WEAP Model Application to Decision-Scaling Using Paleo Climate: A Pilot Study of the Merced River Planning Area, California

California Water Plan Update 2023
Supporting Document
Technical Report

DEPARTMENT OF WATER RESOURCES
STATE OF CALIFORNIA

WEAP Model Application to Decision-Scaling using Paleo Climate: A Pilot Study of Merced River Planning Area, California

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California Department of Water Resources

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Acronyms and Abbreviations

CVPA	Central Valley Planning Area
CWP	California Water Plan
DWR	California Department of Water Resources
Flood-MAR	flood-managed aquifer recharge
GCM	global climate models
HR	hydrologic region
maf	million acre-feet
PA	planning area
taf	thousand acre-feet
WEAP	Water Evaluation and Planning
WY	water year

Executive Summary

Water managers and planners constantly face the challenges of planning for an uncertain future where the only constant is change. While 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.

California Water Plan Updates 2005, 2009, 2013, and 2018 have progressively and proactively reported the best available information and state-of-the-art analytical tools and techniques for describing 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. Decision-scaling is an emerging cutting edge, risk-based, “bottom-up” approach for conducting climate vulnerability assessments (Brown et al. 2012) that can better inform regional and local investment decisions about climate adaptation strategies and projects (California Department of Water Resources 2013).

To prepare the climate change vulnerability assessment for Update 2023, the California Department of Water Resources (DWR) Future Scenario Team completed a pilot study to test if and how the Central Valley Planning Area Water Evaluation and Planning Model (WEAP-CVPA) can be applied using the decision-scaling approach. For the pilot study, the portion of WEAP-CVPA model covering the Merced River watershed was used as a proof of concept. The study also provided the opportunity for a high-level comparison of results with the more detailed Merced River Flood-Managed Aquifer Recharge (Flood-MAR) Watershed Study.

This technical report describes the model refinements, study methodology, and results of applying the decision-scaling approach to the Merced River Watershed portion of the CVPA-WEAP model. These are key findings of the pilot study:

- With model refinements the WEAP-CVPA can be used to apply the decision-scaling approach with numerous paleo-climate scenarios for Update 2023.
- The model captures the impacts of extreme paleo-climate scenarios on

the performance of the Merced River basin and its delivery system.

- The model predicted risk-based system performance under a wide range of climate change conditions for the following metrics: basin-wide water demand and supply delivery capabilities to agricultural and urban sectors, groundwater contributions to agricultural and urban sectors, surface storage, and change in groundwater storage in the basin.
- The model mirrored the long-term trends and average system responses to climate change impacts from the more detailed Merced Flood-MAR Watershed Study.

Based on these findings, DWR is applying the decision-scaling approach to the entire WEAP-CVPA model of California’s Central Valley and San Francisco Bay region to study system-wide performance and vulnerabilities in support of California Water Plan Update 2023, as described in the “Next Steps” section (page 46) of this report.

1. Introduction

1.1 Purpose

Water managers and planners constantly face the challenges of planning for an uncertain future where the only constant is change. While 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.

To prepare the climate change vulnerability assessment for Update 2023, the California Department of Water Resources (DWR) Future Scenario Team completed a pilot study to test if and how the Central Valley Planning Area Water Evaluation and Planning Model (WEAP-CVPA) can be applied using the decision-scaling approach. For the pilot study, the portion of WEAP-CVPA model covering the Merced River watershed was used as a proof of concept. The study also provided the opportunity for a high-level comparison of results with the more comprehensive Merced River Flood-Managed Aquifer Recharge (Flood-MAR) Watershed Study.

This technical report describes the model refinements, study methodology, and results of applying the decision-scaling approach to the Merced River Watershed portion of the WEAP-CVPA model.

1.2 Background

California Water Plan Updates 2005, 2009, 2013, and 2018 have progressively and proactively reported the best available information and state-of-the-art analytical tools and techniques for describing 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.

The climate change vulnerability assessments for prior updates of the California Water Plan used a “top-down” approach based on a series of plausible future climate scenarios downscaled from global climate models (GCMs) to quantify and compare general trends of system-wide water performance. That approach provided information about possible future water supply and demand conditions including unmet demands (supply shortfalls). But the limited and discrete number of GCM scenarios used might not be able to capture the entire range or frequency of climate change conditions that California may experience in the future.

1.3 Risk-based Approach

Decision-scaling is an emerging cutting edge, risk-based, “bottom-up” approach for conducting climate vulnerability assessments (Brown et al. 2012) that can better inform regional and local investment decisions about climate adaptation strategies and projects (California Department of Water Resources 2013). As a sensitivity analysis, the approach enables a climate “stress test” by predicting how a water system performs in response to a wide range of future climate conditions. Decision-scaling applies changes to historical climate data to generate a dataset of perturbed temperature and precipitation data, and the reconstructed climate dataset is then used to evaluate how a wide range of climate change conditions can impact water systems.

Climate response surfaces generated from the decision-scaling approach provide insights about climate vulnerability and system performance across a wide range of future climate scenarios. The results, coupled with statistical analyses, can quantify risk and the relative likelihood of future changes in system performance from different water management strategies and levels of investment.

2. Analytical Tool: Central Valley Planning Area Model

2.1 WEAP-CVPA Model Description

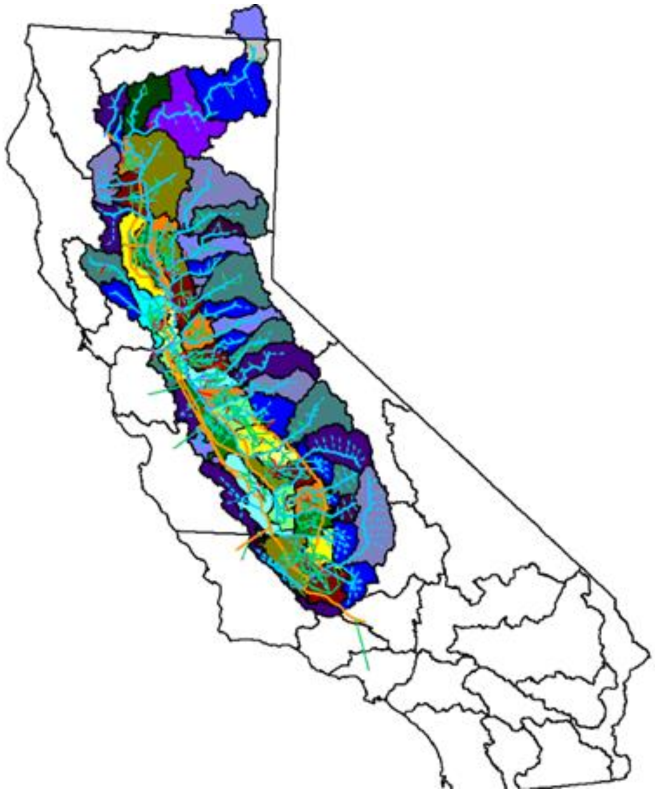
The CWP supports the development of a model for the Central Valley based on a WEAP analytical tool (www.weap21.org). The model, called WEAP-CVPA, covers the Central Valley floor and high elevations at a planning-area scale. It uses elevation bands for high-altitude catchments to capture rainfall runoff, snowpack accumulation, and snowmelt runoff processes. The WEAP analytic is a comprehensive, highly modular, and fully integrated demand-driven supply allocation model. It is a simulation model that includes a robust and flexible representation of water demands from different sectors and the ability to include operating rules for infrastructure elements such as reservoirs, canals, and hydropower projects. It has a very powerful, and yet flexible, scenario-building capability that allows to build an extensive array of scenarios with ease. It has built-in graphical display interface to view the results under multiple scenarios for comparisons. It also has the capability to project the study area schematics, with latitude and longitude coordinates, on Google Earth for global view of the international applications.

Its watershed rainfall runoff modeling capabilities allows the water infrastructure and demand to be dynamically nested within the underlying hydrological processes. This functionality allows the analyses of how specific configurations of infrastructure, operating rules, and operational priorities will affect water uses as diverse as instream flows, irrigated agriculture, and municipal water supply under hydrological input data and physical watershed conditions. This integration of watershed hydrology with a water-systems planning model makes WEAP ideally suited to study the potential effects of various uncertainties, including climate change.

In WEAP, water-demand sites receive supply deliveries based on the volumes of computed demand and a system of user-defined "demand priorities." The highest-priority demand sites will receive their supply deliveries first. If any water is left in the system, it will be delivered to the next demand sites on the priority list. If there is not enough water is left in the system, the demands in lower-priority sites will not get their full demand met, 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 form a hierarchical matrix of supply allocation “order” for supply deliveries. WEAP uses a linear programming optimization solver to solve the matrix of allocation order in the objective function. The objective function is to maximize 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 major demand sectors in the current WEAP-CVPA model application are agricultural, urban indoor, urban outdoor, and environmental flows. Major supply sources to meet the requested demands are from stream diversions, surface reservoirs, groundwater aquifers, and return flows. Figure 1 shows a schematic of the WEAP-CVPA model at planning-area scale.

Figure 1 **Schematic Representation of WEAP — Central Valley Planning Area Model**



2.2 WEAP-CVPA Model Geographic Coverage

The WEAP-CVPA model covers three hydrologic regions (HRs) in the Central Valley (Sacramento River, San Joaquin River and Tulare Lake) and performs detailed water supply and demand computations at the planning area (PA) level for each hydrologic region.

2.2.1 Sacramento River HR Planning Areas

Sacramento River HR consists of 11 PAs as shown in Figure 2.

1. PA 501 (Shasta-Pit).
2. PA 502 (Upper NW Valley).
3. PA 503 (Lower NW Valley).
4. PA 504 (NE Valley).
5. PA 505 (Southwest).
6. PA 506 (Colusa Basin)
7. PA 507 (Butte-Sutter-Yuba).
8. PA 508 (Southeast).
9. PA 509 (Central Basin-West).
10. PA 510 (Sacramento-San Joaquin Delta).
11. PA 511 (Central Basin- East).

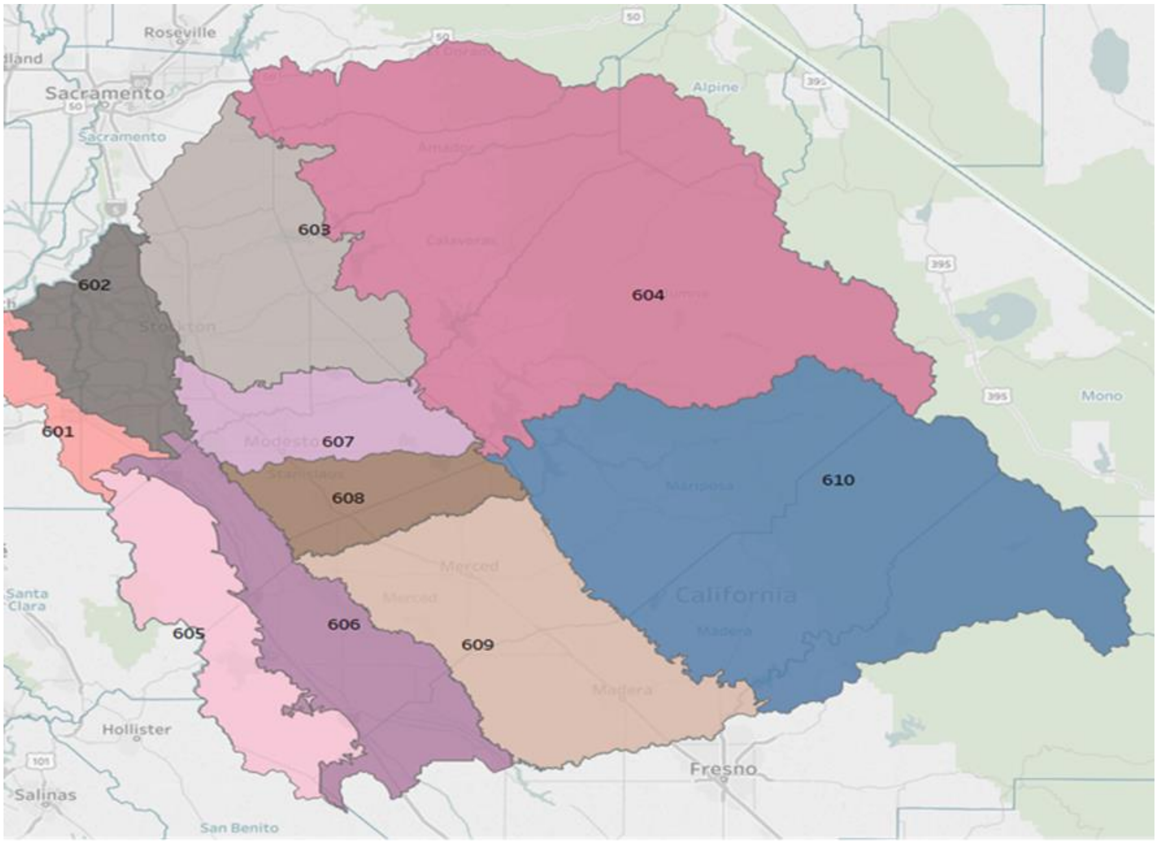
Figure 2 Sacramento River Hydrologic Region Planning Areas

2.2.2 San Joaquin River HR Planning Areas

San Joaquin River HR consists of 10 PAs as shown in Figure 3.

