CLIMATE CHANGE RISK FACED BY THE CALIFORNIA CENTRAL VALLEY WATER RESOURCE SYSTEM

A Report for:

California's Fourth Climate Change Assessment

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report assesses future performance of key water resources management factors for the Central Valley water system using probability-based climate change risk assessment.

ABSTRACT

Observed climate trends and projections of accelerated future change have motivated several studies of the impacts of climate change on water resources management in California. This paper presents a methodology that improves on previous approaches, revealing fundamental climate change risks to one of the State of California's key water resource systems — the integrated California Central Valley System (CCVS). By using a bottom-up decision scaling approach, starting with a systematic climate change stress test of the performance of the system to changes in temperature and precipitation, specific vulnerabilities to the system are identified. This study also improves on previous water resource vulnerability analyses by incorporating and evaluating a much wider range of inter-annual precipitation variability than has previously been used. By drawing from the 1,100-year (reconstructed dendrochronology) record of Sacramento and San Joaquin river flows, vulnerabilities to low frequency natural climate variability are analyzed in concert with expected potential climate changes. The results of this analysis provide a comprehensive summary of the sensitivity of the system to climate change. This paper provides results and discussion of select future system performance metrics at 2050. Results indicate that declines in almost every category (e.g., supply, storage, delta outflow) of system performance are likely. The likelihood of severely degraded future performance is especially high for north-of-Delta carryover storage and Delta exports. The results of this study are expected to provide water managers and decision-makers with more actionable science because they provide probabilistic results that can be used in more traditional risk management approaches to planning of climate change adaptation investment decisions.

Keywords: Climate Change Vulnerability, Water, Stress Test, California Central Valley Water System, Decision Scaling

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HIGHLIGHTS

- The performance of the Central Valley Water system, which includes the California State Water Project and the Federal Central Valley Project, is expected to diminish significantly from historical levels of performance by 2050 as a result of climate change.
- A 93 percent likelihood of diminished Delta exports in the future based on general circulation models (GCM)-based probability estimates. Delta exports are the combined SWP and CVP water exports from the south Delta pumping plants operated by the Department of Water Resources and U.S. Bureau of Reclamation. These exports are delivered to State Water Project and Central Valley Project contractors who, in turn, deliver the water to millions of Californian households, businesses, and farms.
- A 95 percent likelihood of diminished drought resilience and operational control for meeting downstream river flow temperature requirements in the future based on GCM-based probability estimates of future north-of-Delta reservoir carryover storage.
- Additional water will be required to be released from reservoirs or Delta exports will need to be reduced to maintain summer and fall regulatory conditions in the Delta resulting from increased sea levels and associated salinity intrusion.
- While it is possible that future Delta exports and water storage performance might be better than current performance, the GCM-based likelihood of such outcomes is small.
- GCM-based probability estimates of system performance are expected to provide decision-makers with more actionable information that can be used in more traditional risk management approaches to planning, especially those related to climate change adaptation investments.
- This study includes greater consideration of historical inter-annual variability than past studies by exploring extreme droughts and floods of the last 1,100-years but does not explore potential increases in inter-annual variability that may occur as a result of climate change. Even without inclusion of such changes in inter-annual variability, water system performance shows significant vulnerabilities and risks which would likely by intensified by increased inter-annual variability.

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ACRONYMS AND ABBREVIATIONS

CCC4A	4th California Climate Change Assessment
CCVS	California Central Valley Water System
cdf	cumulative distribution function
CMIP5	Fifth Coupled Model Intercomparison Project
cm	centimeters
CVP	Central Valley Project
Delta	Sacramento-San Joaquin Delta
DWR	California Department of Water Resources
GCM	general circulation model
in.	inches
IPCC	Intergovernmental Panel on Climate Change
maf	million acre-feet
NDO	net Delta outflow
NOD	north of Delta
NSE	Nash-Sutcliffe efficiency
NWS	National Weather Service
pdf	probability distribution function
RCP	representative concentration pathway
Reclamation	U. S. Bureau of Reclamation
SAC-SMA	Sacramento Soil Moisture Accounting
SWP	State Water Project

1: Introduction

The California Department of Water Resources (DWR) and the U. S. Bureau of Reclamation (Reclamation) oversee the operation of the integrated California Central Valley Water System (CCVS) that stores and manages water supplies originating in the Sierra Nevada mountains and flows through the Sacramento-San Joaquin Delta (Delta) to water users throughout the state. The catchment area of the Sacramento and San-Joaquin rivers (Figure 1) provides at least a portion of the water supply for approximately two-thirds of California's population.

The CCVS can be understood to be the interconnected system of natural river channels and human-made facilities that comprise the Central Valley Project (CVP), owned and operated by Reclamation, and the State Water Project (SWP), owned and operated by DWR. The CVP includes more than 13 million acre-feet (maf) of storage capacity in 20 reservoirs and provides water to approximately 3 million acres of irrigated agricultural fields, as well as municipal water uses, and rivers and wetland water releases to meet State and federal ecological standards. The SWP, with functions including flood control, maintenance of environmental and water quality conditions, water supply, hydropower, and recreation, includes more than 30 storage facilities, reservoirs and lakes, and approximately 700 miles of open canals and pipelines, providing water to approximately 25 million Californians and approximately 750,000 acres of irrigated farmland. The CVP and SWP are typically not the exclusive water supplier for those they serve; many customers supplement the water provided by CVP and SWP with local or imported sources.

