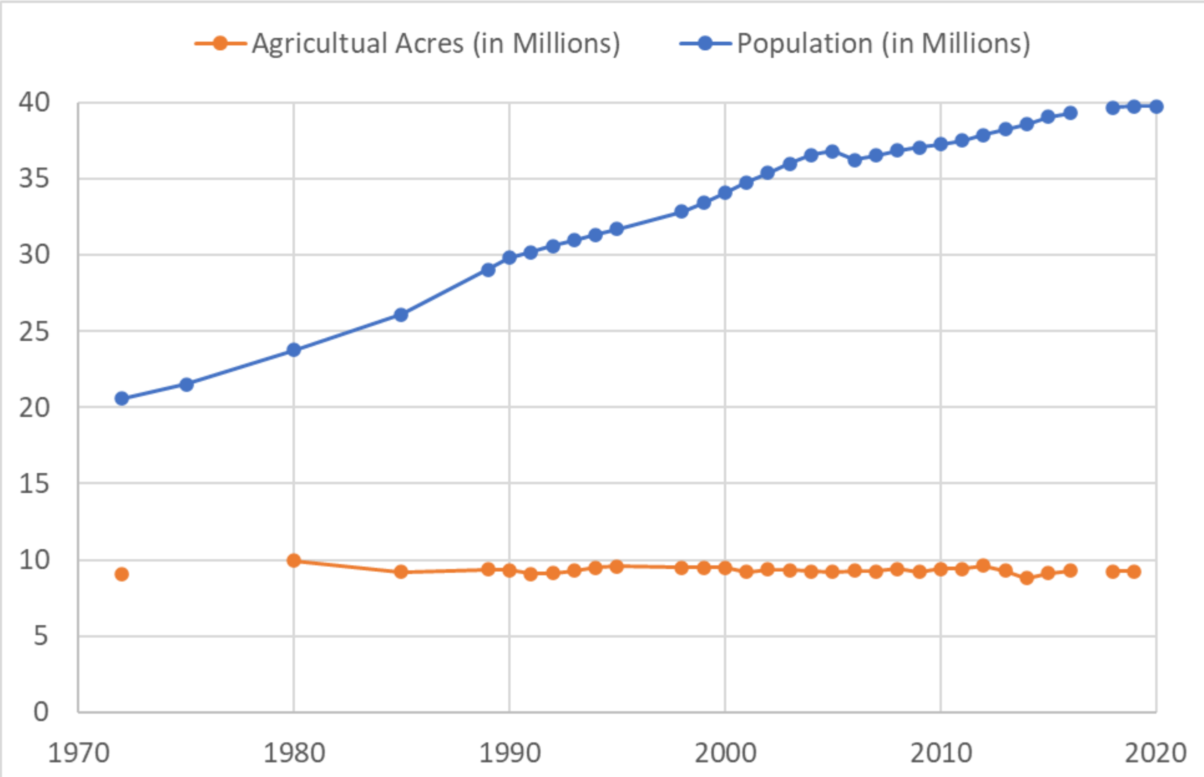
The Delta ANN was originally developed for CalSim to closely represent flow-salinity relationships in the Delta that would have been modeled by the Delta Simulation Model. CalSim uses these relationships to set Sacramento River flow targets and export limits to meet salinity standards at various locations within the Delta. The ANN determines salinity (micromhos per centimeter) at these locations given estimates of Delta total inflows, total exports, Delta net channel depletions, and the position of Delta cross-channel. The total inflows include the Sacramento River, San Joaquin River, Yolo Bypass, and combined flows from the Cosumnes, Mokelumne, and Calaveras rivers (east-side streams). The total exports include the SWP, CVP, North Bay aqueduct, and Contra Costa Canal diversions. These features of Delta ANN were implemented in the current application of the WEAP-CVPA model to set flow targets in the Sacramento River and to limit Delta exports in meeting Delta salinity standards. This task required linking WEAP-CVPA to the dynamic-linked-library containing the ANN functions and then using values returned from these calls to set targets for Sacramento River inflows and limits on Delta exports. In the current application of the WEAP-CVPA model, the sea level rise in the ANN is set at 1.8 feet (55 centimeters). For more detailed information on ANN implementation, refer to the SEI Technical Memorandum, provided as Appendix A.

2.5 Expansion of Urban Lands into Native Vegetation

Previous Water Plan updates used an evolving land use pattern, including expanding urban land use, a dynamically changing trend of agricultural land use encroached upon by the urban uses, and native land use that remains static through the simulation. The urban land use was based on growth estimates from the California Department of Finance (DoF) and local government plans regarding likely future expansions. The agricultural land use was based on projections developed Reclamation with a transition to more water-efficient crops in mind.

For Update 2023, the transition of agricultural lands to urban lands was revised. Previously, it was assumed that urban use typically replaced agricultural land use over time. However, when examined against long-term trends, as shown in Figure 2-1, agricultural irrigated acres have remained relatively static at the statewide scale despite significant urban growth during the same periods, indicating that the previous assumption is invalid. As conservation of spatial areas is essential, for Update 2023, it was decided to instead have urban growth encroach on native land use as cities expand.

Figure 2-1 Historical Land Use and Agricultural Applied Water from Water Supply and Balances



2.6 Flexible Time Horizon Simulation

In previous Water Plan updates, WEAP model simulation time horizons were consistent among key variables. For example, urban growth and demographics (e.g., population, single-family, and multifamily homes), land use, and climate data used synchronized timelines throughout the simulation period. However, Update 2023 employs the WEAP model application using the decision-scaling approach, and several key variables, such as climate, have time-series data in the past historical Paleo times (WY 901–WY 2000), whereas urban and land use data have present and future timelines (WY 2020 and WY 2070). The WEAP-CVPA model was updated to access timelines of the different key input variables with different time stamps by introducing an "Offset Year" control variable. With this change, while the model accesses past historical climate data, it uses current and future levels of urban and land-use data during the simulation.

Another significant update made to the WEAP-CVPA model allows model executions to utilize model outputs for an extended simulation period to generate the vulnerability statistics for the decision-scaling approach. This allowed each 1,100-year-long, Paleo-based simulation period (WY 901–WY 2000) to be divided into 22 distinct 50-year cycles, each starting from the same initial conditions. The resulting model outputs provided 22 distinct 50-year-long average system performance information to generate decision-scaling statistics, such as mean values, percentiles, and frequency of occurrences. The feature modification allows the user to apply the approach to any different planning horizon (e.g., 20, 40, or 100 years).

Chapter 3. Data Modifications for Update 2023

Many of the underlying datasets of the WEAP-CVPA model were modified for Update 2023 to improve the representation of the observed trends and updated information since Update 2018. These modifications include changes to land use, population, water use, and instream flow requirements (IFRs) data.

3.1 Land Use Data

Future agricultural crop mix trends were revisited as part of Update 2023. The previous assumption included an evolving crop use mix reflecting inferences about future land use in the early 2010s. A comparison of current crop use to the original projections indicated that the past projections did not accurately reflect the trends over the last 10 years. Additionally, the Sustainable Groundwater Management Act (SGMA) will apply new stresses to agricultural use that are not yet fully understood as groundwater sustainability agencies plan to employ different land use and other strategies to reach sustainability. For this reason, it was concluded that future agricultural crop mixes are too uncertain to be accurately projected. Thus, the baseline land use was repeated for all years of the study. The baseline land use, based on the statewide land use survey for 2018, is being used to represent 2020 as a baseline condition.

Urban population data was updated based on more recent DoF projections and information from local government plans following the approaches used in previous Water Plan updates. The urban data could not incorporate the more recently available DoF projections using the 2020 census data as that data was not available until 2023, which was beyond the cutoff date for inclusion in this Water Plan update. Unlike previous Water Plan updates, no high or low trend for population growth is projected, nor is a high or low density for urban growth; only the current trend is used. High and low population trends were not used as there was significant uncertainty about future population growth. Prior to 2015, California was following a generally increasing growth pattern for population. Between 2015 and 2020, California hit an inflection point in its growth pattern and is in a flat or slightly decreasing growth pattern based on most recent DoF projections. This change in population growth led to a lack of confidence in previous projected trends.

Native land use was not updated from the original 2006 National Land Cover Database (NLCD) dataset as the determination was that the 2016 dataset was not sufficiently different to justify the update, and there was not enough funding in this update cycle to recalibrate the model based on the updated data.

3.2 Water Use Data

Water use data was updated based on the urban water use rates for each PA from the water supply and balance data. The water supply and balance data include an approximation of per capita water use for single-family and multifamily indoor use, which was incorporated into the future scenarios data. The most up-to-date of per capita water use was used in the updated WEAP-CVPA model. It was then scaled down by 8 percent by 2070 based on guidance from DWR’s Water Use and Efficiency Program to account for the background conservation that likely will result from existing and implemented water conservation legislation and codes. Outdoor water use efficiency remains unchanged from 2020 to 2070 and is based on irrigated urban areas identified in the NLCD.

3.3 Instream Flow Requirements

Instream flow requirements were revisited based on information in the water supply and balance data. Most related data were consistent with the water supply and balance data. Still, for better consistency with the water supply and balance data, a few modifications were made to the instream flow requirements used in the WEAP-CVPA model.

Chapter 4. Vulnerability Metrics Used in Update 2023 Analysis

Future scenarios analysis for Update 2023 includes a suite of metrics designed to identify future water vulnerabilities in specific water sectors. The metrics are grouped into six categories to illustrate the vulnerabilities of the water sectors: surface water; groundwater; agricultural water supply; urban water supply; environmental water; and flood risk. Generally, these metrics are developed by comparing the average 2070 conditions to the average 2020 conditions, and the vulnerability is identified as the increase in adverse conditions in 2070 relative to 2020. Two exceptions are the environmental water and flood risk metrics, as explained in the section below.