1. PA 601 (Central Basin- East).
2. PA 602 (Sacramento-San Joaquin Delta).
3. PA 603 (Eastern Valley Floor).
4. PA 604 (Sierra Foothills).
5. PA 605 (West Side Uplands).
6. PA 606 (Valley West Side).
7. PA 607 (Upper Valley East Side).
8. PA 608 (Middle Valley East Side).
9. PA 609 (Lower Valley East Side).
10. PA 610 (East Side Uplands).

Figure 3 San Joaquin River Hydrologic Region Planning Areas

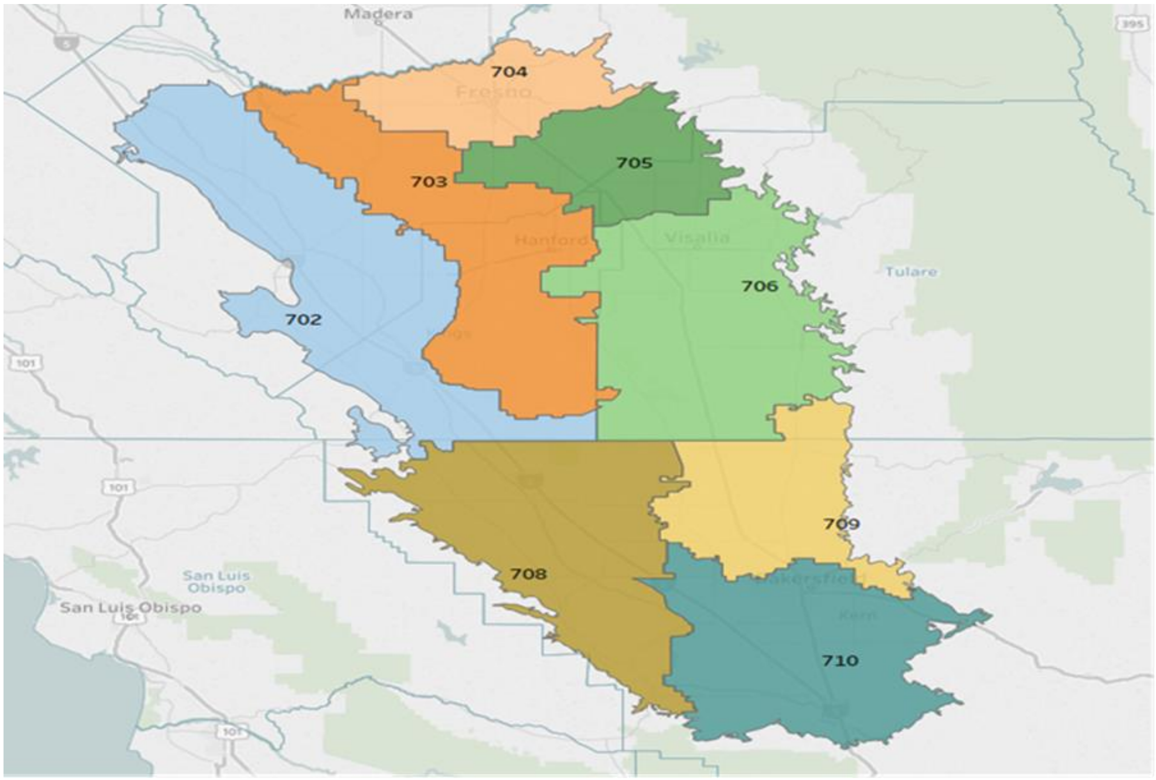


2.2.3 Tulare Lake HR Planning Areas

Tulare Lake HR consists of 10 PAs as shown in Figure 4.

1. A 701 (Western Uplands).
2. PA 702 (San Luis Side).
3. PA 703 (Lower Kings-Tulare).
4. PA 704 (Fresno Academy).
5. PA 705 (Alta-Orange Cove).
6. PA 706 (Kaweah Delta).
7. PA 707 (Uplands).
8. PA 708 (Semitropic).
9. PA 709 (Kern Valley Floor).
10. PA 710 (Kern Delta).

Figure 4 **Tulare Lake Hydrologic Region Planning Areas**



2.3 WEAP — Merced River Sub-model

2.3.1 Sub-model Description

The WEAP-Merced River model is a sub-system of the WEAP-CVPA model. The sub-model was developed for this pilot study by partially disconnecting the system-wide network of supply and demand links in the larger CVPA model. The dissecting process was done in a way that it would leave behind only the links that connects supply and demand nodes in study area of the Merced River water system. The study area includes planning areas 607, 608, and 609 (north and south) fed by the Stanislaus River, Tuolumne River, and Merced River systems, all draining into the San Joaquin River. Careful consideration was given to preserve the overall system integrity of the supply and demand links within the sub-model after dissection.

2.3.2 Sub-model Schematic Development

To develop Merced River sub-system schematics, dissection of the larger WEAP-CVPA schematics started from the far ends of the network at the peripheries working inward toward the Merced River sub-system. Supply and demand links within peripheral planning areas were disconnected one-by-one until reaching the perimeters of Merced River sub-system. Outer links on the perimeter affecting the internal links were kept and those not physically connected were carefully removed. This created a stand-alone sub-system representing the Merced River watershed, completely isolated from the larger CVPA model. Test runs were made to check for possible issues, errors, and system integrity. This sub-system model would result in faster simulation and shorter processing time to test applicability of the WEAP platform in a decision-scaling process to study system vulnerabilities. The Merced River sub-system within the larger WEPA-CVAP system is shown in Figure 5 and in close-up in Figure 6.

Figure 5 WEAP — Merced River Sub-model Schematics within the WEAP — Central Valley Planning Area Model

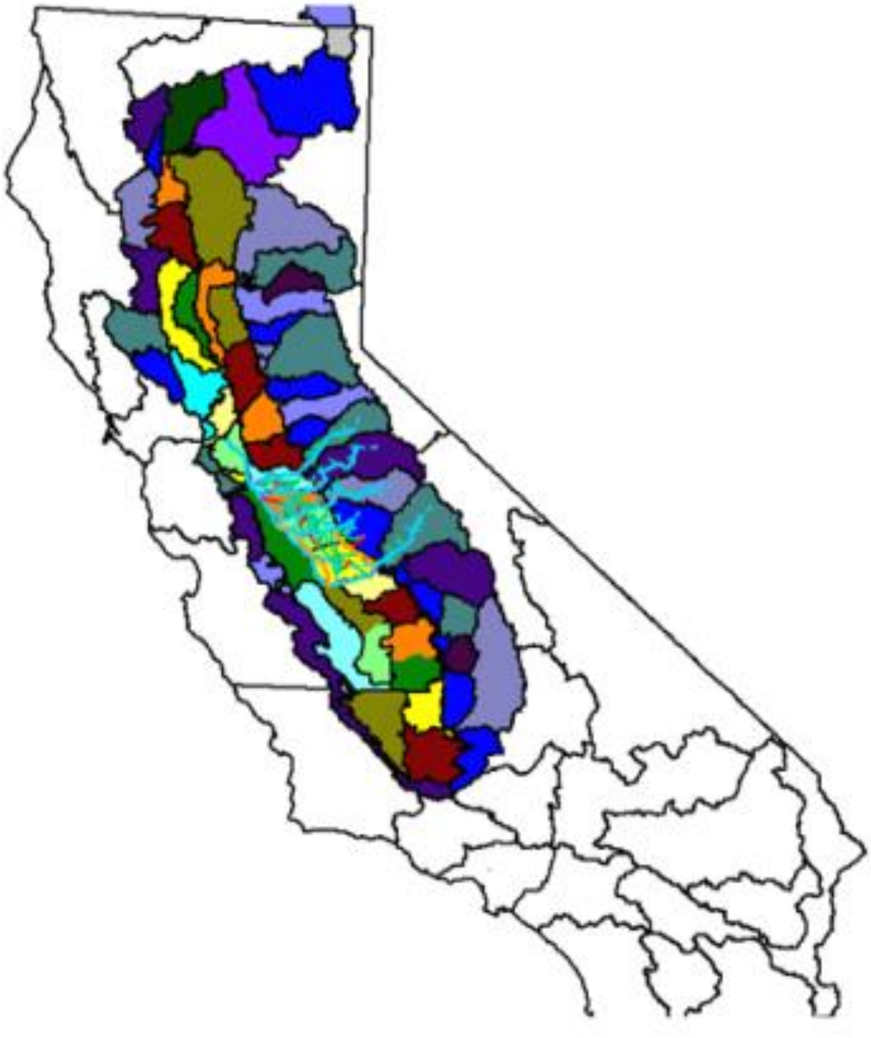
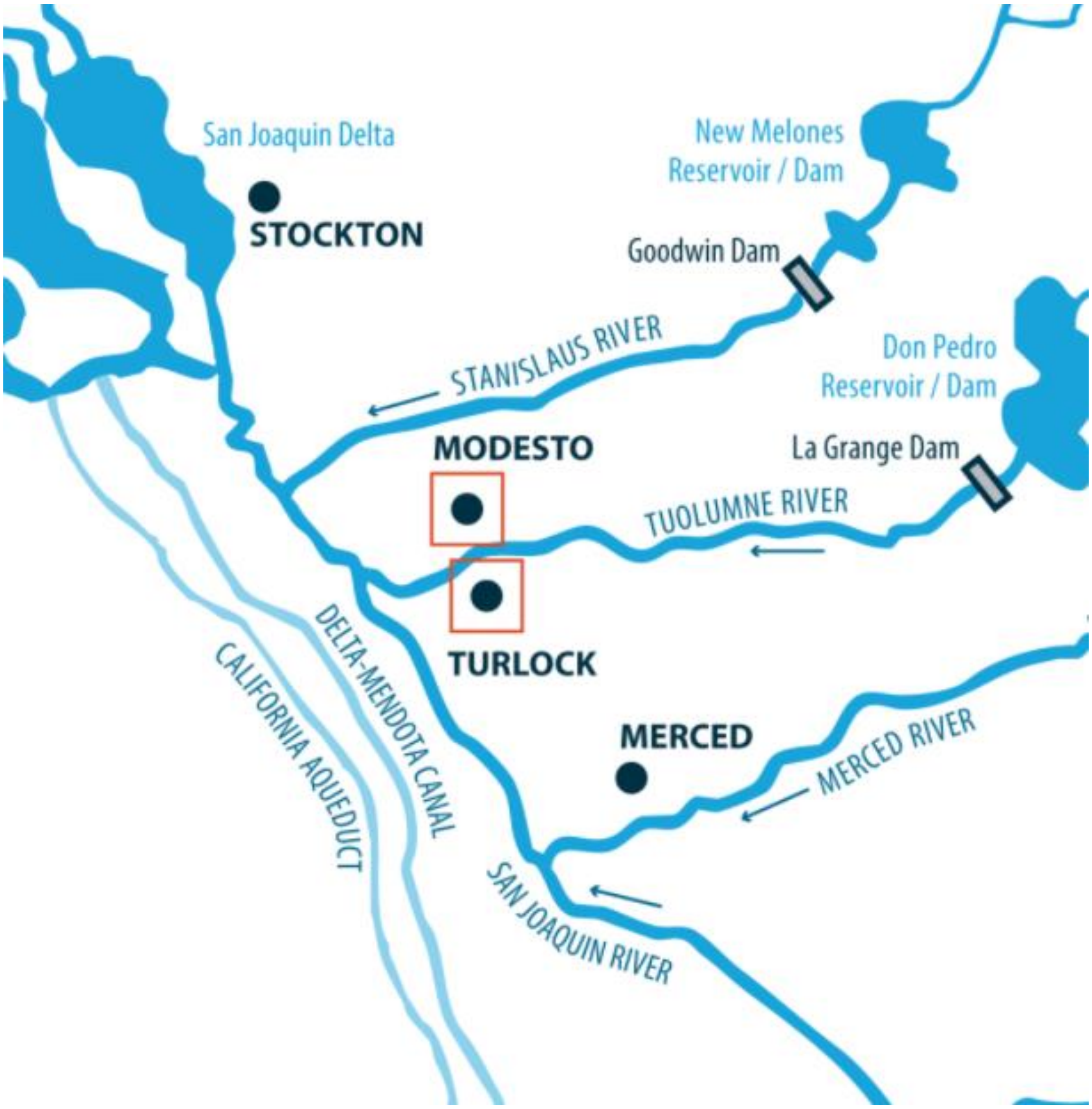