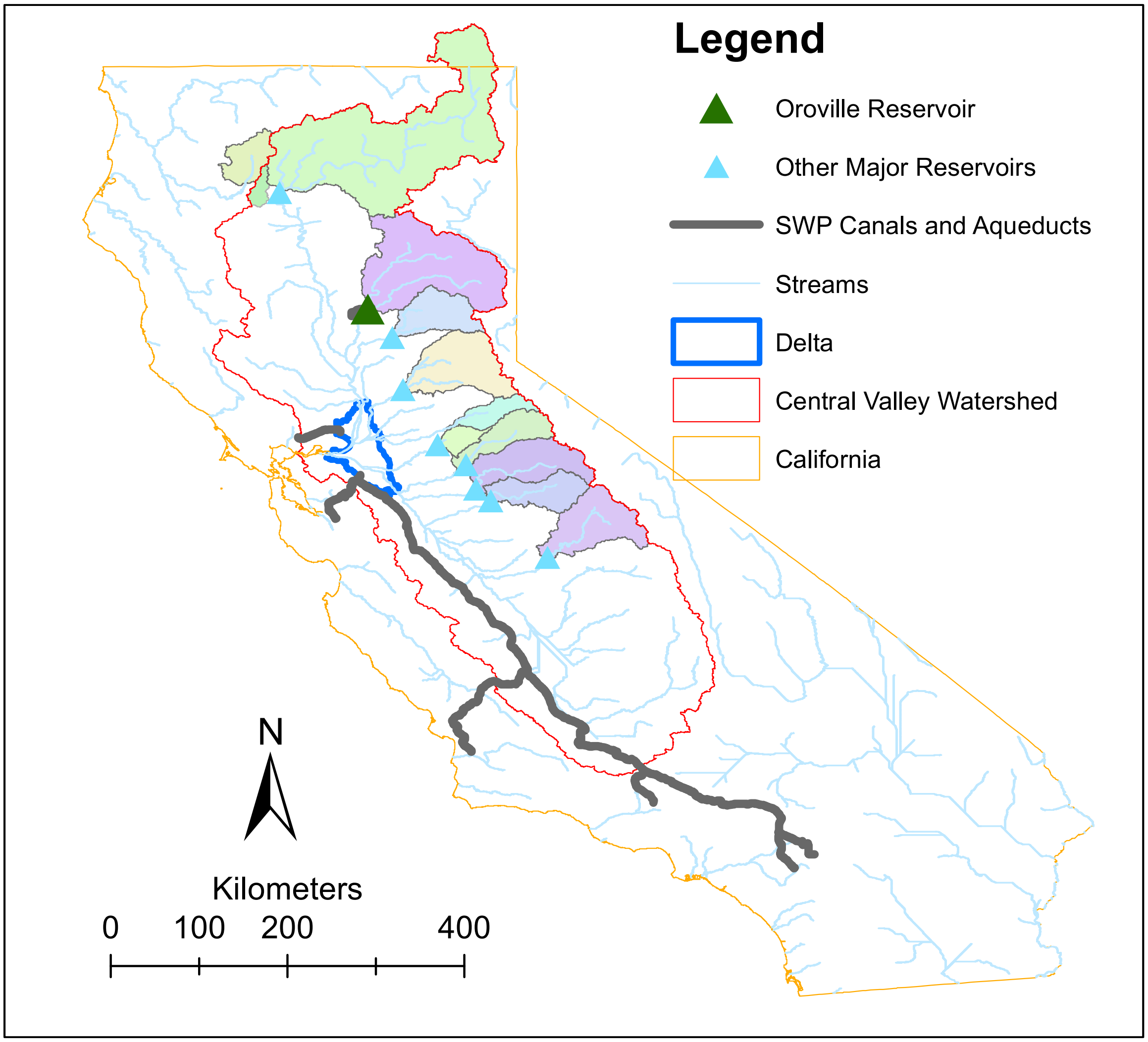


Figure 1: California Central Valley Water System and Rim Subbasins

Recent global (Intergovernmental Panel on Climate Change 2013), national (Melilo et al. 2014), regional (Garfin et al. 2014), and statewide (California Climate Change Center 2012) climate change assessments have highlighted climate-change-driven impacts on water supply, water demand, increased flooding and drought, and changes to hydrologic processes of relevance to the CCVS. The effects of climate change on the hydro-climatology of California have begun, and substantial further effects are likely to emerge throughout this century, creating larger challenges for water resources management in a state already grappling with some of the greatest variability in the nation (Dettinger et al. 2011).

Mean temperature has increased approximately 1° C since 1900 (LaDochy et al. 2007, Seager et al. 2015), and temperature change is accelerating (Ashfaq et al. 2013), with the greatest change in temperature minimums (Cordero et al. 2011). Rising temperatures in the Sierra Nevada and Northern California have triggered decreasing snowpack and earlier snowmelt (Cayan et al. 2010; Dettinger and Anderson 2015; Mote et al. 2005). Warmer temperatures also cause sea level rise, with 0.2 meters (8 inches [in.]) of rise recorded in San Francisco Bay in the past century

(National Oceanic and Atmospheric Administration 2016), and rates of rise are accelerating (Kopp et al. 2016). The San Francisco Bay is connected to the Delta which serves as an important component of the CCVS because most of the water delivered by the CCVS passes through the Delta, and salinity control in the Delta is an important management objective of the system.

Projections of future temperature across California suggest an intensification of hot extremes (Diffenbaugh and Ashfaq 2010). By the end of this century, the Sierra snowpack is projected to experience a 48 percent to 65 percent loss relative to the historical April 1 average on which summer and fall water supply is dependent (Cayan et al. 2013).

Since 1970, it appears that California has gotten wetter in its north and drier in its south (Killam et al. 2014), though the large historical variability of precipitation in California makes it difficult to separate trend from natural variability (Higgins et al. 2007; Swetnam and Betancourt 1998). Drought conditions in California are increasing in intensity and length (Diffenbaugh et al. 2015). Though the recent 2011-2014 drought in California can be mostly attributed to natural precipitation variability, not warming (Mao et al. 2015; Seager et al. 2015), climate change is expected to amplify droughts in California. The amplification may result from both rising temperatures (Cayan et al. 2010; Williams et al. 2015), and the possibility of an intensification of El Niño-Southern Oscillation (ENSO) activity (Yoon et al. 2015), though a conclusive answer on whether ENSO is going to become stronger or weaker as the tropics warm is not yet available (Wang et al. 2017).

Decrease in snowpack storage, and the concentration of streamflow in winter months, would increase dry-season deficits. During this time, demand for irrigation water will likely increase because of increased evapotranspiration (Rosegrant et al. 2009)).

Recently, DWR has observed increases in the volume of runoff that arrives at reservoirs during the flood protection season, and reductions in the stored water available to meet summer peaks in water demand. These events have coincided with increasing peak summer demands beyond historical levels that are the result of higher-than-normal temperatures. These observations cause DWR to conclude that "existing infrastructure will need to be adapted to the new timing of runoff, as well as accommodate higher flows from more powerful individual storm events in a warmer atmosphere (California Department of Water Resources 2015)."

All of this change is occurring on top of a baseline of some of the highest coefficients of variation in historical precipitation in the United States (Dettinger et al. 2011). The effect of climate change on atmospheric rivers, the source of 30 percent to 50 percent of all precipitation for the U.S. West Coast and principal cause of winter floods (Dettinger 2013), is not yet well understood (Steinschneider and Lall 2015). However, a number of simulation experiments using climate models have indicated that projected changes are mostly at the extremes (Dettinger 2011), with California's atmospheric rivers becoming longer and more intense, but not more frequent (Shields and Kiehl 2016). They carry warmer water vapor more likely to fall at high altitudes as rain than snow (Dettinger 2011). The net effect is exacerbated winter floods, but not reduced water stress, despite increases in winter mean precipitation (Warner et al. 2015). While the evaluation of the effect of potentially increasing climate variability is outside of the scope of this analysis, California's high precipitation variability creates challenges for general circulation models (GCMs), and results in a particularly wide spread of projections (relative to precipitation projection ranges throughout the rest of the United States) for future precipitation values in the region (Roy et al. 2010).

