State of California
California Natural Resources Agency
Department of Water Resources

Risk-Informed Future Climate Scenario Development for the State Water Project Delivery Capability Report

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Acronyms and Abbreviations

ANN	artificial neural network
AW	applied water
CCTAG	Climate Change Technical Advisory Group
CDF	cumulative distribution function
CIMP6	Coupled Model Intercomparison Project Phase 6
cm	centimeter
CVP	Central Valley Project
CWP	California Water Plan
DCD	Delta channel depletion
DCP	Delta Conveyance Report
DCR	Delivery Capability Report
DMDU	decision-making under deep uncertainty
DP	deep percolation
DSM2	Delta Simulation Model II
DWR	California Department of Water Resources
EIR	environmental impact report
GCM	global circulation model
HEC-DSS	Hydrologic Engineering Center Data Storage System
HUC	hydrologic unit code
IPCC	Intergovernmental Panel on Climate Change
LOCA	localized constructed analog
m	meter
MSL	mean sea level
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
OPC	California Ocean Protection Council
Reclamation	U.S. Bureau of Reclamation
RCP	representative concentration pathway

RF	return flows
SAC-SMA	Sacramento soil moisture accounting model
SLR	sea level rise
SR	surface runoff
SSP	shared socioeconomic pathway
SV	State variable
SWP	State Water Project
TCR	transient climate response
TW	tailwater
VFM	valley floor model
VIC	variable infiltration capacity
VPD	vapor pressure deficit
WEAP	Water Evaluation and Planning
WG1	Working Group 1
WGEN	weather generator
WSIP	Water Storage Investment Program
WW	wastewater

Chapter 1. Introduction

This report introduces and documents an extensive effort undertaken by the California Department of Water Resources (DWR) to develop risk-informed future climate scenarios for the State Water Project (SWP) Delivery Capability Report (DCR), a report issued by the SWP every two years. These reports present DWR's analysis of the SWP system and planning information for users of SWP water. The analysis provides information about how climate change, regulatory, and operational considerations affect SWP delivery capability. Specifically, the report must provide "…under a range of hydrologic conditions, the then existing overall delivery capability of the project facilities and the allocation of that capacity to each contractor. The range of hydrologic conditions shall include the historic extended dry cycle and long-term average." (Settlement Agreement 2003).

Chapter 2. Purpose and Need

Through consultation with internal and external stakeholders, the DCR has been identified as the key source of future SWP water supply capability information for a wide range of uses, including integrated regional water management plans, urban water management plans, agricultural water management plans, local and regional integrated resource plans, SWP power resource planning, SWP operations studies, SWP and public water agency feasibility studies, environmental impact reports, and vulnerability assessments. Based on the wide range of uses and importance of these studies, DWR executive leadership has identified enhancement of the SWP future climate scenarios provided in the DCR as a key climate change adaptation activity.

Multiple studies have shown that climate change will result in significant reductions to the reliability of SWP water supplies (California Department of Water Resources 2019a; Ray et al. 2020; Wang et al. 2018) and will drive the need for changes in SWP operations and investments. Many of these studies also highlight the wide range of uncertainty about the timing and severity of these impacts. Although past versions of the DCR (starting in 2009) included a single scenario depicting future SWP capabilities 20 years into the future, the need to provide additional scenarios that explore the range of uncertainty is now essential to encourage more informed risk analysis and planning.

The single SWP future conditions scenario provided in past DCRs was developed to represent a median or central tendency of impacts in the SWP watershed area across the ensemble of global climate models. This approach provided a useful starting point for thinking about and planning for future risks. But, considering multiple future scenarios would allow for more robust planning. Further, the risk tolerance or risk aversion for different uses of the DCR future scenario may be different for different users or different purposes. Providing a tractable range of SWP future climate scenarios, developed through the process described in this report, provides users with additional climate risk information that is more transparent about known unknowns, allows users to make their own decisions about risk tolerance, and ultimately will lead to better more informed planning and operational decision making.

The approach used in this report draws on a wide range of source materials and decades of continuous effort by DWR, its partners, and the research community to understand and refine climate change impact analysis. Although this approach draws heavily on previous work developing "top-down" climate scenarios, it diverges from that approach to also incorporate more novel techniques drawn from the field of research known as decision-making under deep uncertainty (DMDU). These techniques are growing in application and have been used previously by DWR (Ray et al. 2021; California Department of Water Resources 2019b) and others, such as the World Bank (Mendoza et al., 2020), Ocean Protection Council (2018), and San Francisco Public Utilities Commission (2020). The approach outlined below also draws on DWR's *Climate Change Analysis – Climate Change Analysis* (California Department of Water Resources 2018) and DWR's internal processes for aligning climate change analyses across departmental activities.

Chapter 3. Background

CalSim 3 (and previously CalSim 2) is the primary water resources modeling tool used by DWR to simulate operations of the SWP and the Central Valley Project (CVP) and much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region. CalSim 3 modeling is a key component of the DCR. Additional information about CalSim 3 is provided in Appendix A, "CalSim 3 Summary" and on the DWR CalSim 3 webpage. Evaluation of climate change analysis at DWR, and specifically in the DCR, has been a long-standing and evolving activity. Appendix B, "Past Approaches to Climate Change Analysis in DCRs and other Climate Studies"" provides a short history of this evolution and a chronology of the data and approaches that have been used in past studies.

Chapter 4. Scenario Objectives

In developing the SWP risk-informed future climate scenarios, three key objectives were sought: (1) explicit representation of climate change uncertainties, (2) improved transparency and information for local planners, and (3) maintain the utility of the DCR and the information it provides.

4.1 Explicit Representation of Climate Change Uncertainties

Despite significant progress and advancements in climate modeling, downscaling, hydrologic modeling, and impact tool development, there remains significant uncertainty in how quickly, to what degree, and in what ways our climate will change. Further, there remains uncertainty in how those changes will translate to changes in the ways in which the SWP operates and the demands (both timing and amount) for water provided by the SWP. A single deterministic future scenario is less robust for representing that uncertainty, and additional scenarios are important for SWP customers and beneficiaries to explore multiple uncertainties. However, providing hundreds, or even thousands, of scenarios that explore each dimension of this uncertainty are also untenable and do not meet the needs of DCR users. The SWP risk-informed scenarios presented in this report attempt to balance these competing needs in a way that aggregates uncertainties and summarizes them in terms of risk to SWP performance.

4.2 Improved Transparency and Information for Local Planners

The public water agencies that use SWP water supplies are a diverse group. Some of the agencies are predominantly municipal and industrial water demand driven, and others are agricultural water demand driven. Some rely predominantly on SWP water supplies; others have wider portfolios of supplies. Some have significant local facilities to store water; others rely on supplies being timed to demand. This heterogeneity results in SWP water users having different risk tolerances to changes in SWP reliability and year-to-year variations in water supply delivery. Provision of a limited array of SWP risk-informed climate scenarios will allow each agency to explore how different levels of climate change affect their systems. This approach provides additional transparency about known unknowns that must be addressed within the unique context of each public water agency that relies on SWP water.

4.3 Maintain the Utility of the DCR and the Information It Provides

Since 1995, the DCR has provided SWP water reliability information and has proven to be a critical component of water resource planning throughout the state. Urban water management plans, agricultural water management plans, integrated regional water management plans, integrated resource plans, and sustainable groundwater management plans throughout the SWP service area have relied on information provided in the DCR. Public water agencies have developed tools, models, and processes for using the information in their planning. In developing the SWP risk-informed scenarios, DWR took great care to ensure that the new scenarios would be similar in format, information, and structure so that they could be easily incorporated into existing frameworks and tools.

Chapter 5. Climate Risk-Based Scenario Development

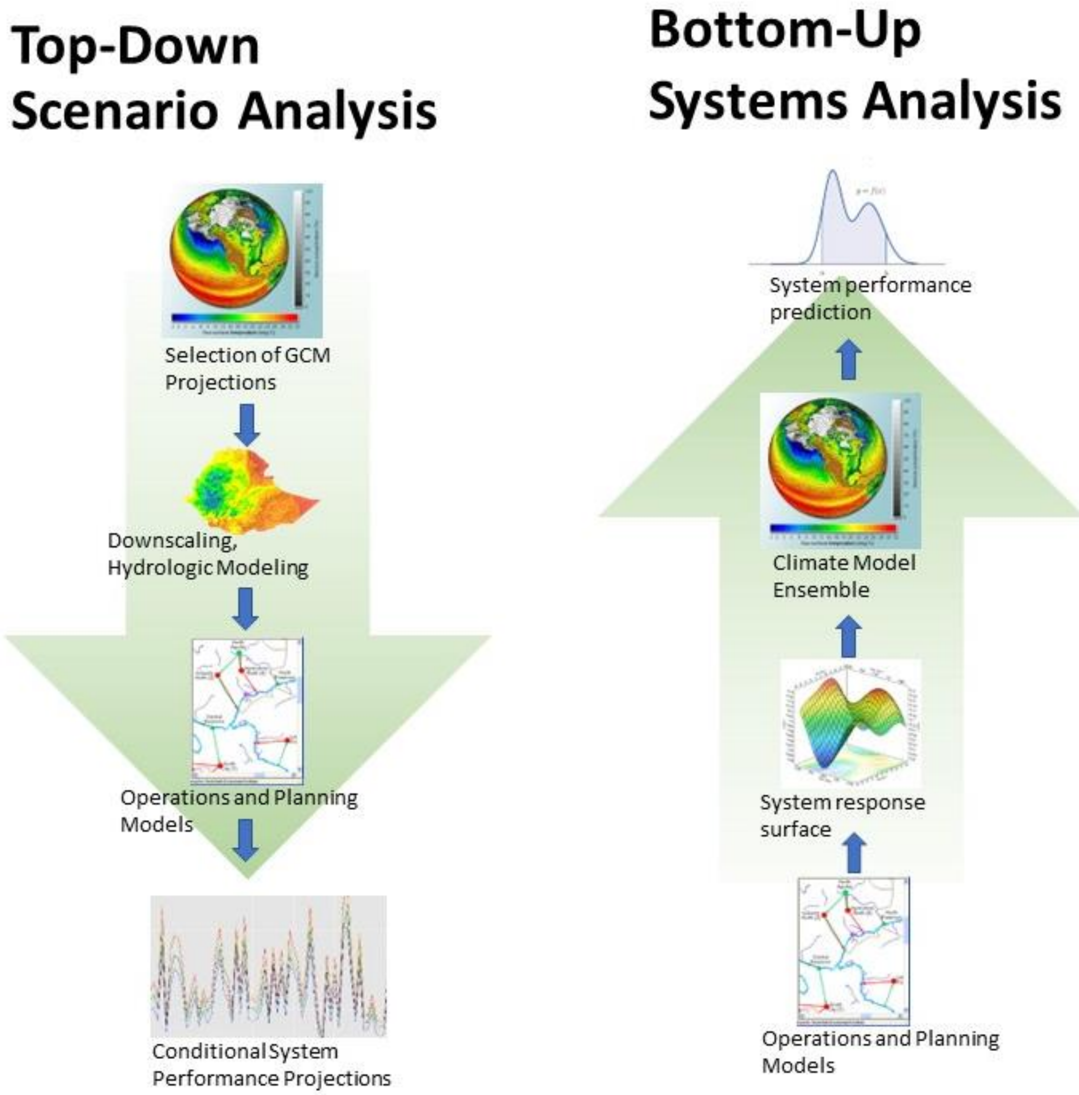
5.1 Overview

As described in Appendix B, DWR has employed several top-down and bottom-up approaches to evaluate climate change and other uncertainties in water resource planning studies.

Top-down approaches generally start with global climate models, where an individual model projection or ensemble of projections is selected, downscaled, and the gridded meteorological outputs of the downscaled model are used to drive a hydrologic model to produce streamflow estimates under the given conditions. The streamflow outputs are then used either directly as inputs to an operations model or a planning model or to develop change factors that are applied to adjust baseline inputs to an operations or planning model. The operations or planning model then provides estimates of system performance under the given climate condition.

Bottom-up approaches generally start with an operations or planning model being “stress tested" across a wide range of plausible future conditions to generate a response surface of the system to the stressors applied. Information from a global climate model ensemble or downscaled climate model ensemble are then superimposed over the response surface to provide information about the likelihood of different future performance outcomes as informed by the climate model ensemble. Figure 5-1 provides a graphic representation of these two approaches.

Figure 5-1 Top-Down vs. Bottom-Up Climate Change Analysis Approaches



Both top-down and bottom-up approaches have strengths and weaknesses.

Top-down approaches generally result in scenarios of future conditions that are easy to explain and can provide a range of impacts that explore possible outcomes. But, scenarios are not able to be placed in a probabilistic context and are generally not informed by specific factors that drive system risk or vulnerability. They are also highly sensitive to decisions about which climate models are included and cannot easily explore sensitivity to model selection.

Bottom-up approaches address the weaknesses of top-down approaches by providing probabilistic, system risk-informed information and can easily test sensitivity to climate model selection or incorporation of new climate model data. But, unlike top-down approaches, bottom-up approaches typically generate dozens or even hundreds of scenarios, often in formats that are difficult to feed into downstream planning models or integrated model chains.

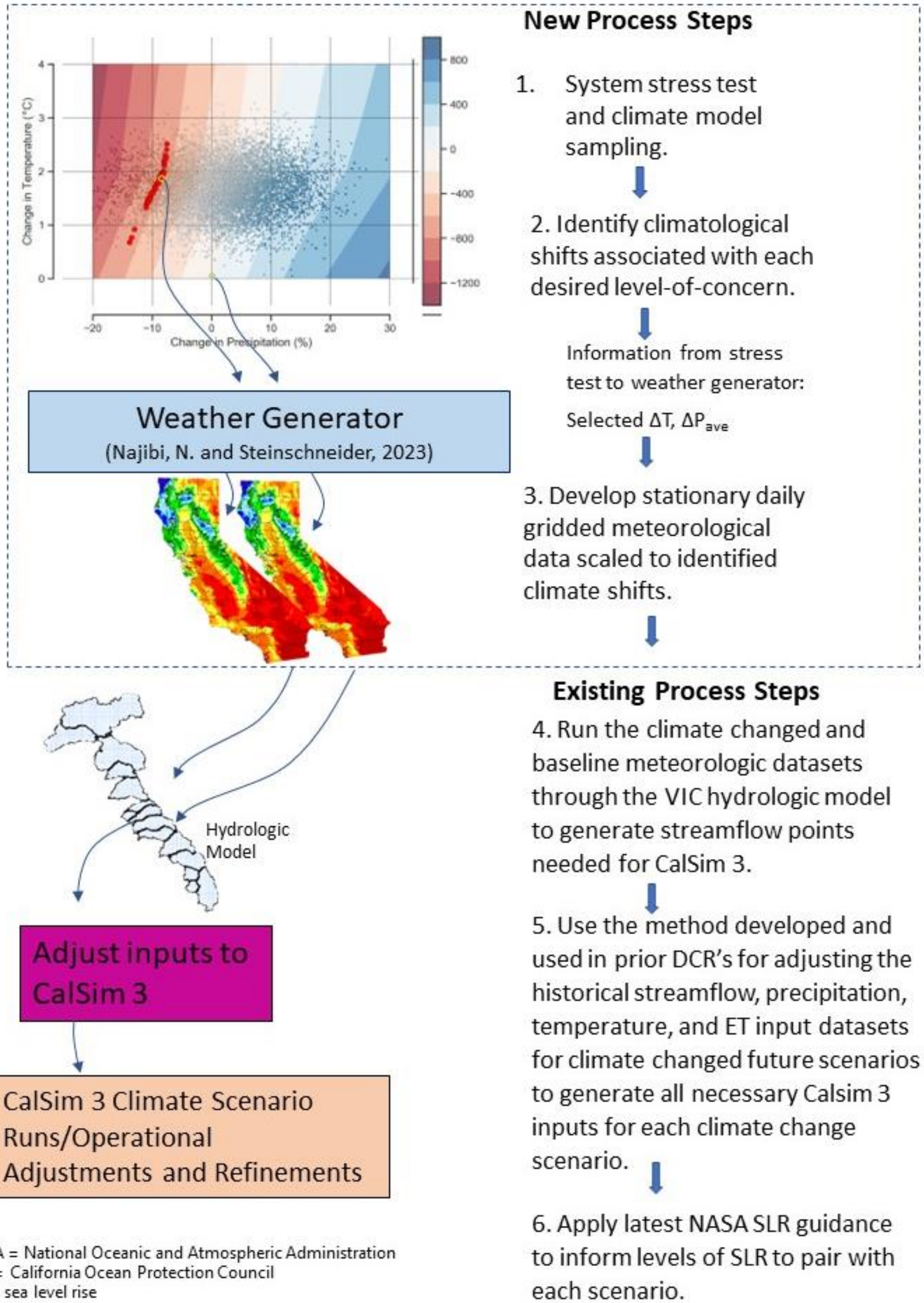
The method of system risk-based scenario development described here attempts to hybridize the bottom-up and top-down approaches to maximize their strengths and minimize their drawbacks. Important to the development of this method was the request from state water contractors (the key "customers" of the information provided by the DCR) that the system risk-based scenarios have the following characteristics:

1. Scenarios must provide timeseries data consistent with previous DCR scenarios to ensure useability.
2. Scenarios should follow the historical pattern of wet and dry years to retain ability to evaluate historical droughts under future conditions.
3. Statewide gridded temperature and precipitation data for each scenario would be a plus to allow for consistent evaluation of other portfolio supplies.

Some state water contractors also asked for large ensembles of stochastic hydrology that was run through CalSim 3 for use in Monte Carlo-type simulations and evaluations. This request was not able to be fulfilled for this DCR but remains a focus and a priority for future iterations of the DCR. Additionally, the methodology developed here provides a direct bridge to the inclusion of greater exploration of stochastic hydrologic traces in future DCRs.

Figure 5-2 outlines the major steps in developing system risk-based scenarios. The figure highlights that the modified scenario development process used differs from the process used in previous DCRs, in steps 1, 2, and 3 (listed within the dashed box). The remaining steps (4, 5, and 6) are largely consistent with recent DCRs and with other analyses. Steps 1, 2, and 3 employ a new approach and new tools (described in detail in sections 5.2 thru 5.7) that allow DWR to specifically select the climate conditions (based on a detailed understanding of SWP system response to climate stressors and a large ensemble of downscaled climate model data) that would result in specific levels of stress on the SWP. This differs from previous approaches that used the ensemble average or central tendency of projected climate conditions. In this new approach, DWR applies a bottom-up stress test and use a climate-model-informed probability density function to develop "level-of-concern" scenarios at specified system risk and climate-informed performance levels (e.g., a 95-percent level-of-concern scenario depicts a future condition in which 95 percent of model-informed climate outcomes result in better SWP system reliability). Although SWP performance is the focus of the DCR, the system risk metrics used (and described in section 5.3.1, "Stress-Test Response Surfaces of Various Performance Metrics") apply to generalized Central Valley conditions and are, therefore, valid for systems throughout the Central Valley. Non-SWP/CVP users should refer to the Chapter 6, "Limitations," for considerations about the spatial domain and use in other watershed areas.

Figure 5-2 Major Processing Steps for Development of Climate Risk-Based Scenarios



NOAA = National Oceanic and Atmospheric Administration
OPC = California Ocean Protection Council
SLR = sea level rise

5.2 Preparation of Climate Projection Data

5.2.1 CMIP6-LOCA2 Data

Analysis of the potential effects of climate change on SWP operations depends on climate models developed by research organizations across the globe. These climate models, known as global circulation models (GCMs), are periodically updated to represent new understanding of physical processes and increased spatial representation. The most recent update to GCMs and their applications, and those used in this analysis, are known as Coupled Model Intercomparison Project Phase 6 (CMIP6) models (Eyring et al. 2016). The CMIP6 GCMs rely on shared socioeconomic pathways (SSPs) to incorporate societal, demographic, and economic changes over the next century to represent a broader view of conditions than the representative concentration pathways (RCPs). For purposes of this analysis, three SSPs are used: SSP245, SSP370, and SSP585.

The CMIP6 GCM climate outputs typically have a resolution of approximately 100 kms; this scale is too coarse to capture the fine-scale processes and regional variations that are important for understanding climate impacts at a local level. Of particular importance to this analysis, GCMs may not adequately represent topography and orographic effects on precipitation and temperature. To address these limitations, downscaling techniques are employed. Downscaling is the process of generating high-resolution climate information at local or regional scales from the coarse-scale output of GCMs. This analysis relies on a statistical downscaling method of Localized Constructed Analogs (LOCA2) developed by Scripps Institute of Oceanography (Pierce et al. 2023). LOCA2 datasets are bias-corrected using monthly mean conditions; daily and monthly timeseries are available for a 3-kilometer spatial domain throughout California. The LOCA2 datasets represent the latest CMIP6 downscaling effort and aligns with other state-of-the-art research and planning scenarios being used in California for the Fifth California Climate Assessment, part of California’s comprehensive strategy to combat climate change based on cutting-edge climate research.

Fifteen GCMs, listed in Table 5-1, have been downscaled with LOCA2 and were available for use at the time of project development (winter 2022–2023). Each GCM is provided with a historical scenario, representing conditions between 1950 and 2015, and future scenarios for 2016 through 2100. Each scenario was available with one to 10 initial conditions variants and future scenarios are available for one to three SSPs. A total of 199 simulations (70 historical runs and 129 SSP projections from 15 GCMs) were available. Krantz et al. 2021 provides additional information about the selection of models included in this archive.