4.1 Overview of Metrics Selected

Surface Water. The reservoir storage level at the end of the irrigation season is used as the surface water metric. End-of-September reservoir storage levels are the most susceptible to climate change impacts. Low reservoir levels at the end of the irrigation season indicate a vulnerability in case the following year is dry. A vulnerability in the surface water system suggests that the average end-of-September reservoir levels under most likely future climatic conditions are lower relative to that under the current average conditions. For example, on average, a reservoir with 100 thousand acre-feet (taf) storage at the end of the irrigation season currently may have only 80 taf under likely future conditions. In other words, under future conditions, the reservoir would have 20 percent less water available to meet future demands.

Groundwater. The groundwater metric measures the percentage of the supply provided by groundwater compared to total water supply. This metric is intended to identify when a region is becoming increasingly dependent on groundwater, indicating a vulnerability to overdraft conditions. For example, if an area currently receives 10 taf of its supply from surface water deliveries and 5 taf from groundwater pumping. Under future conditions, that same area might receive less surface water and demand could increase, for example, only 8 taf, while increases in demand cause the area to pump 8 taf from groundwater. In this example, the region has increased its relative percentage of groundwater contributions by 60 percent.

Urban Water Supply. The initial urban water supply metric selected was intended to assess the system's reliability to meet a threshold demand (95 percent of urban water demand met). However, this metric posed challenges when an area could not reliably meet the 95-percent threshold demand under the current conditions. As such, future vulnerabilities are masked by the fact that demand was not met reliably under the baseline conditions, and high vulnerabilities under future conditions might appear less vulnerable than they are. For this reason, the urban water supply metric used is the percent of urban demand met. For example, an area may meet 97 percent of urban demand under existing conditions. Under future conditions, the same area may only meet 93 percent of the demand on average, indicating a 4-percent increase in vulnerability in the urban water supply.

Agricultural Water Supply. The agricultural water supply metric is similar to the urban water supply metric except that it is based on the percent of agricultural demand met.

Environmental Water. The environmental water metric does not look at average values; instead, it counts the percentage of time the IFRs are met during the driest months (April through September) at IFR control points throughout the Central Valley. The WEAP-CVPA model, in its current configuration, typically prioritizes water supply to meet IFRs; so if the IFR is not met, it indicates an especially dire situation for the water system as other demands lower in priority would also not be met. Real-time water system operations may temporarily lessen environmental requirements during very dry conditions. But this provision cannot be effectively incorporated into the WEAP model at this time. As an illustration of the environmental water metric for Update 2023, a stream meets the IFR 100 percent of the time under current conditions. However, under future conditions, the same stream may only meet the IFR 98 percent of the time, representing a 2-percent increase in vulnerability for IFR violations.

Flood Risk. The flood risk metric is based on the 90th-percentile flow (10-percent exceedance flow) during the December through March period at specific flood control points throughout the Central Valley. The 90th-percentile flows were chosen to represent a significant flood event within the 50-year planning horizon. December-through-March flows were selected as those represent the high flow conditions in a year. The 90th-percentile flows under current conditions are compared to the same metric under future conditions to indicate the additional flood risk to the water system. For example, the 90th-percentile flow at a control point might be 10,000 cfs under current conditions. But under future conditions, the 90th-percentile flow at the same location could be 15,000 cfs, representing a 50-percent increase in vulnerability to flood risk.

4.2 Metrics Calculations from WEAP Model Outputs

Results from the WEAP-CVPA model runs were post-processed to generate statistics on the six metrics, including mean values, percentiles, and frequency of occurrences to assess water system vulnerability. The model outputs were reported as monthly, annual, or monthly average (averaged over the 50-year period depending on the specific metric). Below is a brief description of the calculations for each metric:

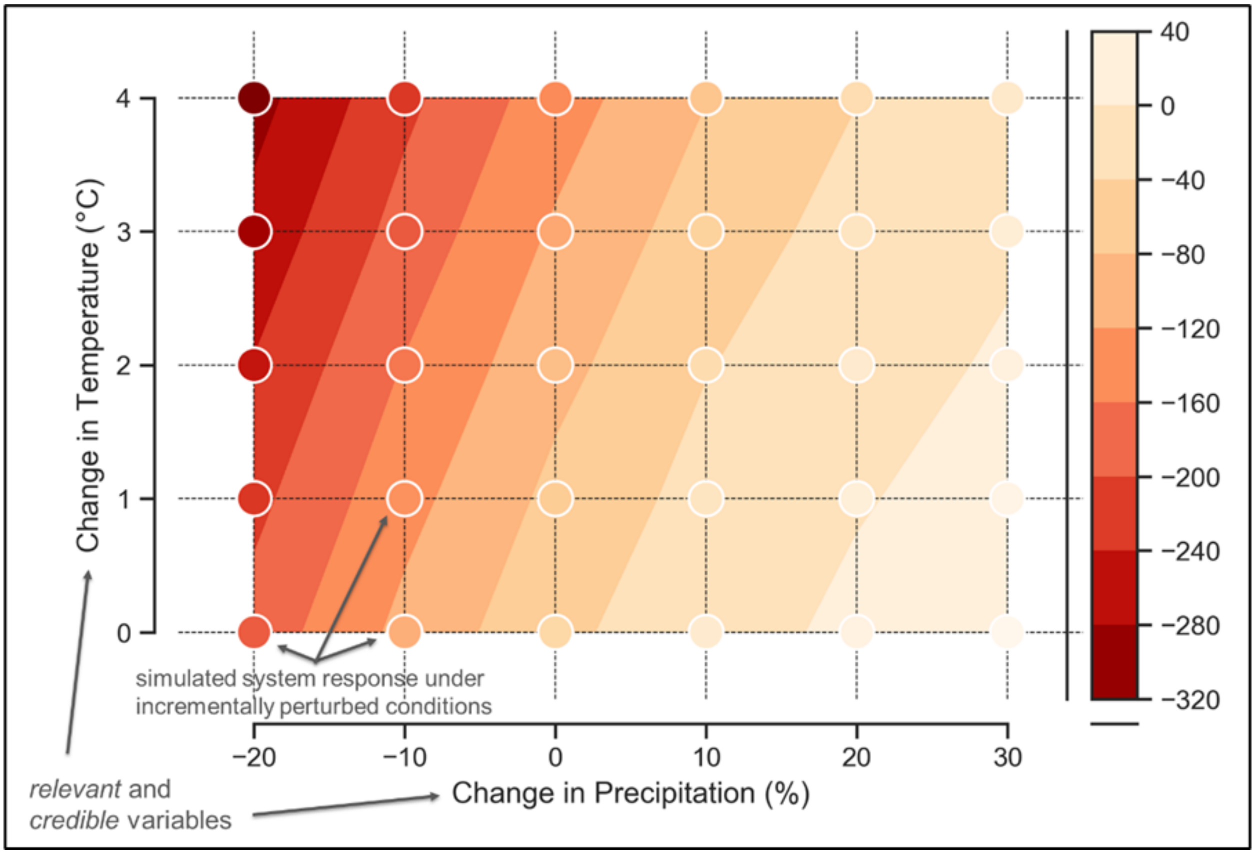
- **Surface Water**. This metric represents the end of water-year (September) storage in major reservoirs in the Central Valley. The model internally calculates and reports the monthly average September storage over the 50-year period for each of the 22 cycles in the 1,100-year Paleo climate data. Then the data for the 22 cycles are post-processed to calculate the average September storage over the 1,100-year period.
- **Groundwater.** This metric measures the percentages of groundwater contributions of the total surface and groundwater supplies to meet the agricultural and urban demands. For this metric, a post-processing similar to the surface water metric was utilized to calculate the average groundwater contributions to the total over the 1,100-year period.
- **Urban Water Supply**. This metric measures the reliability of the system to meet urban demand. Urban demand includes urban indoor and urban outdoor demand in an area. The model internally calculates and reports annual unmet urban demands (annual shortages) over the 50-year period for each of the 22 cycles in the 1,100-year Paleo climate data. Then the data for the 22 cycles are post-processed to calculate the average annual shortages in the urban sector over the 1,100-year period.

- **Agricultural Water Supply**. This metric is similar to the urban water supply metric, except it is based on the percent of agricultural demand met and is a measure of system reliability to meet water demand in the agricultural sector. For this metric, a post-processing similar to the urban water supply metric was utilized to calculate the average annual shortages in the agricultural sector over the 1,100-year period.
- **Environmental Water.** This metric counts the percentage of time the IFRs are met during the driest months of the year, April through September, at IFR control points in the Central Valley. As the demand priority for IFR in the current application of the WEAP-CVPA model is set very high, any unmet IFR implies systemwide distressed conditions because lower priority demands in the system would also face shortages. The model internally calculates and reports monthly average stream flows at IFR sites from April through September over the 50-year period for each of the 22 cycles in the 1,100-year Paleo climate data. Then the data for the 22 cycles are post-processed to calculate the average IFR stream flows over the 1,100-year period.
- **Flood Risk**. This metric is based on the 90th-percentile flow (10-percent exceedance flow) during the four wet months from December through March at major flood control points in the Central Valley. This metric was calculated for 13 stream locations downstream of major reservoirs and stream confluences vulnerable to flooding. The WEAP-CVPA model internally calculates and reports monthly stream flows from December to March over the 50-year period for each of the 22 cycles in the 1,100-year Paleo climate data at the flood control points selected. Then the data for the 22 cycles are combined and post-processed to calculate the 90th-percentile flow at each flood control utilizing data for the entire 1,100-year period.