The observed climate trends and projections for accelerated future change have motivated studies of the impacts of climate change on water resources management in California. Recent exercises in climate change data analysis, water system modeling, and impact assessment have yielded substantial insights for policy-making and public discussion related to the CCVS. Previous climate change studies of the CCVS surveyed for this paper include Tanaka et al. (2006), Anderson et al. (2008), Medellin-Azuara et al. (2008), California Department of Water Resources (2008), Anderson et al. (2008), California Climate Change Center (2009), Harou et al. (2010), Connell-Buck et al. (2011), Tanaka et al. (2011), Wang et al. (2011), Willis et al. (2011), Huang et al. (2012), Groves and Bloom (2013), U.S. Bureau of Reclamation (2014), and U.S. Bureau of Reclamation (2016). Each of these studies has taken a "top down" approach to future climate change conditions. That means they have all used some variation on a scenario analysis approach that begins with (1) extraction of future climate conditions from a global climate model or models, (2) downscaling of those climate conditions to a locally applicable scale, (3) use of downscaled climate results to drive a rainfall-runoff model to generate runoff and streamflows of interest to the CCVS, and (4) use of the generated streamflow information to drive a model of the water system to calculate changes in system performance as a consequence of the changed climate conditions. This approach provides important insights into how the CCVS would likely perform under prescribed future climate conditions. However, several of the studies used just a small number of climate change projections, leaving many possible future climate outcomes left unevaluated. In studies where multiple climate scenarios are run, performance of the system often varies considerably across those scenarios, with many cases showing results that would indicate improved performance (such as increased ability to deliver water) for some scenarios while others indicate severely reduced performance. With little or no indication as to which scenario might be more likely, the results of these studies have often been taken as cause for concern, but have not yielded significant investment or action toward adaptation.

This report takes a fundamentally different approach to climate change analysis; a "bottom up" approach called "decision scaling" (Brown et al. 2012). It starts with a systematic evaluation of the water system's sensitivity to changes in temperature and precipitation and then uses the most reliable signals from a large GCM ensemble to evaluate the relative likelihood of each future climate state to understand how likely the outcomes are that create problems for the system. Using the decision scaling approach, this report presents a systematic climate vulnerably assessment of the CCVS across a range of potential future climate conditions that span the climate change uncertainty domain for changes in average temperature and precipitation. GCM-based probabilities are then used in concert with system simulations across this climate change uncertainty domain to calculate the relative likelihood of potential future performance levels. The results of this analysis are explicit about the uncertainty involved in estimation of future climate impacts. By providing probabilistic climate change impact results on an array of important system performance metrics, listed in Table 1, decision-makers and stakeholders are provided a clearer picture of the potential climate change risks to the system and the relative likelihood of various levels of future performance. While the other studies of CCVS climate change vulnerability have previously identified similar vulnerabilities and risks, none has placed these vulnerabilities in a probabilistic risk framework. The explicit recognition of this uncertainty allows the results to be more readily used in traditional risk management planning approaches used to make investment decisions.

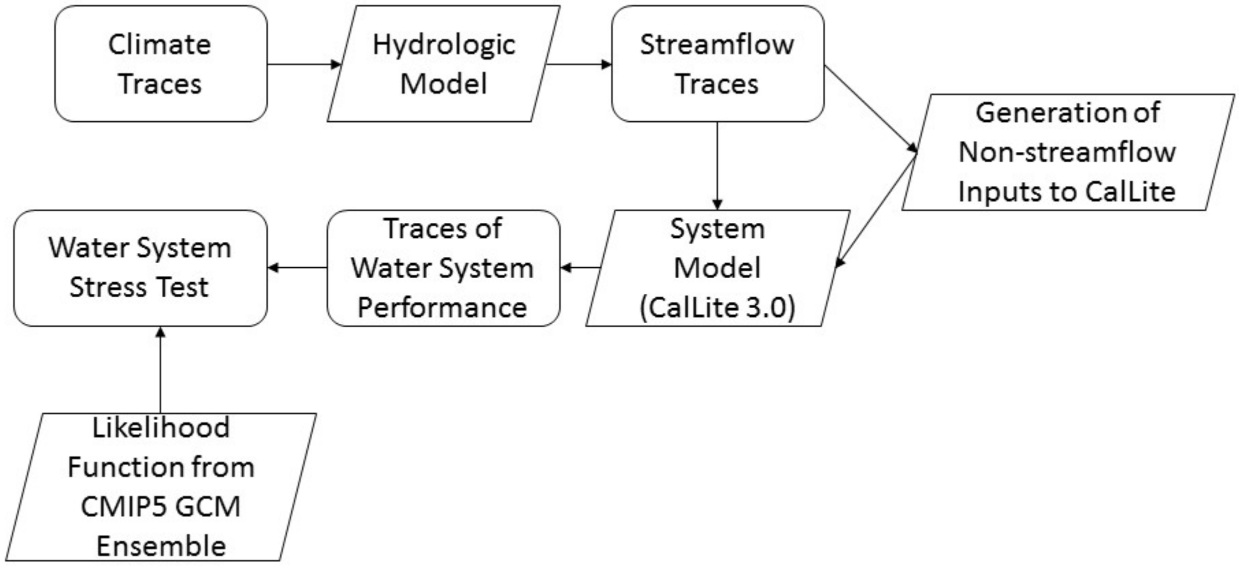
Table 1: California Central Valley Water System Performance Metrics

1	North-of-Delta (NOD) Storage Levels
	Total NOD End of April Storage
	Total NOD Carryover Storage
	Shasta Carryover Storage
	Oroville Carryover Storage
	Folsom Carryover Storage
	Trinity Carryover Storage
2	Net Delta Outflow
	Winter
	Spring
	Summer
	Fall
3	Delta Exports
	Average Annual

2: Methodology

Figure 2 presents the workflow used for this study. This workflow allows the systematic exploration of climate change impact in response to a wide range of meteorological input. Table 1 lists the CCVS metrics evaluated using this approach. When the response of a given performance metric to a systematically explored climate space is presented relative to a performance threshold (in this case, historical performance), the approach is referred to as a stress test.

Each step in the workflow is described in detail in this chapter.



Note: CMIP5 = Fifth Coupled Model Intercomparison Project, GCM = general circulation model

Figure 2: Modeling Workflow for Climate Change Vulnerability Assessment

This analysis focuses on persistent medium- and long-term conditions evaluated at a monthly time-step. Short-duration extreme-precipitation events that cause flooding may also stress water resource management, but this analysis does not explicitly evaluate flood risk.

2.1 Generation of Climate Traces

In order to represent current climate conditions this study uses the paleo-dendrochronology reconstructed streamflow record of the Sacramento 4-river flow (900–2013) (Meko et al. 2014) coupled with historical daily temperature and precipitation 1950–2013 (Livneh et al. 2013). The reconstructed streamflow record of the Sacramento 4-river flow provides information about long-term inter-annual variability by providing an 1,100-year record of the wet and dry cycles that the basin has endured.

The Sacramento 4-river flow is the aggregate annual water-year (October 1st-September 30th) streamflow on the Sacramento River at Bend Bridge, the American River inflow to Folsom Reservoir, Yuba River at Smartsville, and Feather River inflow to Oroville Reservoir. The Sacramento 4-river flow covers the major inflow points to the CVSS. Additional flows into the CVSS not covered by the Sacramento 4-river flow are highly correlated to the Sacramento 4-river flow (Meko et. al. 2014). While the paleo-dendrochronology reconstructed streamflow record of the Sacramento 4-river flow provides important long-term inter-annual variability information, the annual streamflow values do not provide sufficient information about the spatiotemporal distribution of temperature and precipitation that would have produced such runoff.