Table 5-1 LOCA2 Global Circulation Model Simulations Downloaded from Cal-Adapt

Global Circulation Model	SSP245 Variants	SSP370 Variants	SSP585 Variants
ACCESS-CM2	3	3	3
CESM2-LENS	0	10	0
CNRM-ESM2-1	1	1	1
EC-Earth3	3	2	3
EC-Earth3-Veg	5	4	4
FGOALS-g3	3	4	3
GFDL-ESM4	1	1	1
HadGEM3-GC31-LL	1	0	3
INM-CM5-0	1	5	1
IPSL-CM6A-LR	5	10	4
KACE-1-0-G	3	3	3
MIROC6	3	3	5
MPI-ESM1-2-HR	2	10	2
MRI-ESM2-0	1	5	1
TaiESM1	1	1	0

5.2.2 CMIP6/LOCA2 GCM Realizations Used in Calculation of Climate Change Signal

Of the 199 simulations, all simulations from two models (TaiESM1 and HADGEM3-GC31-LL) have been excluded from the analysis because the GCMs are considered "Hot," based on the likely transient climate response (TCR) screening of 1.4-2.2 degrees Celsius (°C) (Hausfather, Marvel, Schmidt, Nielsen-Gammon, Zelinka 2022). Other Hot GCMs (EC-Earth3-CC, EC-Earth-Veg, and IPSL-CM6A-LR), according to the likely TCR range, are preserved because they had multiple simulations for each SSP. Ten additional simulations from four models (CNRM-ESM2-1, GFDL-ESM4, INM-CM5-0, and MRI-ESM-0) were excluded from the analysis because only a single variant of the GCM-SSP combination was available in the archive (shown in Table 5-2). Simulations with only one initial conditions variant have been excluded from the analysis because of the difficulty in separating the climate change trend signal from natural variability noise in the simulation variant. This issue is discussed in detail in section 5.2.4.

Table 5-2 Model, SSP, and Variants Included and Excluded from Analysis

Model	SSP	Variant Count	Excluded	Reason
ACCESS-CM2	SSP245	3		
	SSP370	3		
	SSP585	3		
CESM2-LENS	SSP370	10		
CNRM-ESM2-1	SSP245	1	X	1-variant
	SSP370	1	X	1-variant
	SSP585	1	X	1-variant
EC-EARTH3	SSP245	3		
	SSP370	2		
	SSP585	3		
EC-EARTH3-VEG	SSP245	5		
	SSP370	4		
	SSP585	4		
FGOALS-G3	SSP245	3		
	SSP370	4		
	SSP585	3		
GFDL-ESM4	SSP245	1	X	1-variant
	SSP370	1	X	1-variant
	SSP585	1	X	1-variant
HADGEM3-GC31-LL	SSP245	1	X	hot model/1-variant
	SSP585	3	X	hot model
INM-CM5-0	SSP245	1		1-variant
	SSP370	5		
	SSP585	1	X	1-variant
IPSL-CM6A-LR	SSP245	5		
	SSP370	10		
	SSP585	4		
KACE-1-0-G	SSP245	3		
	SSP370	3		

Model	SSP	Variant Count	Excluded	Reason
	SSP585	3		
MIROC6	SSP245	3		
	SSP370	3		
	SSP585	5		
MPI-ESM1-2-HR	SSP245	2		
	SSP370	10		
	SSP585	2		
MRI-ESM2-0	SSP245	1	X	1-variant
	SSP370	5		
	SSP585	1	X	1-variant
TAIESM	SSP245	1	X	hot model/1-variant
	SSP370	1	X	hot model/1-variant

Note: SSP = shared socioeconomic pathway

5.2.3 Watershed Averaging and Processing

Output from the downscaled GCM simulations provides daily gridded data from the nearly 40-million-acre Central Valley watershed area (Figure 5-3) for each simulation listed in Table 5-2. These data have very high levels of spatial variation—with some simulations showing more warming at lower elevations, others showing more warming at high elevation, some showing more precipitation change in the north, others showing more precipitation change in the south, and nearly every combination thereof. Because of the wide spatial variation, a method was needed to summarize these gridded daily data for comparison and use. The following paragraphs describe how these data were aggregated and summarized.

The 3-kilometer gridded daily air temperature (minimum and maximum) and precipitation data from each GCM was averaged by month for the full period of record (1950 to 2100). Rather than simply averaging the precipitation and air temperature from each GCM for the full CalSim 3 domain, the data was averaged across each of the 20 major watersheds within the CalSim 3 domain, shown in Figure 5-3. Major watersheds, shown as different colors, are made up of smaller (roughly hydrologic unit code [HUC] 8 watersheds shown in Figure 5-3) and are defined based on their downstream confluence with larger tributaries or outflow point. Each major watershed has similar hydrologic conditions or regulation throughout its area. Watersheds can be characterized as rim watersheds, characterized by higher gradients and minimal development, or as valley floor watersheds, that are relatively low gradient and are highly developed for agricultural or urban use. The downscaled climate data from the GCMs are aggregated for each watershed with the assumption that effects of climate change on hydrology are relatively similar at a watershed scale, whereas those effects are a primary interest for this evaluation.

Figure 5-3 CalSim 3 Watersheds used for LOCA2 Analysis

After computing the average monthly precipitation and minimum and maximum air temperature for each watershed, average monthly values over the full CalSim 3 domain were computed using two approaches, described below. The CalSim 3 domain average is needed to provide a generalized metric of the climate change signal.

1. Area-weighted Average: The averages for each watershed were multiplied by each watershed’s percentage of the total area, and the resulting weighted precipitation and air temperatures were added for the full area. Each watershed’s percentage of the total area is shown in Table 5-3.
2. Flow-weighted Average: Similar to the area-weighted average approach, each watershed’s contribution to Delta outflow, based on historical CalSim 3 flows was computed, and the resulting percentages were applied to each watershed’s precipitation and air temperature. The resulting weighted values were added together for the full area. Each watershed’s percentage of the total Delta outflow is shown in Table 5-3. The flow-weighted average was constructed to provide a representation of the Central Valley watershed climate that is more representative of the importance of some watersheds to the overall water supply. For example, the Upper Feather watershed represents only 6 percent of the area, but 14 percent of Delta outflow, and the Tulare Basin represents 28 percent of the area but provides essentially zero flow.

Table 5-3 Flow and Area Weighting Factors for CalSim 3 Watersheds

Watershed	Area (acres)	Annual Flow (taf)[1]	Percentage of Total Area	Percentage of Delta Outflow
Goose Lake	696,399	0	2%	0%
Lake Shasta-1	4,216,609	5,571	11%	17%
Upper Feather	2,305,037	4,325	6%	14%
Upper Yuba	709,791	2,194	2%	7%
Upper American	1,189,780	2,702	3%	8%
Upper Stanislaus	637,576	1,151	2%	4%
Upper Tuolumne	980,207	1,840	3%	6%
Upper Merced	663,089	956	2%	3%
Lake Millerton	1,048,192	1,745	3%	5%
Eastside Streams of Delta	1,356,755	1,474	3%	5%
Westside Streams (Sac)	2,277,139	2,474	6%	8%
Westside Streams (SJR)	774,722	86	2%	0.3%
Valley Floor (Sac)	4,576,150	2,113	12%	7%
Valley Floor (SJR)	3,151,894	262	8%	1%
Tulare Basin	10,752,166	0	28%	0%
Lake Trinity	460,158	1,269	1%	4%
Other Sac Rim inflow	1,251,676	2,042	3%	6%
Other SJR Rim Inflow	761,740	281	2%	1%
Lower Yuba-Bear Rim Inflow	361,732	584	1%	2%
Delta	679,699	835	2%	3%
Total	**38,850,510**	**31,903**	**100%**	**100%**

Notes: [1]Average annual flow for 1922 to 2020, based on CalSim 3 historical hydrology. Sac = Sacramento; SJR = San Joaquin River; taf = thousand acre-feet.

The area-weighted and flow-weighted monthly averages of precipitation and air temperature were computed for each GCM for historical and SSP variants and combined to construct a continuous period of record for 1950–2100. Area-weighted and flow-weighted averages were found to have some significant differences on a model-by-model basis. The flow-weighted averaging method was considered a better indicator for capturing heterogeneous change signals and, particularly, differences in precipitation change effects along the north-south transect of the CalSim 3 domain. For example, there are regions (particularly in the southern end of the domain), such as the Tulare Basin, that have negligible contribution to Delta outflow but make up a large portion of the CalSim 3 domain on an area-basis; conversely, there are regions (particularly in the northern end of the domain), such as the Feather Basin, that provide significant contribution to Delta outflow while representing a smaller portion of the CalSim 3 domain, on an area-basis. Using the flow-weighted average approach effectively weighs the importance of major flow contributing subbasins on the CalSim 3 domain calculated average.

5.2.4 Calculation of Climate Change Signal

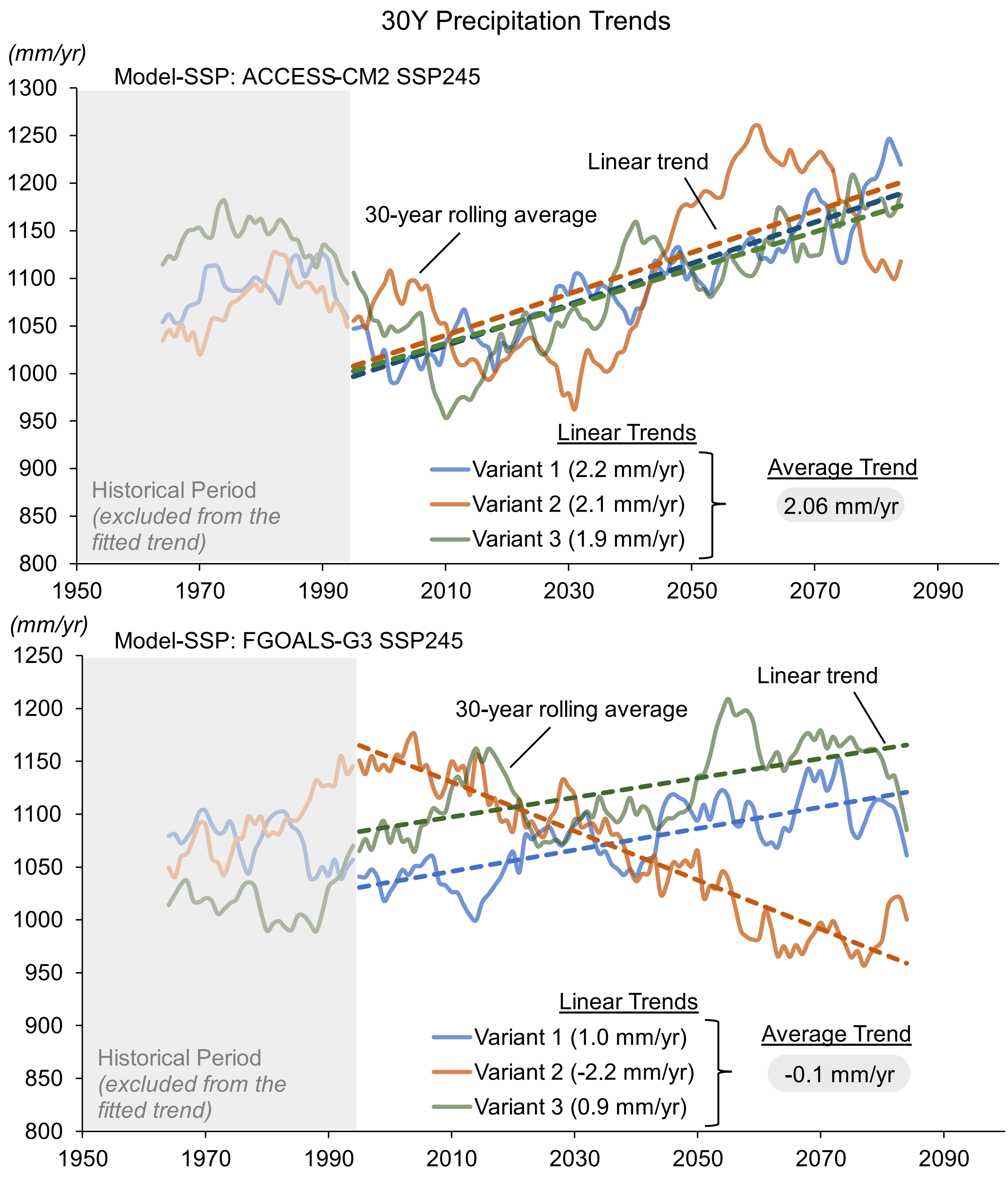
Extracting the climate change signal from the background natural variability of precipitation in global climate models and their downscaled equivalents is a challenge in regions of high precipitation variability, such as California. The addition of several simulations (or “initial condition variants”) from the same GCM-SSP combinations that are available in the CMIP6 LOCA2 ensemble has provided important new data that allows greater separation of the climate change signal from natural variability.

The following section describes the process DWR undertook to separate the precipitation change signal resulting from climate change from the underlying natural variability in each realization of the CMIP6 LOCA2 archive.

The followings steps were taken to process each GCM-SSP-initial conditions variant combination from the Coupled Model Intercomparison Project (CIMP6) LOCA2 archive, starting from the flow-weighted average values across the CalSim 3 domain previously described in section 5.2.3:

1. Fit a linear trendline to the 30-year rolling window averages for precipitation for the period 1981–2100 (Figure 5-4).
2. Calculate the change in precipitation from the 30-year baseline climate period (1992–2021) to the future climate period (2028–2057) using the linear trend slope and intercept.
3. Calculate the change in temperature by subtracting the baseline period average (1992–2021) from the future period average.
4. Average the change values calculated in steps 2 and 3 across variants of the same GCM-SSP (Figure 5-4).

Figure 5-4 Demonstration of Linear Models and Variant Averaging for Two GCM-SSPs



These steps yield 27 datapoints (8x SSP245, 8x SSP585, and 11x SSP370), each with a delta T (°C)-delta P (percent change) value (Figure 5-5 and Table 5-4). These values constitute a reasonable, climate model ensemble-informed, uncertainty distribution of climate change driven temperature and precipitation change, independent of natural variability, that would affect the SWP and CVP.

Figure 5-5 shows the CMIP6/LOCA2 projected range of likely climate changes over the CalSim 3 domain for the future 30-year period centered on 2043 (2028–2057) relative to the baseline 30-year period (1992–2021). Red dots are SSP585 (n=8); orange dots are SSP370 (n=11); green dots are SSP245 (n=8). Darker blue shades indicate higher probability density from bivariate Gaussian PDF. Contour lines indicate 68 percent and 95 percent cumulative probability of the bivariate Gaussian distribution.

Figure 5-5 CMIP6/LOCA2 Projected Range of Likely Climate Changes over CalSim 3 Domain for Future 30-Year Period Centered on 2043 (2028–2057) Relative to Baseline 30-Year Period (1992–2021)

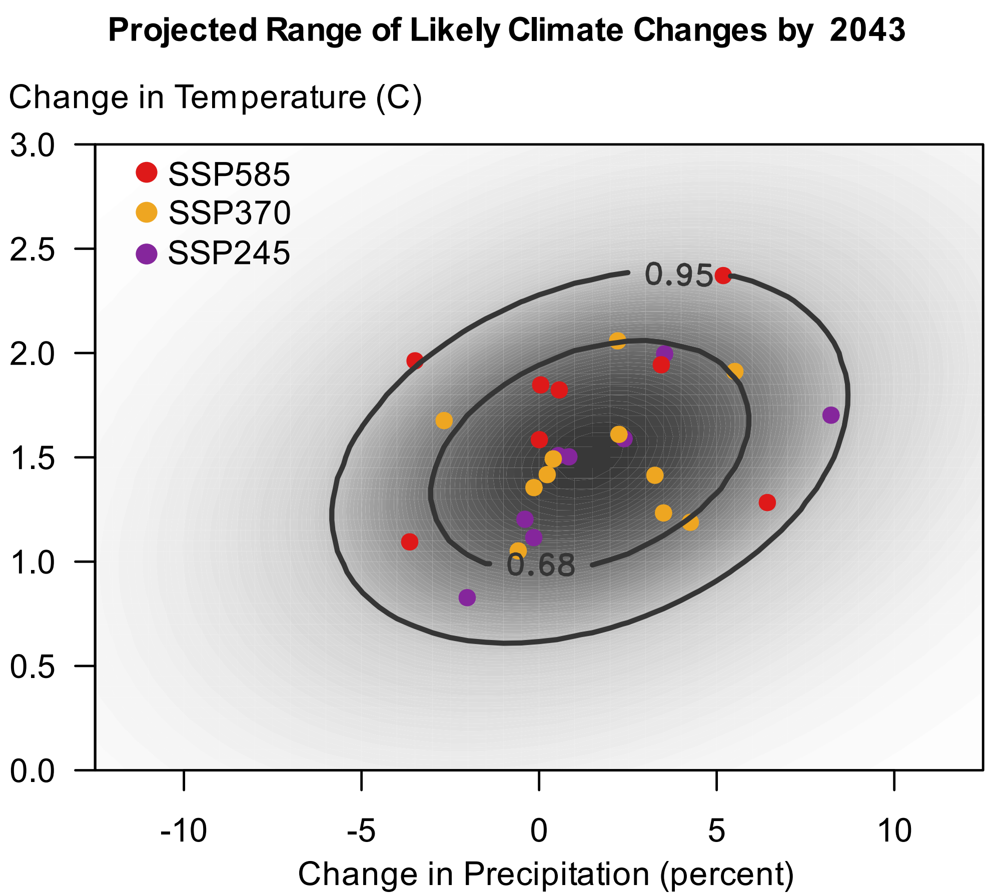


Table 5-4 Changes in Precipitation and Temperature over the Calsim 3 Domain by 2043 Relative to Baseline Period 1992–2021 for Processed CMIP6/LOCA2 Models

Model	SSP	Change in Precipitation (%)	Change in Temperature (°C)
ACCESS-CM2	SSP245	8.2%	1.7
	SSP370	5.5%	1.9
	SSP585	3.4%	1.9
CESM2-LENS	SSP370	3.3%	1.4
EC-EARTH3	SSP245	2.4%	1.6
	SSP370	-2.7%	1.7
	SSP585	-3.5%	2.0
EC-EARTH3-VEG	SSP245	0.8%	1.5
	SSP370	0.4%	1.5
	SSP585	0.0%	1.8
FGOALS-G3	SSP245	-0.2%	1.1
	SSP370	4.3%	1.2
	SSP585	6.4%	1.3
INM-CM5-0	SSP370	0.2%	1.4
IPSL-CM6A-LR	SSP245	0.5%	1.5
	SSP370	2.2%	1.6
	SSP585	0.6%	1.8
KACE-1-0-G	SSP245	3.5%	2.0
	SSP370	2.2%	2.1
	SSP585	5.2%	2.4
MIROC6	SSP245	-0.4%	1.2
	SSP370	-0.1%	1.4
	SSP585	0.0%	1.6
MPI-ESM1-2-HR	SSP245	-2.0%	0.8
	SSP370	-0.6%	1.1
	SSP585	-3.6%	1.1
MRI-ESM2-0	SSP370	3.5%	1.2
	Average	***1.47%***	***1.5***
	Maximum	***8.2%***	***2.4***
	Minimum	***-3.6%***	***0.8***

Notes: SSP = shared socioeconomic pathway; °C = degrees Celsius.

Figure 5-4 highlights the degree to which initial conditions variants of the same GCM and SSP can produce a high degree of agreement in the slope trends for some models (lower panel) as other models show significant disagreement (upper panel). In theory, the only differences between these variants should be initial conditions and underlying climate stochasticity. This figure highlights some of the difficulty with identifying climate change trends from individual GCM-SSP combinations. By first averaging precipitation over 30-year rolling windows much of the annual stochasticity is removed, but there are still significant deviations from the long-term mean (as much as +/-30 percent). Deviations of this magnitude are also common in the observed and reconstructed precipitation record prior to significant anthropogenic climate change (Meko et al. 2014).

Figure 5-6 highlights why the linear trend is needed. Each line represents a GCM-SSP combination where the points at 2043 and 2070 are the percent change in precipitation from the baseline calculated without using linear trends but after averaging across variants. Most GCM-SSP combinations show inconsistent trends in precipitation with the model getting wetter and then changing to drier or starting out drier and then getting wetter (red lines). The changing direction of change is interpreted as arising from long-term climatic stochasticity obscuring any anthropogenic climate change signal. Fitting a linear trend to 30-year average precipitation helps smooth out the underlying variability, but the trendline fitting is sensitive to the initial baseline conditions. Averaging across variants of the same GCM-SSP combination after fitting the linear trends serves to remove additional noise attributed to initial conditions differences.

Figure 5-6 shows precipitation changes at 2043 and 2070 using variant-averaging without linear trends for eight GCMs and three SSPs, where each line is one GCM-SSP combination. Red lines (n=12) indicate a GCM-SSP changing the direction of signal (i.e., positive to negative or precipitation changes at 2043 and 2070 using variant-averaging without linear trends for eight GCMs and three SSPs, where each line is one GCM-SSP combination. Red lines (n=12) indicate a GCM-SSP changing the direction of signal (i.e., positive to negative or vice versa) from the 2043–2070 horizons, gold (n=4) indicate a significant reversal in magnitude (but consistent direction), and grey (n=8) indicate consistent direction and change in magnitude.