4.3 Development of Response Surfaces and Cumulative Distribution Functions

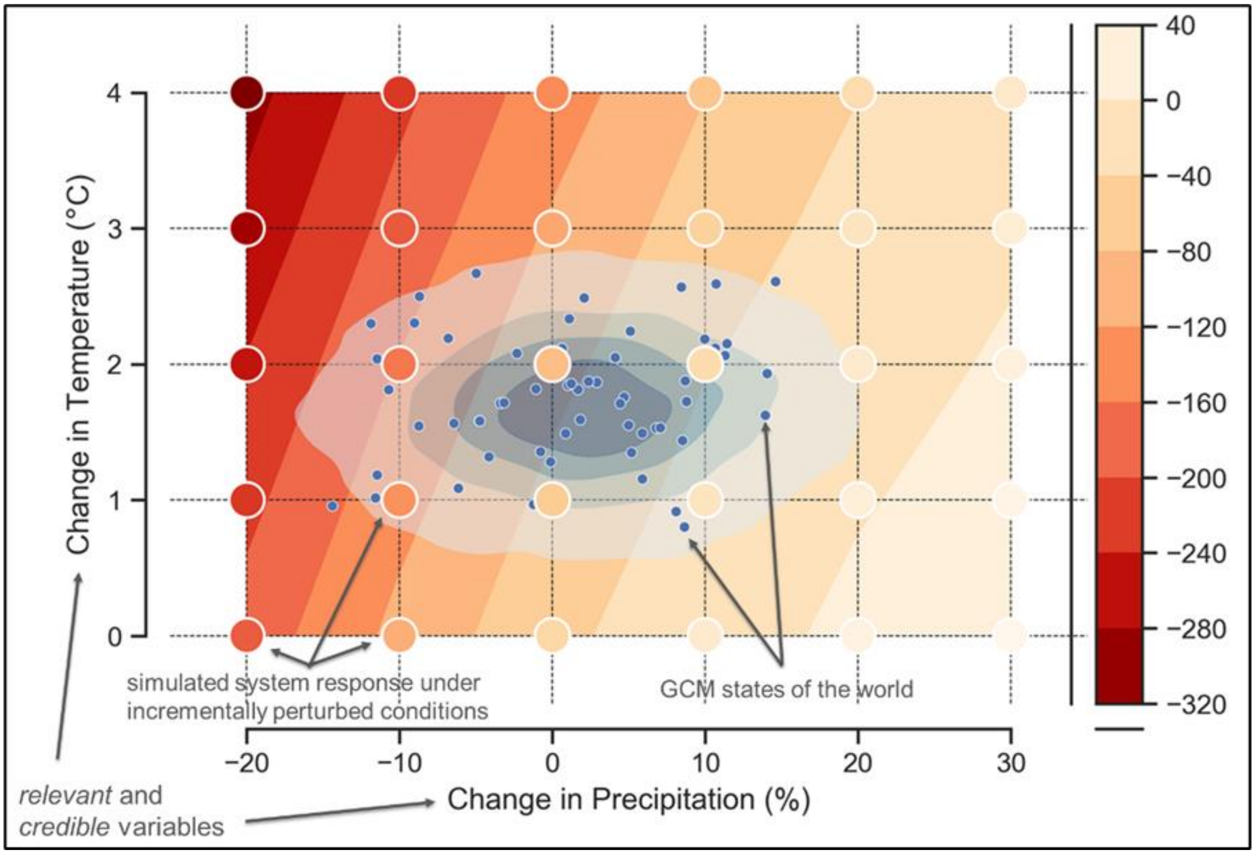
After the metrics are calculated based on the WEAP model outputs as described in the previous sections, those results are used to generate response surfaces for each combination of temperature and precipitation changes. Contours intervals are then developed based on a linear interpolation between modeled point data, as shown for a theoretical example metric in Figure 4-1.

Figure 4-1 Development of a Response Surface



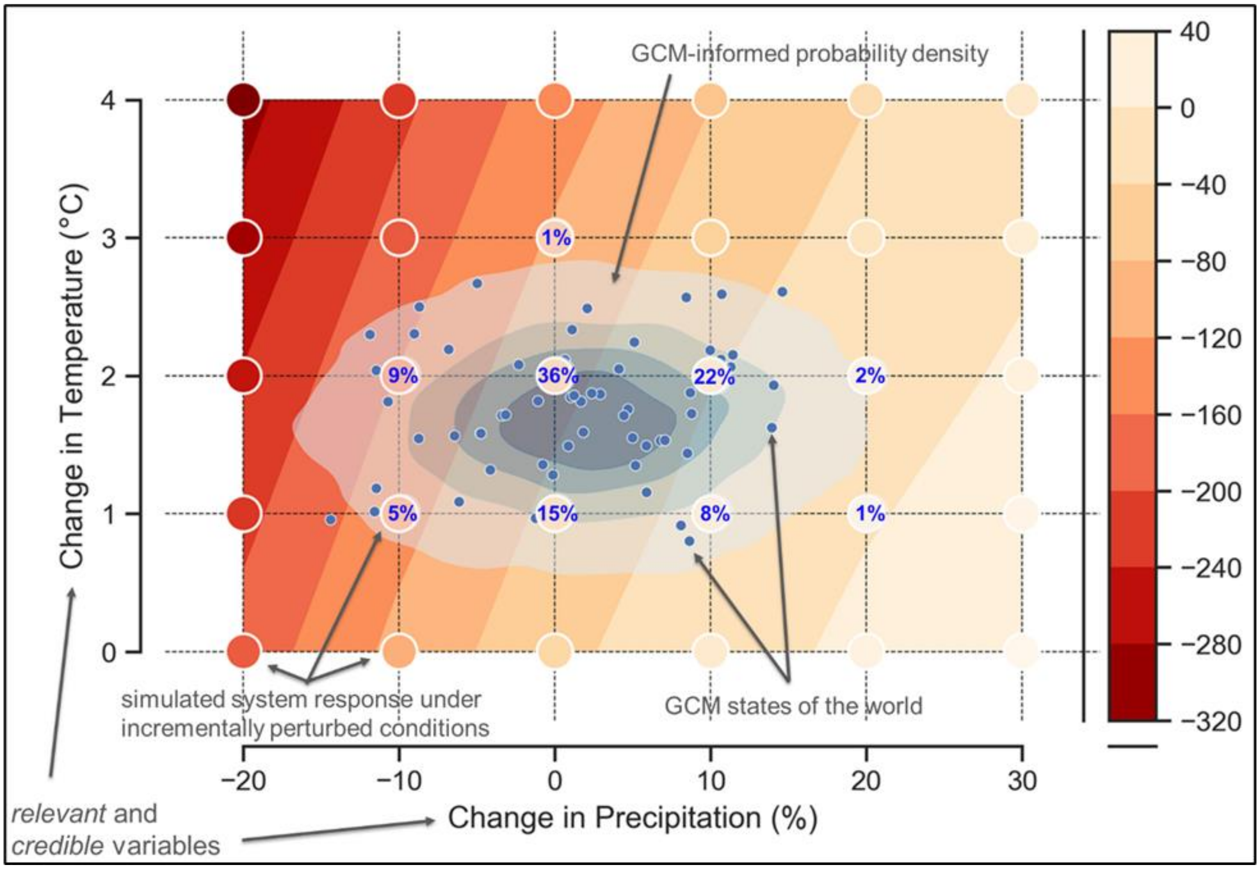
After the system response has been developed to ascertain the system performances under various temperature and precipitation conditions, the probability of occurrence for those conditions is calculated. Data from the full suite of CMIP5 GCMS are accessed, and their respective projections for climate by the year of interest are processed to compute average changes in temperature and precipitation. These results are then overlayed on the response surface, and probability envelopes are drawn around the GCM projections, which indicate the probability of GCM projections falling within those ranges. The resulting plot is shown in Figure 4-2. More details on the process of identifying probability from GCM projections are provided in *Decision Scaling Evaluation of Climate Driven Hydrologic Risk to the State Water Project – Final Report* (California Department of Water Resources 2019).

Figure 4-2 Projection of GCMs Overlaid on a Response Surface



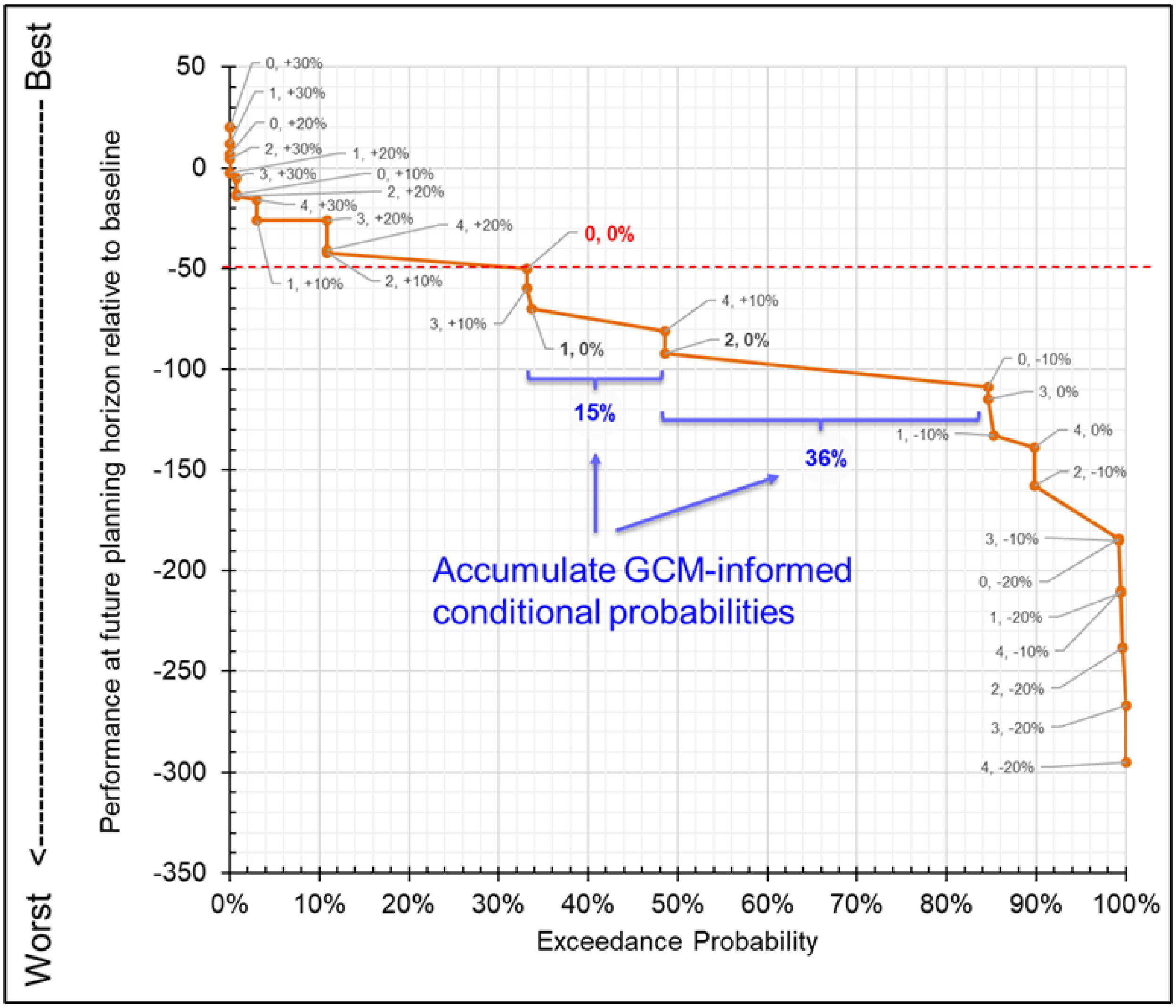
After GCMs have been mapped onto the response surface, the probability of occurrence of any point (temperature and precipitation combination) can be calculated by identifying the concentration of GCM forecasts that fall closest to each point, allowing the identification of an approximate probability of occurrence for each modeled scenario, as shown in Figure 4-3.