To reconstruct plausible spatiotemporal distributions of temperature and precipitation, the historical daily temperature and precipitation data (Livneh et al. 2013) provide detailed information about the spatial distribution across California and temporal distribution across each year of temperature and precipitation at 1/16 degree (approximately 6 kilometer-by-6 kilometer grid spacing).

In order to create a timeseries of gridded temperature and precipitation over the CCVS watershed area that reflects the long-term inter-annual variability of the reconstructed streamflow record of the Sacramento 4-river index while maintaining the spatial and temporal distributions of the observed climate data, the following steps were taken:

1. Prior to using the historical observed temperature data, it was necessary to remove the warming trend in the data. Temperature detrending was achieved by applying a linear trend to the data so that the detrended temperature time series had trend line of slope zero and average value equal to the average temperature from 1981 through 2010. This procedure was applied gridcell by gridcell across the CCVS watershed area. The detrended historical temperature allows reference to current/recent historical conditions when developing the stress test matrix (as opposed to more abstract reference to mid-20th-century temperatures at the mean of the historical timeseries). The observed historical precipitation data showed no similar trend. As a result, it required no detrending.

2. The SAC-SMA-DS hydrologic model (described in Section 2.2 "Hydrologic and Streamflow Traces") was used to simulate streamflows in the Sacramento, Feather, Yuba, and American rivers of the Sacramento basin using the historical (1950–2003) detrended temperature and precipitation data. These four river flows make up the Sacramento 4-river index flows.

3. Simulated Sacramento 4-river index flows were calculated for the years 1950-2003 using the SAC-SMA-DS model output.

4. For each year, 900-1949, the reconstructed Sacramento 4-river streamflow as calculated by Meko et al (2014), was associated with the historical simulated flow (1950–2003) that was closest to it to identify the closest observed analogue year that produced similar flow conditions.

5. For each year, 900-1949, the gridded (detrended) temperature and precipitation data for the analogue simulated flow year was then copied in as the gridded daily temperature and precipitation record for each of the historical reconstructed year (900-1949).

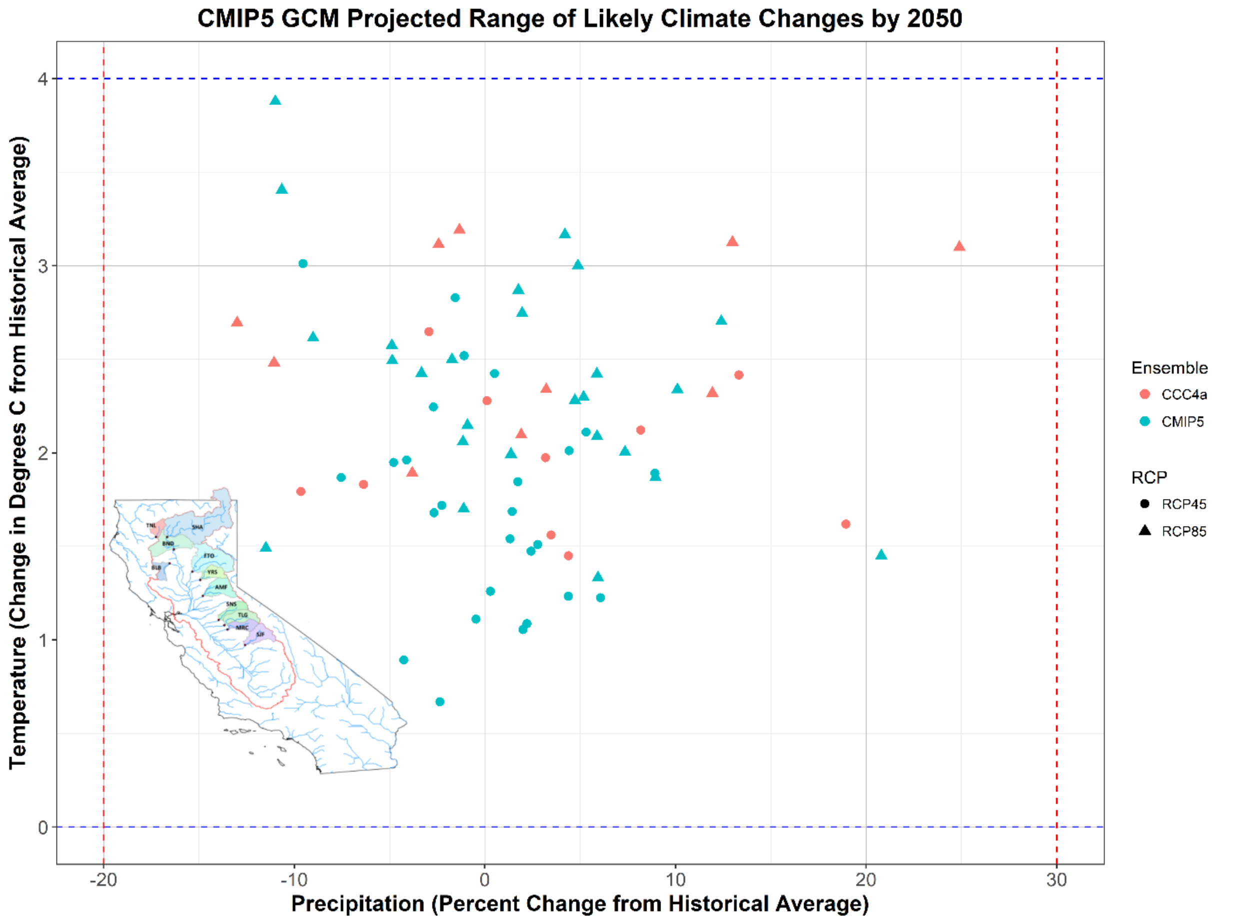
6. For years 1950 through 2000, observed temperature and precipitation data are available, thus for the years 1950-2000 the gridded (detrended) observed data were incorporated chronologically to complete the 1,100-year record of (detrended) temperature and precipitation (900-2000).

This method of copying full years of temperature and precipitation ensures that spatial and temporal correlations are maintained. It also allows for exploration of a much wider range of hydrologic inter-annual variability than is present in just the observed record. While not evaluated in this study, the 1,100-year record of wet and dry periods provides additional data to be used for the evaluation of future drought risk, which will be the focus of a future study.

The resulting 1,100-year record (900–2000) of temperature and precipitation was then perturbed systematically in order to explore a wide range of climate changes. The resulting temperature and precipitation data were then input to SAC-SMA-DS.