Figure 5-6 Precipitation Changes at 2043 and 2070 using Variant-Averaging without Linear Trends for 8 GCMs and 3 SSPs, where Each Line is One GCM-SSP Combination

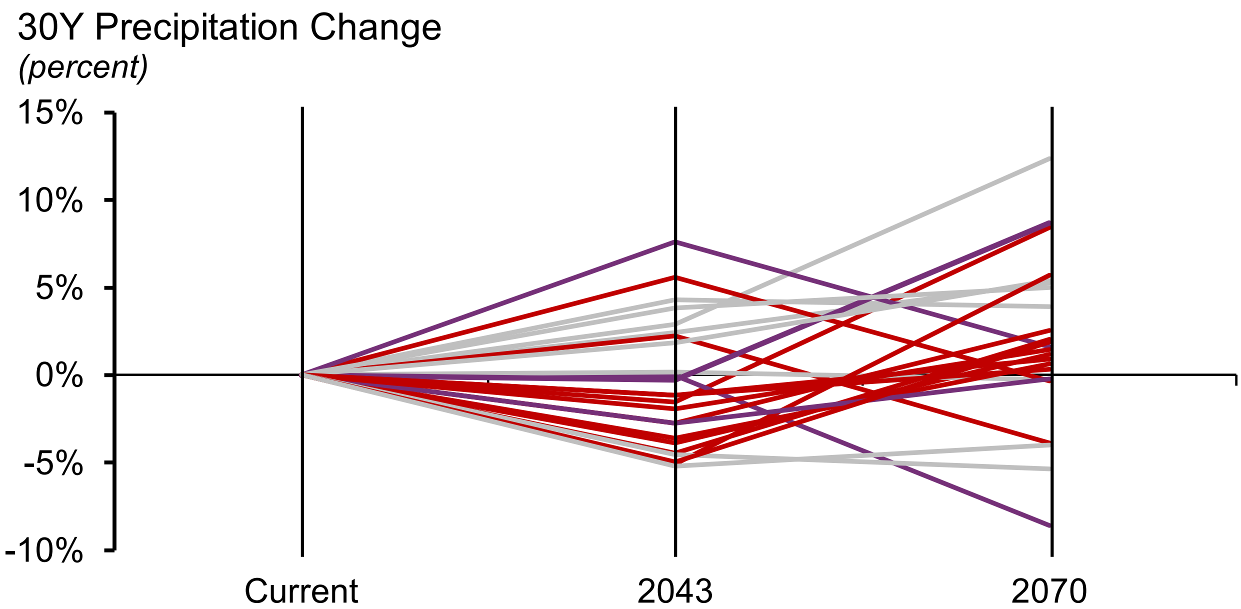


Figure 5-7 shows how the variant averaging affects the size and distribution of the bivariate gaussian probability density functions. Note that for both approaches, the temperature change and distribution remain about the same, with the 5th to 95th percentile range for both being 1.0 to 2.1 °C because the temperature data have less interannual and long-term variability and, thus, maintain a very consistent response in each variant. For precipitation, natural variability (at annual to decadal scales) is much higher than for temperature. This variability exists in addition to climate change and may be exacerbated by climate change. However, in the following steps of this procedure, the climate change signal will be added on top of underlying natural variability. So, the goal of this step is to isolate, to the degree possible, the climate change signal from the underlying natural variability. Applying both a linear trend and variant averaging narrows the uncertainty range in a way that more specifically captures the climate change signal because this narrowing reflects the removal of additional natural variability and a clearer focus on the remaining climate change signal.

Figure 5-7 shows the CMIP6/LOCA2 projected range of likely climate changes over the CalSim 3 domain for the future 30-year period centered on 2043 (2028–2057) relative to the baseline 30-year period (1992–2021). Red dots are SSP585 (n=8); orange dots are SSP370 (n=11); green dots are SSP245 (n=8). Darker blue shades indicate higher probability density from bivariate Gaussian PDF. Contour lines indicate 68 percent and 95 percent cumulative probability of the bivariate Gaussian distribution. Left panel includes linear trends fitted to all initial conditions variants with no averaging across variants. Right panel includes variant averaging.

Figure 5-7 CMIP6/LOCA2 Projected Range of Likely Climate Changes over CalSim 3 Domain for Future 30-Year Period centered on 2043 (2028–2057) Relative to Baseline 30-Year Period (1992–2021)

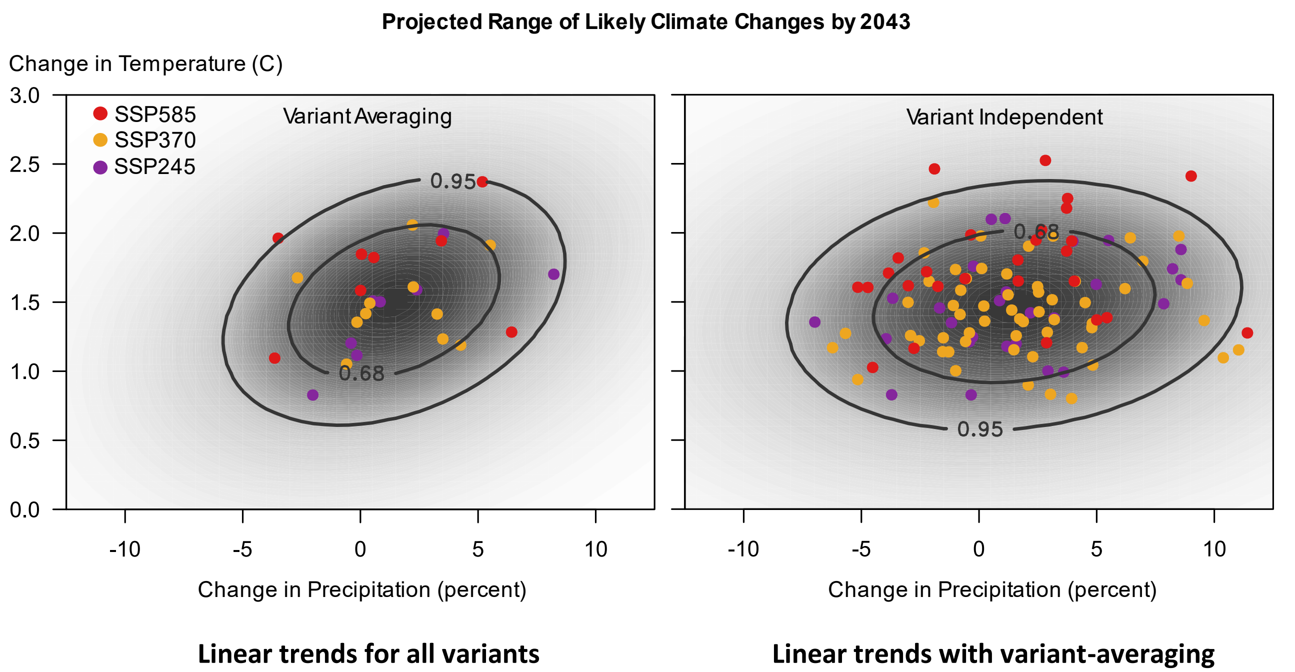
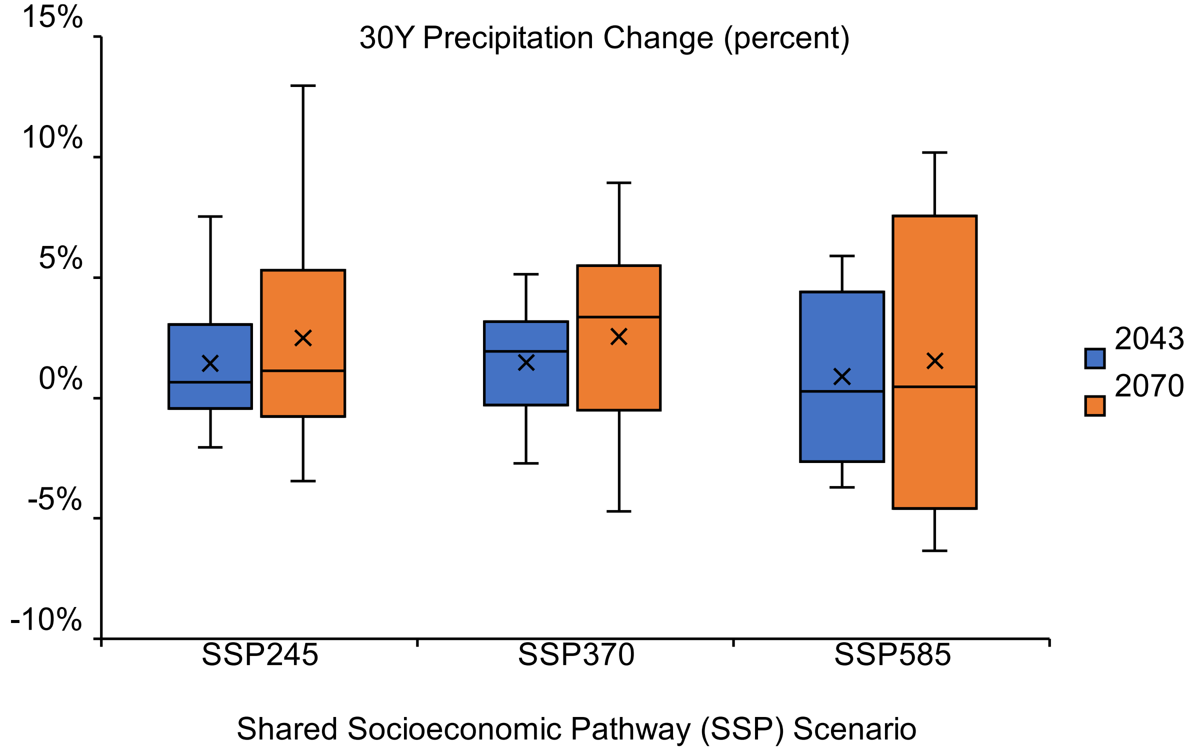


Figure 5-8 shows boxplots of precipitation changes by SSP based on values produced using the linear model with variant-averaging approach. There is no significant change in mean precipitation change across SSPs at the same time horizon. The only apparent SSP driven change (i.e., a change driven by increasing greenhouse gas forcing at a given horizon) was increasing variance in precipitation. This trend is consistent for both the 2043 and 2070 time periods and becomes more pronounced at 2070, the time period which is associated with higher levels of forcing and warming both within and across the SSPs. This suggests that the two reliable signals of climate change-induced precipitation change for the study area are (1) an overall slight (1 to 2 percent) positive shift in precipitation and (2) increasing precipitation variability enhanced with additional warming.

Figure 5-8 Precipitation Changes Estimated through Linear Trends with Variant Averaging (8 GCMs Sampled in SSP245 and SSP585; 11 GCMs Sampled for SSP370)

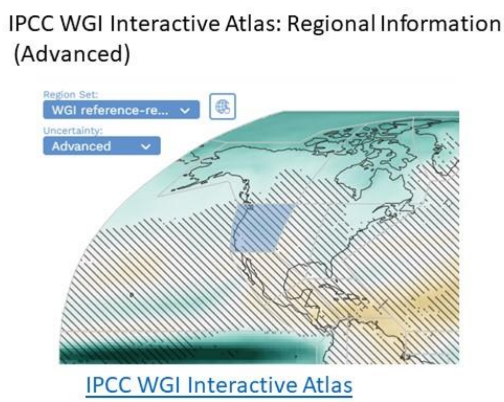


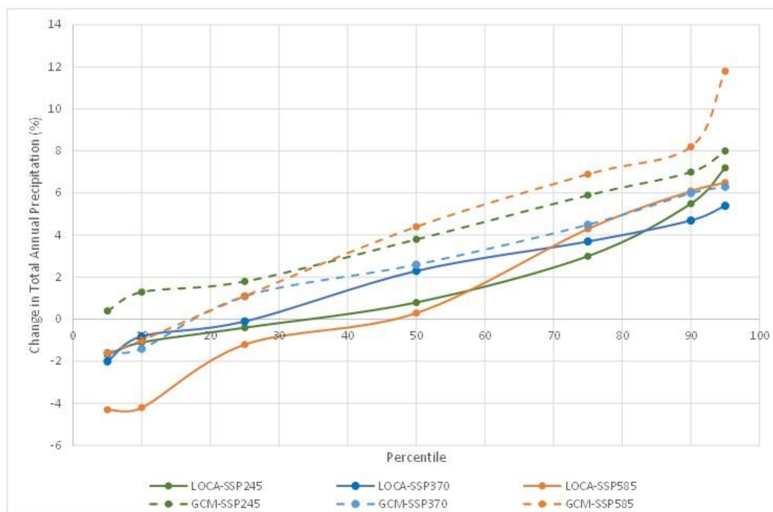
Similar analysis of precipitation trends has been done by the Intergovernmental Panel on Climate Change (IPCC) Working Group 1 (WG1) and are presented in the Interactive Atlas. Although DWR was unable to find clear documentation of the methods by which the IPCC WG1 calculate the trend values, DWR concluded that the values calculated by employing the method described above (using LOCA2 data over the SWP watershed area) fall within the range of the values reported by IPCC WG1. Figure 5-9 shows a range of percentile values as reported in the Interactive Atlas for the GCM ensemble over the Western North America Region for precipitation change at each SSP at 2040–2050 as compared to a 1981–2010 baseline period. The GCM-LOCA2 ensemble values computed though the methodology described above are also provided in the graph as depicted by the solid lines.
The comparison shows that the values computed using the LOCA2 ensemble

are similar to those computed by the IPCC using the raw GCM ensemble but are generally drier at all percentiles and SSPs. This finding is consistent with expectations as the larger Western North American Region includes a large area north of California that is generally expected to get wetter.

Figure 5-10 shows the same analysis but with an expanded area covering both the Western North American and Northern Central American regions. Here, the LOCA2 ensemble values are generally wetter at all percentiles and SSPs. This finding is also consistent with expectations as the inclusion of more area south of California, which is expected to get drier, pulls the ensemble values lower.

Figure 5-9 IPCC WG1 Interactive Atlas Precipitation Change Values for the Combined Western North America Region

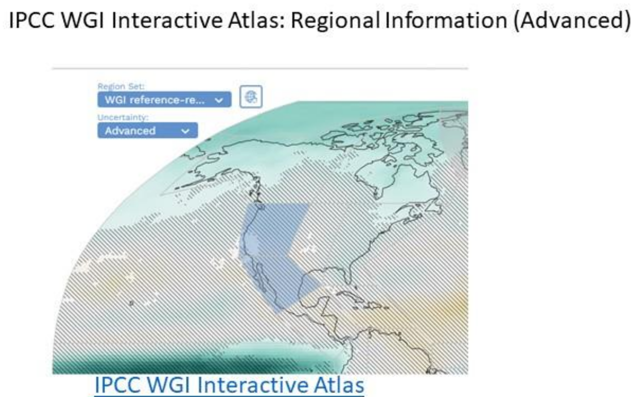


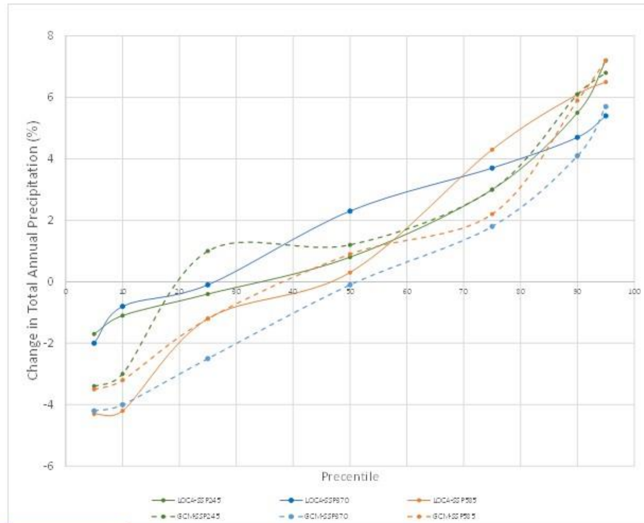


Medium Term (2041-2060)

Scenario	Median	P25\P75	P10\P90	P5\P95
SSP1-2.6	3.7	2.0 | 5.9	-0.2 | 7.8	-1.4 | 9.0
SSP2-4.5	3.8	1.8 | 5.9	1.3 | 7.0	0.4 | 8.0
SSP3-7.0	2.6	1.1 | 4.5	-1.4 | 6.0	-1.6 | 6.3
SSP5-8.5	4.4	1.3 | 6.9	-1.0 | 8.2	-1.6 | 11.8

Figure 5-10 IPCC WG1 Interactive Atlas Precipitation Change Values for the Combined Western North America Region and Northern Central American Region





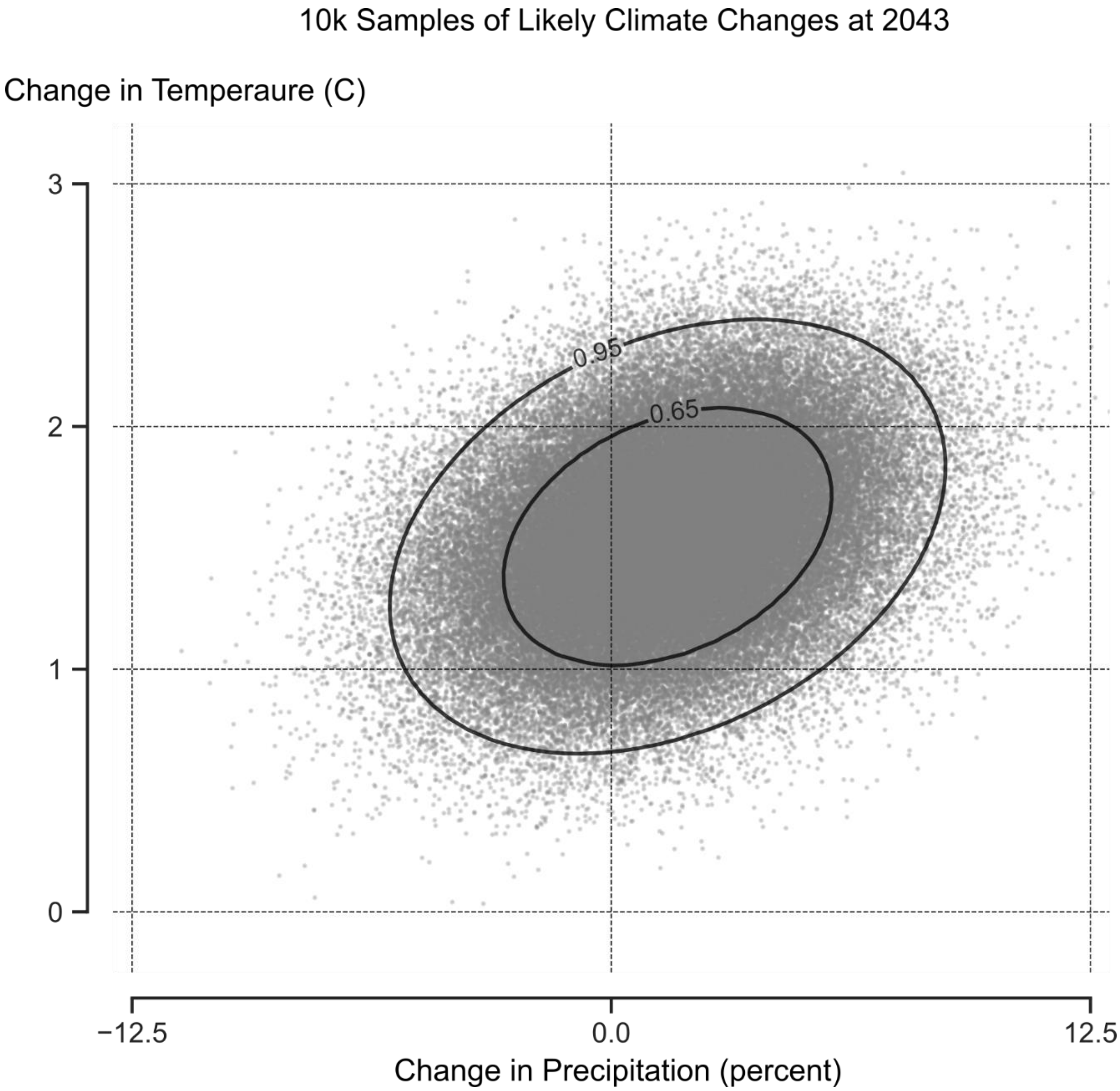
Medium Term (2041-2060)

Scenario	Median	P25\P75	P10\P90	P5\P95
SSP1-2.6	2.3	0.3 | 3.9	-1.4 | 5.4	-1.6 | 7.3
SSP2-4.5	1.2	-1.0 | 3.0	-3.0 | 6.1	-3.4 | 6.8
SSP3-7.0	-0.1	-2.5 | 1.8	-4.0 | 4.1	-4.2 | 5.7
SSP5-8.5	0.9	-1.2 | 2.2	-3.2 | 5.9	-3.5 | 7.2

5.2.5 Climate Uncertainty Sampling

From the bivariant probability density function shown in Figure 5-5 above, a 10,000-member random sample is drawn (see Figure 5-11). This sample will be used in later methodological steps to explore model-informed climate uncertainty and future likelihood. Recognizing that defining a probability density function based on inherently unknowable conditions is imperfect and is conditional to the assumed distribution function (i.e., bivariate normal), the source and quality of the information used to fit the function (LOCA2 data over CalSim 3 watershed area), and the considered socioeconomic and radiative concentration pathways forcings (SSP 245, SSP 370, SSP 585), DWR draws on and adapts the method develop by Francois et al. (unpub.), to define these quasi-probabilities as “levels-of-concern” to separate them with the true and unknown probabilities.