Figure 4-3 Identification of Probability of Occurrence of Model Results based on GCM Overlay



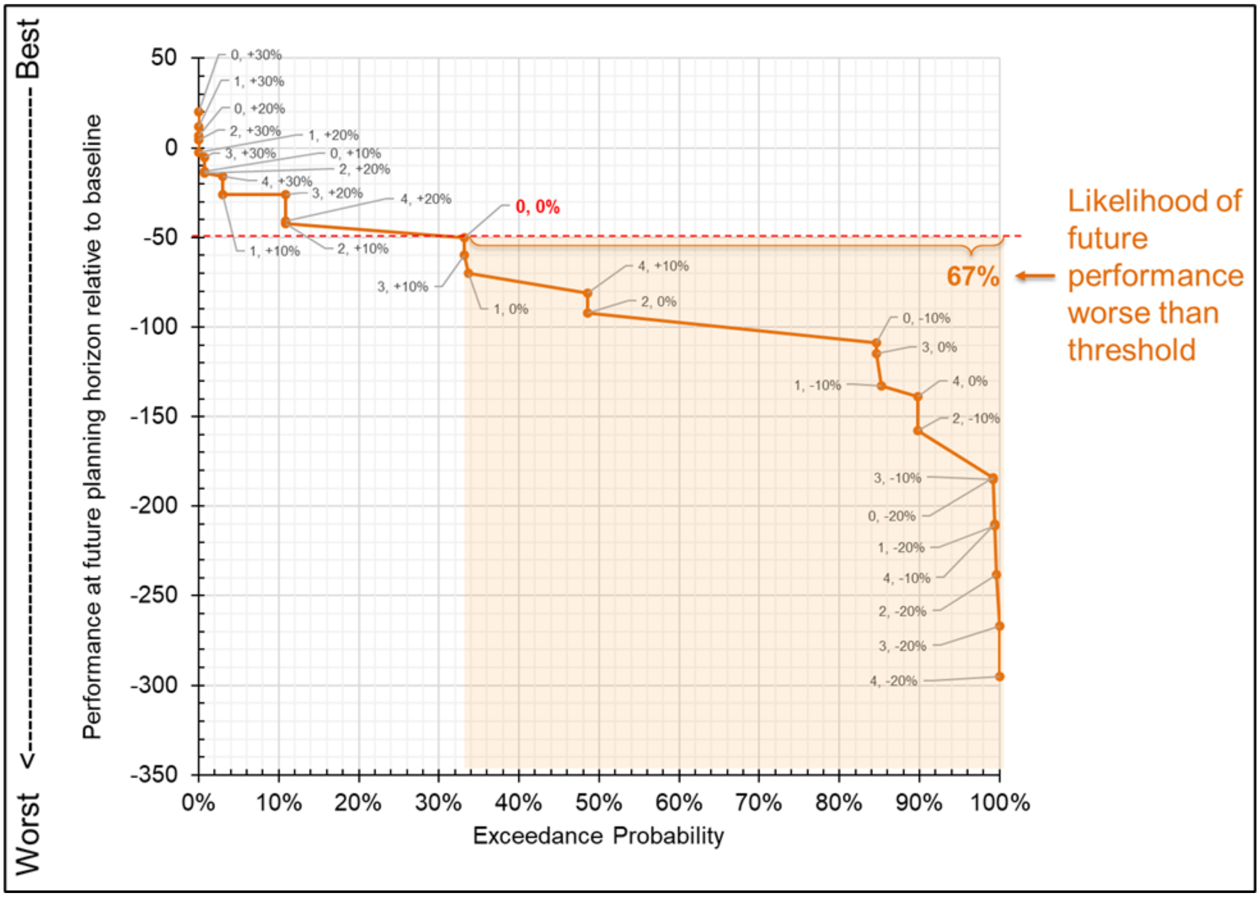
With probabilities assigned to outcomes, those outcomes can be mapped onto a cumulative distribution function (CDF) depicting all the results from the "best" (most beneficial outcome) to the "worst" (most detrimental outcome) system performance, as shown in Figure 4-4.

Figure 4-4 CDF Resulting from GCM Overlay



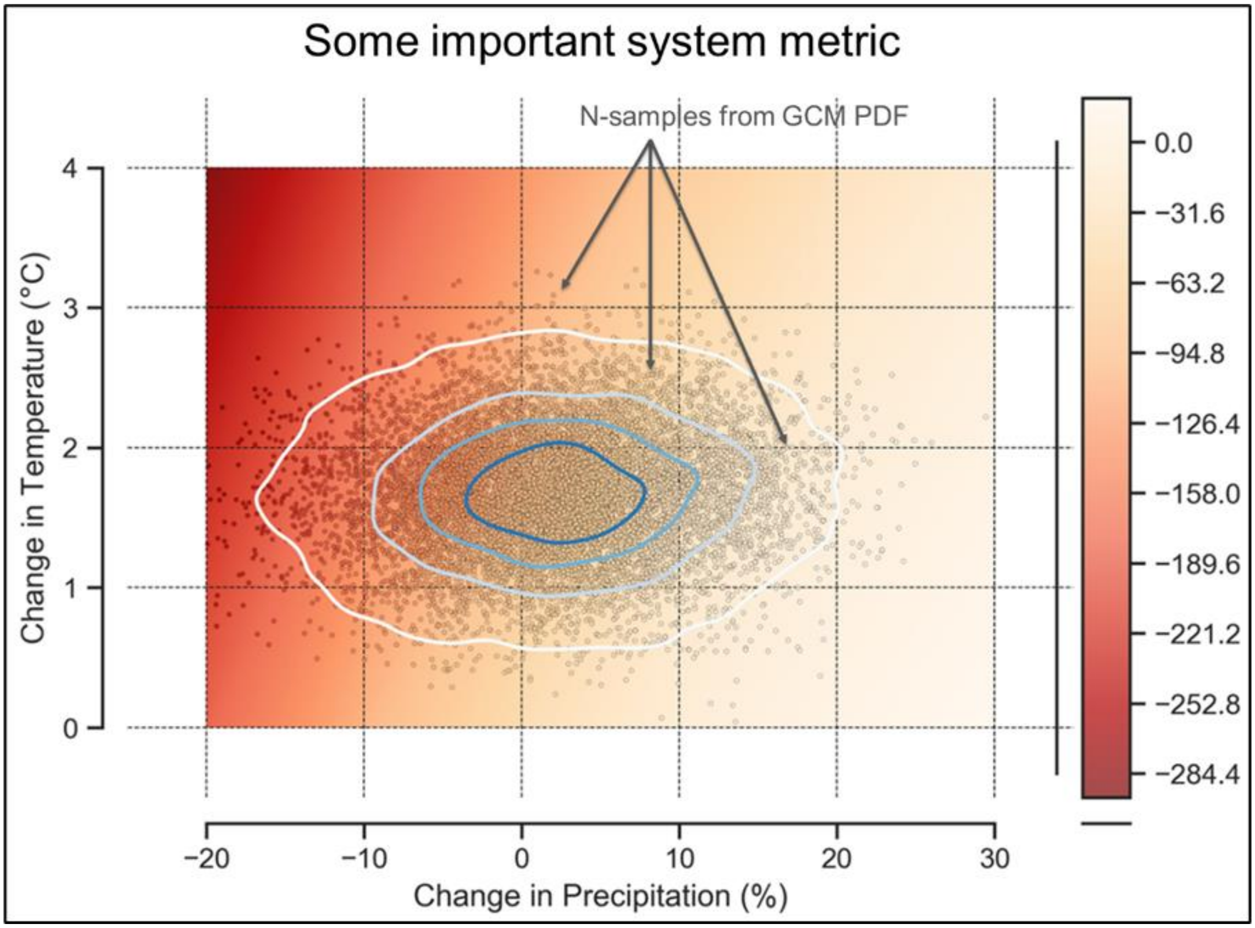
Using the CDF developed, threshold probabilities can be determined, as shown in Figure 4-5. For example, the probability that a future condition is worse than the performance threshold of -50 is computed by summing all the probabilities that produce an outcome worse than -50, resulting in a 67 percent likelihood of performance worse than the threshold.