Figure 6 WEAP Merced River Sub-model Major Rivers and Geographic Coverage



Source: California Ag Today

2.3.3 Sub-model Geographic Coverage

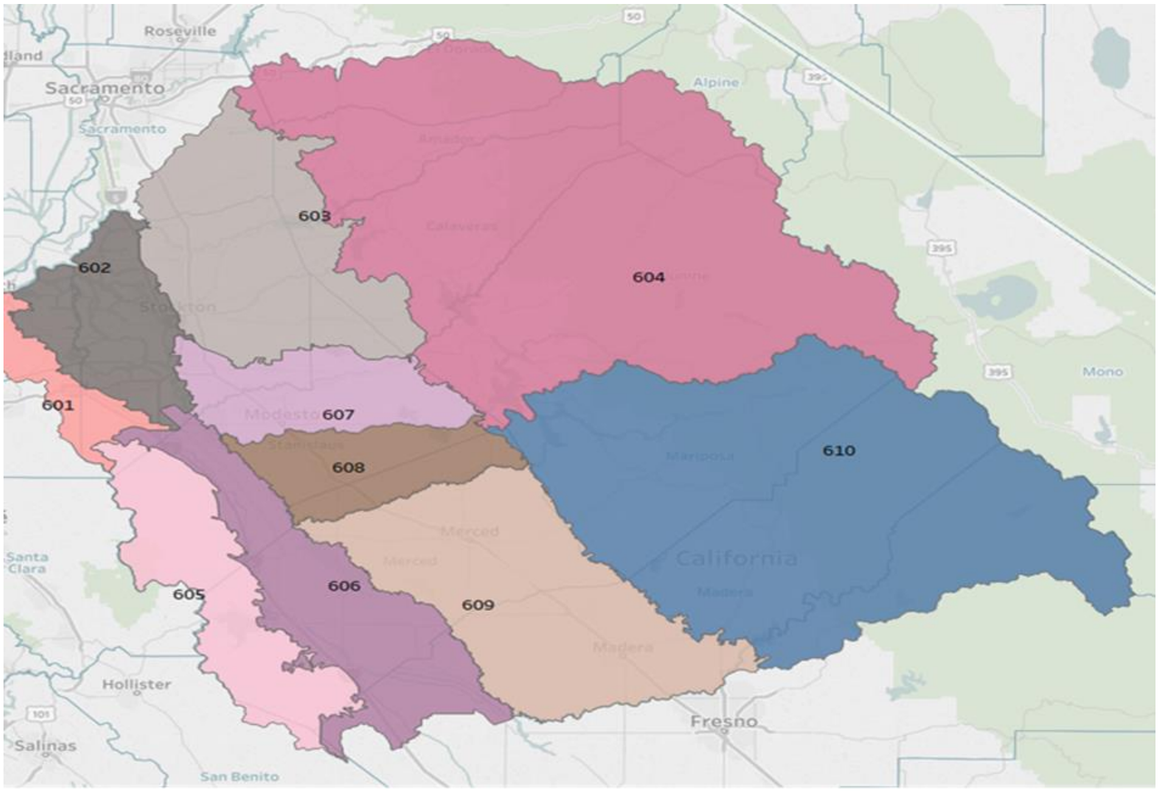
Merced River sub-system is located within San Joaquin River HR. It covers three PAs, 607, 608, and 609 (highlighted green) within the 10 PAs of San Joaquin River HR listed below.

1. PA 601 (Central Basin-East).
2. PA 602 (Sacramento-San Joaquin Delta).

3. PA 603 (Eastern Valley Floor).
4. PA 604 (Sierra Foothills).
5. PA 605 (West Side Uplands).
6. PA 606 (Valley West Side).
7. PA 607 (Upper Valley East Side).
8. PA 608 (Middle Valley East Side).
9. PA 609 (Lower Valley East Side).
10. PA 610 (East Side Uplands).

Figure 7 shows Merced River sub-system PAs 607, 608, and 609 within the 10 PAs of San Joaquin hydrologic region.

Figure 7 **Merced River Planning Areas within 10 Planning areas of the San Joaquin River Hydrologic Region**



3. Decision-scaling and Paleo Climate

3.1 Decision-scaling

3.1.1 Concept

The decision-scaling approach is a relatively new concept that can allow a direct “stress test” of existing system from “bottom-up” at project-level scale to inform future investment decisions. It is based on a relative change approach that can apply extensive and wide-range perturbations to historical data to capture extreme future climatic conditions and its potential impacts on system performance. This contrasts with a future-scenario approach that uses a limited number of global climate model (GCM) simulations, or to an ensemble-informed approach that applies an ensemble of larger number of downscaled future climate simulations. But both GCM-based approaches generally provide future trends that may potentially miss the extreme conditions.

3.1.2 Application

Decision-scaling can be applied to allow quantification of significant future climate shifts like extremely hot or dry conditions relative to natural variabilities as well as the critical climate thresholds causing the system to fail. Extreme climatic conditions, based on historical paleo-climate time-series can be constructed through perturbation process, to “stress test” the system which may not be possible to capture through GCM-based climate scenarios. Additionally, the resulting climate-driven response surface provides an insight into the expected performance and vulnerabilities of existing water system relative to its historical performance across a wide range of future perturbed climates. Lastly, the climate information coupled with formal statistical estimates can be used to directly quantify risks and relative likelihood of potential system performance under different levels of future water management and investment strategies.

3.2 Paleo Climate

3.2.1 Context

For the purpose of the decision-scaling analysis in this pilot study, urban growth and agricultural land use were fixed at their 2020 levels to provide system assessment at the existing level of development. But climate factors, such as precipitation and temperature, based on paleo-climate time-series, were allowed to vary over time to capture seasonal, annual variabilities, and extreme conditions. This contrasts with the conventional scenario-based approach used in recent CWP updates. In CWP updates, urban growth and climate varied concurrently over time to track their combined effects on future system demand under a selected number of GCM climate scenarios. In the decision-scaling approach explored in this study, urban growth and land use were fixed at a given level of development (2020 level) to isolate the effect of a climate stressor on system performance.

3.2.2 Paleo-based Climate (63 scenarios)

Paleo-based climate scenarios used in this pilot study were developed and provided by the DWR Climate Adaptation Section. The data consisted of 63 separate climate scenarios based on historical paleo-climate time series of mean-monthly temperature and monthly-total precipitation. It spanned a 1,100-year period from Water Year 901 through Water Year 2000. The 63 scenarios were obtained through a perturbation process performed by the DWR Climate Adaptation Section to generate a historical paleo-climate baseline time series (California Department of Water Resources 2020). The result was a temperature shift, ranging from 0 to +4.0 °C, at 0.5 °C increments, to the historical climate. Similarly, precipitation was shifted (ranging from −30 percent to +30 percent at 10 percent increments) from the historical baseline. This resulted in 63 combinations of temperature and precipitation time-series representing 63 distinct climate scenarios including the baseline historical no-change climate. Figure 8 and Table 1 show the 63 combinations of the perturbed Paleo-based climate scenarios. The scenario number from 1 to 63 in the table for tabular order and does not bear any other significance.

Figure 8 The 63 Combinations of Paleo-based Perturbed Temperature-Precipitation Scenarios

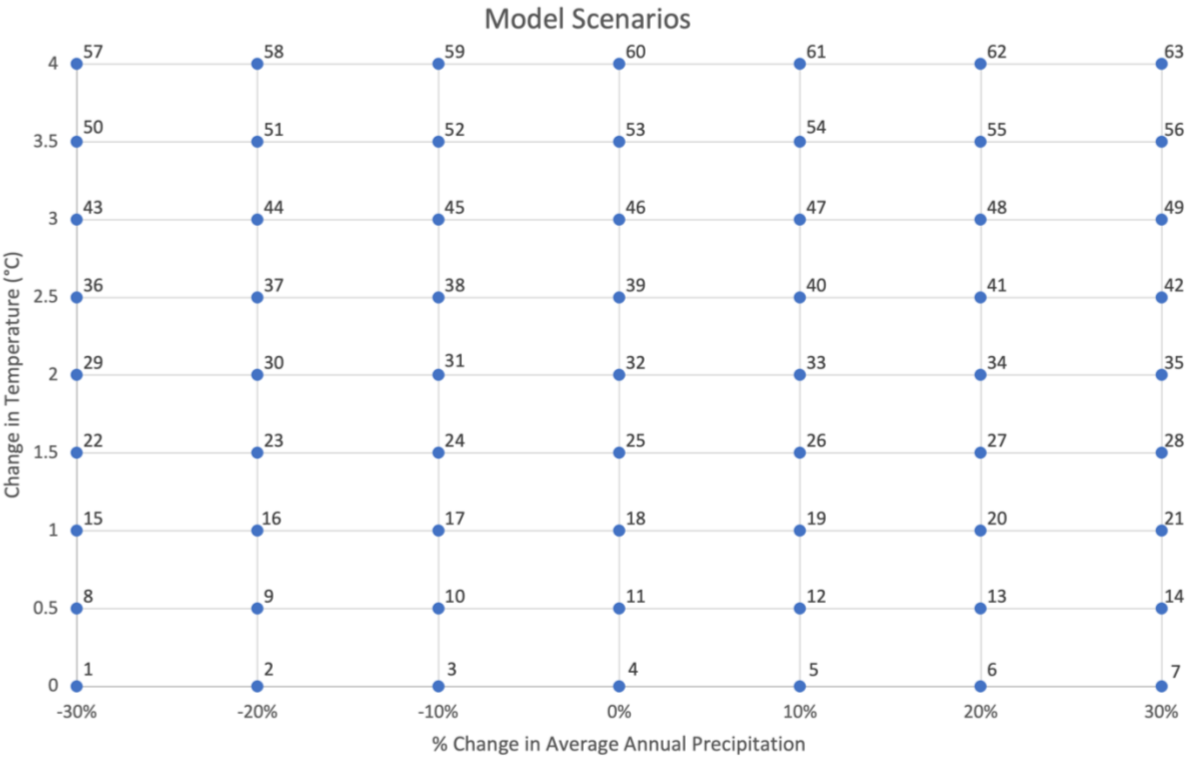


Table 1 The 63 Combinations of Paleo-based Perturbed Temperature-Precipitation Scenarios

Scenario	Temperature Change	Precipitation Change
1	0 °C	-30%
2	0 °C	-20%
3	0 °C	-10%
4	0 °C	0%
5	0 °C	+10%
6	0 °C	+20%
7	0 °C	+30%
8	+0.5 °C	-30%
9	+0.5 °C	-20%
10	+0.5 °C	-10%
11	+0.5 °C	0%
12	+0.5 °C	+10%
13	+0.5 °C	+20%

Scenario	**Temperature Change**	**Precipitation Change**
14	+0.5 °C	+30%
15	+1.0 °C	-30%
16	+1.0 °C	-20%
17	+1.0 °C	-10%
18	+1.0 °C	0%
19	+1.0 °C	+10%
20	+1.0 °C	+20%
21	+1.0 °C	+30%
22	+1.5 °C	-30%
23	+1.5 °C	-20%
24	+1.5 °C	-10%
25	+1.5 °C	0%
26	+1.5 °C	+10%
27	+1.5 °C	+20%
28	+1.5 °C	+30%
29	+2.0 °C	-30%
30	+2.0 °C	-20%
31	+2.0 °C	-10%
32	+2.0 °C	0%
33	+2.0 °C	+10%
34	+2.0 °C	+20%
35	+2.0 °C	+30%
36	+2.5 °C	-30%
37	+2.5 °C	-20%
38	+2.5 °C	-10%
39	+2.5 °C	0%
40	+2.5 °C	+10%
41	+2.5 °C	+20%
42	+2.5 °C	+30%
43	+3.0 °C	-30%
44	+3.0 °C	-20%
45	+3.0 °C	-10%
46	+3.0 °C	0%
47	+3.0 °C	+10%
48	+3.0 °C	+20%
49	+3.0 °C	+30%