Figure 5-11 10,000-Member Sample Drawn from PDF of CMIP6/LOCA2 Climate Uncertainty Distribution over CalSim 3 Watershed Area at 2043



The process laid out above is done for a future time period centered on 2043 (20 years into the future from the issue date of the 2023 DCR). However, this process can easily be performed for any future time period using the CMIP6/LOCA2 processed data.

Importantly, water resource planning in the face of climate change is often thought of as a decision-making under deep uncertainty problem because decision-makers and stakeholders do not know or cannot agree on how likely different future scenarios are. This approach to sampling future climate uncertainty and the way it will be used in the following steps in scenario development allows for exploration and evaluation of other approaches to sampling future climate uncertainty. Other experts or stakeholders may wish to explore other approaches or conceptions of future climate uncertainty and their ultimate impacts on scenario development. Section 5.4 discusses how this system risk-based scenario method allows for these explorations and analyses.

5.3 System Stress Testing

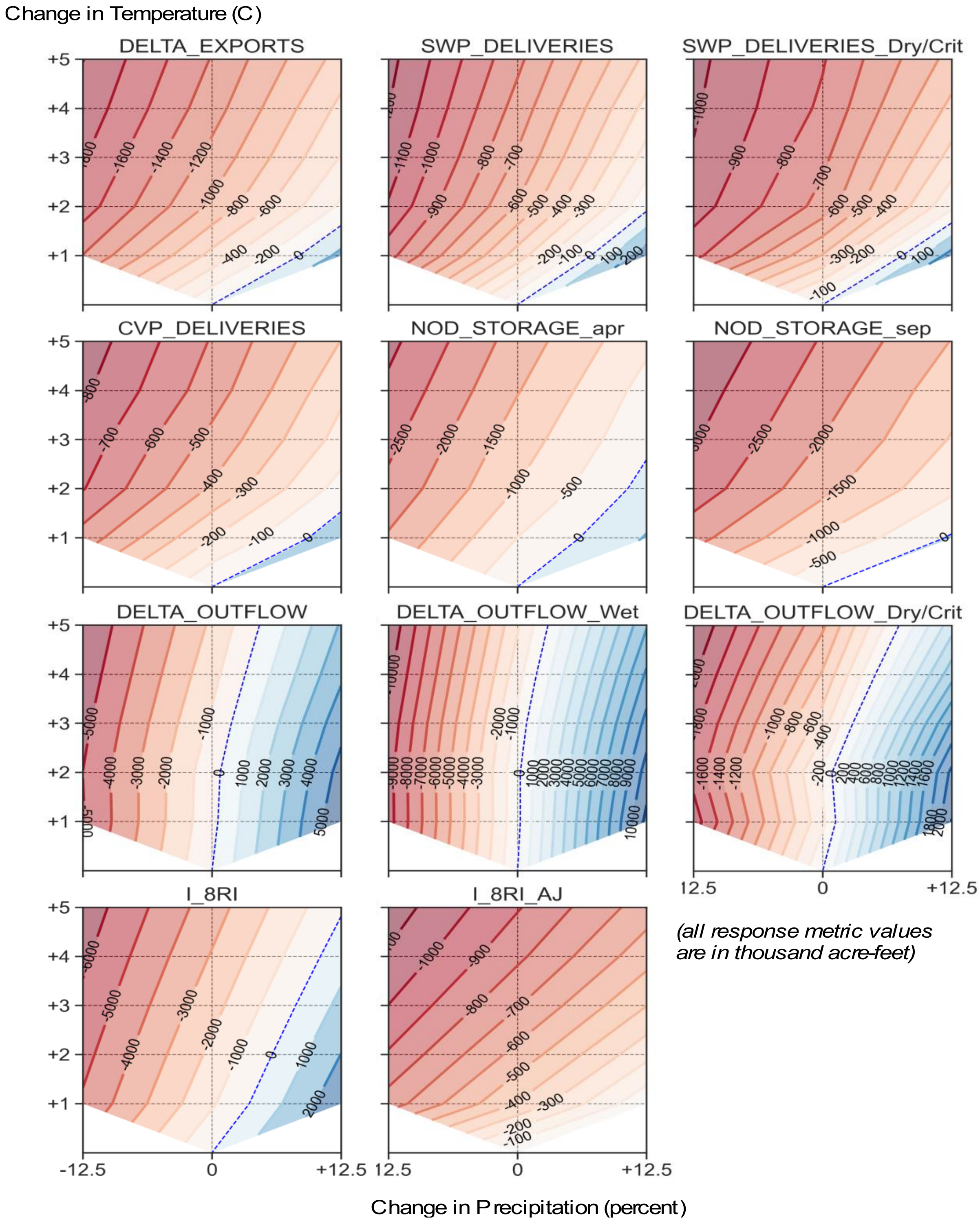
A system stress test is a method used to evaluate the performance, stability, and reliability of a system under a wide range of conditions. It involves subjecting the system to high levels of stress, such as conditions beyond those historical experienced, to identify its limitations, weaknesses, and potential points of failure. Stress tests can also be highly useful for understanding how a system's performance changes as a function of a given stressor or combination of stressors.

Since 2016, DWR has been conducting stress tests of the SWP system for climate vulnerability analysis using a decision-scaling approach (Brown and Wilby 2012) and published an extensive evaluation of the system in 2018 (California Department of water Resources 2019b). Although the variable infiltration capacity (VIC) hydrologic model and CalSim 3 ultimately will be used to develop the final scenarios for this effort, a simpler, faster run hydrologic model and system model are used to stress test the system. These tools are needed to efficiently simulate the wide range of conditions needed for the system stress test. The stress test conducted here relies on new input stress conditions generated by a newly developed and refined weather generator (Najibi and Steinschneider 2023, and further described in section 5.5), updated and re-calibrated distributed the Sacramento soil moisture accounting model (SAC-SMA) hydrologic modeling, and an updated CalLite model. These tools are used to efficiently simulate SWP operations over a range of climate conditions spanning 0 to 5 °C change in temperature and -25 percent to +25 percent change in average annual precipitation. The weather generator used for these simulations also implements a 7 percent per °C Clausius-Clapeyron scaling factor. In each warming condition, the extremeness of precipitation is also scaled resulting in wet days getting wetter and dry days getting drier and increasing in number. Najibi and Steinschneider 2023 provides additional information about precipitation scaling and comparisons to extreme precipitation events in the LOCA2 archive.

5.3.1 Stress-Test Response Surfaces of Various Performance Metrics

The integrated Central Valley water system (including the SWP, CVP, and other integrated water resource infrastructure of the Sacramento-San Joaquin Delta watershed) that is modeled by CalLite and CalSim 3 contain multiple operational components and "system performance" can be measured and monitored in a number of different ways. Figure 5-12 shows 11 different response surfaces to climate stress-tests of the integrated Central Valley water system. In each subfigure, the system response is plotted as a function of changes in temperature and average annual precipitation. Cool, blue colors indicate improved performance over historical averages; warm, red colors indicate degraded performance over historical averages. In each case, the angle of the color bars indicates the relative performance sensitivity to changes in temperature versus changes in precipitation. More vertical color bars indicate a high sensitivity to changes in precipitation, and more horizontal color bars indicate a high sensitivity to temperature. Diagonal or near 45-degree color bars represent a relatively balance in sensitivity to both stressors.

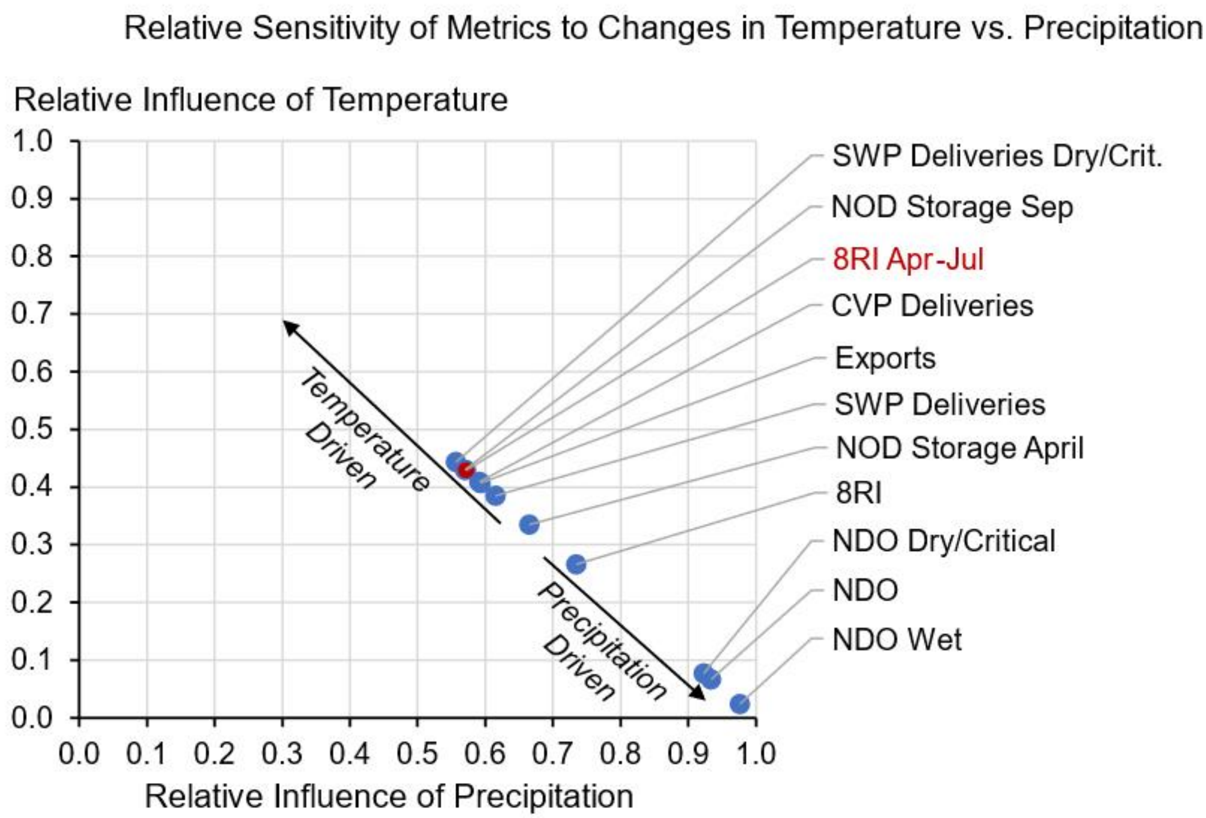
Figure 5-12 Stress Test Response Surfaces for Select Performance Metrics of the Central Valley Water System



These representative response surfaces were chosen through expert elicitation from system operation and modeling experts who indicated that these metrics encompassed a wide range of system performance objectives and concerns. The response surfaces show that different aspects of system performance demonstrate highly varying levels of sensitivity to the climate stressors. Figure 5-13 shows these metrics plotted in terms of relative influence of temperature versus precipitation.

Figure 5-13 shows a relative sensitivity of candidate system metrics to changes in temperature versus precipitation. Influence is calculated as the normalized ratio of the effect of a -10 percent change in precipitation or a 2 °C increase in temperature relative to the total change from a combined -10 percent change in precipitation and 2 °C increase in temperature.

Figure 5-13 Relative Sensitivity of Candidate System Metrics to Changes in Temperature versus Precipitation



5.3.2 Stress-Test Integration and Selection of Representative Performance Metric

The climate stress-test is used to connect potential future climate states to potential future performance changes of the SWP and wider Central Valley water system. These changes in performance represent the consequences of future climate change to water system operations and SWP delivery capabilities under current facility, regulatory, and demand assumptions. For the process outlined in Figure 5-2 above, a single response surface was needed to represent system consequences of future climate change. Although using the SWP annual deliveries response surface (see Figure 5-12, top left corner) would have been a straightforward approach for the SWP DCR, a broader consideration of performance consequences was desired because of the broad uses of the report and to better represent the coordinated operation of the SWP and CVP systems.

After careful examination of the response surfaces, discussions with operations experts from the SWP and CVP, as well as representatives of the State Water Contractors, a consensus decision was made to select the Eight River Index April-to-July flow climate response surface as the key stone metric of system consequence. The Eight River Index includes flows from: (1) Sacramento River at Bend Bridge, (2) Feather River inflow to Lake Oroville, (3) Yuba River at Smartville, (4) American River inflow to Folsom Lake, (5) Stanislaus River inflow to New Melones Lake, (6) Tuolumne River inflow to New Don Pedro Reservoir, (7) Merced River inflow to Lake McClure, and (8) San Joaquin River inflow to Millerton Lake. A summary of the advantages and reasoning for the selection of this metric include the following:

- Provides a very good proxy for generalized system consequences (caveat: slightly higher temperature sensitivity than other system specific metrics, e.g., SWP deliveries, CVP deliveries, September storage).
- Offers higher temperature sensitivity to help pick up important environmental objectives.
- Captures both amount and timing of runoff.
- Makes for an easily understandable metric and is not SWP/CVP specific.
- Produces scenarios more broadly applicable to other purposes and consistent statewide/local modeling.

- Serves as an unimpaired flow metric that is not sensitive to potential changes in regulation or operations (i.e., scenarios would not need to change as a result of regulatory or operational changes because the metric is purely hydrologic and is not affected by operations).
- Performs as a metric that is not sensitive to sea level rise, allowing sea level rise to be incorporated independently into the scenario inputs to CalSim 3.

5.3.3 Combining Future Climate States and System Consequence Response and Selection of Future Climate States for Multiple "Levels-Of-Concern" (Steps 1 and 2 of Figure 5-2)

Risk is the product of probability and consequence. Section 5.2 describes the quantification of future climate state quasi-probabilities or levels of concern. Section 5.3 describes the quantification of system performance consequence (gain or loss of performance) as a function of climate stressors. Drawing on and adapting the method developed by Francois et. al. (unpub.), combines these two sources of information to assess climate risk to the system.

The sampling of 10,000 future climate states from the probability density function discussed in section 5.2.5 is plotted over the top of the system performance response surface (discussed in section 5.3) shown in Figure 5-14. For each sample of climate, represented as a change in precipitation and temperature, expected performance of the system can be calculated from the system response surface. The level of system performance then can be plotted as a cumulative distribution function (CDF) from lowest level of system performance to highest level of system performance, as shown in Figure 5-15.

Figure 5-14 System Stress Test Response Surface with 10,000-Member Sample of CMIP6/LOCA2 Climate Model Ensemble-Informed Climate Uncertainty Space for 2043 Time Period

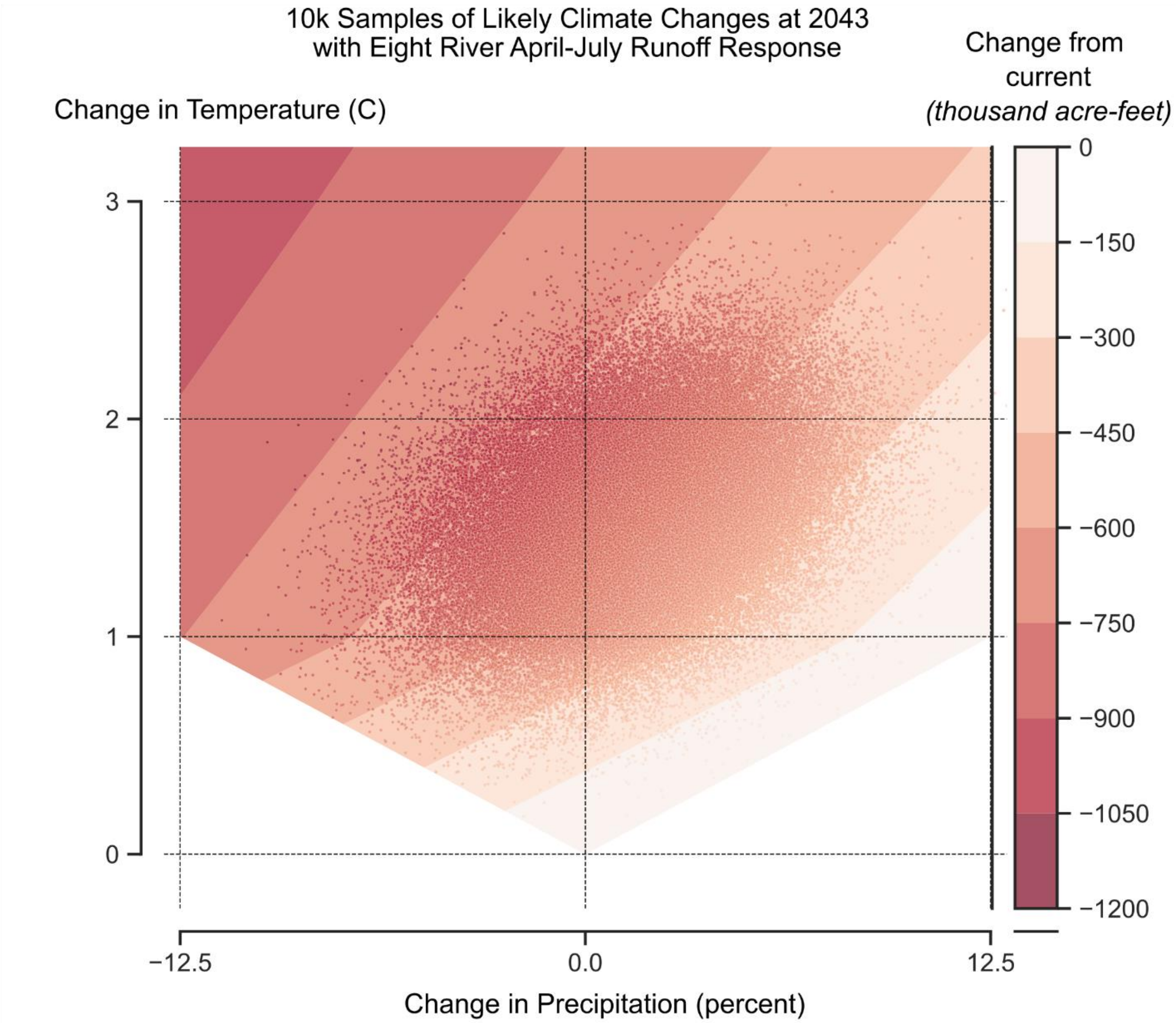
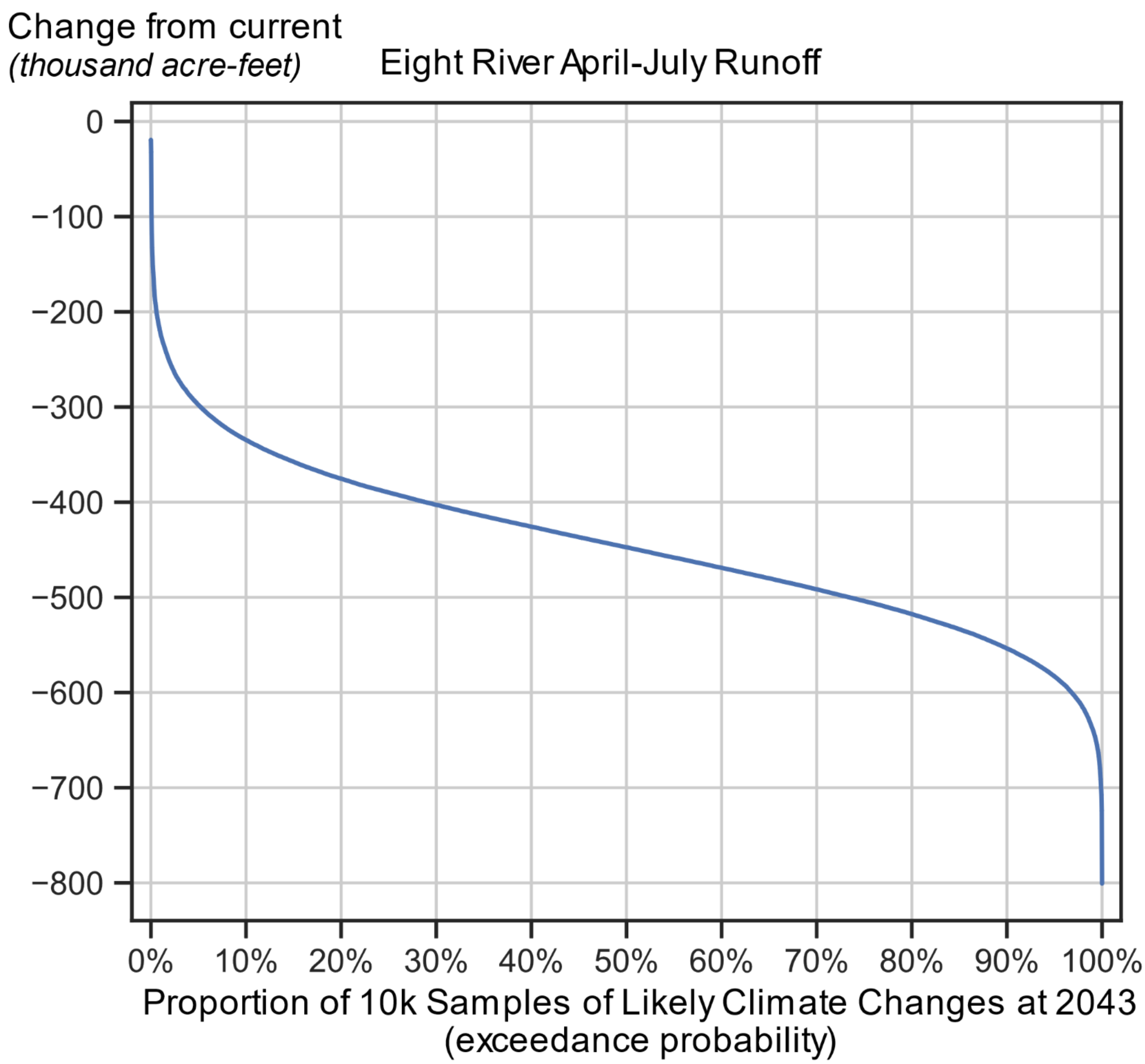