Figure 4-5 Estimation of Probability of Occurrence for any Given Performance Threshold



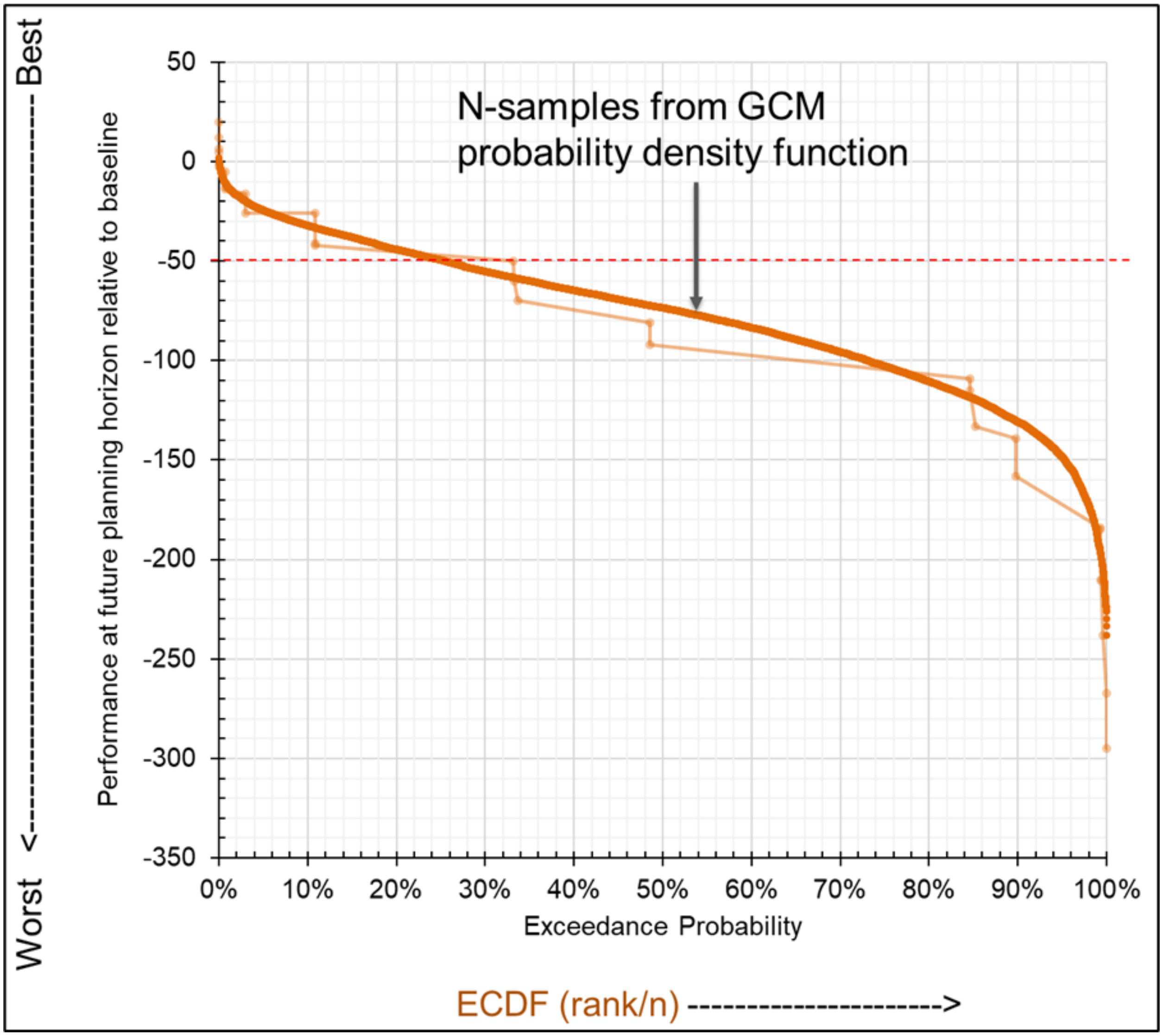
The approach laid out thus far does have limitations as the CDF only has values for model results and therefore is a stepwise function, only supporting results at those intersections of change in temperature and precipitation combination for which the model was run. A robust linear interpolation of the response surface was developed with minute changes in temperature and precipitation to overcome the limitation posed by the stepwise function. The resulting surface was then resampled with a Monte Carlo resampling of more than 1,000 points falling within and around the GCM probability envelopes, as shown in Figure 4-6.

Figure 4-6 Monte Carlo Resampling of Finely Interpolated Response Surface



With this more continuous probability rendition, limited no longer by the specific model runs, a continuous CDF can be drawn that would support the ability to identify a probability of occurrence or exceedance associated with any threshold performance level. As shown in Figure 4-7, the continuous CDF closely follows the performance of the stepwise CDF if there are no significant non-linearities among model runs. Such a continuous CDF provides a more robust risk-based tool and saves time and computing power to run increasingly dense grids of model results.

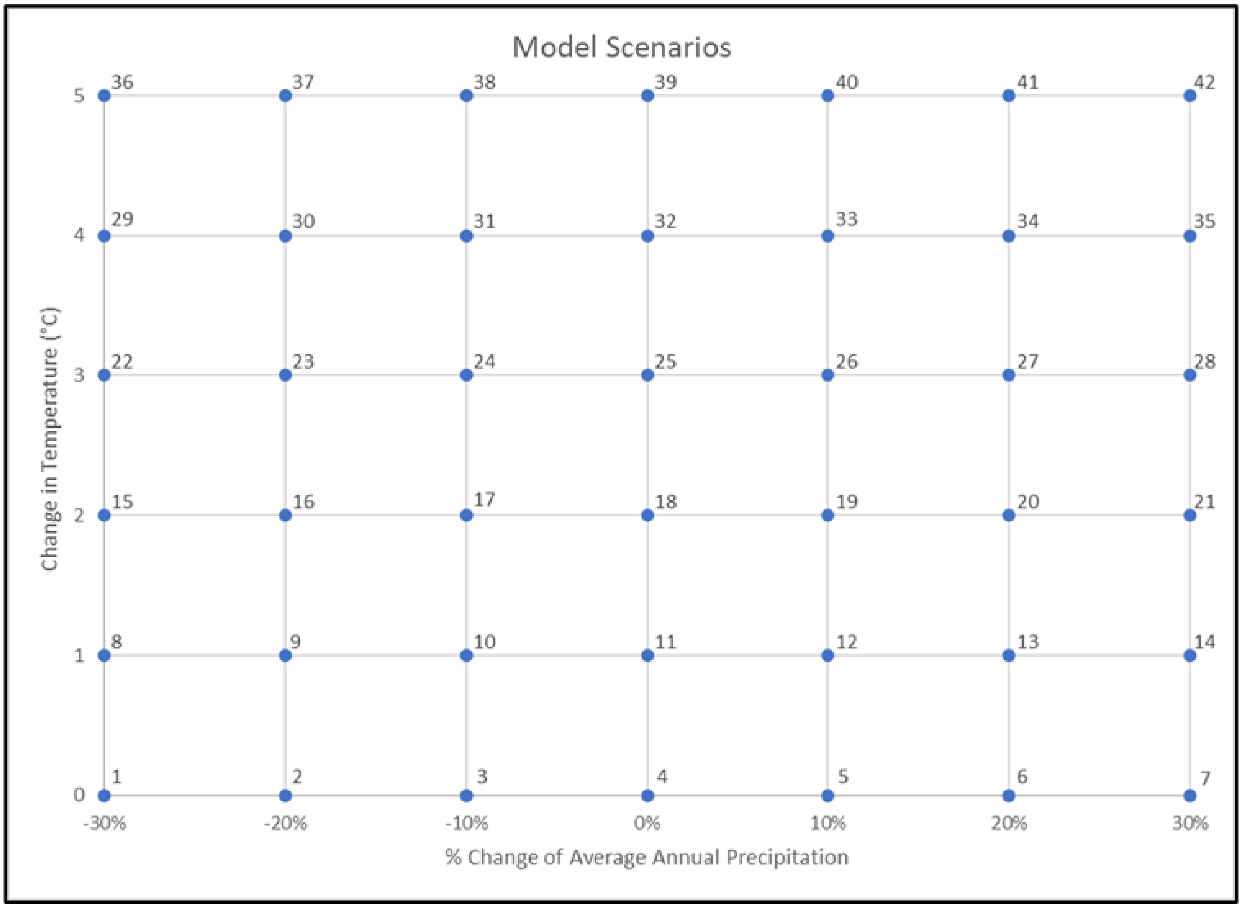
Figure 4-7 Resultant Smooth Cumulative Distribution Function from Monte Carlo Resampling



4.4 Interpreting Response Surfaces and CDFs

In the future scenarios for Update 2023, the response surface has temperature on the y-axis ranging from a 0 °C increase in temperature to a 5 °C increase in 1°C increments and precipitation along the x-axis ranging from a -30 percent reduction in average annual precipitation to a 30-percent increase in average annual precipitation in 10-percent increments, as shown in Figure 4-8. Every intersecting point in Figure 4-8 represents a series of model runs, which include the results of the 1,100-year Paleo climate dataset.