Scenario	Temperature Change	Precipitation Change
50	+3.5 °C	-30%
51	+3.5 °C	-20%
52	+3.5 °C	-10%
53	+3.5 °C	0%
54	+3.5 °C	+10%
55	+3.5 °C	+20%
56	+3.5 °C	+30%
57	+4.0 °C	-30%
58	+4.0 °C	-20%
59	+4.0 °C	-10%
60	+4.0 °C	0%
61	+4.0 °C	+10%
62	+4.0 °C	+20%
63	+4.0 °C	+30%

4. WEAP — Merced River Sub-model Preparation and Application

4.1 Model Modifications and Preparation

Several modifications were made to the WEAP Merced River sub-model to prepare for extensive simulations required in this pilot study. Major modifications include the following:

- **WEAP Software.** A special version of WEAP software was specifically created for this study by WEAP developers at Stockholm Environment Institute. This was done to simulate the 1,100-year-long simulation period required by Paleo climate time series used in this study. The existing WEAP software was designed for a 500-year simulation period.
- **WEAP Automation Code.** The existing automation code, which automatically runs WEAP software for an extensive set of multiple scenarios back-to-back, was also modified. This was done to divide each 11,00–year-long Paleo climate scenario into 22 simulation cycles, each with 50-year simulation period. This was done to allow for the 22 simulation cycles to start from the same initial condition when they are run back-to-back under each of the 63 climate scenarios. The automation code generated a total of 63 x 22 = 1,386 individual simulation runs to cover the 63 perturbed combinations of climate scenarios in this study.
- **Simulation Time Horizon.** In previous WEAP applications to future scenario studies in Water Plan updates, simulation time horizons among various key factors were consistent. For example, urban growth and demographics (e.g., population, single family, and multifamily homes), land use, and climate data had consistent and synchronized timelines throughout the simulation. They all had future time stamps. But, in current pilot study, climate data have timelines in the past historical Paleo times (Water Year [WY] 901–WY 2000) whereas urban and land use have future timelines (WY 2006–WY 2100). WEAP has the capability to access different timelines of the different key input variables. This is done by using the “Offset Year” control variable in READFROMFILE statement to “look-ahead” or “look-back” when accessing time-series data with different timelines. Modifications were

made in all READ statements, using the Offset Year control variable, to properly access correct timelines for all catchments and demand nodes in this study. This way, while the model accesses historical climate data, it uses future level of urban and land-use data during the simulation.

- **Fixed Level of Development.** As with the issue of time horizon discussed above, urban growth and land use were allowed to vary over time in previous WEAP applications in CWP future scenario studies. But, in the current pilot study, based on a decision-scaling approach, the urban and land use development are required to remain fixed at a given level of development (e.g., 2020 level) over the simulation period. A new parameter (LevelofDevelop) was introduced under the KeyAssumptions tab of the model to denote the year of development (e.g., 2020 level in this study). Modifications were made in all related catchment and demand nodes in the study area to access ACTIVITY LEVEL for CurrentAccounts at the level of LevelofDevelop in the datafile. Then, under the selected scenario, set the future ACTIVITY level equal to CurrentAccountsValue. This way, the future level of development can become automatically fixed through the user-defined LevelofDevelop parameter for all scenarios at any level (e.g., 2030, 2050, or 2070) as the model steps through time during the simulation period.

4.2 Model Application

After extensive modifications and preparation of WEAP-Merced River sub-model, the model was applied 63 times at monthly time steps under the 63 distinct Paleo-based climate scenarios, each spanning a 1,100-year period from WY 901 through WY 2000. With each distinct 1,100-year-long simulation period, the model was re-set to its initial conditions at every 50-year cycle. This resulted in 22 individual simulations, each with a 50-year simulation period per climate scenario as explained above. This provided 22 individual 50-year-long average system performance information per climate scenario for use in decision-scaling statistics. A 50-year average was chosen in this study to represent an average condition, assuming no drastic system change over the period. Other average condition periods (e.g., 30 years) could have been assumed to evaluate average system performance on a more refined time period. After model applications using the 63 distinct climate scenarios as the major system stressor, the results were post-processed outside of WEAP application using python scripting tool to generate graphs showing system response surfaces.

4.3 System Performance Key Factors

In previous CWP updates, two major external drivers and key factors affecting system performance were considered: urbanization and climate change impacts. Urban growth can also affect agricultural demand as a result of urban encroachment into agricultural lands. For the purpose of the decision-scaling analysis in this pilot study, urban growth and agricultural land use were fixed at 2020 levels to provide system assessment at a fixed level of development. But climate was allowed to vary over time to evaluate its seasonal and annual variabilities as well as the extreme climatic conditions on system performance. Climate not only affects consumptive water demand in urban outdoor and agricultural sector, but it also affects total available supplies as a result of rainfall runoff, snowpack accumulation, and snow-melt runoff.

4.4 System Performance Metrics

System performances affected by climate change were evaluated based on a larger set of performance metrics and indicators used in a similar Merced River Flood-MAR study (California Department of Water Resources 2020). A smaller set of metrics was selected from the larger set based on its applicability in WEAP modeling system as described below.

4.4.1 Flood Risk

For the Merced River system, flood risks can be measured in terms of reoccurrence of peak flows and flows exceeding 6,000 cubic-feet per second in the Merced River at Cressey, the Bear Creek peak flow rate at McKee Road, and the maximum flood space encroachment at Lake McClure for a 1956-like event. To evaluate these risks, the WEAP model can provide system information such as stream flow time-series, probabilities of flow exceedance, and time-series of reservoir operational spaces including flood space, conservation pool, buffer zone, and dead storage.

4.4.2 Surface Water Conditions

The surface water conditions in the Merced River watershed can be measured in terms of the average annual agricultural consumptive demand met by surface water deliveries, average storage conditions at Lake McClure at the beginning and at the end of the irrigation season, and reoccurrence of Lake McClure storage at or below minimum operable pool storage. To evaluate surface water conditions in the Merced River watershed, the WEAP model is able to project annual agricultural water demand met by all sources combined, the inflow and outflow volumes of the demand sites, as well as the reservoir storage conditions and the probabilities of storage exceedance.

4.4.3 Groundwater Conditions

The groundwater conditions in the Merced River watershed can be measured in terms of average annual agricultural consumptive demand met by groundwater deliveries, average annual agricultural consumptive use demand met by recharged flood-MAR water supplies, basin-wide average annual change in depth to groundwater in the Merced sub-basin, and average annual change in depth to groundwater in the subsidence prone regions of the Merced sub-basin. To evaluate groundwater conditions in the Merced River sub-basin, the WEAP model can project annual agricultural water demand met by all sources combined including groundwater contributions and the inflow and outflow volumes of the demand sites. Although WEAP is not able to provide data on depth-to-groundwater, it is able to provide time-series information on changes in groundwater storage over time.

4.4.4 Ecosystem Management

The health of the ecosystem in the Merced River watershed can be measured in terms of metrics such as reoccurrence of Merced River flow above the required minimum flow threshold, average annual change in gain to stream along the Merced River, average annual floodplain inundation area along the Merced River below Crocker-Hoffman Dam, reoccurrence of groundwater depth at 30 feet or less in regions along Merced River or San Joaquin River supporting groundwater dependent ecosystems. To capture these metrics, WEAP is able to provide information on instream flow requirements time-series and probabilities of exceedance, stream inflows and outflows (gains from and losses to different sources), managed wetlands inundation volume, area and depth time-series, and changes to groundwater storages over time.

4.4.5 Economic Impacts

The economic impacts of flood-MAR operations in the Merced River watershed can be measured in terms of total dollar-value property loss from flooding in the Merced basin, costs and benefits but not flooding costs, operational and maintenance costs associated with flood-MAR operations, and the cost of pumping groundwater in the Merced sub-basin. To evaluate these metrics, WEAP can provide information on project capital costs and the fixed and variable operating costs related to flood-MAR project operation.

4.4.6 Performance Metrics: Selected for this Study

After further screening and investigation, a final set of eight system metrics was selected from the small set described above to provide better and more useful system information. The final set is listed below.

1. Annual agricultural water demand.
2. Annual agricultural supply deliveries.
3. Annual groundwater contributions to agricultural supplies.
4. Annual groundwater contributions to urban supplies.
5. Lake McClure end-of-March reservoir storage.
6. Lake McClure end-of-September reservoir storage.
7. Merced groundwater end-of-March change-in-storage.
8. Merced groundwater end-of-September change-in-storage.

5. Modeling Results and System Performance

5.1 System Performance

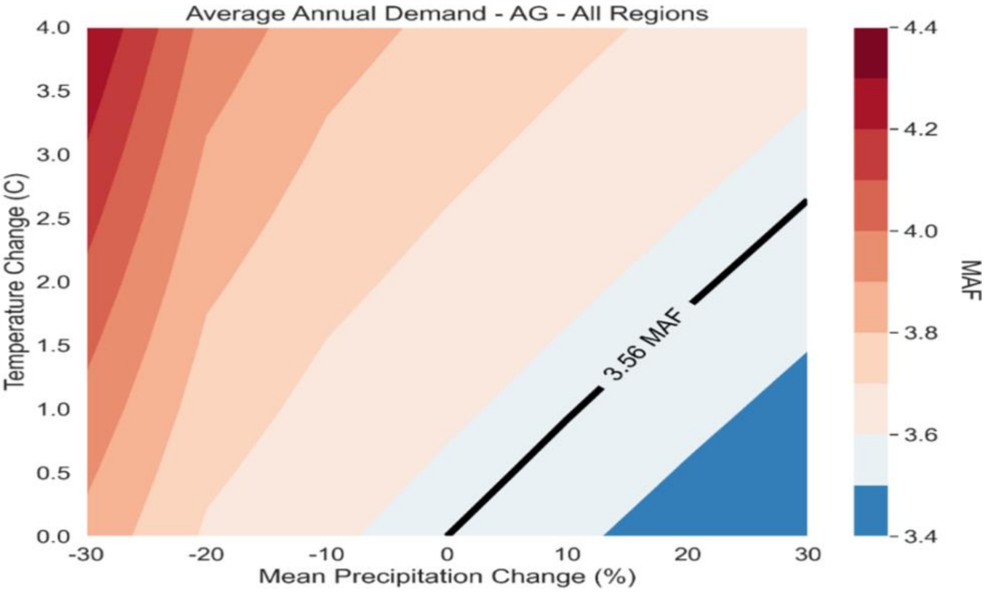
Performance of the Merced River watershed system, subject to climate stressors, is represented by performance metrics discussed in Section 4. The WEAP-Merced watershed model results are presented in graphs depicting response surfaces in the form of contour lines. The contour lines depict equal magnitude performance subject to perturbed changes in precipitation (X-axis) and temperature (Y-axis) relative to the historical baseline zero-change. Precipitation is perturbed at +/-10 percent changes shown on X-axis and temperature is perturbed at 0.5 °C increments shown on Y-axis. The resulting 63 intersectional points on the X-Y coordinates represent 63 distinct climate realizations, each spanning 1,100 years. Each of these 63 points on performance surface contour graphs represent an average value over the span for the performance metrics being evaluated. Below are brief descriptions of results in the form of contour lines depicting response surfaces.

5.2 Response Surfaces

5.2.1 Agricultural Water Demand

Figure 9 shows the response of system-wide demand to changes in climate. It shows how annual agricultural demand (averaged over the 1,100-year period) in the Merced River watershed responds to the 63 Paleo-based climate scenarios. The model shows, the average demand under the historical baseline “no change” scenario (i.e., 0 °C temperature change and 0 percent [no change] precipitation) is approximately 3.56 million acre-feet (maf). Slope of contour lines to the right of 0 percent change precipitation (almost at a 45-degree angle) indicates the demand is equally sensitive to change in temperature and precipitation when future climate is wetter than baseline historical. But when future becomes drier than historical climate (contours to the left of 0 percent change in precipitation), demand becomes more sensitive to temperature than to precipitation, as shown by the steep surface at upper left corner of the graph (compressed vertical contour lines). Slight changes in temperature under dry conditions results in drastic increase in demand. The regional demand almost peaks at 4.4 maf under hot and dry conditions of + 4.0 °C increase in temperature and 30 percent reduction in precipitation relative to 3.56 maf under no-change climate conditions.