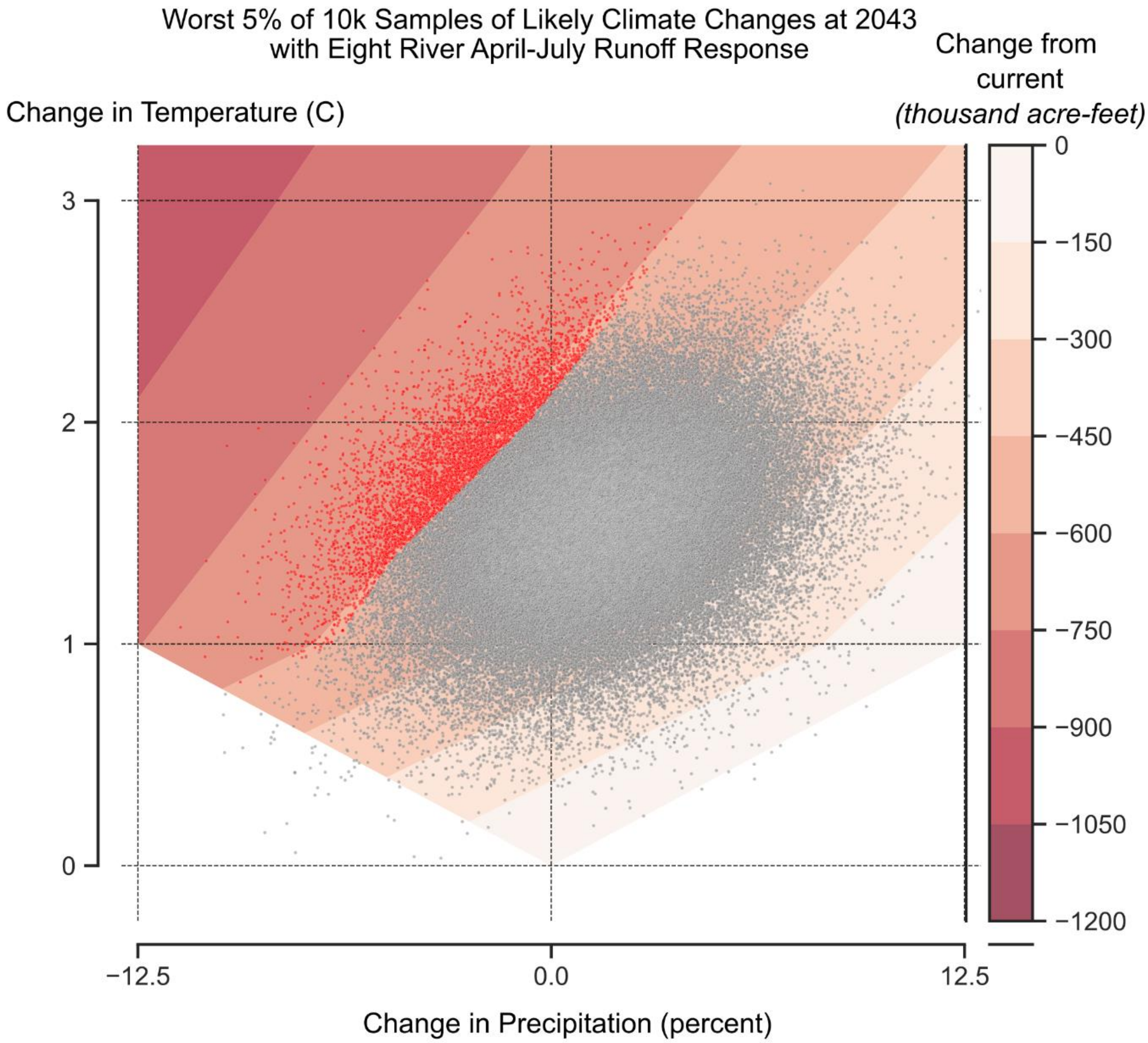
Figure 5-15 Cumulative Distribution Function of System Performance Across Model Ensemble-Informed Climate Uncertainty Space at 2043 (using Eight River Index April-to-July Response Surface)



From the CDF, any level of performance (e.g., 95th percentile exceedance value) can be identified, such that the level of performance represents the quasi-probability or level of concern that system performance would be better than all but 5 percent of the system performance outcomes under alternative model informed conditions. All points on the CDF providing higher level of performance can be plotted back on the response surface—resulting in a clear frontier of equal system performance (Figure 5-16). In the example 95th percentile non-exceedance value/level of concern, the system performance value is approximately -575 thousand acre-feet (change from baseline value), and there are only 5 percent of system performance values the fall below this threshold.

Figure 5-16 shows a system stress test response surface with 10,000-member sample of CMIP6/LOCA2 climate model ensemble-informed climate uncertainty space for 2043 time period. Climate sample members colored for 95th percentile level of concern. Red members represent climate outcomes that yield system performance worse than the 95th percentile non-exceedance value (n=500), grey members represent climate outcomes that yield system performance better than the 95th percentile non-exceedance value (n=9,500).

Figure 5-16 System Stress Test Response Surface with 10,000-Member Sample of CMIP6/LOCA2 Climate Model Ensemble-Informed Climate Uncertainty Space for 2043 Time Period



The last step is to select a single value of change in precipitation and temperature to represent the most likely combination of the two stressors that would result in the given level of performance. To identify this value, the shortest linear distance from the expected value (or center) of the probability density function (green dot) to the performance frontier (the line created by the points of lower performance) is calculated in normalized space (see Figure 5-16). The red dot on the performance frontier denotes the most likely combination of temperature change (approximately 1.8 °C) and precipitation change (approximately -2 percent) that would result in system performance at the 95th percentile exceedance level.

This process is repeated for multiple percentile non-exceedance values along the CDF to define the change in temperature and change in precipitation climate signals that would result in different risk-based probabilistic levels of concern for the Central Valley water system at 2043. Table 5-5 shows the change in temperature and change in precipitation associated with a range of levels of concern. Table 5-5 also shows the level of concern that would be calculated from the given temperature change and precipitation change values using alternative performance metric response surfaces. These additional values show that the Eight River Index April-to-July response surface is providing a good proxy for other important performance metrics of concern and that the temperature and precipitation change values identified using the Eight River Index April-to-July runoff response yields similar levels of concern for other performance metrics.

Figure 5-17 Demonstration of Selecting the 95th Percentile Level of Concern using the Eight River April-to-July Runoff Response

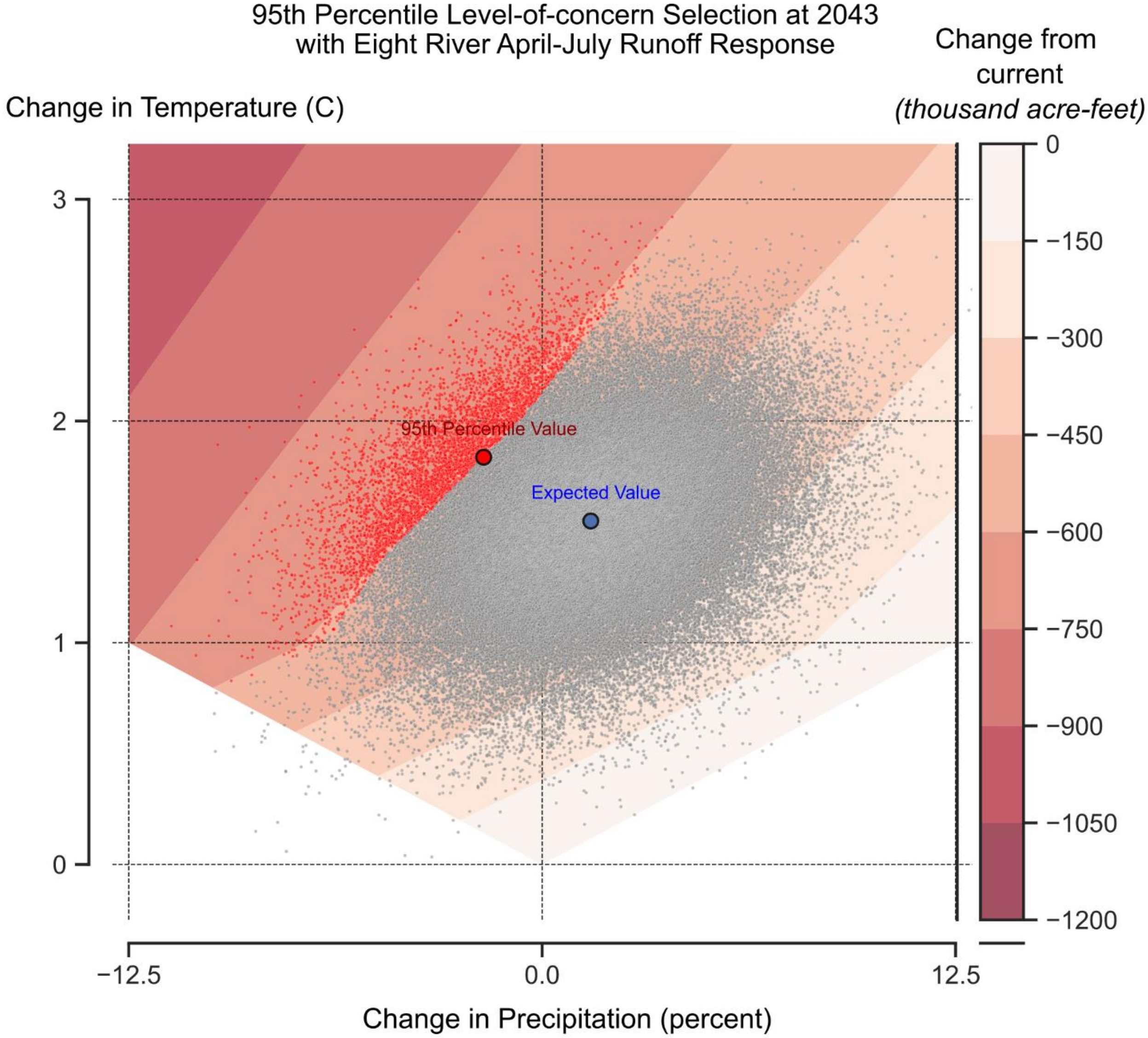


Table 5-5 Selected Changes in Temperature and Precipitation for Levels of Concern Using Eight River April-to-July Runoff Response (and corresponding Level of Concern under Other Select Performance Metrics)

8 River Index April to July			Corresponding Level of Concern at Temperature/ Precipitation Selection for Other Metrics				
Level of Concern (PCTL)	Change in Temperature (°C)	Change in Precipitation (%)	SWP Deliveries (PCTL)	SWP Deliveries Dry/Crit. (PCTL)	CVP Deliveries (PCTL)	Exports (PCTL)	NOD Storage September (PCTL)
50th	1.5 °C	+1.5%	50th	52nd	50th	50th	49th
65th	1.6 °C	+0.8%	66th	69th	65th	66th	65th
70th	1.6 °C	+0.3%	71st	74th	70th	71st	70th
75th	1.7 °C	+0.1%	76th	80th	75th	76th	74th
80th	1.7 °C	-0.1%	80th	84th	81st	81st	80th
95th	1.8 °C	-1.8%	95th	96th	95th	95th	96th

Notes: CVP = Central Valley Project; NOD = north-of-Delta; PCTL = Percentile; SWP = State Water Project; °C = degrees Celsius.

Based on the relatively small spread and separation of values for levels of concern between 50 percent and 95 precent, and in consultation with the State water contractors, system modelers, and operations experts, a determination was made to provide three level-of-concern scenarios that span a range of 50th, 75th, and 95th percentiles (see Table 5-5).

Although some of the geographic heterogeneity across the CalSim 3 domain of temperature and precipitation change exhibited by different GCMs within the ensemble is lost using this approach, the use of flow-based weighting factors acknowledges the importance of heterogeneous impacts. This approach focuses on ensemble behavior and distills the ensemble-informed changes down to a usable metric for use with the system stress test and consequence response approach. The stress test similarly evaluated effects of homogeneous changes in precipitation and temperature across the full CalSim 3 domain. A limitation of this approach is that use of the gridded temperature and precipitation data developed at each levels of concern applied at a sub-watershed scale may not fully represent risk for the area. This limitation is further discussed in Chapter 6, "Limitations."

5.4 Potential Exploration and Sensitivity Analysis of Alternative Conceptions of Future Climate Uncertainty

As noted earlier, some stakeholders or other experts may prefer a different approach or quantification of quasi-probabilities of future climate states. One benefit of the method proposed here is that sensitivity analysis of alternative conceptions of future climate uncertainty is quite straightforward. For any alternative conception of future climate uncertainty proposed, DWR can calculate the probability density function, sample that function, plot the response surface-informed CDF, and extract the associated percentile level-of-concern values for the change in temperature and precipitation values shown above. This method allows DWR to place the level-of-concern scenarios provided in the DCR in the context of alternative conceptions of future climate uncertainty.

5.5 Weather Regime-Based Stochastic Weather Generator (Step 3 of Figure 5-2)

With the specified basin average climate change levels identified in Table 5-4, a method is needed to apply these changes in a physically, spatially, and temporally realistic way. For this step, a weather-regime-based stochastic weather generator (WGEN), developed in collaboration with Cornell University, is deployed.

The WGEN was developed to generate ensembles of climate scenarios to assess the vulnerability of water systems and the effectiveness of adaptation strategies in the face of climate change (Najibi and Steinschneider 2023). The WGEN employs a stochastic generation approach, producing a database of weather regimes that serve as proxies for specific regional weather patterns. These weather regimes are identified using statistical techniques that cluster atmospheric circulation based on its persistence across different time scales (e.g., the resulting weather regimes correspond to well-known climate drivers such as the resilient ridge, atmospheric rivers, and other large-scale circulation modes that contribute to significant droughts and floods in different regions of the state). Daily weather simulations are then generated based on these climate modes. This unique feature of the WGEN allows for the creation of climate scenarios grounded in scientific knowledge, while also supporting decision-making and risk assessments in the field of water resources engineering.

The DCR uses modules of the WGEN to create a set of perturbations to support the stress-test analysis described in section 5.3 and to generate the gridded daily meteorologic conditions for each level of concern scenario (Step 3 of Figure 5-2) that will be fed into the VIC hydrologic model and used to generate climate adjustment factors for the CalSim 3 inputs.

For the stress test component, a total of 23 daily weather traces were generated to cover temperature change from (+0 °C to +5 °C, by 1 °C increments) and precipitation change (-25 percent to +25 percent, by 12.5-percent increments) shifted from historical averages. A third-dimensional climatic signal attributed to thermodynamic responses to a warmer climate was added to the precipitation change as a function of raising temperature. These phenomena, described by the Clausius-Clapeyron relation, represent precipitation intensification by scaling the distribution of daily precipitation in a way that replicates the effects of warming temperatures on precipitation through increases in the moisture-holding capacity of the atmosphere. In California, past work has shown that warming temperatures will lead to an increase in the most intense precipitation events (often associated with atmospheric rivers) but a decline in the magnitude of smaller precipitation events (Gershunov et al., 2019). This type of change effectively stretches the daily precipitation distribution, making extreme events more extreme and suppressing the magnitude and frequency of lighter precipitation events. Generally, a scaling rate of 7 percent per °C is expected. The WGEN stress test includes simulations of 0 percent, 7 percent, and 14 percent rates of scaling.

The 23 perturbations were created from a 104-year record (1915–2018) of historical daily precipitation, maximum, and minimum temperature at all grid cells across the state of California. The WGEN was used to incrementally increase temperature and precipitation by adding step changes to baseline daily maximum and minimum temperature data for each location uniformly across the entire spatial domain. These historically based climate change traces allow water managers to ask questions about the performance of their system if exposed to the same sequences of weather as seen in the historical record, but under shifts in core attributes of the temperature and precipitation distribution that reflect plausible long-term climate change.

This approach provides several advantages over previous approaches and tools. The WGEN and stress testing allows for controlled evaluation of climate stresses, which leads to clearer understanding of what drives vulnerability. The structured stress test allows for exploration of ensemble-informed climate conditions across the uncertainty range, not just at the mean or median of the ensemble. Finally, the WGEN constructs physically realistic and spatially coherent daily gridded weather patterns driven by well-understood weather regimes and the transitions between weather regimes.

To develop daily meteorological time series with the specified level of climate change identified in Table 5-5,Table 5-5 Selected Changes in Temperature and Precipitation for Levels of Concern Using Eight River April-to-July Runoff Response (and corresponding Level of Concern under Other Select Performance Metrics) the WGEN is run with each combination of temperature and precipitation change, and a 7 percent per °C Clausius-Clapeyron scaling factor over the historical period 1922–2021. The output gridded meteorological time series is then inputted to the VIC model as described in section 5.6.

The DCR does not utilize all modules of the WGEN. Additional modules can generate novel meteorological traces using a hidden Markov chain of transition probabilities from weather regimes. This module of the WGEN allows for a more expansive exploration of natural variability including new drought sequences and pluvials not seen in the historical observed record. Although this module was not used in the scenario development for this DCR, exploration and incorporation of expanded stochastic scenarios is a priority for future DCRs, and the method described here and the use of the WGEN in this DCR serves as a bridge to that goal.

5.6 Hydrological modeling and adjustments to CalSim 3 Inputs (Steps 4 and 5 of Figure 5-2)

This section describes a methodology used in several previous DWR and U.S. Bureau of Reclamation (Reclamation) projects with refinements made by Reclamation for the modeling of conditions for the reconsultation of long-term operations. The methodology is adopted here without change, except that the source of the gridded temperature and precipitation data is the WGEN instead of CMIP5 LOCA1 climate projections.

Hydrology modeling for the system risk-informed scenarios relies on the VIC model to translate meteorological inputs generated by the WGEN to hydrologic outputs needed for CalSim 3. The VIC model is run for the CalSim 3 flow domain (Figure 5-3) using the meteorologic input datasets at 1/16th-degree grid resolution for the baseline climate and the future climates produced from the WGEN. Historical and projected surface runoff, baseflow, surface water evaporation and potential evapotranspiration are simulated with VIC model version 4.2.d. Because of potential biases, VIC model outputs are not used directly as inputs to CalSim 3. Instead, CalSim 3 inputs are perturbed using the method described below.

Detailed descriptions of the CalSim 3 rim inflows, surface hydrology in water budget areas, groundwater element areas, and small watersheds as well as valley floor models (VFM) and Delta channel depletion (DCD) model for CalSim 3 are provided in the CalSim 3 report (California Department of Water Resources et al., 2022).

Hydrological inputs to CalSim 3 for this DCR use a perturbation approach to adjust CalSim 3's baseline input timeseries based on differences between the future conditions runs of VIC and the baseline conditions run of VIC. For future climate scenario runs, the perturbed baseline timeseries are directly input to CalSim 3 or are used as inputs to CalSim 3's VFMs, which then generate CalSim 3's input timeseries for climate change scenario runs.

Table 5-6 provides a crosswalk of which VIC and WGEN variables are used to perturb CalSim 3 baseline inputs.

Baseline timeseries are perturbed according to the following steps:

1. Using WGEN output, and appended wind data, create the baseline/current conditions daily VIC forcing dataset (WGENgrid_Base) for all VIC grids in CalSim 3 modeling domain over the simulation period (1921–2021) and run the VIC model using the constructed WGENgrid_Base to obtain the VIC output for the baseline/current conditions climate (VICgrid_Base). It is important to note that VIC requires daily gridded wind data. In this study, climatological averages of daily reanalysis data 1948 through 2015, drawn from Reclamation, were used. The climatological average of this reanalysis data over the period 1948–2015 is used as a repeating annual signal in both baseline and all future climate scenarios because of a lack of available data prior to 1948, after 2015, and for future climate scenarios. Addition discussion of this assumption is provided in Chapter 6.
2. Using WGEN output and appended wind data, create the future climate change scenarios daily VIC forcing dataset (WGENgrid_Fut) for all VIC grids in CalSim 3 modeling domain over the 100-year simulation period (climate adjusted 1921–2021), and run the VIC model using the constructed future climate change VIC forcing dataset (for each future climate scenario) to obtain the VIC output for the future climate condition (VICgrid_Fut).
3. Aggregate spatially and temporally the gridded data in WGENgrid_Base, VICgrid_Base, WGENgrid_Fut, and VICgrid_Fut to obtained area-weighted average values in each CalSim 3 water budget area, rim watershed, small watershed, and exterior element area (WGENarea_Base, VICarea_Base, WGENarea_Fut, and VICarea_Fut) in terms of annual (water year) and monthly timeseries.
4. Compute the monthly perturbation ratios for flow, evaporation, and evapotranspiration in areas as VICarea_Fut/VICarea_Base, precipitation as WGENarea_Fut/WGENarea_Base, and the monthly perturbation changes for temperatures at points as WGENgrid_Fut-WGENgrid_Base.
5. Perturb CalSim 3’s baseline input datasets by applying the annual and monthly perturbation ratios and temperature changes from step 4 to

obtain a perturbed annual timeseries and a perturbed monthly timeseries for each CalSim 3's input variable under the future scenario.