In order to explore the climate vulnerability domain of the CCVS, climate traces similar to the historical trace in pattern, but unique in average temperature and precipitation, were generated. The explored range for temperature and precipitation was informed by the range of changes projected for the CCVS watershed area by the global climate models included in the Intergovernmental Panel on Climate Change's (IPCC's) Fifth Coupled Model Intercomparison Project (CMIP5) (Taylor et al., 2012). Figure 3 shows the range of average temperature and precipitation change projected (1981–2010 relative to 2036–2065) by 36 different models simulated at representative concentration pathway (RCP) 4.5 and 40 different models simulated at RCP 8.5. The scatter of the model projections indicates that the likely range of temperature and precipitation change that the CCVS would experience ranges from -20 percent to +30 percent change in precipitation, and temperature change of 0 °C to +4 °C (0 °F to 7.2 °F). The subset of CMIP5 models that were recommended for use in the California 4th Climate Change Assessment (CCCA4) are colored red in the figure. For this study, inclusion of the large ensemble of climate model projections was desired to ensure that the full range of uncertainty about potential future climate conditions was considered.

A total of 54 combinations of temperature shifts (0 °C to +4 °C, by 0.5 °C increments; 0 °F to 7.2 °F by, 0.9 °F increments) and precipitation shifts (-20 percent to +30 percent, by 10 percent increments) were then imposed on each day of the 1,100-year historical climate record in each of the CCVS grid cells using the Delta method. Climate change differences based on latitude, longitude, elevation, and seasonal differences were considered but analysis of observed and projected trends revealed insufficient evidence for applying spatially or temporally distributed shifts in temperature or precipitation. Additional investigations of observational and projected temperature and precipitation trends will be the focus of future studies to further explore and refine this assumption.



Notes: CMIP5 = Fifth Coupled Model Intercomparison Project, GCM = general circulation model, RCP = repretentative concentration pathway
Changes shown are average annual precipitation and temperature shifts: 2036–2065 relative to 1981–2010.

Figure 3: CMIP5 Ensemble of 36 Different General Circulation Model Outputs for the California Central Valley Water System

2.2 Hydrologic Model and Streamflow Traces

The hydrologic modeling component of this study was completed using the Sacramento Soil Moisture Accounting (SAC-SMA) model (Burnash et al. 1973), a lumped conceptual hydrological model employed by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA) to produce river and flash flood forecasts for the nation (Burnash 1995; McEnery et al. 2005). However, for this study, the SAC-SMA model has been coupled with a river routing model (Lohmann et al. 1998) to be suitable for modeling a distributed watershed system. The coupled model is hereafter referred to as SAC-SMA-DS, in part to distinguish it from the distributed version of SAC-SMA previously developed by NWS and applied to a number of case studies (e.g., Koren et al. 2004; Smith et al. 2004). SAC-SMA-DS is composed of hydrologic process modules that represent soil moisture accounting, potential evapotranspiration (Hamon 1961), snow processes (Anderson, 1976), and flow routing. The model operates on a daily time step and for distributed watershed systems. Details on its development are available in *California Climate Risk: Evaluation of Climate Risks for California Department of Water Resources* (California Department of Water Resources 2017).

SAC-SMA-DS is used to simulate streamflow at 32 locations throughout the CCVS watershed. These 32 streamflow simulations include (1) 12 rim inflows to major reservoirs throughout the CCVS, (2) 11 gauging station streamflows important for calculating water year types used for regulatory constraints, management, and operational decision-making, and (3) nine subbasin inflows that account for a substantial portion of the rain in the system. The streamflow simulations of the nine subbasins represent "unimpaired inflows." They are the modeling results of estimating the runoff that would have occurred had water flow remained unaltered in rivers and streams instead of stored in reservoirs, imported, exported, or diverted (Bay-Delta Office, 2007). The 12 rim inflows are used as direct input to CalLite 3.0, the 11 streamflow gauging stations are used to calculate water year type classification on the Sacramento and San Joaquin watersheds, and the nine "unimpaired" subbasins are used principally to add information to the process for generating non-streamflow inputs to CalLite 3.0 (described in the following section).

2.3 Generation of Non-Streamflow Inputs to CalLite

CalLite 3.0 (released in 2014) is used as the system model to represent CCVS operations. CalLite receives as input all system-wide relational data, such as reservoir area-elevation-capacity data, wetness-index dependent flow standards, and monthly flood control requirements. For each month of the simulation period, CalLite employs a mixed integer program to maximize water deliveries and/or storage according to specified priorities and system constraints. Output includes water supply indicators, environmental indicators, and water use metrics (California Department of Water Resources and U.S. Bureau of Reclamation 2011; Draper et al. 2004).

The usable water resources for the CCVS, allocated monthly by the CalLite 3.0 algorithm, can be approximated as the quantity of streamflow into the Central Valley from the northeast upgradient regions that are comprised of 12 large subbasins, referred to as the rim subbasins (Figure 1). CalLite 3.0 simulates the coordinated operations of the intertied CCVS, and represents reservoir operations, SWP and CVP operations and delivery allocation decisions, existing water sharing agreements, and Delta salinity responses to river flow and export changes. With its CCVS-specific design and substantial complexity come better fidelity to the mechanics of allocation rules and water-sharing agreements. But a consequence of this design and complexity are empirically based relationships in the model, and input data to the model, that pose challenges related to water system simulation under wide-ranging conditions of climate uncertainty.

CalLite's 796 input terms consist of inflows, pumping rates, water demands, evaporation rates, diversion requirements, delivery patterns, losses, water quality requirements, storage rules, withdrawals, environmental triggers, and other variables. In order to perform a climate change stress test on the system, a methodology was needed to vary the 796 input time series in an internally consistent manner which reflected the hydro-climatic influences on each of the inputs.

Because only a small subset of all CalLite inputs were gauged streamflows that could be simulated using SAC-SMA-DS, a procedure was developed to systematically compare each non-streamflow input with one of the 32 SAC-SMA-DS-simulated streamflows (or set of streamflows). First, it was determined which SAC-SMA-DS-simulated streamflow best correlated each non-streamflow CalLite input over the historical time-period (1950–2003). Then, each non-streamflow CalLite input could be quantile mapped to the identified climate-perturbed SAC-SMA-DS-simulated streamflow to generate a climate-adjusted time series of CalLite input.

The majority of non-streamflow CalLite input terms followed a monthly pattern that best correlated with one of two water-year-type indices (Sacramento Valley water year type and San Joaquin Valley water year type), which are calculated using a formula and aggregated streamflow data. Information regarding the calculation methodology of water year classification can be found at http://cdec.water.ca.gov/cgi-progs/iodir_ss/wsihist.

The Sacramento and San Joaquin water year type indices classify the available water of the two major watersheds of the CCVS into one of five discrete states (relative to long-term average streamflow values for each watershed): "wet" classification, two "normal" classifications (above normal and below normal), and two "dry" classifications (dry and critical).

Water year type classification systems "simplify complex hydrology into a single, numerical metric that can be used in rule-based decision-making," (Null and Viers 2013) and have been applied to development of drought indices throughout the United States (Heim 2002; Quiring 2009). They have also been applied to other uses, such as hydropower reservoir management in Chile (Olivares et al. 2015).

SAC-SMA-DS simulates each of the flows necessary to calculate water year type in each of the two watersheds. It was used to simulate water year type under climate adjusted conditions which in turn was used with quantile mapping to generate the non-streamflow CalLite input terms. Details on the water year typing and quantile mapping approaches and procedures developed to apply internally-consistent climate change perturbations can be found in *California Climate Risk: Evaluation of Climate Risks for California Department of Water Resources* (California Department of Water Resources 2017).