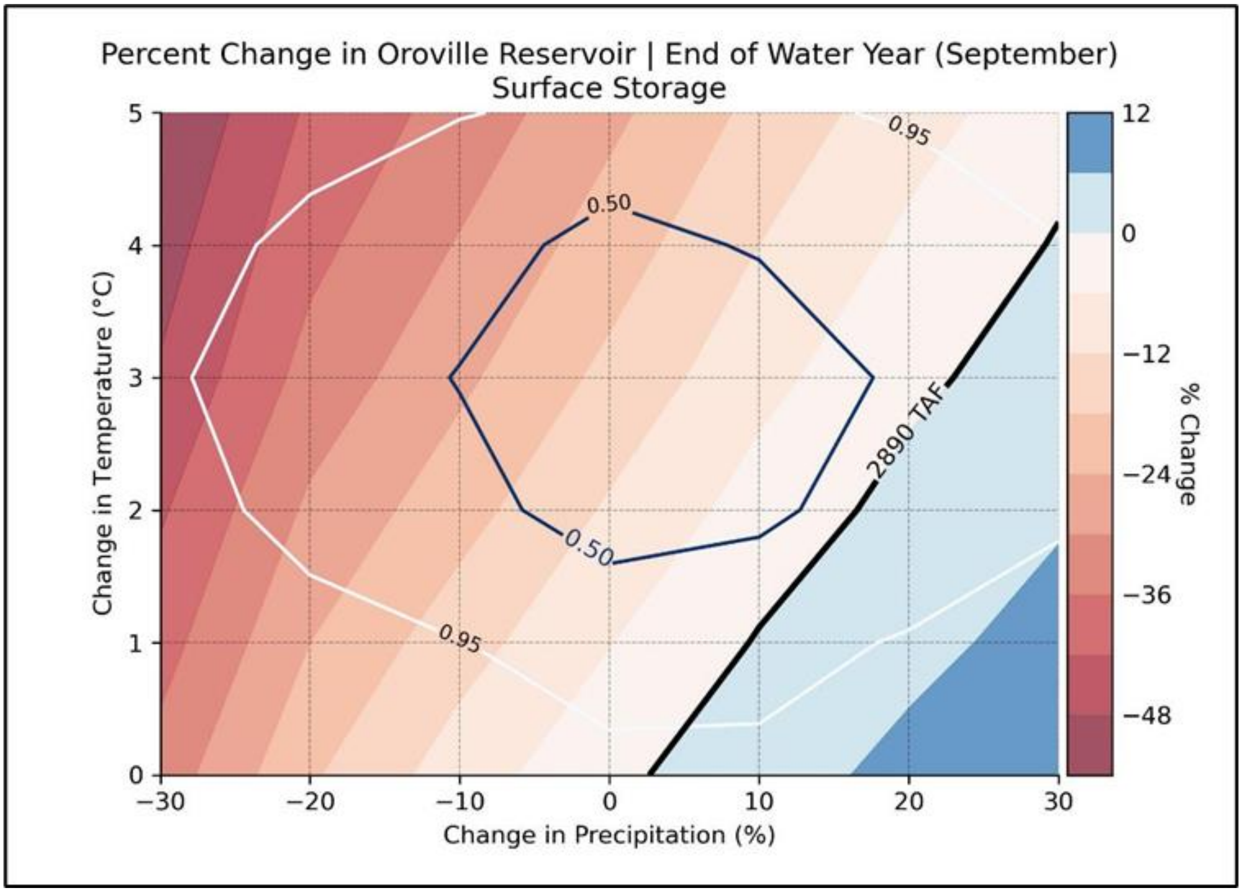
Figure 4-8 Response Surface Framework



These data points are used to create contours by linearly interpolating the results and drawing equal potential lines as described in the previous sections, resulting in graphics, as shown in Figure 4-9. The solid black line in Figure 4-9 represents the baseline performance, which for this study is the 2020 level of development conditions with no change to precipitation or temperature. This baseline condition still represents a synthesis of average conditions across the entire Paleo climate data but represents land use and water efficiency conditions at the 2020 level. In Figure 4-9, the solid black line does not cross at the 0,0 point on the graph, indicating that even without climate change, Oroville reservoir storage will be more stressed in the future simply because of urban growth that relies on Oroville reservoir supply to meet demands.

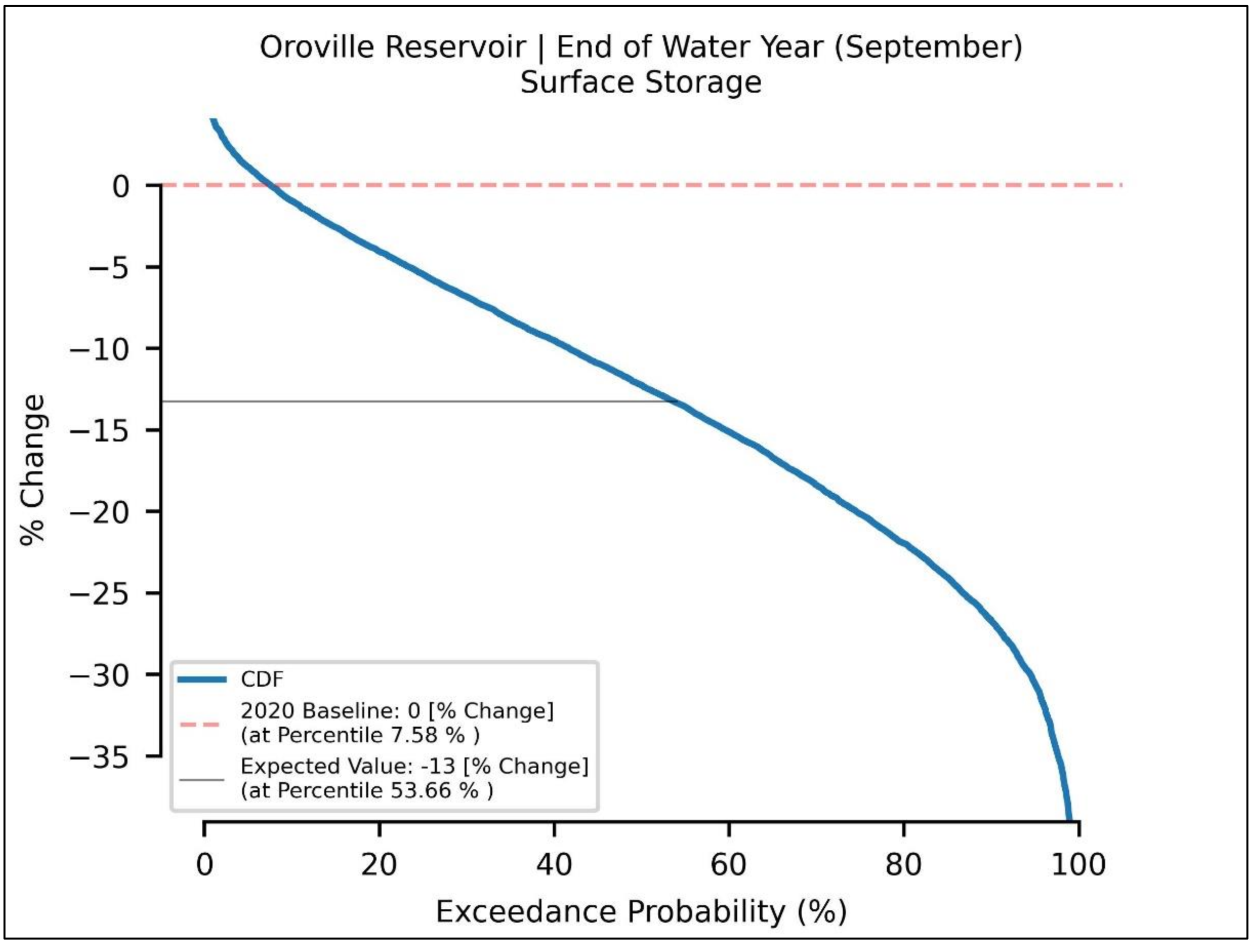
The response surface contours generally range from more beneficial outcomes in the bottom right (wettest and coolest conditions) to the least beneficial outcomes in the top left (hottest and driest conditions). A vertical contour would indicate the metric was sensitive only to precipitation, and a horizontal contour would mean the metric was sensitive only to temperature. For the example shown for Oroville reservoir, the contours are primarily diagonal, indicating sensitivity to both temperature and precipitation. Such a conclusion is not surprising, as precipitation is required to fill the reservoir and can be used to meet some crop evapotranspiration demand, whereas higher temperatures increase both the evaporation of the reservoir surface and water demands resulting from crop evapotranspiration.

Figure 4-9 Example of a Response Surface, End-of-Water-Year Storage in Oroville Reservoir



Also shown in Figure 4-9 are the GCM contours, ovular shapes with the numbers 0.5 and 0.95. The tighter 0.5 contour indicates that 50 percent of the GCMs from CMIP5 project temperature and precipitation to be within the circumscribed range, and the wider 0.95 contour suggests the same for 95 percent of CMIP5 GCMs. In Figure 4-9, the 50-percent GCM contour indicates that the future will have decreased performance as the entirety of the 50-percent contour overlays an area of reduced performance. As discussed in previous sections, the information contained in these contours, with the Monte Carlo resampling, are used to compute the probability of occurrence to generate a CDF. The CDF can be used to identify a probability of occurrence for the baseline and the difference between the baseline condition and the most likely future condition, as shown in Figure 4-10. The y-axis in Figure 4-10 is the percentage decrease in performance of the metric, with higher negative numbers indicating less storage available in Oroville reservoir relative to the baseline condition. The x-axis shows the cumulative probability of occurrence, from the best outcome for Oroville reservoir storage to the worst outcome. Figure 4-10 also shows vertical thresholds at both baseline (2020) and expected 2070 performance levels.

Figure 4-10 Example of a CDF, End-of-Water-Year Storage in Oroville Reservoir



Any risk threshold can be attributed to a probability of occurrence based on the information in Figure 4-10. The percentile for the expected future condition does not always fall at 50 percent because the CDFs are not necessarily normally distributed. For planning purposes, additional performance thresholds could be used. For example, if a more conservative threshold of 80-percent probability of occurrence were selected, a 22-percent decrease in end-of-year Oroville reservoir storage should be used for planning purposes.