6. Make an annual adjustment to the monthly timeseries generated in step 5 step to finalize the perturbed future timeseries. The annual adjustment is to ensure the annual values of the final monthly timeseries are equal to the values of the perturbed annual timeseries that have been obtained in step 5.
7. Apply an additional adjustment for rim inflows that are a contributing watershed to an "anchor location" to ensure that the sum of final perturbed rim inflow from all contributing watersheds to the "anchor location" matches the flow volumes from the final perturbed rim inflow at the "anchor location." "Anchor locations" are those that have reliable historical California Data Exchange Center data and are, therefore, used to bias correct or anchor the adjustments.

Table 5-6 Summary Crosswalk Table of Variables used to Perturb CalSim 3 Variables

Variable	Source Model	CalSim 3 variable perturbed	Perturbation Equation
RUNOFF + BASEFLOW	VIC	Rim inflows, unimpaired flows	VICarea_Fut/VICarea_Base
PET_H2OSURF (surface water evaporation)	VIC	Reservoir evaporation	VICarea_Fut/VICarea_Base
PET_SHORT (potential evapotranspiration for short vegetation	VIC	Crop evapotranspiration for water budget areas and exterior elements	VICarea_Fut/VICarea_Base
PREC (precipitation)	WGEN	Precipitation input to water budget areas and exterior elements	WGENarea_Fut/WGENarea_Base
TMAX and TMIN (daily maximum and minimum temperature)	WGEN	Daily maximum and minimum temperature input to Delta channel depletion model	WGENgrid_Fut-WGENgrid_Base

Notes: WGEN = weather generator; VIC= variable infiltration capacity.

5.7 Sea-Level-Rise Parameterization for CalSim 3 Runs (Step 6 of Figure 5-2)

CalSim 3 simulations require a parameterized sea level boundary condition that is implemented by calling an artificial neural network (ANN) within the model. To evaluate different sea-level-rise (SLR) amounts, different ANNs are called that simulate Delta behavior. Additional information about how CalSim 3 incorporates SLR and how it impacts system performance is provided in Appendix A, "CalSim 3 Summary."

For each level-of-concern scenario, an SLR parameterization is needed. SLR increases hydrostatic pressure from sea water head and can potentially increase salinity intrusion in the Delta if freshwater back pressure is not also increased to balance the sea water head. Assessing the impact of future SLR is important for the SWP and CVP to plan for possible additional reservoir releases or export reductions, or both, to maintain regulatory compliance under future conditions. This section explains how SLR assumptions were determined for the 2043 future climate change scenarios.

SLR assumptions for the DCR scenarios are based on the 2022 sea level rise technical report (Sweet et al., 2022) and accompanying datasets from the Interagency Task Force Sea Level Rise Scenario Tool. The report and datasets provide the latest SLR scenarios, available for all U.S. states and territories up to the year 2150. The technical report provides the most recent science related to SLR and serves as a key technical input for the Fifth National Climate Assessment. The report will inform federal agencies, State and local governments, and stakeholders in coastal communities about current and future SLR to aid in decision-making.

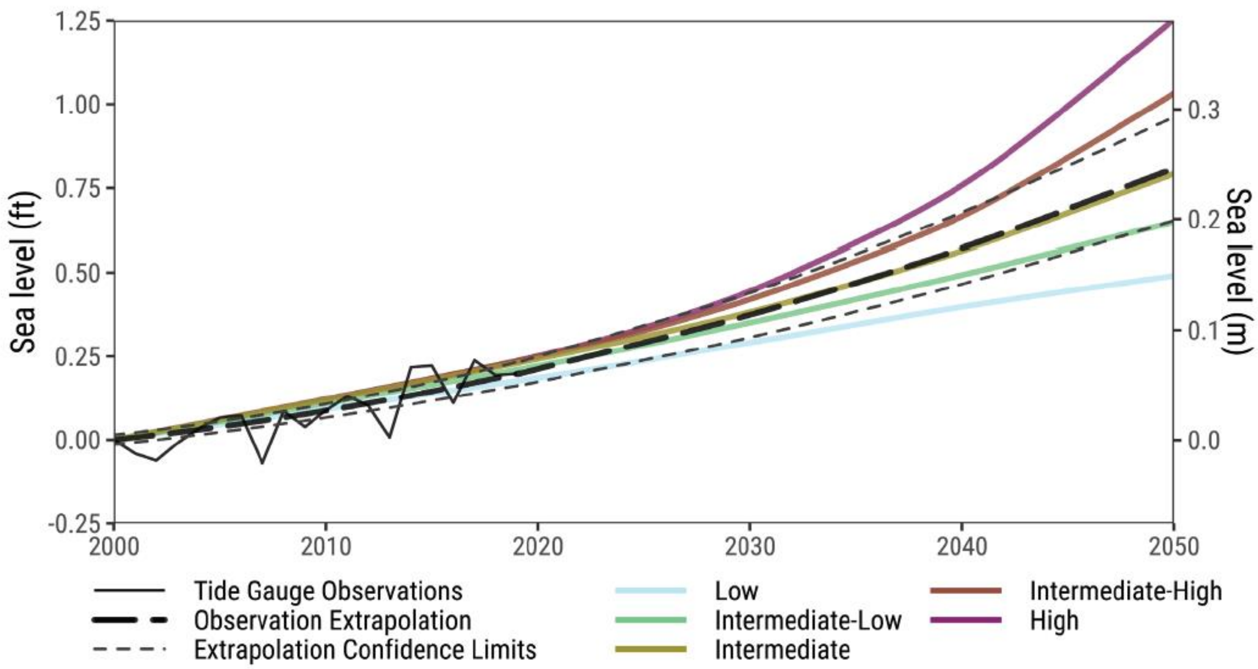
The California Ocean Protection Council (OPC) published SLR guidance in 2018 (Ocean Protection Council 2018). The 2018 OPC report provides a science-based methodology for State and local governments to analyze and assess the risks associated with SLR and to incorporate them into planning, permitting, and investment decisions. OPC is currently in the process of updating the 2018 guidance based on data and analysis from Sweet et al. 2022, but was not available at the time of scenario development. DWR, in an effort to use the best available science and remain consistent with State guidance, determined that use of the Sweet et al. 2022 seal level rise technical report and datasets would best position DWR to be consistent with future updates to the OPC guidance.

5.7.1 SLR Assumptions

The *Application Guide for the 2022 Sea Level Rise Technical Report* (Collini et al., 2022) helped to determine how to use the Interagency Tool data for planning. The Southwest Region gage was ultimately chosen as the most appropriate gage for identifying projected future sea level rise at the mouth of the Sacramento-San Joaquin Delta. Although a San Francisco-specific gage was available, that gage exhibited some anomalous behavior likely resulting from local ground surface movements, which can be ignored for longer-range planning (Hamlington, pers. comm.,March 15, 2023).

The technical report provides a set of five SLR scenarios each with a global mean sea level target value in 2100: Low (0.3 meters [m]), Intermediate-Low (0.5 m), Intermediate (1 m), Intermediate-High (1.5 m), and High (2 m). Median projections and a likely (17th to 83rd percentile) range are provided for each of the five scenarios. Figure 5-18 shows near-term SLR projections for southwest coast in California.

Figure 5-18 California Southwest Coast Projected SLR from 2020 to 2050



Source: Collini et al. 2022.

The application guide states that the observation extrapolation is a useful comparison for assessing the likelihood of SLR scenarios and ranges out to 2050. Figure 5-18 shows that the Intermediate scenario tracks closely with the Southwest region extrapolated observations. The risk-tolerance method indicates that planners with a high-risk tolerance may want to focus on the scenario that closely tracks the observed extrapolation (Intermediate scenario in this case). But, if a project has a low-risk tolerance, planners may want to focus on one or two scenarios above (Intermediate-High and High) the one tracking with the extrapolation.

It is important to note that there is not a single scenario that indicates how much sea levels will rise in the future. There are three general sources of uncertainty that are captured by the set of five scenarios from the 2022 technical report (Sweet et al., 2022) shown in Figure 5-19. But prior to 2050, there is relatively small process uncertainty and little sensitivity to different emissions trajectories. Table 5-7 summarizes the extrapolated and projected SLR at 2040 for the five scenarios and likely ranges for the Southwest region presented in Collini et al. 2022,

Figure 5-19 shows SLR scenarios for the contiguous United States relative to a year 2000 baseline. The ranges within and between the five scenarios represent different sources of uncertainty. Average annual tide-gauge observations and the observation-based extrapolation.

Figure 5-19 SLR Scenarios for the Contiguous United States relative to a Year 2000 Baseline

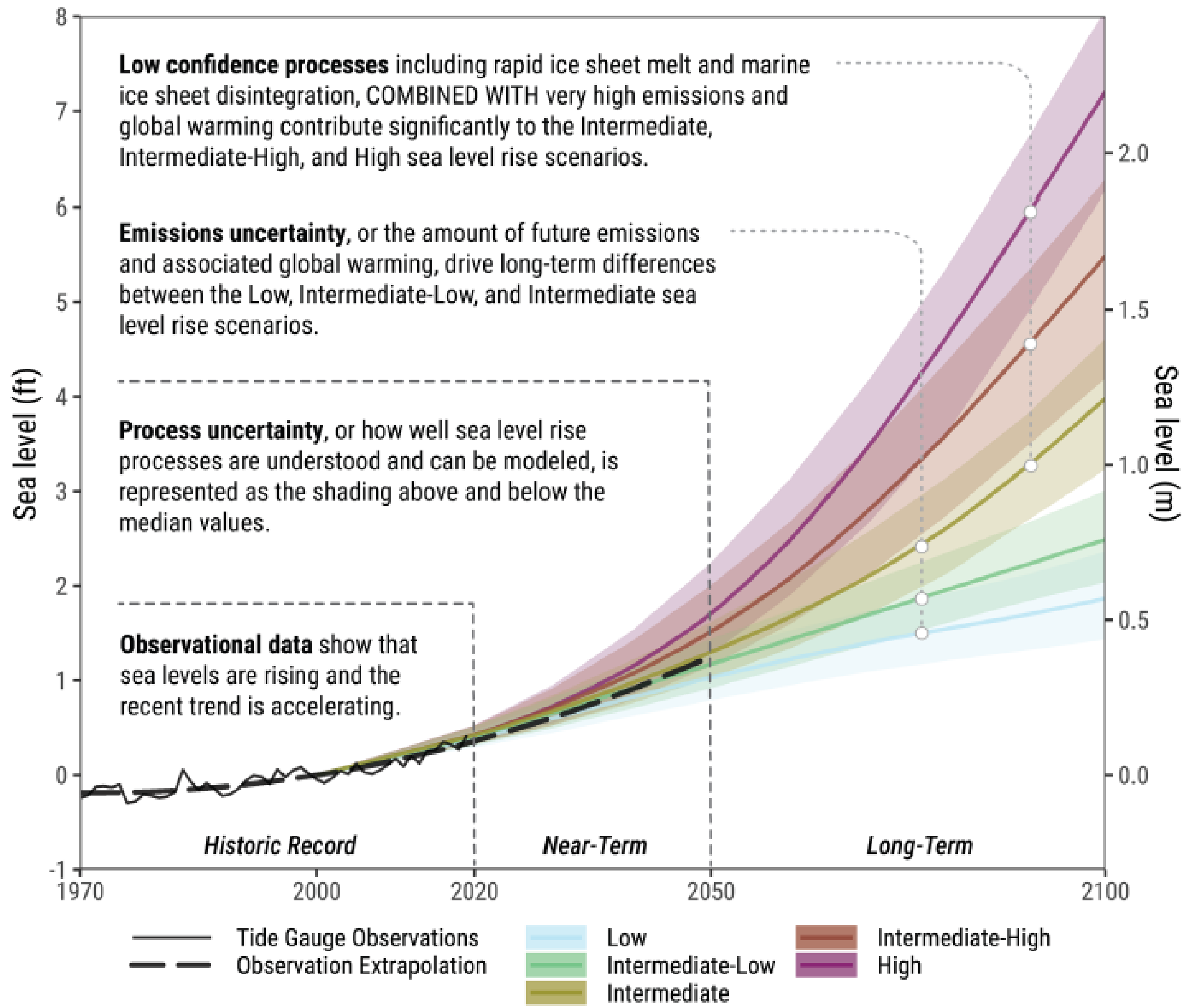


Table 5-7 2040 Global Mean Sea Level Observation Extrapolation and Projections (Median and Likely Ranges) for the Southwest Region (in feet)

GMSL Scenario	17th Percentile	50th Percentile	83rd Percentile
Observation Extrapolation	0.47	0.57	0.68
Low	0.27	0.40	0.54
Intermediate-Low	0.34	0.49	0.64
Int	0.41	0.56	0.76
Intermediate-High	0.44	0.66	0.99
High	0.50	0.76	1.13

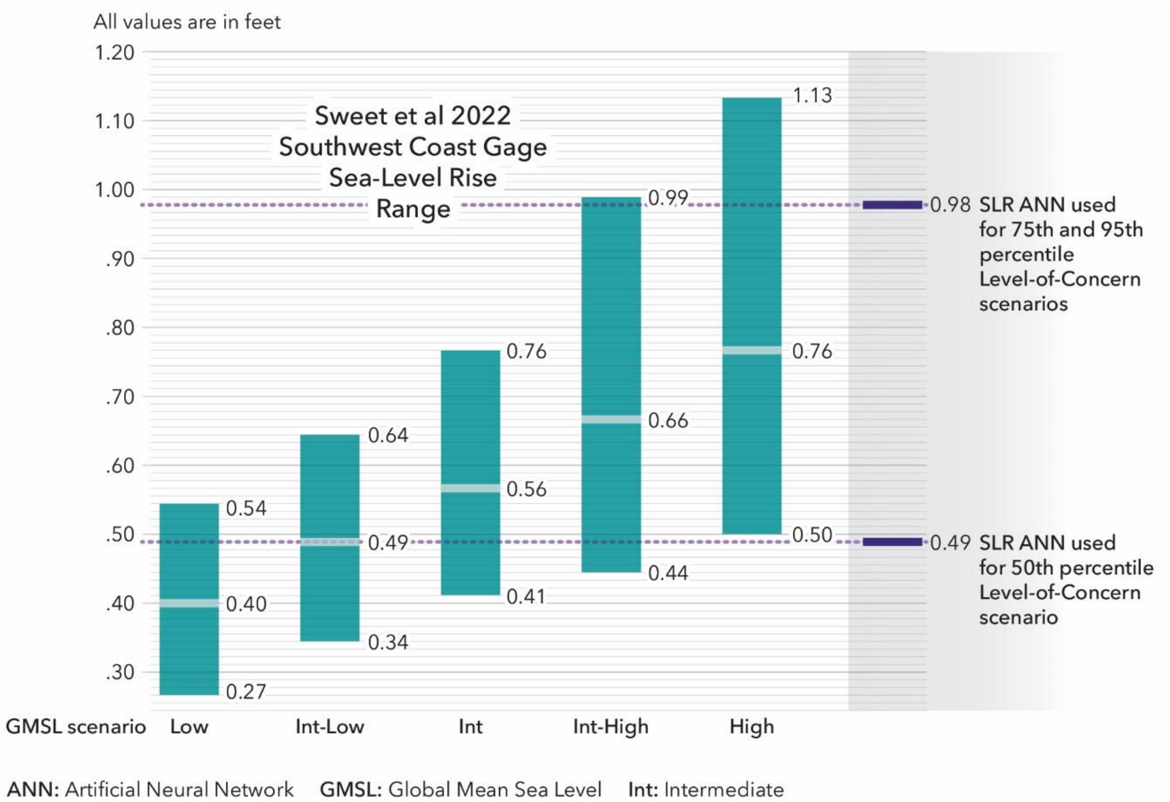
Note: GMSL = global mean sea level observation.

For the 2023 DCR, an SLR level must be chosen for each scenario that is aligned with the system risk informed level of concern. Thus, for the 50th percentile level-of-concern scenario, a median level of SLR is required, and the 95th percentile level-of-concern scenario should be paired with an extreme high SLR.

Based on the risk-tolerance approach from the application guide and the 2022 technical report and interagency tool datasets, the median intermediate SLR projection in 2040 is 0.56 foot. The median-high SLR projection for 2040 is 0.76 foot with an 83rd percentile value of 1.13 feet.

Developing and testing new ANNs that can be used with CalSim 3 can be a resource-intensive process and small increments of SLR are likely to result in little change in operations (California Delta Stewardship Council 2021). For this reason, existing ANNs that have similar levels of SLR to the 2040 median-intermediate (0.56 foot) and median-high (0.76 foot) are used for the DCR 2023 future scenarios. Existing ANNs included 15 centimeters (cm)/0.49 foot, 30cm/0.98 foot, and 55cm/1.8 feet. Based on the alignment of the Sweet et al. 2022, SLR range with the existing ANNs, the 15cm/0.49-foot ANN will be used for the 50th percentile level-of-concern scenario, and the 30cm/0.98-foot ANN will be used for the 75th and 95th percentile level-of-concern scenarios (Figure 5-20).

Figure 5-20 Alignment of CalSim 3 Sea Level Rise ANNs with SLR Projections

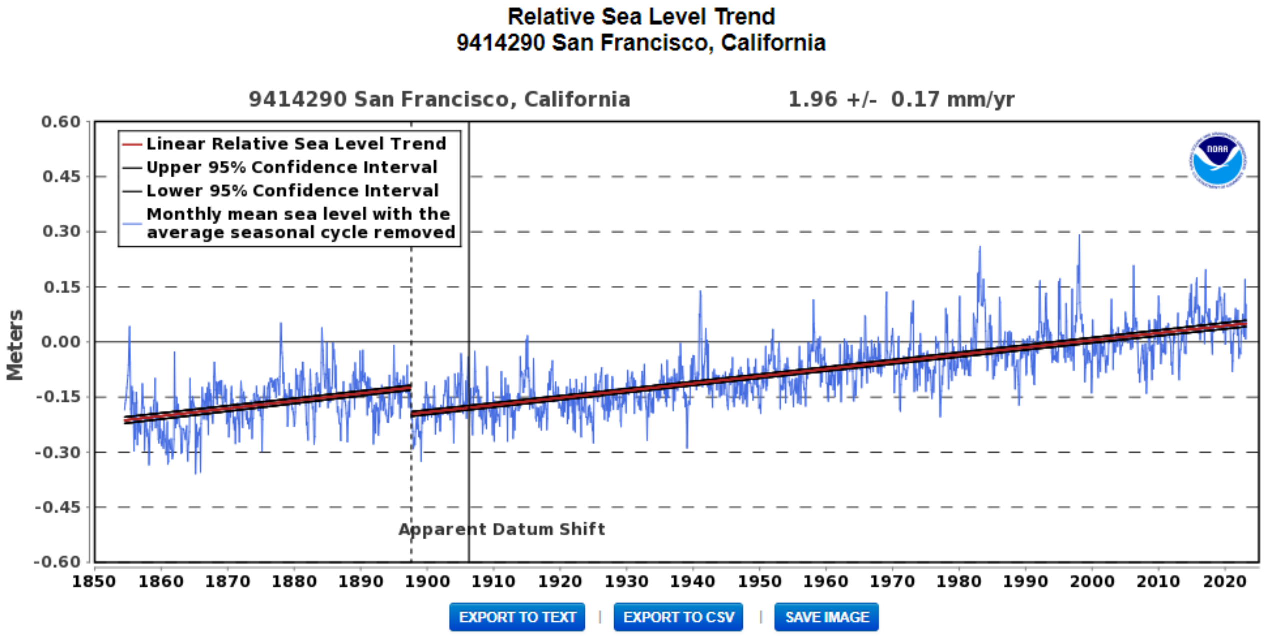


Sources: Sweet et al. 2022; California Department of Water Resources.

5.7.2 Baseline and Future SLR References

SLR is measured as an increase from a baseline. The National Aeronautics and Space Administration (NASA) SLR projections use a baseline year of 2000. DWR's baseline sea level ANN (calibrated and trained using Delta Simulation Model II [DSM2]) is anchored on May 1, 1998. The baseline sea level is generated by pivoting the relative sea level trend compared to mean sea level (MSL) datum established by the National Oceanic and Atmospheric Administration (NOAA) Center for Operational Oceanographic Products and Services when the trend line intersects the MSL. May 1, 1998, is when the sea level trend line intersects the MSL (see Figure 5-21) and represents how sea level appeared at the time. This approximately represents similar baseline conditions that NASA uses (from the year 2000) and, thus, no additional adjustments to the NASA SLR projections from the baseline year to 2040 are needed.

Figure 5-21 Relative Sea Level Trend – San Francisco, California



Source: National Oceanic and Atmospheric Administration 2023.

Chapter 6. Limitations

The approach and methodology for developing system risk-informed future climate scenarios for the SWP DCR described in this report represents DWR's most recent steps in the continuous evolution and improvement of climate change modeling and simulation development for SWP water supplies. These scenarios are developed specifically for the purpose of providing actionable information about future SWP delivery reliability. Although these scenarios may prove valuable for other purposes, they will not fill all needs and may need to be supplemented with other information for specific user needs. The paragraphs below document several known limitations that users of scenarios should be aware of and should consider when using the products developed here.