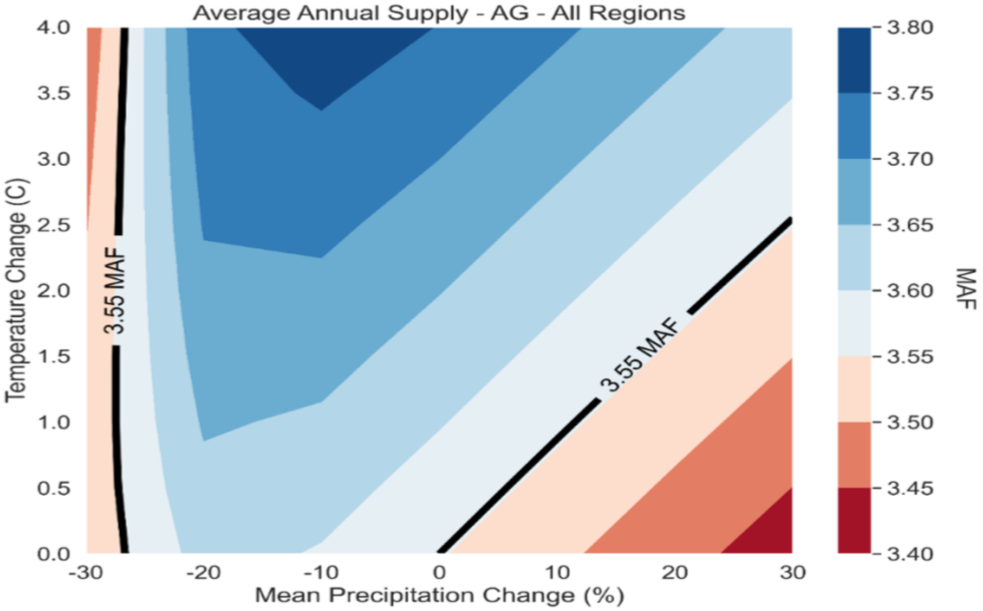
Figure 9 System Response of Annual Agricultural Demand (in million acre-feet) to Paleo Climate Scenarios, Merced River Study Area



5.2.2 Agricultural Water Supply Deliveries

Figure 10 shows response surface of regional water supply deliveries to the agriculture sector under the Paleo-based climate scenarios. As shown on the graph, the baseline supply deliveries under no-change scenario (solid-black contour line) is at 3.55 maf which is slightly lower than its required demand of 3.56 maf shown on Figure 9. This indicates slight water shortages under the historical baseline scenario. But as future climate shifts to wet conditions near the cool-end of temperature change scale, areas to the right of the solid-black baseline contour in the lower-right corner of the graph, supply deliveries also go down because ample precipitation stored in the root zone meets a big portion of crop consumptive demand. Supply delivery declines to approximately 3.4 maf matching the low end of the demand of 3.4 maf (Figure 9 indicating no water shortages under cool and very wet conditions. But, when future climate shifts to drier condition, areas to the left of solid-black baseline, the low supply delivery contour lines also curves into this part of the graph where water demand is continuously rising because of dry conditions. Here, supply deliveries are low, not because of low required demand, but because of limited water supply in the system resulting from lack of precipitation, implying severe water shortages. The water shortage reaches its peak at left-top corner of the graph (4.0 °C increase in temperature and 30 percent reduction in precipitation). Under this worst-case scenario, among all the 63 climate scenarios examined, water shortage is at its worst as expected, where demand is highest (4.4 maf) and supply delivery is at its lowest level (3.4 maf), resulting in the worst shortage of approximately 1.0 maf.

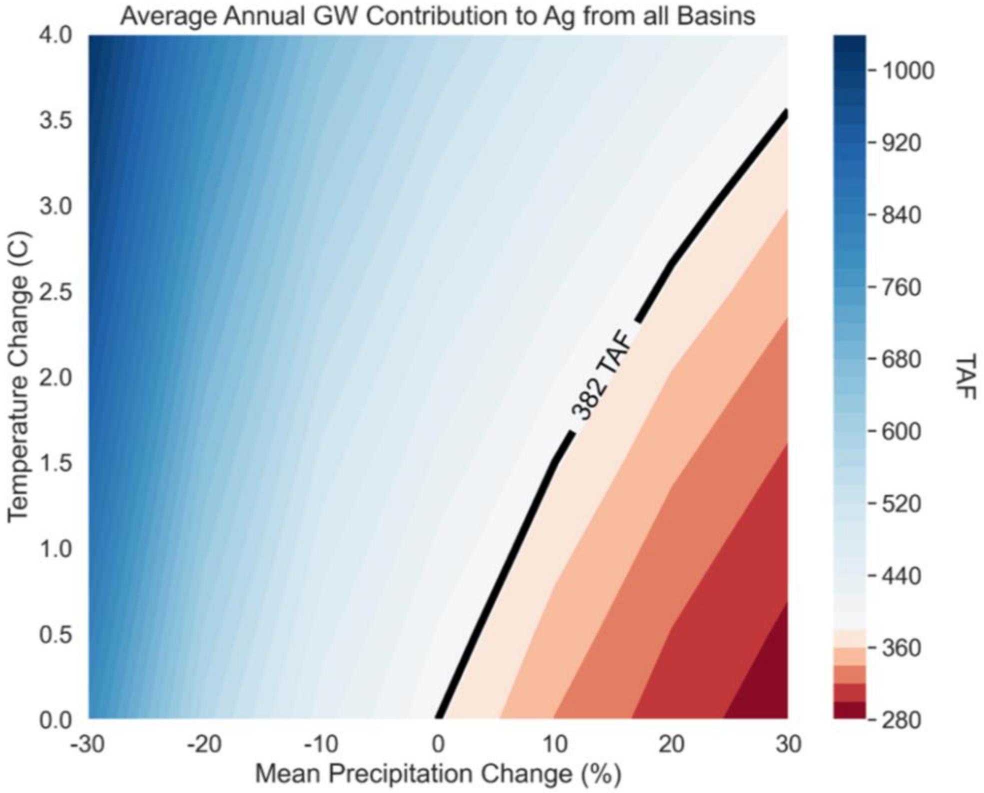
Figure 10 System Response of Annual Agricultural Water Supply Deliveries (in million acre-feet) to Paleo Climate Scenarios, Merced River Study Area



5.2.3 Groundwater Contributions to Agriculture

Contributions from regional groundwater to agricultural sector is shown in the system response graph (Figure 11). It shows average annual contributions in the form of contour lines under the 63 perturbed combinations of precipitation and temperature of Paleo-based historical climate. The graph shows groundwater contribution under the no-change Paleo-based historical climate was approximately 380 thousand acre-feet (taf) shown by a solid-black line. As climate becomes wetter than historical conditions, groundwater contributions, shown by contours to the right of the solid-black line, also declines. This is because wetter climate requires less supply deliveries, including supply contributions from groundwater aquifers, to meet irrigation demand because of increased moisture in the root zone provided by ample precipitation. But, as climate becomes drier (contours to the left of solid-black line), groundwater contribution increases. This may be explained by the fact that as climate becomes drier, total combined surface water and groundwater deliveries declines as shown by total supply deliveries in Figure 10 This decline is mostly the result of a decline in surface supply caused by a lack of precipitation to replenish surface reservoirs. As demand for water increases under dry climate (Figure 10), the WEAP model turns to withdrawal from groundwater aquifer as a second source after the prime source, the surface option, runs low, resulting in increased allocation from the aquifer. In the WEAP supply allocations, surface supplies are given higher preference over groundwater supplies. The groundwater contributions under the extreme hot and dry condition (4 °C increase in temperature and 30percent reduction in precipitation) increases to approximately 1,000 taf (top-left corner of Figure 11).

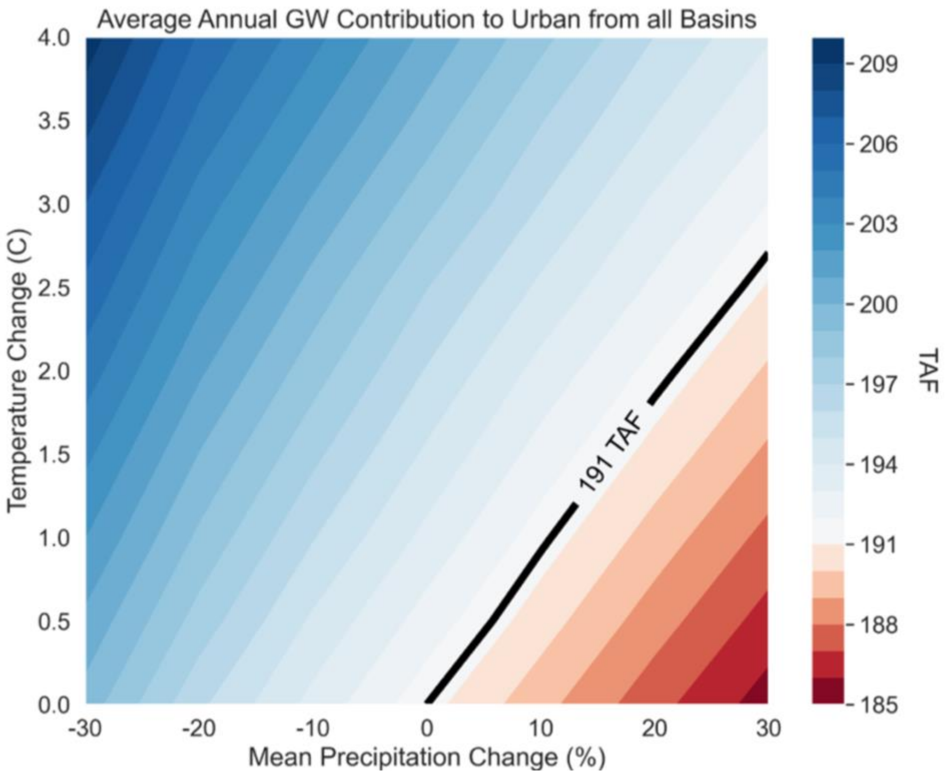
Figure 11 System Response of Annual Groundwater Contributions in the Agriculture Sector (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area



5.2.4 Groundwater Contributions to Urban

Figure 12 shows regional groundwater contributions to the urban sector in Merced River watershed in response to the 63 Paleo-based climate scenarios. Contributions under the baseline historical climate scenario, shown by solid-black line, was approximately 190 taf. Like the agriculture sector, groundwater contributions to the urban sector declines as climate shifts to wetter conditions (contours to the right of baseline historical). It should be noted that although indoor urban demand is not a function of climate factors, the outdoor urban demand is driven by climate stressors. As climate shifts to drier conditions (contours to the left of historical baseline), groundwater contribution to the urban sector increases. Again, like agriculture sector, when surface supply contributions as the prime source runs low because of low precipitation, the WEAP model taps into the aquifer as the second supply option. Under the extreme hot and dry and conditions (left-top corner of Figure 12), groundwater contributions peak at approximately 210 taf. (Note: Supply allocation preferences are user-defined in WEAP and can be switched as a scenario option.)