Chapter 5. Results

For future scenarios analysis for Update 2023, response surfaces and CDFs were generated for all PAs and points of hydrologic interest in the WEAP-CVPA model area, resulting in the following numbers of system response surfaces and CDFs for the metrics considered:

- Metric 1 – Surface water (end-of-year reservoir storage): 25
- Metric 2 – Groundwater (groundwater dependency): 20
- Metric 3 – Urban water supply (urban demand met): 34
- Metric 4 – Agricultural water supply (agricultural demand met): 28
- Metric 5 – Environmental water (IFR counts): 10
- Metric 6 – Flood risk (90th-percentile flow): 13

The system response surfaces and CDFs for all PAs and points of hydrologic interest are provided in Appendix B and are also available through the Future Scenarios Data Explorer website. A synthesis of the results for the most likely future conditions is provided in the following section. An interpretation of the results and what they mean for the California water system is explained in Chapter 7, "Findings."

5.1 Aggregated Results at the Hydrologic Region Scale

In addition to the response surfaces and CDFs presented in the previous sections, a synthesized radar plot (spider plot) was developed. The spider plot illustrated in Figure 5-1 shows the probability of the six metrics being more vulnerable in 2070 than current conditions for the Sacramento River, San Joaquin River, and Tulare Lake HRs. The spider plot shows a greater than 65 percent likelihood that a water system, represented by the six metrics, will be more vulnerable in the future across the Central Valley.

The bar plot in Figure 5-2 illustrates each metric's most probable magnitude of vulnerabilities. It provides a range of possible vulnerabilities resulting from climatic uncertainties as informed by CMIP5 GCM projections. Each HR has unique vulnerabilities and challenges, exacerbated by future climatic conditions. Using the Sacramento River HR as an example, in approximately 74 percent of future climate projections, there is reduced carryover storage in the region's reservoirs at the end of the water year. The most likely reduced average carryover storage is approximately 7 percent (probable value), which could be as large as 26 percent (possible value) because of climatic uncertainty.

Figure 5-1 Central Valley likely to be Increasingly Vulnerable in 2070 based on Six Water Metrics

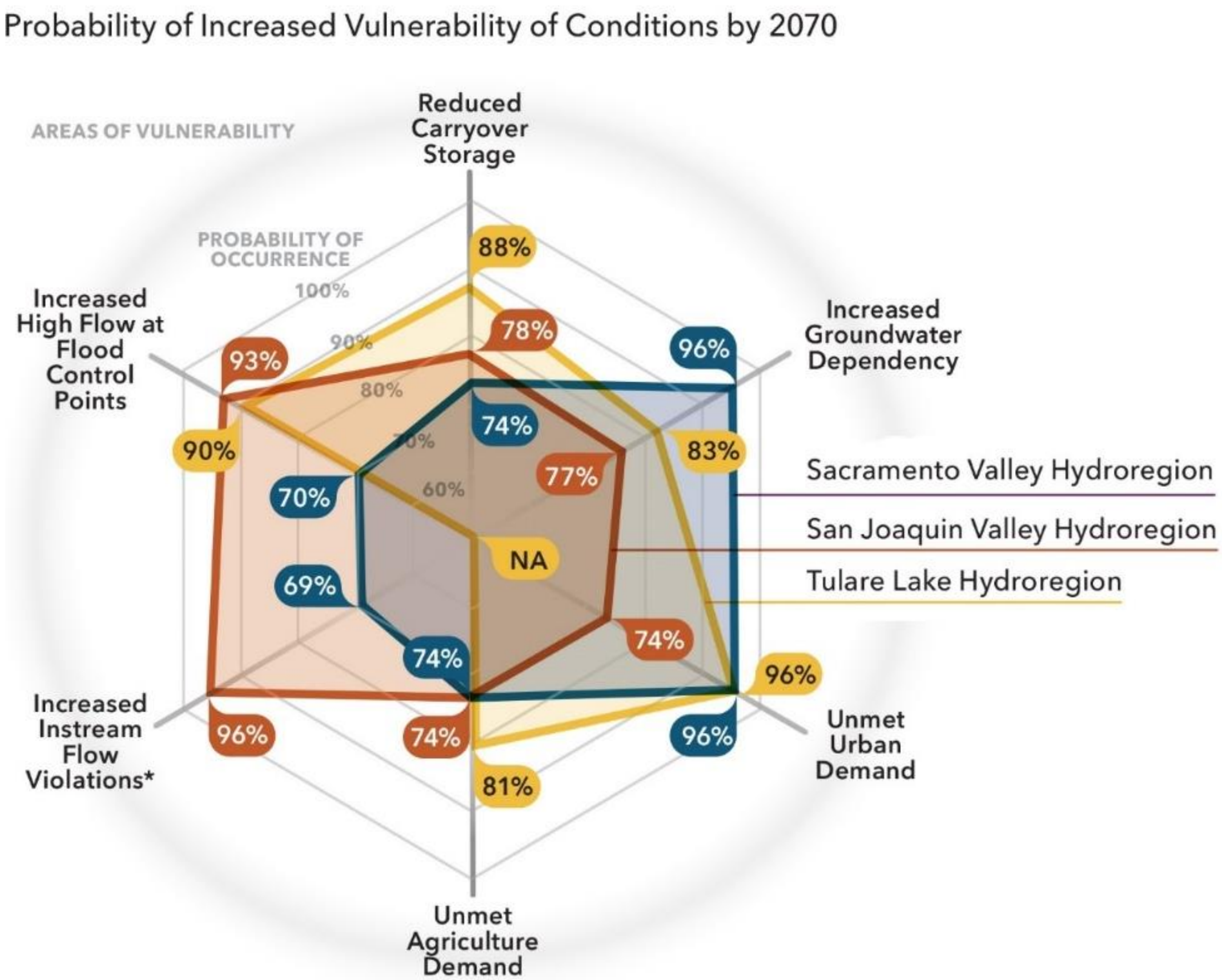
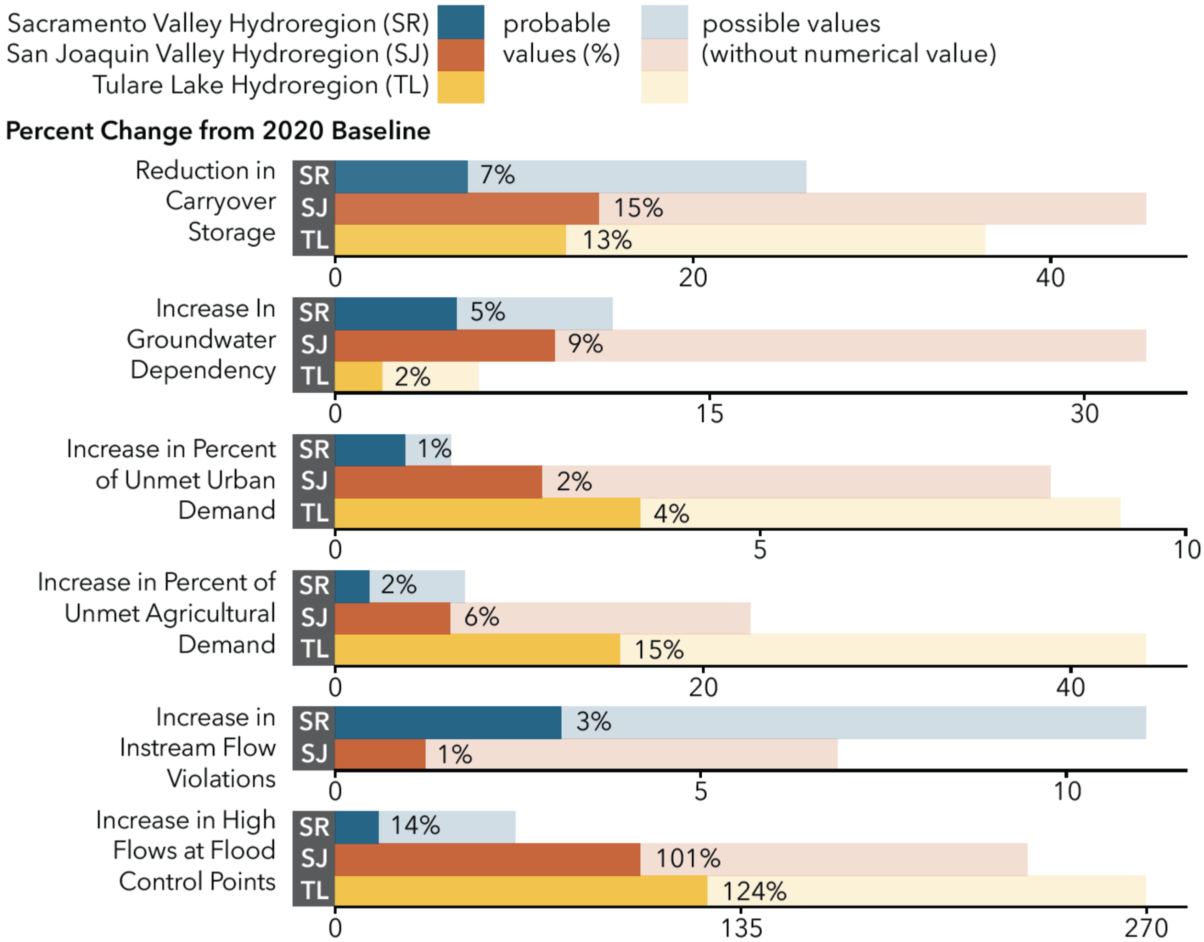


Figure 5-2 Bar Plot Shows Large Magnitude Changes for Six Water Metrics by 2070



Chapter 6. Findings

6.1 Overarching Vulnerabilities at Expected Future Conditions

The most significant finding of the future scenarios analysis for Update 2023 is that every metric representing an aspect of the water system health in the future showed a high probability (83 percent average) of worsening conditions by 2070 compared to current conditions. The analysis reveals that without implementing adaptation actions to improve the water system performance for addressing the effects of changing climate, Californians are likely to experience more frequent water shortages based on current climatic projections.