CalSim 3 Monthly Timestep. Although CalSim 3 has its own limitations and assumptions that apply to any CalSim 3 study, CalSim 3's use of a monthly timestep should be specifically noted as a potential limitation in these scenarios. CalSim 3 uses monthly inflow to rim reservoirs and simulates monthly operations. In a future climate where precipitation and runoff are expected to become more extreme, treatment of flood season operations at a monthly timestep has the potential to under simulate or average out short-duration extreme high flows. These flows temporarily may result in reservoir spills or high outflows that are not represented at the monthly timestep.

Incorporation of Wind Speed Data. Running the VIC hydrologic model requires daily gridded windspeed data. Observational data for wind are generally sparce and do not extend back prior to about the mid-20th century. Several reanalysis datasets exist for historical data, but very little data are available for future wind conditions (although project documentation indicates that the LOCA2 data eventually will include downscaled future projections of windspeed). In this study, climatological averages of daily reanalysis data from 1948 through 2015, received from Reclamation and used in modeling analysis for the consultation on Coordinated Long-Term Operation of the CVP and SWP were used. The climatological average of this reanalysis data over the period 1948–2015 is used as a repeating annual signal in both baseline and all future climate scenarios because of a lack of available data prior to 1948, after 2015, and for future climate scenarios. This simplification is made because there is low confidence in historical observations and potential changes in wind speeds or dynamics. Windspeed can have impacts on evapotranspiration, snow ablation, soil moisture, and other important hydroclimate variables. However, previous analysis has shown that VIC has a modest sensitivity to windspeed. Users should consider these scenarios to be representative of the potential changes in precipitation and temperature, and not an exhaustive exploration of all potential climate change impacts.

Spatial Domain. The DCR provides information about the performance of the SWP, which necessitates consideration of a very large watershed area covering almost 39 million acres (Figure 5-3). Temperature and precipitation change over this area undoubtably will be heterogeneous. Each of the 15 models and 129 future climate realizations evaluated for this study provide a unique pattern of temporal and spatial changes, with little consistency across all models. This study uses a large ensemble of climate realizations and a flow-weighted averaging approach (described in section 5.2.3) that acknowledges the importance of heterogeneous impacts. But, ultimately, it applies a consistent boundary forcing of average precipitation change over the entire scenario period and a monotonic step change in temperature over every day of the simulation and every grid cell of the domain to represent future climate conditions. This approach focuses on ensemble behavior and distills the ensemble informed changes down to a usable metric that is consistent with the system stress test and consequence response approach. The stress test similarly evaluated effects of homogeneous changes in precipitation and temperature across the full CalSim 3 domain. Users of these CalSim 3 scenarios and the associated WGEN-gridded temperature and precipitation data and VIC hydrologic data should understand that using these data at a sub-watershed scale may not fully represent risk for the specific area and additional analysis may be warranted. Also, many users of the DCR are public water agencies that have multiple water sources within their portfolios. For these agencies, application of a consistent future climate condition applied to all portfolio sources may be desirable. Users should consider carefully and consult with DWR and other experts before adopting these datasets for evaluation of other water supplies originating in watersheds outside the Central Valley.

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Chapter 8. Useful Web Links

DWR CalSim 3 webpage

https://water.ca.gov/Library/Modeling-and-Analysis/Central-Valley-models-and-tools/CalSim-3

Intergovernmental Panel on Climate Change Working Group 1
Interactive Atlas

https://interactive-atlas.ipcc.ch/

Localized Constructed Analogs-Variable Infiltration Capacity (LOCA-VIC) Runs

https://loca.ucsd.edu/loca-vic-runs/

Appendix A. CalSim 3 Summary

CalSim 3 is a keystone tool used by the California Department of Water Resources (DWR) to simulate operations of the State Water Project (SWP) and the Central Valley Project (CVP) and much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region. CalSim 3 is the principal model used to inform the results of the biennial SWP Delivery Capability Report (DCR) and other regulatory and planning processes pertaining to the operations of the SWP and CVP. This section provides a summary overview of CalSim 3, including the model domain, hydrologic input parameters and key operational considerations. For additional details, please refer to the CalSim 3 documentation (California Department of Water Resources et al. 2022).

A.1 Purpose and Usage

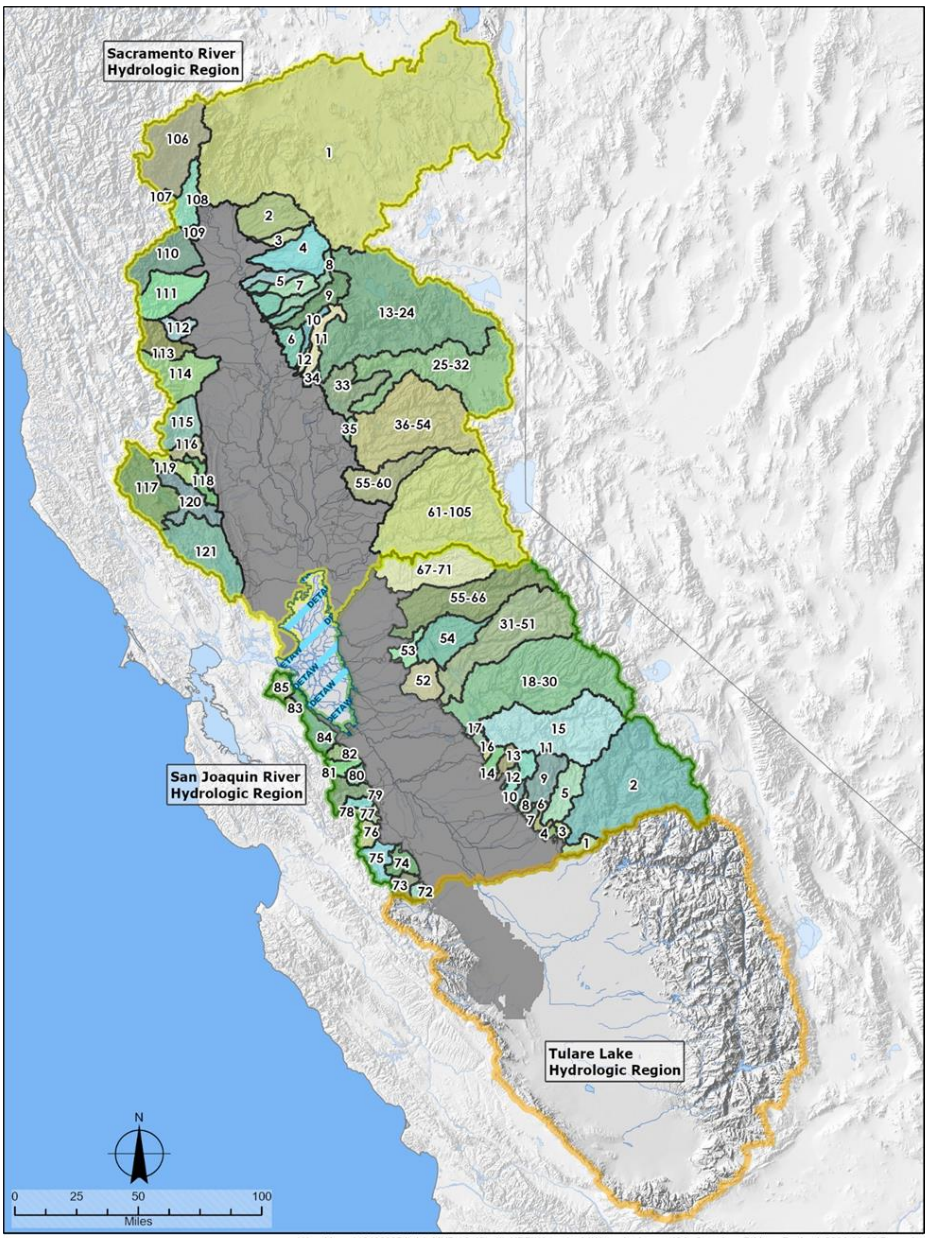
CalSim 3 is a water resources planning and water management model developed jointly by DWR and U.S. Bureau of Reclamation (Mid-Pacific Region) (Reclamation). The main purpose of CalSim 3 is to analyze operations of the SWP and the CVP and much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region. The model is routinely used to estimate the delivery capability to SWP contractors under current and future conditions. CalSim 3 is also utilized (and co-developed by Reclamation) to assess the operations of the CVP.

CalSim 3 is a monthly timestep model that simulates a 100-year hydrologic sequence with outputs that include (1) flows in major rivers, tributaries and water conveyance infrastructure, (2) reservoir storage, (3) project and non-project water diversions, and (4) salinity estimates at selected locations in the Sacramento-San Joaquin Delta. In addition, CalSim 3 incorporates a distributed, finite element-based groundwater module that simulates streamflow-groundwater interaction throughout the Sacramento and San Joaquin valleys and the Delta islands. This allows for the representation of regional and local conjunctive use projects and the subsequent effects they have on Central Valley tributary (and mainstem) surface flows.

A.2 Extents

The CalSim 3 model domain incorporates the hydrologic regions of the Central Valley, including the Sacramento and San Joaquin valleys, the Delta, and a portion of the Tulare Lake region, as shown in Figure A-1. In addition, the domain includes several upper watershed modules that represent water infrastructure systems situated in the Sierra Nevada and serve as a boundary to the main, centrally located watersheds.

Figure A-1 Rim Watersheds in Sacramento River, San Joaquin River, and Tulare Lake



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A.3 Input Data

Timeseries inputs to CalSim 3 include, but are not limited to, rim inflows, applied water demands, seepage, return flows, surface runoff, and Delta accretion. These monthly inputs to CalSim 3 are stored in the U.S. Army Corps of Engineers' Hydrologic Engineering Center Data Storage System (HEC-DSS) and are commonly known as the State variable (SV) inputs. All timeseries data span between water years 1922–2021. Relational input data, such as those dependent on indexed flow standards, are kept in the model as text-based relational data tables. The following subsections elaborate on the inputs typically adjusted for climate change scenarios, which draws upon the Delta Conveyance Project (DCP) Draft Environmental Impact Report (EIR) modeling technical appendix (California Department of Water Resources 2022).

A.4 Rim Inflows

CalSim 3 operates a system of reservoirs, channels, and diversions with rim inflows, or inflows from the "rim" of the California watershed. Inputs to CalSim 3 include 204 unimpaired and two impaired streamflows from 121 rim watersheds in the Sacramento River Hydrologic Region and 85 rim watersheds in the San Joaquin Hydrologic Region (California Department of Water Resources et al., 2022). All available historical gage data were unimpaired for upstream water management (storage regulation, reservoir evaporation, imports, exports, stream diversions and return flows). Subsequently, unimpaired outflows from each rim watershed were determined as follows:

- **Complete Record.** Stream gage data or reservoir release records exist at the watershed outflow point.
- **Streamflow Correlation.** Streamflow data exist at the watershed outflow point only for a limited period. These data were extended through linear correlation with streamflow records from adjacent watersheds, assuming statistical relationships between (unimpaired) streamflows in adjacent watersheds are constant. Double mass plots of monthly flows were used to check that a constant (and linear) relationship exists between the dependent and independent variables.
- **Proportionality.** No gage data exist for the watershed. It is assumed that runoff is proportional to the product of drainage area and average annual precipitation depth over the watershed. Outflow was

determined through association of the watershed with a similar but gaged watershed and the use of multiplicative factors representing the ratio of watershed areas and the ratio of precipitation depths. As with streamflow correlation, it is assumed that no significant land use change has occurred during the historical period.

For climate change scenarios, monthly rim inflows or inflow boundary conditions are perturbed. The approaches used are the monthly and annual (water year) adjustments with error distribution. For more details on these perturbation approaches, please refer to the DCP Draft EIR modeling technical appendix (California Department of Water Resources 2022).

A.5 Valley Floor Flows

CalSim 3 simulates the movement of surface water and groundwater in the valley floor. But, not all parts of the hydrologic cycle need to be simulated dynamically. CalSimHydro is an external hydrology model that develops all valley flow CalSim 3 inputs. It consists of the following modules:

- Daily runoff model.
- Monthly crop water use model – non-ponded crops.
- Monthly crop water use model – rice crops.
- Monthly managed wetlands water use model.

CalSimHydro outputs estimated applied water (AW), surface runoff (SR), tailwater (TW), return flows (RF), wastewater (WW), and deep percolation (DP) with inputs as precipitation, evapotranspiration, surface water evaporation, land use and urban demands. For more details, please refer to the CalSimHydro Reference Manual (California Department of Water Resources 2019).

For climate change scenarios, adjusted CalSimHydro input variables include daily precipitation and monthly evapotranspiration. These inputs are perturbed using monthly change factors and annual adjustment factors. This process ultimately produces climate adjusted inputs (AW, SR, TW, WW, DP) to CalSim 3.

A.6 Runoff Forecasting

CalSim 3 uses a dynamic forecasting routine to mimic DWR's procedures and account for uncertainty in water supply. Forecasting water supply is needed for SWP and CVP allocation decisions and establishing water year types and hydrologic indices for regulatory standards. The forecasting routine is based on statistical regression equations that take historical unimpaired flows, precipitation, vapor pressure deficit (VPD), and temperature as inputs. Both the unimpaired flows and precipitation originate from the California Data Exchange Center. VPD and temperature used in the forecasting routine comes from PRISM (Polarized Radiation Imaging and Spectroscopy Mission).

For climate change scenarios, sensitivity factors were developed using the monthly and water year change ratio process, similar to the approach applied under for the valley floor flows.

A.7 Delta Channel Depletion

CalSim 3 uses the Delta channel depletion (DCD) model to determine the Delta Islands surface water hydrology such as irrigation, drainage, and seepage. Inputs include daily precipitation and temperature timeseries at several locations in the Delta, land use, crop evapotranspiration, crop coefficients, seepage assumptions, and leach water amounts. For more details on the DCD model, please refer to *Methodology for Flow and Salinity Estimates in the Sacramento – San Joaquin Delta and Suisun Marsh*, Chapter 2, "Calibrating and Validating Delta Channel Depletion Estimates," for more details regarding the DCD model (California Department of Water Resources 2018).

For climate change scenarios, adjusted DCD input variables include daily precipitation, daily maximum temperature, and daily minimum temperature. These inputs are also perturbed using monthly change factors and water year climate change-rate based adjustment factors. This produces climate-adjusted Delta drainage, irrigation, and seepage inputs to CalSim 3.

A.8 Reservoir Evaporation

Evaporation rate boundary conditions are applied to reservoirs within the CalSim 3 spatial domain. Gross evaporation rates were applied at most reservoirs. But net evaporation rates (evaporation rate minus precipitation) boundary conditions were applied at terminal reservoirs (California

Department of Water Resources 2022). Reservoir evaporation rates serve two purposes in CalSim 3: (1) estimated historical evaporation is one of the parameters used to develop reservoir rim watershed inflows, and (2) reservoir evaporation rates are also used to dynamically calculation evaporative losses during model runtime. There are almost 100 lake and reservoir evaporation rate timeseries that are calculated within spreadsheets similar to the rim inflows timeseries. Inputs to the reservoir evaporation spreadsheets are as follows:

- Area capacity relationship.
- Historical reservoir evaporation.
- Temperature.
- Precipitation.
- Extraterrestrial radiation.

The modified Hargreaves-Samani equation is then used to estimate evaporation rates. For more details, please refer to Chapter 9, "Evaporation and Evapotranspiration," in the CalSim 3 report (California Department of Water Resources et al. 2022).

For climate change scenarios, monthly evaporation and precipitation are perturbed separately to develop net evaporation. Surface water evaporation and precipitation data are perturbed with the monthly and water year climate change rate-based factors such as the one applied to valley floor flows.

A.8.1 Groundwater

CalSim 3 required two types of groundwater boundary conditions: (1) deep percolation, and (2) lateral flows. These are generated by the CalSimHydroEE and SmallWatersheds models, respectively. The assumptions in these models are consistent with those used in the CalSimHydro model. For more information on these models, please refer to Chapter 15, "Groundwater Representation," in the CalSim 3 report (California Department of Water Resources et al. 2022).

For climate change scenarios, adjusted CalSimHydroEE and SmallWatersheds inputs include daily precipitation and monthly evapotranspiration. These are also perturbed using monthly and water year climate change rate-based factors. This process generates climate adjusted baseflows (groundwater lateral inflows) from the SmallWatersheds model and deep percolation from CalSimHydroEE.

A.8.2 Delta Operations and Sea Level

CalSim 3 simulates reservoir operations and export levels while maintaining minimum flow requirements in streams and meeting the State Water Regional Control Board D-1641 regulations that include salinity objectives as specified Delta locations. This effort requires solving an inverse problem that needs to predict flow required to meet a given salinity level. This inverse flow-salinity relationship is implemented in CalSim 3 using a trained artificial neural network (ANN) that has been trained using water quality parameters calculated from the Delta Simulation Model II (DSM2) hydrodynamic model. Use of DSM2 to simulate salinity in an operational model is a challenge because DSM2 has longer simulation times and needs to run multiple times in an iterative manner (Jayasundara et al., 2020). Therefore, a flow-salinity relationship ANN is used to emulate DSM2-simulated salinity. ANNs are trained using DSM2 simulations using the Martinez stage as the stage boundary. More background on the CalSim 3 ANNs is available in California Department of Water Resources et al. 2022.

For simulation of future conditions operations, sea level rise increases hydrostatic pressure from sea water head and can potentially increase salinity intrusion in the Delta if freshwater back pressure is not also increased to balance the sea water head. For flow-salinity relationship with sea-level-rise considerations, the ANN is retrained using a version of DSM2 with updated Martinez boundary conditions.

A.9 References

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Appendix B. Past Approaches to Climate Change Analysis in DCRs and other Climate Studies

B.1 Introduction

This appendix presents a summary of the climate change analyses incorporated in the State Water Project (SWP) Delivery Capability Report (DCRs) published from 2007 to 2021. This appendix also provides a comparison of the data sources used and analytical methods adopted to generate SWP delivery capability results. It also compares the methods used in the DCRs to other reports and modeling studies within the California Department of Water Resources (DWR) that also include analysis of the impact of climate change on SWP deliveries.

B.2 Climate Change Modeling Approaches

An important concept to understand when reviewing the information presented in this appendix is the distinction between two climate change modeling approaches: top-down versus bottom-up. All past DCRs used the top-down approach—an approach that involves creating individual climate change scenarios by selecting a single global climate model (GCM) or ensemble of GCMs and deriving a projection of future climate conditions based on what the GCM data show.

An alternate approach that has been used in other studies is termed "bottom-up." The bottom-up approach involves stress testing a water resource system across a range of possible climate futures, then using information from GCM ensembles or other sources to evaluate the likelihood that system performance (e.g., SWP deliveries) will fall below a given threshold at a given future time period. This appendix includes discussion of some studies that were conducted using the bottom-up approach to compare those methods with the approaches used in the DCR.

B.3 SWP Delivery Capability

The DCRs present SWP delivery capability as the annual quantity of SWP water that can be delivered to the users at specific locations and specific times with a certain numeric frequency. Typically, SWP delivery capability is analyzed for two conditions or specific points in time: (1) the existing conditions that generally represent the year of DCR being published, and (2) the future conditions projected 20 years from the existing conditions year.

B.4 Climate Change Analysis

For analysis of SWP delivery capability under future conditions, CalSim is used to evaluate how changing hydrology and sea level rise will affect SWP operations. The input boundary conditions for CalSim are adjusted for climate change, including changes to hydrology because of the projected changes to temperature, rainfall, and the resulting runoff and evapotranspiration patterns, and projected sea level rise. Using these input boundary conditions, the CalSim simulation outputs are generated and are used to evaluate changes to SWP operations including deliveries, storage, and Delta outflow for the future conditions under fixed regulatory and operational targets. As discussed earlier, all DCRs to date have used a top-down approach that uses one or a small number of individual climate change scenarios to analyze SWP delivery capability.

B.5 Climate Change Hydrology

A generalized approach used in all DCRs to develop CalSim climate change hydrology input is presented in this section. The sections that follow present specific information on the approaches that vary by each iteration of the DCR.

1. Downscaled GCM projection output representing a combination of GCM models and representative concentration pathways (van Vuuren et al. 2011) that result in a high, medium, or low level of change of radiative forcing of the atmosphere.
2. The downscaled GCM projection output in the gridded data format was used as input to a macro-scale hydrologic model, variable infiltration capacity (VIC) model to convert downscaled GCM scenario precipitation and temperature data to runoff.
3. The VIC model simulated runoff was processed to generate monthly streamflow at key locations in the Central Valley.

4. The VIC model simulated monthly streamflows at the key locations were used to generate long-term climatological timescale (30 years) averages centered around selected historic and future reference years.
5. Perturbation ratios were calculated by dividing the future long-term average of monthly streamflows by historic long-term average of monthly streamflows.
6. CalSim historical reservoir and other tributary inflows were adjusted by multiplying historical period of record timeseries with computed perturbation ratios based on the month and location.
7. Computed CalSim reservoir inflows are further adjusted to represent the seasonal and annual projected runoff trends simulated by VIC model.

B.6 Sea Level Rise

Sea level rise was used as a boundary condition along with the climate change hydrology for CalSim to simulate SWP operations under future conditions. CalSim uses artificial neural networks (ANN) to simulate Delta flow requirements to meet salinity regulatory standards. The ANNs are developed for each sea-level-rise scenario and incorporated into CalSim to generate outputs for future conditions.