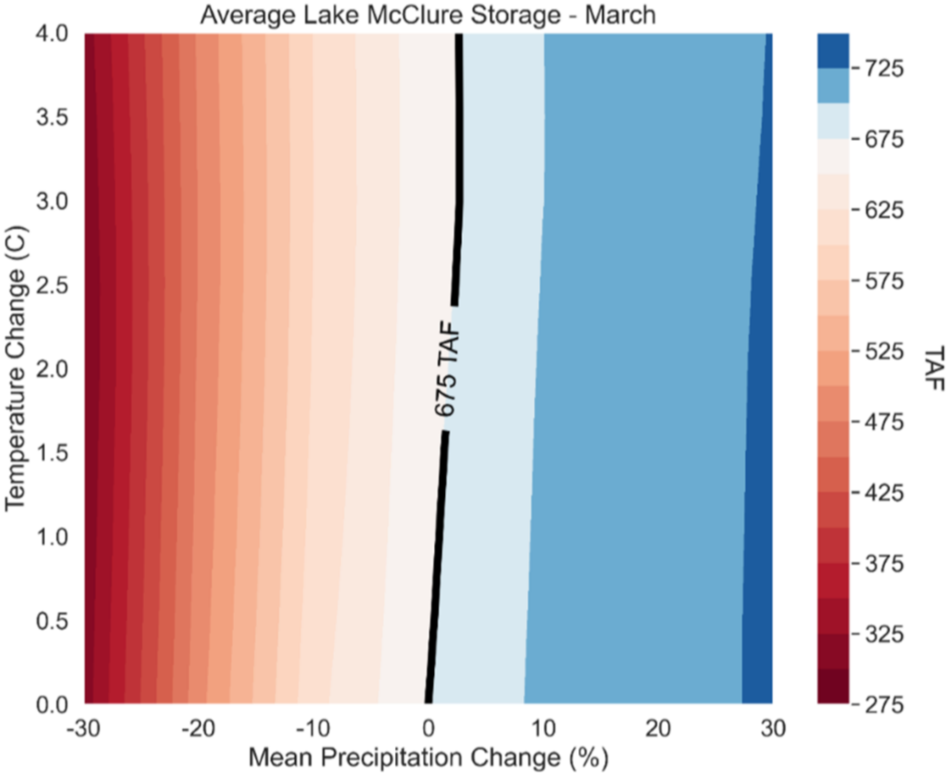
Figure 12 System Response of Annual Groundwater Contributions in the Urban Sector (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area



5.2.5 Lake McClure Reservoir Storage, End-of-March

Figure 13 shows contours of end-of-March storage conditions in Lake McClure under the 63 Paleo-based climate scenarios. The end-of-March graph shows storage stands at 675 taf under the historical baseline climate scenario depicted by the solid-black contour line. All contour lines show vertical inclination, implying March storage is highly sensitive to precipitation and no sensitivity to temperature, as expected. This is because the reservoir conservation pool goes through filling cycle with inflows from precipitation runoff during the first six months of rainy season, October through March. This makes reservoir storage highly responsive to precipitation rather than to temperature during the filling cycle, even under warm climate scenarios where early-season snowmelt provides a large portion of runoff to fill the reservoir (top end Figure 13). The graph also shows the minimum storage (275 taf) occurs at lowest end of the precipitation scenario (30 percent decrease) and the maximum storage (750 taf) occurs at the highest end of precipitation scenario (30 percent increase) regardless of the temperature scenarios.

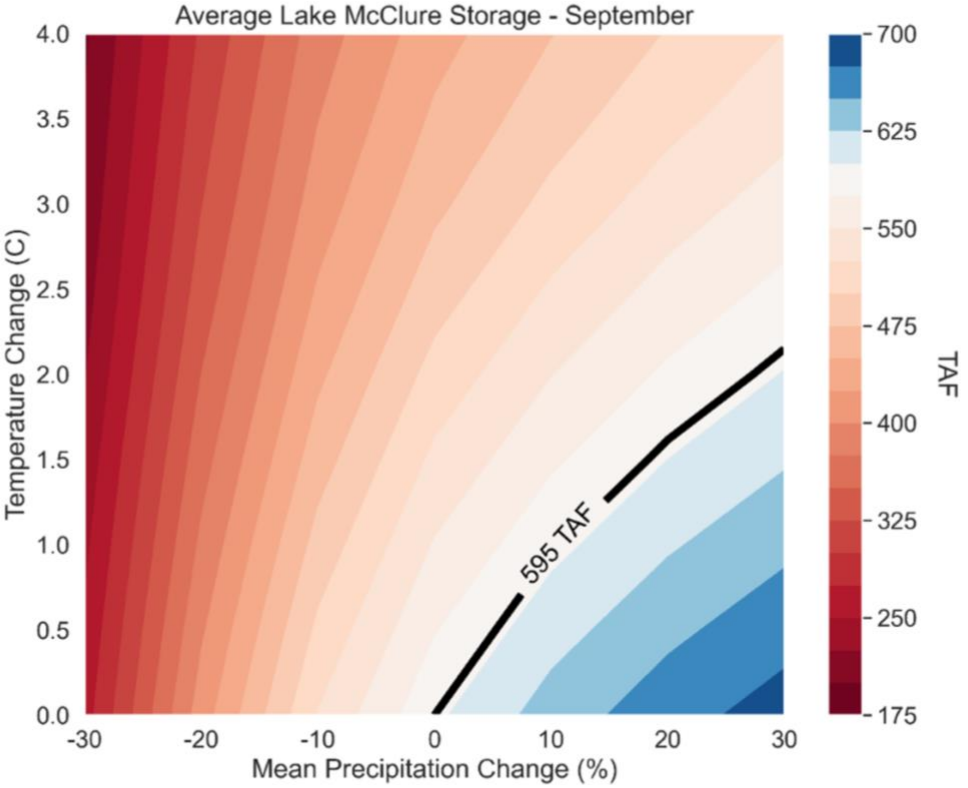
Figure 13 **System Response of Annual Lake McClure Reservoir End-of-March storage (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area**



5.2.6 Lake McClure Storage, End-of-September

Figure 14 shows contours of end-of-September storage as a function of precipitation and temperature in Lake McClure under the 63 Paleo-based climate scenarios. The graph shows September storage stands at 595 taf under the historical baseline climate scenario, depicted by the solid-black contour line. It shows as precipitation scenarios shift to wetter conditions (contours to the right of historical base line), September storage shows double sensitivity, changing with both precipitation and temperature. It increases with precipitation and decreases with temperature under wet climate scenarios. This is because by September, reservoir storage is depleted because of the dry period of the year and downstream releases to meet irrigation demands. But, as temperature rises towards warm scenarios demanding more releases, the September storage loses its sensitivity to temperature. One possible explanation is that high downstream demand caused by high temperature does not give the reservoir an opportunity to recover. This condition exacerbates storage recovery even further under drier conditions (contours to the left of historical base line) where storage contours gradually shift to almost vertical position indicating total insensitivity to temperature. This implies September storage has no chance of recovery under extreme dry conditions regardless of temperature increase. The results show the lowest September storage was at approximately 175 taf under the driest and hottest condition; 30 percent reduction in precipitation and 4 °C increase in temperature. The highest September storage was700 taf under the wettest and the least temperature increase scenario; 30 percent increase in precipitation and 0 °C increase in temperature.

Figure 14 **System Response of Annual Lake McClure Reservoir End-of-September Storage (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area**



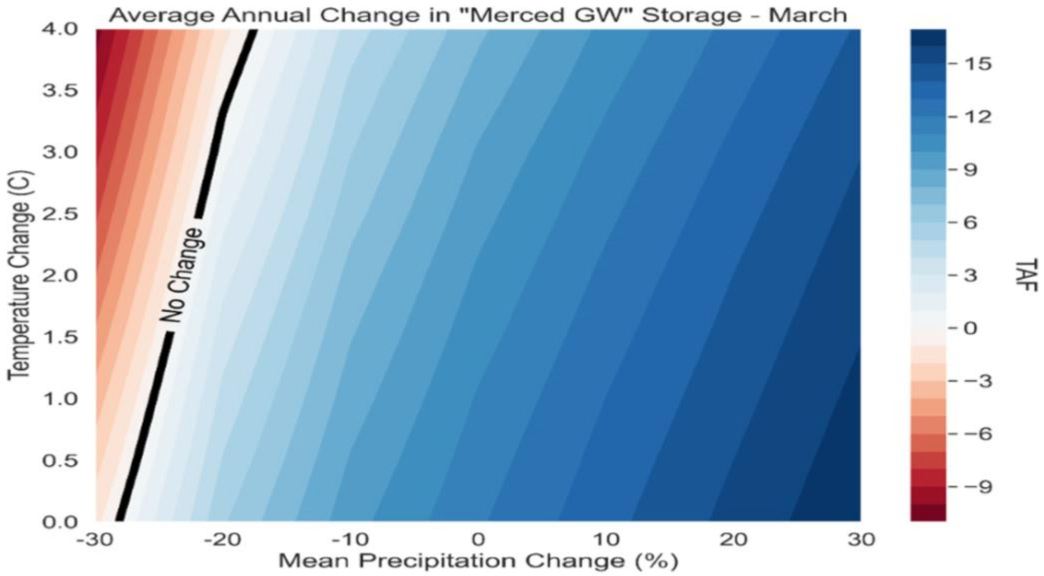
5.2.7 Merced Groundwater Storage Change, End-of-March

Figure 15 shows average annual contour lines of the Merced groundwater storage-change at the end of March as a function of precipitation and temperature under the 63 Paleo-based perturbed climate scenarios. Groundwater change-in-storage, rather than the actual storage, was selected as system performance metric because of uncertainties associated with the actual capacity of groundwater storages. The graph shows positive changes in groundwater storage under most of the climate scenarios considered, implying it was constantly recharging. Even under the historical baseline (0 percent change in precipitation and 0 °C change in temperature), the average annual change in storage was at approximately +12 taf (recharging). As climate shifted to wetter conditions (contours to the right of the graph), groundwater storage was also shifting to more fillings and recharging. Peak storage gain (recharge) of approximately 17 taf occurred under the extreme wet (30 percent increase in precipitation) and least warm (0 °C increase in temperature) climate scenario.

When climate shifted to less-wet scenarios, groundwater was still recharging but at lesser rate. This decline in recharge continued until drier condition of about 15percent to 28 percent reduction in precipitation, no-change in storage was captured by the model as shown by the “no change” solid-black contour line. But, below this very low precipitation level, Merced groundwater showed negative change in average annual storage, signifying the beginning of aquifer depletion (drawdown) trends. Extreme drawdown (approximately –11 taf) occurred under the extreme dry (30 percent reduction in precipitation) and hot (4 °C increase in temperature) climate scenarios. Figure 15 also shows storage in Merced groundwater is more sensitive to changes in precipitation than to temperature, as indicated by near-vertical inclination of contour lines.

The results suggest end-of-March storage in the Merced aquifer is very resilient to changes in climatic conditions. It was recharging under most of climate scenarios tested. This included dry conditions where there were shortfalls between supply deliveries and regional demand, implying shortages. In part, this can be explained by surface and groundwater storage usually going through a filling cycle during the first six months of the water year because of higher precipitation and lower demand during this period. Also, most of the demand is met first by surface supplies as indicated by surface and groundwater contribution graphs. This is because surface supply is given a higher preference in supply allocations in current version of the WEAP-Merced model. This provides an opportunity for groundwater storage to recharge during the first six months of the water year, ending in March.

Figure 15 **System Response of Annual Merced Groundwater End-of-March Change in Storage (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area**



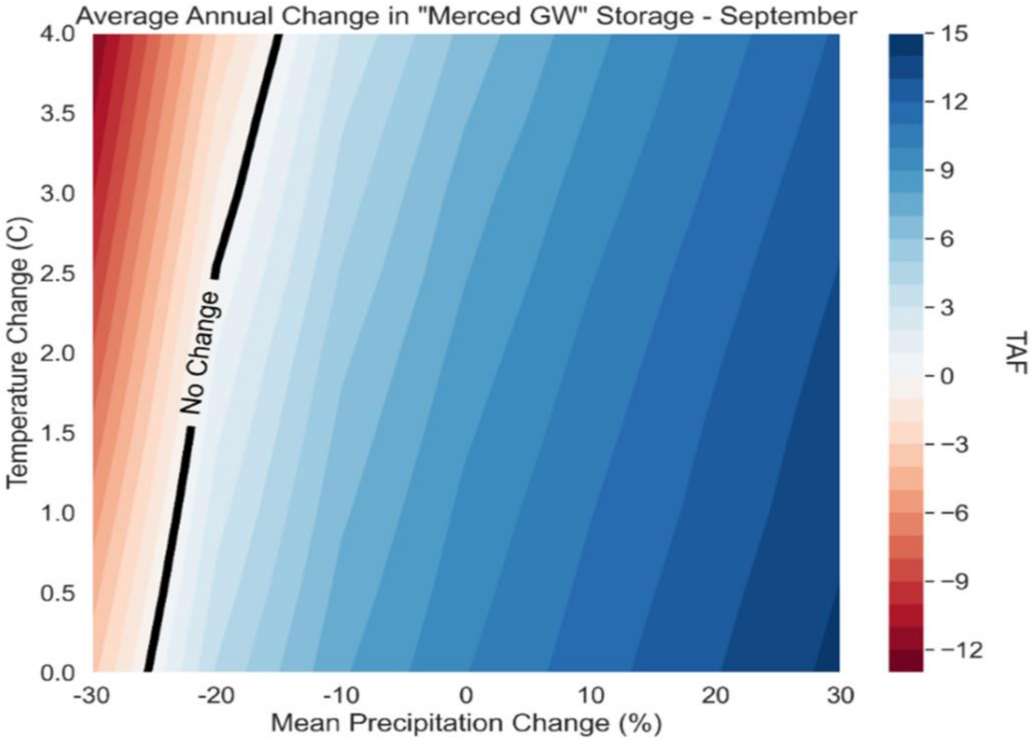
5.2.8 Merced Groundwater Storage Change, End-of-September

Similar to Figure 15, Figure 16 shows average annual contours of Merced groundwater storage change at the end of September as a function of precipitation and temperature under the 63 Paleo-based perturbed climate scenarios. It shows positive changes in groundwater storage under most of the climate scenarios considered, implying replenishment of the aquifer. Even under the historical baseline (0 percent change in precipitation and 0 °C change in temperature), the average annual change in storage was at approximately +10 taf (recharging); slightly less recharge than that of March. As climate shifts to wetter conditions (contours to the right of the graph), groundwater storage also shifted to more filling cycle and recharge. Peak storage gain (recharge) was approximately 15 taf and occurred under the extreme wet (30 percent increase in precipitation) and least warm (0 °C increase in temperature) climate scenario.