2.3.1 Sea Level Rise

For operational purposes, it was important to estimate sea level rise as a function of temperature, and to associate the appropriate amount of sea level rise with the temperature perturbation to which each CalLite run was subjected. Sea level rise increases saline intrusion into the Delta. During the spring and fall, when regulations dictate maximum salinity conditions in the Delta and minimum outflow requirements from the Delta, DWR and Reclamation must release additional water from reservoirs, or reduce exports from the Delta, to offset this increased head and maintain required regulatory conditions.

At the time of this study, three sea level rise scenarios were parameterized in CalLite: 0 centimeters (cm) (0 in.), 15 cm (6 in.), and 45 cm (18 in.). The National Research Council (2012) approximated the anticipated future rate of sea level rise along the California coast, south of Cape Mendocino, for the years 2030, 2050, and 2100. These projections, in conjunction with values for projected global temperature increase by year from IPCC (2013), were used to estimate the amount of sea level rise that should be expected along the California coast, south of Cape Mendocino, for each temperature band shown in Table 2. These coarse discretizations of sea level rise are a limitation of the model, and may cause underestimation of impacts at higher temperatures (e.g., more than 2.5 °C [4.5 °F], when sea level rise would likely exceed 45 cm [18 in.]). Further, sea level increases beyond 45 cm would likely begin to cause significant changes in Delta hydrodynamics as such levels of increased sea level would likely result in levee overtopping and additional inundation of lands that are currently protected by levees. Modeling such changes would require making assumptions about future levee investments and land uses which are beyond the scope of this project.

Table 2: Sea Level Rise Discretization – Expected Sea Level Change as A Function of Temperature Change

Temperature Change relative to Recent Historical Average Temperature	Sea Level Rise Relative to Recent Historical Average Sea Level
0 °C (0 °F)	0 cm (0 in.)
0.5 °C - 1.0 °C (0.9 °F - 1.8 °F)	15 cm (6 in.)
≥ 1.5 °C (2.7 °F)	45 cm (18 in.)

2.4 Traces of Water System Performance

CalLite is designed to run as a steady state simulation model with land use, sea level, and water demand held constant throughout the simulation period. For all simulations in this study, land use patterns were fixed at projected 2030 levels. Water demand was assumed to be full allocation demand, meaning that all SWP and CVP contractors would take delivery of the maximum amount of water available, up to their contracted allocation quantity. But other water demands, such as direct diversions of water from Central Valley rivers and streams, were adjusted and scaled according to their historical response to changes in climate (as described in Section 2.2 "Hydrologic and Streamflow Traces"). Sea level was varied by simulation as indicated in Table 2. CalLite's mixed integer linear program then maximized monthly water deliveries, and/or storage, according to specified priorities and system constraints (Draper et al. 2004). The system constraints and weights are specified using the Water Resources Engineering Simulation Language (WRESL) (DWR, 2000): "The objective function in the CALSIM (CalLite) model is a linear combination of decision variables and their associated priority weights. In addition, slack and surplus variables added to the objective function from 'soft' constraints are multiplied by their associated negative penalties."

2.5 GCM Likelihood Function

Using RCPs 4.5 (36 GCM runs) and 8.5 (40 GCM runs) of the CMIP5 ensemble (76 GCM runs total), the relative weights assigned to the climate states were obtained in five steps.

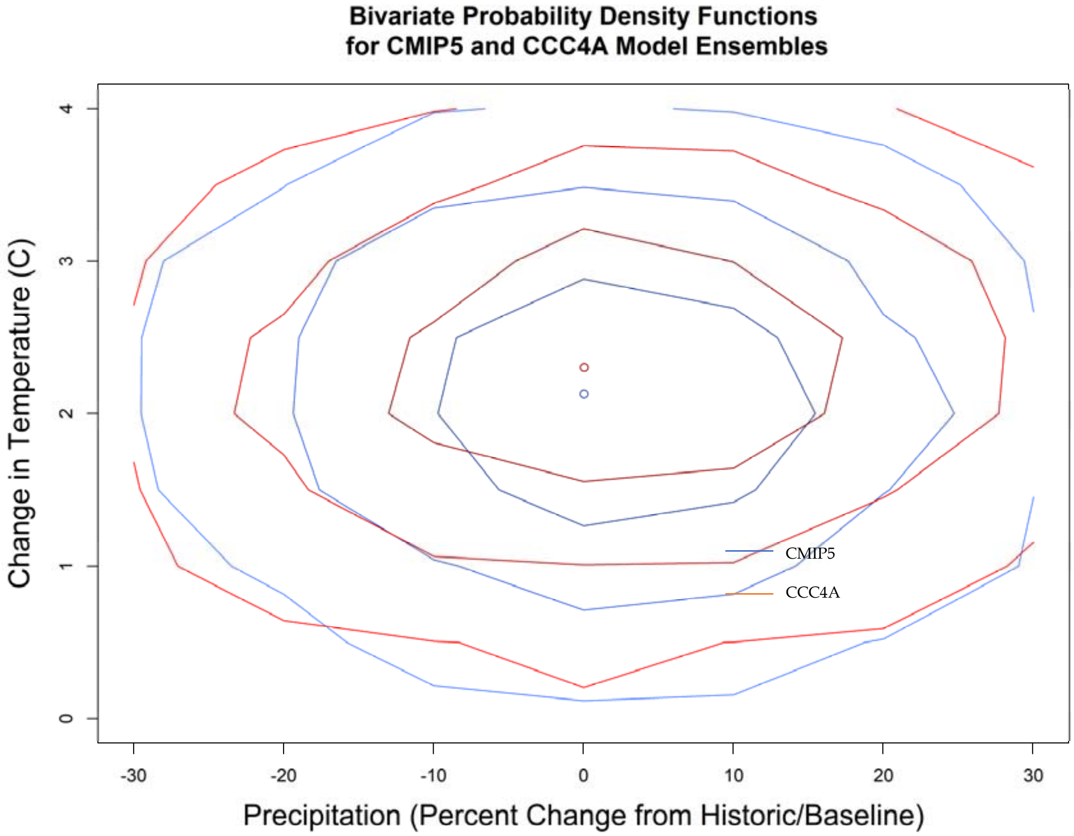
1. The vector of future mean annual precipitation and temperature changes was calculated from all climate projections.
2. The computed mean changes from the full ensemble of GCMs were reduced to 14 data points to account for the potential sampling biases due to the structural similarities in GCMs (Knutti et al., 2013). In so doing, all model runs were weighted equally, and combined by arithmetic averaging within each model group.

3. The computed 14 data points were used to define a probability distribution function (pdf) for the domain of climate change. In this case, a bivariate Gaussian distribution was fit to the data (e.g., Whateley et al. 2014).

4. The Gaussian pdf was used to obtain the contingent normalized probability weights of the 54-plausible mean temperature and precipitation changes, hereafter referred to as the GCM-based pdf. Similar approaches have been taken by others (Borgomeo et al. 2015; Steinschneider et al. 2015; Tebaldi et al. 2005).