B.7 Comparison of DCR Climate Change Analyses

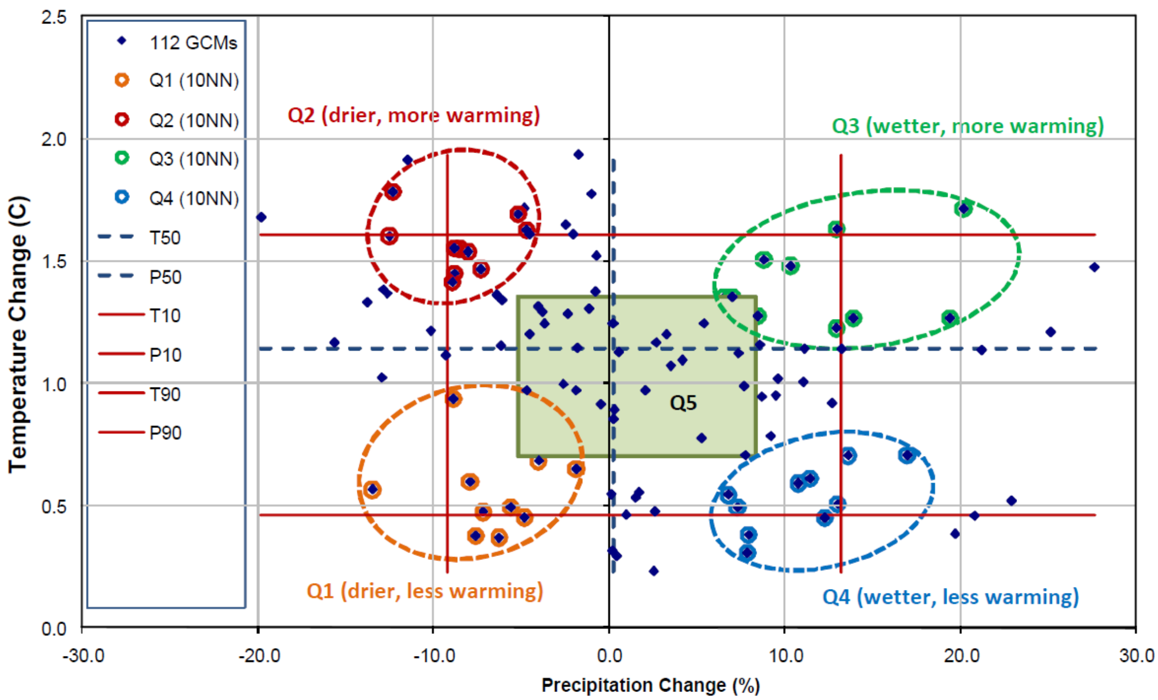
The climate change analysis incorporated in the DCRs published since 2007 are summarized in Table B-1. Select attributes defining various aspects of the analysis, such as data sources, assumptions, and model versions, are presented for comparison.

All DCRs to date (except 2017) have used one or a small number of individual climate change scenarios derived from downscaled GCM data to analyze SWP delivery capability, with the VIC model used for simulating runoff and CalSim II or CalSim 3 for simulating operations. The DCRs up to 2015 used Coupled Model Intercomparison Project Phase 3 (CMIP3)-based GCM scenarios, and 2019 and 2021 DCRs used CMIP5-based GCM scenarios.

The 2007 DCR incorporated climate change analyses based on the scenarios from DWR's 2006 *Progress on Incorporating Climate Change into Management of California's Water Resources 1st Progress Report* (California Department of Water Resources 2006). The scenarios included two individual GCMs with two

RCP emissions scenarios. The 2009 and 2011 DCRs selected only one of the scenarios from the 12 individual scenarios available to use (ECHAM5-A2) from DWR's 2009 study (Chung et al. 2009). The 2013 and 2015 DCRs analyzed the late-long-term central-region Q5 scenario selected from the ensemble of 112 GCM projections produced from 16 GCMs and three RCPs that were analyzed as part of the Bay Delta Conservation Plan Environmental Impact Report/Environmental Impact Statement. Figure B-1 shows how the Q5 scenario was derived from the results of a subset of the 112 GCMs. The Q5 scenario is bounded by the 25th and 75th percentile joint temperature-precipitation change.

Figure B-1 Example Downscaled Climate Projections and Sub-Ensembles used for deriving Climate Scenarios (Q1-Q5)



Source: California Department of Water Resources 2013b.

The 2017 DCR did not include climate change scenario analysis because such an analysis for that DCR was not requested by the State water contractors. The 2019 and 2021 DCRs incorporated a central tendency scenario constructed from localized constructed analog (LOCA) downscaled CMIP5 models. The scenario was generated by calculating the ensemble mean of 20 GCM projections produced from 10 GCMs and two RCPs selected by DWR's Climate Change Technical Advisory Committee in 2015 (California Department of Water Resources Climate Change Technical Advisory Group 2015).

Table B-1 Summary of DCR Climate Change Analysis Attributes

DCR Year	Reference	Planning Model	Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
2007 (DWR 2008)	DWR (2008)	CalSim II	2007 and 2027	CMIP3	BCSD	Two individual GCMs with two RCP emissions scenarios at 2050: GFDL-A2 GFDL-B1 PCM-A2 PCM-B1	Progress on Incorporating Climate Change into Management of California's Water Resources 1st Progress Report, July 2006 (DWR 2006).	None
2009 (DWR 2010a)	DWR (2010a)	CalSim II	2009 and 2029	CMIP3	BCSD	One individual GCM and RCP emissions scenario at 2050: ECHAM5-A2	Using Future Climate Projections to Support Water Resources Decision Making in California, May 2009 (Prepared by DWR for California Climate Change Center) (Chung et al. 2009).	1 ft (mid-century), 2 ft (end of century)

DCR Year	Reference	Planning Model	Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
2011 (DWR 2012)	DWR (2012)	CalSim II	2011 and 2031	CMIP3	BCSD	One individual GCM and RCP emissions scenario at 2050: ECHAM5-A2	Using Future Climate Projections to Support Water Resources Decision Making in California, May 2009 (Prepared by DWR for California Climate Change Center) (Chung et al. 2009).	1 ft (mid-century), 2 ft (end of century)
2013 (DWR 2013a)	DWR (2013a)	CalSim II	2013 and 2033	CMIP3	BCSD	Late-long-term central-region Q5 selected from ensemble of 112 GCM projections produced from 16 GCMs and 3 RCPs at 2050.	Bay Delta Conservation Plan EIS/EIR (Appendix 5A Attachment 1) (DWR 2013b).	45 cm (~1.5 ft)

DCR Year	Reference	Planning Model	Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
2015 (DWR 2015)	DWR (2015)	CalSim II	2015 and 2025	CMIP3	BCSD	Early-long-term central-region Q5 selected from ensemble of 112 GCM projections produced from 16 GCMs and 3 RCPs at 2025.	Bay Delta Conservation Plan EIS/EIR (Appendix 5A Attachment 1) (DWR 2013b).	15 cm (~0.5 ft)
2017 (DWR 2017)	DWR (2017)	CalSim II	2017	N/A	N/A	N/A	N/A	N/A
2019 (DWR 2020a)	DWR (2020a)	CalSim II	2020 and 2040	CMIP5	BCSD	Central Tendency selected from ensemble mean of 20 GCM projections produced from 10 GCMs and 2 RCPs at 2040.	Delta Conveyance Project (DCP) EIR (Modeling Appendix 5A, Modeling Technical Appendix, Section B, Attachment 4) (DWR 2022b).	45 cm (~1.5 ft)

DCR Year	Reference	Planning Model	Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
2021 (DWR 2022c)	DWR (2022c)	CalSim 3	2020 and 2040	CMIP5	LOCA	Central Tendency selected from ensemble mean of 20 GCM projections produced from 10 GCMs and 2 RCPs at 2040.	Delta Conveyance Project (DCP) EIR (Modeling Appendix 5A, Modeling Technical Appendix, Section B, Attachment 4) (DWR 2022b).	55 cm (~1.8 ft)

Notes: BCSD = bias correction and spatial disaggregation; cm = centimeter; CMIP = Climate Model Intercomparison Project Phase 3; DCR = Delivery Capability Report; DCP = Delta Conveyance Project; DWR = California Department of Water Resources; EIR = environmental impact report; EIS = environmental impact statement; ft = foot or feet; GCM = global circulation model; ITP = incidental take permit; LOCA = localized constructed analog; N/A = not available; RCP = representative concentration pathway.

B.8 Comparison to Other DWR Climate Change Analyses

To put the climate change analysis methods used in the DCRs in the context of all climate change studies conducted by DWR, this section discusses methods used in DWR studies other than the DCRs. Tables B-2 and B-3 summarize the attributes of these other studies. Table B-2 shows top-down analyses, and Table B-3 shows bottom-up analyses. Select attributes defining various aspects of the analysis such as data sources, assumptions, model versions are presented for comparison purposes.

B.9 Top-Down Studies

Independent of the DCRs, development of data for top-down climate change studies has been conducted by DWR for the 2009, 2013, and 2018 California Water Plan (CWP) reports and the Water Storage Investment Program (WSIP). The data and models from WSIP were also used for analysis of the California Aqueduct Subsidence Program and the Sustainable Groundwater Management Act. This section discusses these top-down studies and compares them to the most similar DCR study.

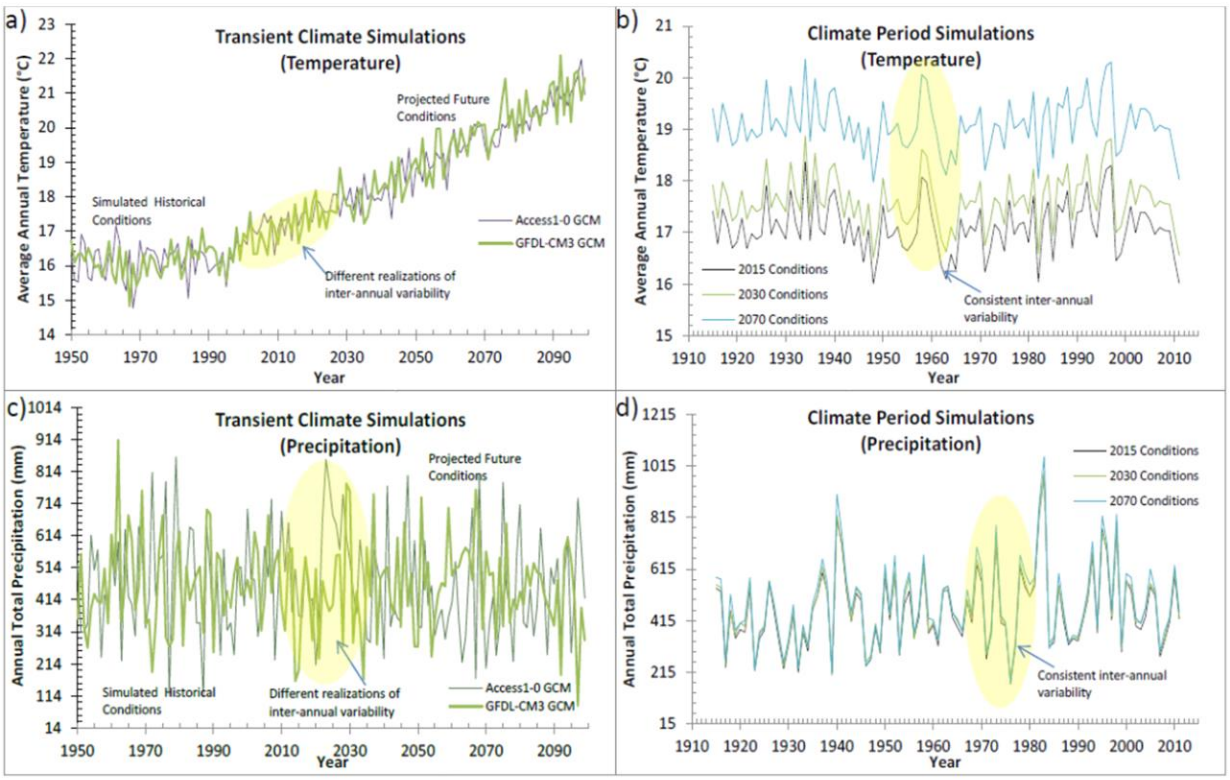
The 2009 and 2013 CWPs incorporated climate change analyses and were most similar to the 2009 DCR, as the source of the climate change scenarios was the same (Chung et al. 2009). But, there were some important differences. First, the 2013 CWP analysis was conducted by analyzing all of the 12 individual scenarios available, and the 2009 DCR selected only one of those scenarios to use (ECHAM5-A2). Because the goal of the CWP is to provide a more generalized analysis of water supply conditions, compared to the DCR which is very specifically focused on SWP supply reliability and meeting certain operational criteria, the CWP was better suited to support analysis of multiple climate scenarios. Second, the Water Evaluation and Planning (WEAP) model was used for analysis, rather than using the VIC model for simulating runoff and CalSim II for simulating operations. WEAP provides a more integrated modeling framework that was preferred for the CWP. And third, the CWP analyses were conducted using a transient analysis, rather than fixing the planning horizon on a specific year. The latter approach, also called the climate period approach, was used in all DCRs. Figure B-2 illustrates the difference between these two approaches.

The 2018 CWP was most similar to the 2019 DCR, as it used the 20 GCM projections recommended by DWR Climate Change Technical Advisory Group

(CCTAG) (2015). Differences between the 2018 CWP and the 2019 DCR are parallel to those described above for the 2009 and 2013 CWPs. The 2018 CWP used WEAP to conduct transient analyses. It also analyzed 20 scenarios individually, rather than deriving a single central tendency scenario from the 20 GCMs, as was done in the 2019 DCR.

The methods used to develop climate change models for WSIP were also most similar to the 2019 DCR, as the 20 GCM projections used were those recommended by DWR CCTAG (2015). Because WSIP used CalSim, the overall approach was more similar to the 2019 DCR than the 2018 CWP. As with the 2019 DCR, the approach was to develop a single central tendency scenario using the 20 GCM projections from the DWR CCTAG. There were, however, some differences. These include the downscaling method, as WSIP used LOCA, and the 2019 DCR used bias correction and spatial disaggregation/constructed analogues, and the planning horizon (2030–2070 versus 2020–2040). The hydrology development in WSIP also differed slightly in that it employed a spatially consistent temperature and precipitation adjustment method that differed from the DCR’s heterogeneous median climate adjustment method. WSIP also developed two extreme climate change scenarios at 2070, which was not done for the 2019 DCR. These were extreme dry/hot and wet/warm scenarios, each of which were based on an individual GCM scenario (see Table B-2).

Figure B-2 Comparison of Transient and Climate Period Simulation Approaches



In a **transient analysis**, the climate change signal strengthens incrementally over time, as has been occurring in recent decades. In general, years further into the future are warmer than years closer to the beginning of the simulation, and the most severe changes to climate tend to occur toward the later years of the simulation. Conversely, in a **climate period analysis**, climate change is modeled as a shift from a baseline condition (usually historical observed climate) where every year of the simulation is shifted in a way that represents the climate change signal at a future 30-year climate period. The figures above illustrates some of the differences in transient and climate period simulations for both temperature changes and precipitation changes. Figures 2a and 2b compare the difference in the ways that these two approaches represent changes in temperature. Figure 2a (**transient analysis**) shows the clear increasing trend in temperature over time. Figure 2b (**climate period analysis)** shows that a step change in temperature occurs between 2015 conditions and 2030 or 2070 conditions. Figure 2c (**transient analysis)** illustrates how noisy the precipitation data are for transient climate simulations but also how each run explores novel examples of inter-annual variability. Conversely, Figure 2d (**climate period analysis)** illustrates how a climate period simulation follows the historical pattern of inter-annual variability and the only differences come from the ways in which climate models project certain year-types will shift to wetter or drier conditions.

Source: Department of Water Resources 2018.

Table B-2 Summary of Other DWR Climate Change Analysis Attributes (Top-Down)

Study	Reference	Planning Model	Scenario Period/ Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
CWP 2009 and 2013	(DWR 2010a, 2014)	WEAP	2011–2099 (Transient)	CMIP3	BCSD	6 individual GCMs with two RCP emissions scenarios (A2 and B1).	Using Future Climate Projections to Support Water Resources Decision Making in California, May 2009 (Prepared by DWR for California Climate Change Center) (Chung et al. 2009).	Not included
CWP 2018	(DWR 2019a)	WEAP	2006-2100 (Transient)	CMIP5	LOCA	10 individual GCMs with two RCP emissions scenarios (4.5 and 8.5).	Used 20 models selected by CCTAG (2015)	Not included

Study	Reference	Planning Model	Scenario Period/ Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
WSIP	(CWC 2016)	VIC and CalSim II	2030 and 2070 (ensemble mean); 2070 (extreme dry/hot and wet/warm)	CMIP5	LOCA	Central Tendency developed from the median CDF of the ensemble of 20 GCM projections produced from 10 GCMs and 2 RCPs at 2030 and 2070. Extreme scenarios used one individual GCM and emissions scenario each. CNRM-CM5 (RCP4.5) and HadGEM-ES (RCP 8.5).	Used 20 models selected by CCTAG (2015)	15 cm (~0.5 ft) at 2030; 45 cm (~1.5 ft) at 2070

Study	Reference	Planning Model	Scenario Period/ Planning Horizon	CMIP Archive	Downscaling Method	GCM and RCP	Climate Change Data Source	Sea Level Rise
SGMA		Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP
CASP		Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP	Same as WSIP

Notes: BCSD = bias correction and spatial disaggregation; CASP = California Aqueduct Subsidence Program; CCTAG = Climate Change Technical Advisory Group; CDF = cumulative distribution function; cm = centimeter; CMIP3 = Climate Model Intercomparison Project Phase 3; CWP = California Water Plan; DWR = California Department of Water Resources; ft = foot or feet; GCM = global circulation plan; LOCA = localized constructed analog; RCP = representative concentration pathway; SGMA = Sustainable Groundwater Management Act; VIC = variable infiltration capacity; WEAP = Water Evaluation and Planning; WSIP = Water Storage Investment Program.

B.10 Bottom-Up Studies

Four bottom-up studies, all of which used similar methods, were identified for comparison to the methods used in the DCRs (see Table B-3). All of these studies use an approach called “decision scaling” (Brown and Wilby, 2013). Because bottom-up is a different approach than is top-down, these studies are by definition very different from the DCRs. But, some areas of comparison can be identified. All the bottom-up studies used CMIP5 GCMs, which is the same source of GCMs as was used in the 2019 and 2021 DCRs. However, a larger number of GCMs was used than in the DCRs because of the additional flexibility of the bottom-up approach with respect to GCM and climate information.

Between 36 and 40 GCMs were used in combination with two emissions scenarios, depending on the study. This differs from the 2019 and 2021 DCRs, which both developed a single central tendency scenario based on 10 GCMs and two emissions scenarios. The bottom-up studies shown all used different planning horizons than the 2019 and 2021 DCRs, ranging from 2040 to 2070, depending on the study. However, although these bottom-up studies focused on summarizing and outputting results from the time periods listed, an important advantage of decision scaling is that it is quite flexible with respect to time, and other time periods can be quickly and easily extracted from the modeling already completed.

Lastly, the hydrology and system operations modeling tools were different in these bottom-up studies compared to DCR studies. The bottom-up studies used WEAP or CalLite for system operations, in conjunction with the Sacramento soil moisture accounting model (SAC-SMA) for simulating streamflows. This contrasts with the use of VIC and CalSim II/CalSim 3 in the DCR studies.

Table B-3 Summary of Other DWR Climate Change Analysis Attributes (Bottom-Up)

Study	Reference	System/ Hydrologic	Planning Horizon	CMIP Archive	Downscaling Method	GCM Probabilities	Perturbed variables	Sea Level Rise
SWP Vulnerability Assessment	DWR (2019b), Hydrosystems Research Group and DWR (2019)	CalLite/SAC-SMA	2050	CMIP5	LOCA	36 CMIP5 models with 2 RCPs (4.5/8.5)	Temperature 0-4 C; Precipitation -20% - +30%	0 cm, 15 cm, or 45 cm (0, ~0.5, or ~1.5 ft), depending on scenario
Delta Adapts	DSC (2021)	CalLite/SAC-SMA	2050	CMIP5	LOCA	36 CMIP5 models with 2 RCPs (4.5/8.5)	Temperature 0-4 C; Precipitation -20% - +30%	0 cm, 15 cm, 30 cm, 45 cm, or 60 cm (0, ~0.5, ~1.0, ~1.5, or ~2 ft) depending on scenario
Merced Reconnaissance Study	DWR (2022c)	WEAP/SAC-SMA	2040, 2070 "Tipping Points"	CMIP5	LOCA	40 CMIP5 models with 2 RCPs (4.5/8.5)	Temperature 0-4 C; Precipitation -30% - +30%	N/A
CWP 2023	DWR (2022d)	WEAP/SAC-SMA	2070	CMIP5	LOCA	40 CMIP5 models with 2 RCPs (4.5/8.5)	Temperature 0-5 C; Precipitation -30% - +30%	Not mentioned in available report

Notes: = centimeter; CMIP5 = Climate Model Intercomparison Project Phase 5; CWP = California Water Plan; DSC = Delta Stewardship Council; DWR = California Department of Water Resources; ft = foot or feet; GCM = global circulation plan; LOCA = localized constructed analog; N/A = not available; RCP = representative concentration pathway; SAC-SMA = Sacramento soil moisture accounting model; = State Water Project; WEAP = Water Evaluation and Planning.

B.11 References

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