When climate shifted to less-wet scenarios, groundwater was still recharging, but at lesser rate. This decline in recharge continued until under drier condition of about 13 percent to 26 percent reduction in precipitation where no-change in storage (no recharge) was captured by the model, as shown by “no change” solid-black contour line. Below this dry precipitation range, Merced groundwater showed negative change in average annual storage implying start of depletion (drawdown). Extreme drawdown (approximately -13 taf) occurred under the extreme dry (30 percent reduction in precipitation) and hot (4 °C increase in temperature) climate scenarios. Figure 16 also shows storage change in the Merced aquifer by the end of September, like March storage, is more sensitive to changes in precipitation than to temperature as indicated by near-vertical inclination of contour lines.

The results suggest end-of-September storage in the Merced aquifer, like its end-of-March storage, was very resilient to changes in climatic conditions, albeit slightly less. It was recharging under the most of climate scenarios tested in this study. This included dry conditions where there were shortfalls between supply deliveries and regional demand, implying shortages. The question would be: Why was the Merced aquifer recharging during the second six-month period with relatively high demand ending in September? This, again, can partly be explained by most of the demand being met by surface supplies because surface water is given a higher preference in supply allocations in current version of the WEAP-Merced model.

Figure 16 System Response of Annual Merced Groundwater End-of-September Change in Storage (in thousand acre-feet) to Paleo Climate Scenarios, Merced River Study Area



6. Comparison with Ensemble Modeling of Merced River Watershed

The Merced River watershed system was the subject of a similar vulnerability study known as the Merced Study (California Department of Water Resources 2020). The study used a similar decision-scaling approach, but it was based on a more complex ensemble of several system models. This contrasts with the WEAP modeling platform used in this pilot study, which is based on a single stand-alone, but fully integrated, demand-driven supply allocation model requiring less effort and processing time. This provides an opportunity to assess if the results of these two modeling approaches are comparable. This way the performance and applicability of a simpler and coarser WEAP modeling tool can be evaluated, relative to an ensemble of more complex but more refined analytical tools, in studies of future water conditions and system vulnerabilities. It should be noted, in absence of a reference model or field data to use for test of model performance and accuracy, the present comparative analysis was undertaken to evaluate if results of these two modeling approaches were reasonably comparable.

6.1 Key Assumptions and Differences

To make meaningful and objective comparisons, the key assumptions and differences between these two modeling approaches need to be carefully considered and taken into account when interpreting the results. Some are listed below.

- **Simulation Period and Time Step.** As explained earlier, WEAP in this pilot study used 63 perturbed climate scenarios, each 1,100 years long. Perturbation was done on the historical baseline Paleo climate time series data spanning 1,100 years from Water Year (WY) 901 through WY 2000. The time series data consisted of mean-monthly temperature and monthly total precipitation. To perturb the monthly data, the historical baseline temperature was shifted from 0 to +4.0 °C, at 0.5 °C increment and precipitation was shifted from −30 percent to +30 percent at +/-10 percent (increase or decrease) increment. This gave a total of 63 climate scenarios each 1,100-years long at monthly time steps. For actual WEAP simulation, each 1,100-year-long scenario, the perturbed climate data were divided into

22 simulation cycles, each with a 50-year simulation period re-starting from the same initial condition at the beginning of each 50-year period. This resulted in a total of 63 x 22 = 1,386 WEAP simulations, each having 50-year-long continuous hydrology. This was done to provide a 50-year average hydrologic condition for use in decision-scaling statistics to evaluate system performance. Other periods of average condition (e.g., 30 years) could have been used to assess average system performance on a more refined time period.

In the Merced Study (California Department of Water Resources 2020), using the ensemble modeling, a 100-year-long historical climate data period was used as the baseline in the perturbation process. The temperature was perturbed from 0 to 4 °C, at 1-degree increments. Precipitation was perturbed from -20 percent to +30 percent change in precipitation at 10 percent increments This resulted in 30 perturbed climate scenarios, each with 100-year-long continuous hydrology, each running over a 100-year-long simulation period, giving a total of 30 simulation outcomes. This contrasts with the WEAP simulations with 63 perturbed climate scenarios, each with 22 cycles of 50-year-long continuous hydrology, each running over a 50-year-long simulation period, giving a total of 1,386 simulation outcomes. Although, WEAP uses a higher number of perturbed climate scenarios (63 vs. 30) with higher number of simulation outcomes (1,386 vs. 30) resulting in finer resolution of system performance metrics compared with the ensemble modeling approach, the result to capture trends in system performance and indicators should still be comparable.

- **Geographic Coverage and Spatial Scale**. Merced River watershed in WEAP model for this pilot study covers three planning areas (PAs), 607, 608, and 609. PA 607 is in the upper valley’s east side, PA 608 is in the middle valley’s east side, and PA 609 is in the lower valley’s east side of the watershed. PA 609 is split into PA 609 North and PA 609 South. The agricultural, urban, and environmental sector demands in WEAP are approximated at the spatial scale of planning areas. But ensemble modeling used in the Merced Study is based on more realistic spatial representations with finer resolutions. The study area covers Merced River to the north, Chowchilla to the south, and San Joaquin River to the west. Demand service areas are represented at much finer spatial scale across the watershed. There are few demand areas serviced by Northside Canal on north side of the Merced River.

In general, geographic coverage in ensemble modeling for the Merced Study closely resembles PA 609 North planning and some portion of PA 608 in WEAP modeling for this pilot study.

- **Level of Development**. Although climate factors such as temperature and precipitation were allowed to vary over time in the current pilot study, the urban development and land use were fixed at the 2020 level of development over the simulation period. This was a part of the decision-scaling process to isolate the impact of climate change on system performance from other variables. The Merced Study used a more updated land-use data than the WEAP application in this study. It used 2014–2015 Land IQ land-use data and 2015 urban demands from the C2VSim-FG model.

6.2 System Performance and Comparison Graphs

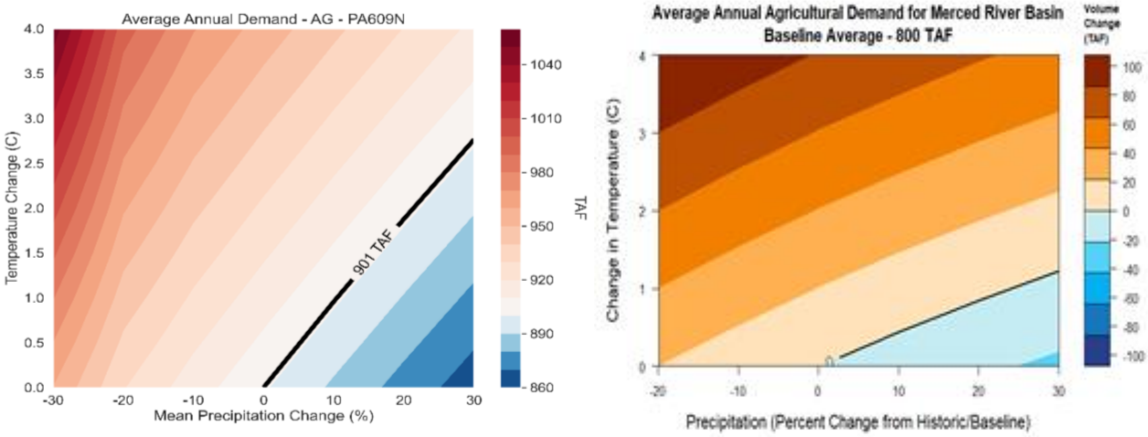
Graphs and discussions in this section give a descriptive comparison of response surfaces for a few selected system performance metrics available from WEAP modeling results used in the current pilot study versus those of ensemble modeling used in the Merced Study. It should be noted, even though both modeling approaches report long-term annual averages, graphs from WEAP modeling show absolute values whereas graphs from the Merced Study show values relative to baseline conditions where baseline values are given at the top of each graph. To convert to absolute values, the baseline values should be algebraically added to relative values in the Merced Study graphs to be comparable with WEAP modeling graphs. The few selected performance metrics available to compare the results of these two modeling approaches are:

- Agricultural water demand.
- Groundwater contribution to agricultural water supply.
- Merced groundwater end-of-September change-in-storage.
- Lake McClure Reservoir end-of-September storage.

6.2.1 Agricultural Water Demand

Figure 17 shows response surfaces of average annual agricultural water demand (in million acre-feet) for applied irrigation water in the Merced River watershed simulated by WEAP model on the left (a) and by ensemble models on the right (b) under the perturbed paleo-climate scenarios. The results show the demand for applied water under the historical baseline paleo climate simulated by the WEAP model was approximately 901 taf, while the ensemble model reported approximately 800 taf. This difference could partly be the result of coarser representation of agricultural land areas in the WEAP model. Both models generally show that as climate becomes drier and warmer, the demand for agricultural water increases. But the results show contour lines depicting the agricultural water demand having steeper vertical inclination in the WEAP model (shown on the left), than those from the ensemble model (shown on the right). This indicates the WEAP model is more sensitive to drying conditions than warming trends in predicting agricultural water demand when compared with the ensemble model. The difference could be because of differences in modeling assumptions and input data between these two modeling systems.

Figure 17 Comparison of System Response. Agricultural Water Demand (in thousand acre-feet); (a) WEAP Model, (b) Ensemble Model



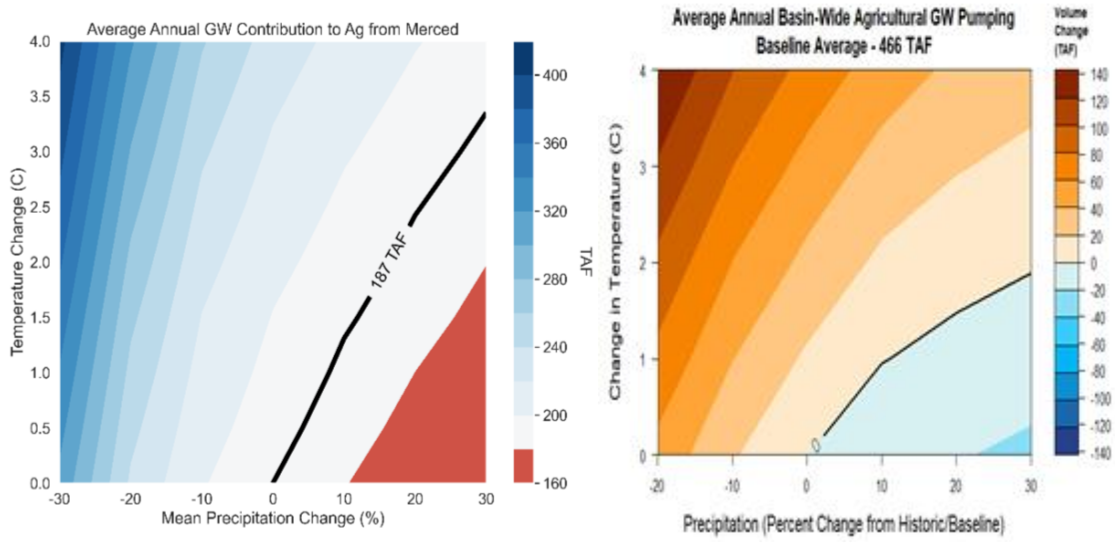
6.2.2 Groundwater Contribution to Agricultural Water Supply

Contribution from the Merced aquifer to the agricultural water supply are shown in Figure 18 in the form of response surfaces for WEAP model on the left (a) and for ensemble models on the right (b). It should be noted, on these graphs, magnitudes of response surfaces for WEAP are in absolute values, while the ensemble models are relative to the baseline value. With that in mind, the graph for WEAP model shows groundwater contribution to the agricultural water supply under the historical baseline Paleo climate was approximately 187 taf, shown by the solid-black line. The ensemble models predicted higher contributions at approximately 466 taf. This difference, and the lower groundwater contributions in WEAP, may be partly explained by

(1) the groundwater representation in WEAP being assumed as a one-dimensional control volume and given lower supply preference than surface supply options, and (2) pumping rates constrained by the historical minimum groundwater level. These make supply deliveries in WEAP to be less reliable on groundwater option.