5. When applying GCM-based probabilities to individual years in the development of cumulative density functions (cdf's) of possible future system performance, though each climate trace is more or less likely based upon its assigned shift in precipitation and temperature from the historical, each year within a given climate trace was assigned equal likelihood. Probability notions were thereby extended from "scenario" (shift in precipitation and temperature) to the realization of any given year within that scenario of shift.

As described above, a large ensemble of CMIP5 GCMs was used to inform the bivariate Gaussian distribution and all results presented below are based on that bivariate distribution. However, an additional analysis was conducted to calculate the bivariate Gaussian distribution informed by a subset of the full CMIP5 ensemble that included just the 10 models recommended for inclusion in the CCC4A. Figure 4 below shows the two distributions plotted on top of each other for comparison. While slight differences are present, the CCC4A distribution is slightly warmer and has slightly higher uncertainty with respect to precipitation, although generally the distributions are quite similar. System performance under the CCC4A GCM-based probability distribution of future climate was also evaluated and a description of those results is included below.



Notes: Circles represent mean of probability density function, lines represent 0.68, 0.95, and 0.998 probability density areas (i.e., 1, 2, and 3 standard deviations from the mean, respectively)

Figure 4: Comparison of Bivariate Probability Density Functions of CMIP5 and CCC4A Model Ensembles

3: Model Verification

3.1 Hydrologic Model Performance

To calibrate the SAC-SMA-DS, we utilized a genetic optimization algorithm (Conn et al. 1991) in which the Nash-Sutcliffe efficiency (NSE) (Nash and Sutcliff 1970) was used as an objective function. The simulated historical inflows of the 12 rim subbasins show very good performance for both calibration (1951–1980) and validation period (1981–2002) (Table 3). NSEs evaluated on the monthly simulated streamflow show values of more than 0.9 for all except for the Mokelumne subbasin. Considering the recommendation of Moriasi, et al. (2007) that model simulation can be judged as satisfactory if NSE is more than 0.50, these simulation results are highly satisfactory and will greatly reduce the errors stemming from the hydrology.

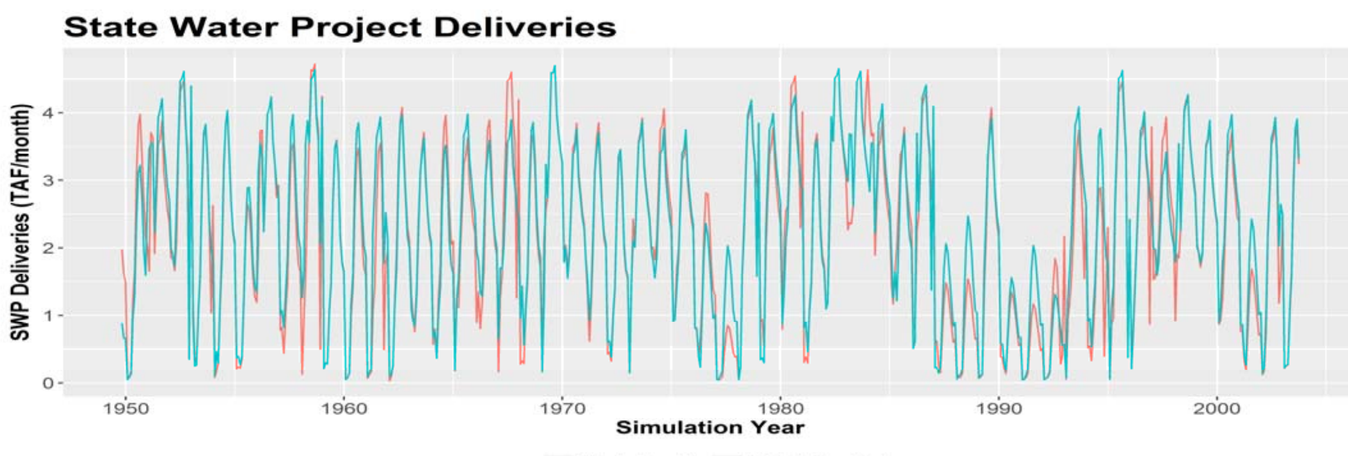
Table 3: Hydrologic Model Performance by Subbasin

Subbasin	Nash Sutcliffe Efficiency	
	Calibration (1951-1980)	Validation (1981-2002)
American	0.96	0.94
Merced	0.95	0.93
Stanislaus	0.91	0.90
San Joaquin	0.92	0.90
Mokelumne	0.77	0.85
Calaveras	0.96	0.93
Feather	0.95	0.94
Tuolumne	0.94	0.93
Sacramento	0.97	0.97
Trinity	0.94	0.89
Yuba	0.91	0.95
Clear Creek	0.95	0.93

3.2 System Model Performance

The validation of water system performance compares CalLite model output from a baseline run to CalLite model output from a simulation run under historical climate conditions. Using historical temperature and precipitation data, all necessary inputs to CalLite were generated using the methodology described above. Focus was given to three validation metrics that describe the three major aspects of system conditions: water supplied (deliveries to SWP contractors, shown in Figure 5), storage in the system's major reservoirs (Supplemental Information, Figure 12), and Delta outflow, which is important for meeting regulatory requirements governing system operation (Supplemental Information, Figure 13).

The simulated system was compared to a baseline that is a model run driven by historical streamflows (not historical climate) and other observational datasets used to calibrate water allocation and other system performance metrics to the historical record. However, the baseline CalLite run holds several characteristics of the CCVS system constant at current conditions (e.g., land use, sea level, disaggregated demand), and does not represent change in these characteristics over the course of the 1950–2003 historical period. The baseline run should not be taken to be a reproduction of observed historical CCVS performance. *California Climate Risk: Evaluation of Climate Risks for California Department of Water Resources* (California Department of Water Resources 2017) has further details on model workflow validation.



Notes: SWP = State Water Project
Top: Scatterplot fit of validation trace values to baseline trace values.
Bottom: Baseline (red) and validation (blue) trace monthly SWP deliveries.

Figure 5: Validation of CalLite Stress Test Modeling Workflow for State Water Project Monthly Deliveries

4: Risk Assessment Results

The decision scaling approach described in Chapter 1 was used to explore system performance for each of the metrics listed in Table 1. For each metric, a system performance response surface (Figures 6, 9, 10, and 11) was generated. These describe how the system would perform over a wide range of temperature and precipitation changes if no changes are made to the existing operational rules and regulatory constraints that govern operation of the system[1]. On each of the response surfaces, the heavy black line represents performance at historical levels; warm colors represent performance worse than historical levels while cool colors represent performance better than historical levels with each color band representing a 5 percent change in performance. The bivariate normal distribution of GCM-based year 2050 (average of years 2036–2065) shifts in average annual temperature and precipitation (relative to the period 1981–2010) are superimposed on the climate response surface and are represented as concentric blue polygons with the heavier black polygons representing the 68 percent and 95 percent confidence intervals. Attention will be drawn to the area inside the concentric circles. This area represents the range and relative likelihood of conditions indicated at mid-century for the CCVS by the CMIP5 model ensemble. At mid-century, the GCM-based pdf is roughly centered at 2 °C warming and little change in precipitation with the 95 percent confidence range extending from 0.5 °C to 3.5 °C (1 °F to 6 °F) and from -20 percent to +25 percent change in precipitation.