Although the probabilities of worsening conditions are very high, some of the expected magnitude of impact appear manageable. But, considering California's already water-stressed situation, any reductions in prime supply can be significant. For example, the expected decline in average carryover storage for reservoirs in the Sacramento River HR is approximately 7 percent or more than 700,000 acre-feet of water that will no longer be available on an average annual basis. That is the statistically most likely condition. Possible conditions exist within the 95-percent confidence limit that would result in much more severe average annual impacts, including a possible reduction in surface water storage in the Sacramento River HR as high as 26 percent.

6.2 Non-Uniformity of Climatic Vulnerability

Another important finding is that vulnerability to a changing climate is not uniform at the HR scale or within a region. For example, for the surface water metric (reservoir carryover storage), the Sacramento River HR will see expected reductions of approximately 7 percent on average. In comparison, the San Joaquin River HR will see a considerably more average percentage reduction of approximately 15 percent. However, specific reservoirs can experience much higher variability ranging from one reservoir experiencing a decrease in average carryover storage of 44 percent and a few reservoirs showing less than a 1-percent reduction. Climate change will not uniformly impact regions and areas within a region. For that reason, more detailed analyses, such as the Merced River Flood-MAR Watershed Study, are required to assess areas with high predicted future vulnerabilities.

6.3 Interdependency of Metrics

Some metrics selected for Update 2023 are interconnected and cannot be viewed in isolation. Specifically, unmet agricultural demand, unmet urban demand, and groundwater dependency are interrelated. For example, not all urban demands can be met by taking water from agriculture or allowing more groundwater withdrawal. The model incorporates constraints to prevent these metrics from negatively impacting each other. The model also attempts to mimic existing water rights priorities for allocations and caps groundwater extraction at maximum historic extraction levels. The combined unmet urban demand, unmet agricultural demand, and increased groundwater dependency represent the widening gap between supply and demand for future conditions (2070) relative to current conditions (2020).

6.4 Need for Adaptation Actions to Mitigate Future Vulnerability

Overall, the current analysis shows increasing vulnerability for all tracked indicators related to water supply in the Central Valley. There will be moderately significant reductions in carryover storage from year to year, increasing vulnerability to droughts. Increasing groundwater dependency for the future indicates that without the implementation of SGMA, the existing overtaxed groundwater system will be depleted even further. Unmet urban demand, on average, shows mild increases, with some areas regionally revealing a disproportionate rise in unmet urban demand because of the existing priority system and water rights structure. A more significant increase in unmet agricultural demand in the future likely would lead to a need to fallow additional land. Mild increases in instream flow violations are predicted. But the IFR control points experiencing these violations are significant as IFRs in the model have the highest priority; so if IFRs are not met, few other demands will be met. Finally, for the flood risk metric, the San Joaquin River and Tulare Lake HRs show significant increases in high flows during the winter months, indicating a high probability of worsening flood conditions in the future. The impacts indicated by Update 2023 future scenarios analysis may be able to be mitigated by adaptive actions, including strategies like flood-managed aquifer recharge (Flood-MAR).

Chapter 7. Future Work

Transitioning into Water Plan Update 2028 (Update 2028), much work is planned to further refine the analysis conducted in Update 2023, as presented in this report. The refinements for Update 2028 will include the following:

- Update the WEAP-CVPA model.
- Expand San Francisco Bay HR.
- Expand South Coast HR.
- Update vulnerability metrics and conduct adaptation strategy analyses.
- Develop interactive future scenarios dashboard.

7.1 Update the Current WEAP-CVPA Model

As part of Update 2028, the current model will be updated by incorporating newly acquired data reflecting the most current information. The possible data sources will include the Weather Generator, CalSim 3; the Sacramento Water Allocation Model (SacWAM); the San Joaquin Water Allocation Model; California Central Valley Groundwater-Surface Water Simulation–Fine Grid (C2VSim-FG) model; groundwater sustainability plans (GSPs); agricultural water management plans; and urban water management plans. Groundwater data and system simulation will be refined based on C2VSim-FG and GSPs to characterize the HR’s groundwater conditions, system characteristics, and inter-basin flows. The refined model will be recalibrated to reflect updated representations of irrigation management, land use, urban water use, infrastructure operations, south-of-Delta exports, and groundwater.

7.2 San Francisco Bay Hydrologic Region Expansion

Preliminary work for the San Francisco Bay HR was initiated in Update 2023 to expand the geographic coverage of the current model to include the San Francisco Bay HR. This expansion aims at providing a more detailed water supply transfer to San Francisco Bay HR from the existing model for the Central Valley. The expansion includes supply coverage for Solano, Napa, Alameda, Contra Costa, and San Francisco counties.

For Update 2028, the existing partially calibrated model for the San Francisco Bay HR will be refined and updated with more recently available data. The best available groundwater data will be used to characterize groundwater conditions, flows, and system characteristics in the HR. The model will be calibrated based on historical surface water and groundwater data to ensure that its simulations approximate recent historical surface water and groundwater conditions and that the model functions correctly across the range of climate extremes.

7.3 South Coast Hydrologic Region Expansion

As part of Update 2028, future scenarios analysis will be expanded by developing a model for the South Coast HR based on data and information collected about the surface water and groundwater conditions and operations in the HR. As in the San Francisco Bay HR expansion, the best available data will be used to properly characterize the South Coast HR's surface water flows and groundwater basins. This effort will include calibrating the model to ensure that its simulations approximate recent historical surface water and groundwater conditions.

7.4 Update Vulnerability Metrics and Conduct Adaptation Strategy Analyses

Metrics for Update 2023 were limited by existing model functionality, and metrics, such as IFR violations, that did not adequately represent the full vulnerability of the water sector. Additionally, for Update 2028, drought-specific metrics will be included as most metrics in Update 2023 are based on average conditions and might mask significantly increased vulnerability during droughts under future conditions. A set of revised metrics will be developed, which may require revisions to the WEAP model, including potential additions or changes in operations. The metrics being considered for Update 2028 include the following focus areas:

- Evaluate surface water and groundwater system resilience.
- Evaluate sustainable water use, including agricultural, urban, and managed wetlands.
- Evaluate stream and ecosystem health.
- Evaluate regional water budgets for water supply reliability.
- Assess and compare the economic costs of different adaptation strategies.
- Demonstrate how multi-sector and multi-scale economic connections can mitigate or exacerbate water shortages.

Adaptation strategy analyses also will be conducted to help identify the best management practices to enhance surface water and groundwater sustainability locally, regionally, and statewide.

7.5 Develop Interactive Future Scenarios Dashboard

As part of Update 2028, an interactive future scenarios dashboard will be developed. This online data viewer and explorer will be designed to communicate key strategic messages derived from future scenarios data and analysis from the future scenarios analysis conducted for the Central Valley, San Francisco Bay, and South Coast HRs. The dashboard will provide high-level insights on future vulnerabilities for State decision-makers and will provide system response information that would be helpful at local levels for understanding resource vulnerability to future climate projections.

Chapter 8. References

Brown C, Ghile Y, Laverty M, Li K. 2012. "Decision Scaling: Linking bottom-up vulnerability analysis with climate projections in the water sector." Water Resources Research Volume 48 (Issue 9). [Journal.] Viewed online at: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2011WR011212. Accessed: Sept. 21, 2023.

California Department of Water Resources. 2013. *California Water Plan 2013: Investing in Innovation and Infrastructure*. Bulletin 160-13. Resource Management Strategies. 858 pp. [Government Report.]

California Department of Water Resources. 2018. *California Water Plan 2018: Future Scenarios: Looking Ahead.* Bulletin 160-18. 148 pp. [Government Report.] Viewed online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/Update2018/Final/SupportingDocs/Future-Scenarios-of-Water-Supply-in-the-Central-Valley.pdf. Accessed: Sept. 21, 2023.

California Department of Water Resources. 2019. *Decision Scaling Evaluation of Climate Change Driven Hydrologic Risk to the State Water Project*. 107 pp. [Government Report.] Viewed online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/All-Programs/Climate-Change-Program/Climate-Action-Plan/Files/CAP-III-Decision-Scaling-Vulnerability-Assessment.pdf. Accessed: Sept. 21, 2023.

California Department of Water Resources. 2020. *Merced River Flood-MAR Reconnaissance Study Technical Memorandum 1 Plan of Study–Draft*. 34 pp. [Government Report.] Viewed online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/Flood-Management/Flood-MAR/Merced-River-Flood-MAR-Reconnaissance-Study.pdf. Accessed: Sept. 21, 2023.

California Department of Water Resources. 2022. *WEAP Model Application to Decision-Scaling Using Paleo Climate: A Pilot Study of the Merced River Planning Area, California*. 60 pp. [Government Report.] Viewed online at: https://water.ca.gov/-/media/DWR-Website/Web-Pages/Programs/California-Water-Plan/Docs/Update2023/Supporting-Documents/WEAP-Model-Application-to-Decision-Scaling-Using-Paleo-Climate---Pilot-Study.pdf. Accessed: Sept. 21, 2023.

Denton R, Sullivan G. 1993. *Antecedent Flow-Salinity Relations: Application to Delta Planning Models.* Prepared for: Contra Costa Water District. 20 pp. [Government Report.] Viewed online at: http://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/deltaflow/docs/exhibits/ccwd/spprt_docs/ccwd_denton_sullivan_1993.pdf. Accessed: Sept 21, 2023.

Useful Web Link

Future Scenarios Data Explorer

https://tableau.cnra.ca.gov/t/DWR_Planning/views/FutureScenariosInteractiveDataExplorerVersion1/StoryofCVVulnerability?%3Aembed=y&%3AisGuestRedirectFromVizportal=y

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