The WEAP model shows groundwater contributions decline as climate becomes wetter than historical averages, as shown by contours to the right of the solid-black line. This is because wetter climate requires less supply deliveries by taking advantage of increased moisture in the root zone provided by ample precipitation. Similar trend is also shown by the ensemble models. But, as climate becomes drier (contours to the left of the solid-black line), groundwater contribution increases in both modeling approaches. This may be explained by the fact that as climate becomes drier, total combined surface water and groundwater deliveries decline. This decline is mostly the result of a decline in surface supply that is caused by a of lack of precipitation to replenish surface reservoirs. As demand for water increases under dry climate, both models turn to withdrawal from groundwater, resulting in increased allocation from aquifer.

Figure 18 **Comparison of Groundwater Contributions to Agricultural Water Supply; (a) WEAP Model, (b) Ensemble Model**

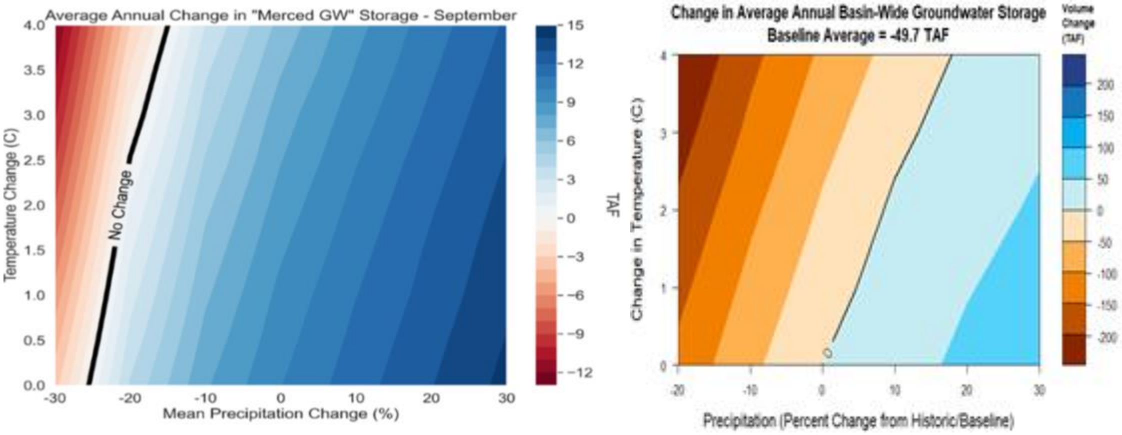


6.2.3 Merced Groundwater End-of-September Change-in-Storage

Figure 19 shows responses of average annual end-of-September storage change to climate signals based on Paleo-based scenarios in the Merced aquifer predicted by the WEAP model on the left (a) and by the ensemble model on the right (b). The WEAP model shows positive changes in groundwater storage under most of the climate scenarios, implying recharging of the aquifer. Even under the historical baseline (0 percent change in precipitation and 0 °C increase in temperature), the average annual change in storage was at approximately +10 taf (recharging). This contrasts with the results from ensemble model where the average annual change-in-storage in September was about -50 taf (depleting). As climate shifts to wetter conditions (contours to the right of the graph), groundwater storage predicted by the WEAP model also shifted to more recharge. Peak storage gain was approximately 15 taf and occurred under the extreme wet (30 percent increase in precipitation) and least warm (0 °C increase in temperature) climate scenario near the bottom right corner of the graph. A similar recharge trend was predicted by the ensemble model, but at higher rate. The gain in storage peaked to approximately +50 taf under the similar extreme wet (30 percent precipitation increase) and cool (0 °C increase in temperature) weather conditions.

When climate shifted to less-wet scenarios, the WEAP model predicted the aquifer was still recharging, but at lesser rate. This decline in recharge continued until under the dry and warm condition of 20 percent reduction in precipitation, and 4 °C increase in temperature where WEAP showed a mild depletion in the storage of approximately 10 taf. Again, this is in sharp contrast to the results from the ensemble model where the depletion was approximately 250 taf (left top corner of the graph). It seems groundwater storage in WEAP responds moderately to changes in climatic conditions, while in the ensemble model, responses are more drastic. Although it would be difficult to pinpoint the exact sources of discrepancies, it can generally be traced back to (1) the one-dimensional coarse representation of groundwater aquifers in WEAP where the groundwater surface is assumed flat and the storage gain (recharge) or loss (depletion) occurs uniformly in horizontal plane with no surface slope (gradient), or (2) connectivity with and flow contributions from adjacent aquifers. This contrasts with the very detailed and refined representations of groundwater systems in current application of the ensemble modeling approach. In addition, as mentioned earlier, groundwater in the current application of WEAP is given lower preference as a supply source than surface supply. Also, groundwater pumping is constrained such that the groundwater storage does not go below the historical minimum. These limitations, assumptions, and differences between the WEAP and the ensemble modeling approaches may not allow an accurate comparison related to changes in groundwater storages, but the groundwater issue can be further investigated in the full WEAP-CVPA model for CWP Update 2023.

Figure 19 Comparison of System Response. Merced Groundwater End-of-September Storage (in thousand acre-feet); (a) WEAP Model, (b) Ensemble Model

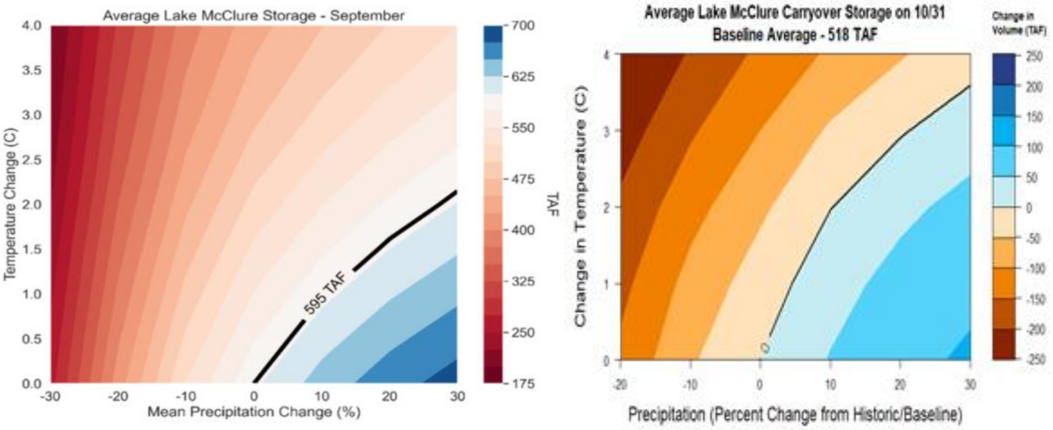


6.2.4 Lake McClure Reservoir End-of-September Storage

Figure 20 shows contours of annual end-of-September storage in Lake McClure as a function of precipitation and temperature under the perturbed scenarios of Paleo-based climate. The graph (a) on the left shows predictions by the WEAP model for Lake McClure reservoir end-of-September storage. Predictions by the ensemble model were available for end-of-October as shown by graph (b) on the right. This one-month lag in results may not create a great deal of uncertainty when making comparison between these two modeling approaches. This is because September and October are near the end of operational season of the water year for the reservoir. The graph on the left shows September storage predicted by the WEAP model at 595 taf under the historical baseline Paleo climate shown by solid-black contour line. The prediction of 518 taf by the ensemble model under the same baseline condition was very close to that of WEAP model. This shows representation of Lake McClure reservoir, its operation, and other factors affecting the operation, in these two modeling approaches are very similar.

When precipitation scenarios shift to wetter conditions (contours to the right of both graphs), both models respond similarly to changing climate. Both models show Lake McClure annual storage toward the end of the water year increases with precipitation and decreases with temperature under wet-climate scenarios. This is because. by September or October, reservoir storage is depleted to meet the downstream irrigation demand in previous months during the irrigation season. But, as temperature rises toward warm scenarios that demand more releases, both models show September or October storage becomes less sensitive to temperature as shown by vertical inclination (slope) of the contour lines. One possible explanation is that high downstream demand caused by high temperatures does not give the reservoir an opportunity to recover. This condition exacerbates storage recovery even further under drier conditions (contours to the left of the graphs) where storage contours gradually shift to almost vertical inclination, indicating total insensitivity to temperature. This implies September or October storage has no chance of recovery under extreme dry conditions regardless of temperature. The results show the lowest September storage given by the WEAP model was approximately 280 taf under the dry and hot condition of 20 percent reduction in precipitation and 4 °C increase in temperature. Under the same extreme condition, the ensemble model shows a very similar result for annual average reservoir storage at the end of October at 268 taf. Comparison of reservoir storages in Lake McClure demonstrate that that WEAP and the ensemble model agree in capturing the overall trend in reservoir storage over the wide range of climatic scenarios tested.

Figure 20 Comparison of System Response. Lake McClure Reservoir End-of-September Storage (in thousand acre-feet); (a) WEAP Model, (b) Ensemble Model



7. Conclusion and Next Steps

7.1 Conclusions

Decision-scaling is an emerging cutting edge, risk-based, “bottom-up” approach for conducting climate vulnerability assessments (Brown et al. 2012) that can better inform regional and local investment decisions about climate adaptation strategies and projects (California Department of Water Resources 2013). As a sensitivity analysis, the approach enables a climate “stress test” by predicting how a water system performs in response to a wide range of future climate conditions. Decision-scaling enables quantification of significant climate shifts relative to natural variability, such as extremely hot or dry conditions, and to examine critical climate thresholds that cause a system to fail. The resulting climate response surfaces generated from the decision-scaling approach provide insights about climate vulnerability and system performance. The results, coupled with statistical analyses, can quantify risk and the relative likelihood of future changes in system performance from different water management strategies and levels of investment.

To prepare the climate change vulnerability assessment for Update 2023, the California Department of Water Resources (DWR) Future Scenario Team completed a pilot study to test if and how the Central Valley Planning Area Water Evaluation and Planning Model (WEAP-CVPA) can be applied using the decision-scaling approach. For the pilot study, the portion of WEAP-CVPA model covering the Merced River watershed was used as a proof of concept. The study also provided the opportunity for a high-level comparison of pilot study results 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.

7.2 Key Findings

These are key findings of the pilot study using the Merced River portion of the WEAP-CVPA:

- With model refinements the WEAP-CVPA can be used to apply the decision-scaling approach with numerous paleoclimate scenarios for Update 2023.

- The model captures the impacts of extreme paleoclimate scenarios on the performance of the Merced River basin and its delivery system.
- The model predicted risk-based system performance under a wide range of climate change conditions for the following metrics: basin-wide water demand and supply delivery capabilities to agricultural and urban sectors, groundwater contributions to agricultural and urban sectors, surface storage, and change in groundwater storage in the basin.
- The model mirrored the long-term trends and average system responses to climate change impacts from the more detailed Merced Flood-MAR Watershed Study.

7.3 Next Steps

Based on these findings, DWR is applying the decision-scaling approach to the entire WEAP-CVPA model of California's Central Valley and San Francisco Bay region to study system-wide performance and vulnerabilities in support of California Water Plan Update 2023. Next steps include:

1. Evaluate two levels of urban growth and development for 2020 and 2070.
2. Increase the upper temperature threshold from 4 °C used in the pilot study to 5 °C to evaluate more extreme and hotter climatic conditions in California. Increase the temperature increment from 0.5 °C used in the pilot study to 1 °C for the range of perturbation from 0 °C to 5 °C.
3. Use the same precipitation variation from -30 percent to +30 percent at 10 percent intervals.
4. Update the input data, such as land use patterns, to reflect current system conditions.
5. Refine and improve representation of groundwater simulations.
6. Incorporate sea level rise to assess the impacts of salinity intrusion from San Francisco Bay on the availability of upstream fresh water supplies to meet system-wide water demands.
7. Use metrics for system performance like those used in the pilot study, such as changes to urban and agricultural water demands and supply deliveries and changes to surface and groundwater conditions.
8. Simulate the WEAP-CVPA model for the entire range of climate scenarios at 2020 and 2070 levels of development.
9. Report model results for each metric including response surfaces (contours) to assess climate vulnerability and system performance.

8. References

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