Table 4 presents the GCM-based probabilities that mid-century water system performance will be worse than current performance. Results are provided using both the bivariate Gaussian pdf informed by the large CMIP5 ensemble of GCMs and the bivariate pdf informed by only the subset of CMIP5 models recommended for inclusion in CCC4A studies. Detailed explanations of findings are provided in the following sections. Probabilistic estimates of annual performance are also provided for each of the selected performance metrics using a cumulative distribution function (cdf) and a pdf, which weight each trace by the likelihood of its climate change space (assuming every year within each trace to be equally likely).

Table 4: GCM-Based Probability that Mid-Century Performance will be inferior to Current Performance

Performance Metric	GCM-Based Probability that Mid-Century Performance will be inferior to Current Performance (Full CMIP5 Ensemble pdf)	GCM-Based Probability that Mid-Century Performance will be inferior to Current Performance (CCC4A Ensemble pdf)
North-of-Delta Storage		
Total NOD April Storage	65%	59%

[1] The authors acknowledge that while operational rules and regulatory constraints have changed over time, predicting exactly how and when those changes will occur involves substantial uncertainty and thus a status quo assumption is the most reasonable. Potential changes in operations and regulations are thus best explored as adaptation strategies or alternative futures.

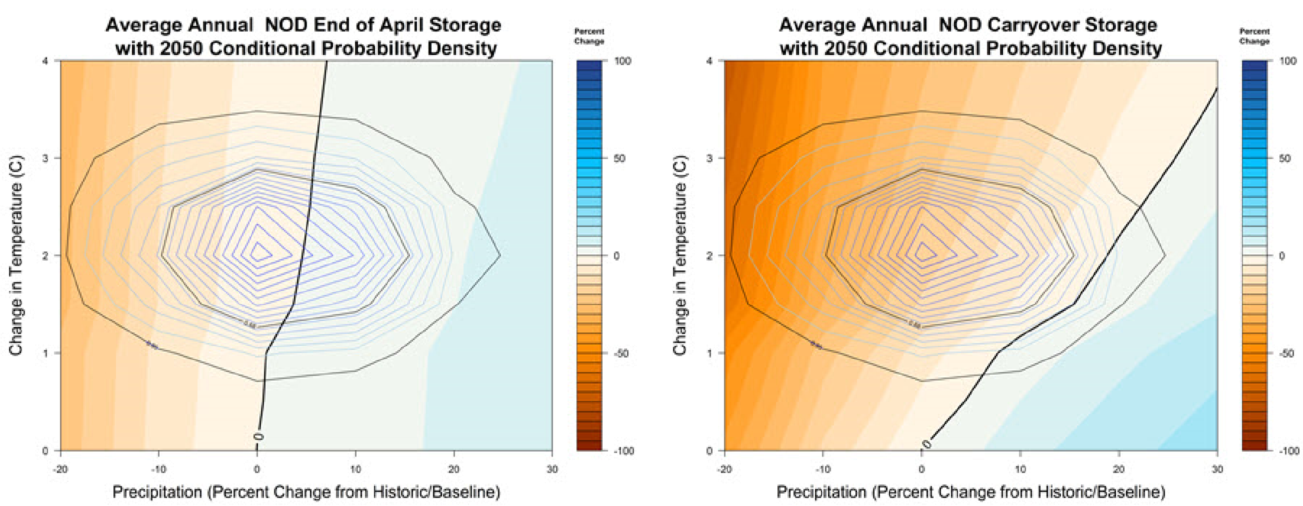
Total NOD Carryover Storage	95%	95%
Shasta Carryover Storage	97%	97%
Oroville Carryover Storage	95%	95%
Folsom Carryover Storage	99%	99%
Trinity Carryover Storage	87%	86%
Net Delta Outflow		
Winter	63%	58%
Spring	65%	59%
Summer	21%	21%
Fall	40%	42%
Annual Delta Exports	93%	89%

4.1 Performance Metric 1: North-Of-Delta Storage

North-of-Delta (NOD) storage includes the combined storage volumes in the four reservoirs that provide water to the CCVS that are north of the Delta — Shasta on the Sacramento River, Trinity on the Trinity River, Oroville on the Feather River, and Folsom on the American River. Two different performance metrics are provided for measuring impacts to storage in CCVS reservoirs: end of April storage and end of September storage, also called carryover storage. End of April storage represents the amount of water the CCVS has in storage at the end of the main runoff season and the beginning of the irrigation and high-water demand season, and thereby informs summer water supply availability and regulatory conditions. Carryover storage represents the amount of water the CCVS has in storage at the end of the irrigation and high-water-demand season but before winter rains begin. It describes water carryover from one year to the next and is an indication of the drought resilience of the system. NOD carryover storage is also important for river-water-temperature control downstream of CCVS reservoirs managed for salmonid rearing and survival conditions.

The solid black lines on the response surface for end of April (Figure 6a) and carryover storage (Figure 6b) shows that historical storage levels can be maintained at various future climate conditions (all combinations of temperature and precipitation change along the black line). With 2 °C of warming and no change in precipitation (approximately the centroid of the GCM bivariate pdf), there would be an approximate 5 percent decrease in end of April NOD storage and an approximate 20 percent decrease in NOD carryover storage. While the centroid of the GCM bivariate pdf indicates the consensus of the GCM projections, the concentric circles radiating from the center indicate the range of potential impacts with impacts further from the center having lower likelihood. Within the 95 percent confidence interval, NOD carryover storage impacts range from -55 percent to an increase of 5 percent. The GCM bivariate pdf provides the GCM-based probability weighted likelihood space of future outcomes. Consideration of the entire pdf space indicates that based on the GCM projections there is a 95 percent likelihood that future climate conditions will result in average annual NOD carryover storage being less than current average annual levels.

End of April storage is less sensitive to temperature increases than carryover storage because end of April storage measures accumulated runoff into NOD reservoirs during the winter rainy season. Higher temperatures are likely to generate less snow and accelerated melting rates, with the result that a higher proportion of the winter precipitation would flow immediately to the reservoirs, and less would remain high in the watershed as snow storage. As this additional water enters the reservoir it increases winter/spring storage levels but leaves less water in the upper watershed to replenish the reservoir later in the year. Carryover storage, on the other hand, is affected by the diminished snow reserves associated with higher temperatures, with smaller late-spring/early-summer snow-fed flows culminating in much lower storage levels at the end of the summer. Carryover storage response is also related to the higher sea levels assumed at higher temperature values. At an increase of 1.5 °C (2.7 °F), 45 cm (18 in.) of sea level rise is assumed, requiring more water to be released from storage (especially during the summer months) to repel sea water intrusion, and meet Delta outflow and salinity requirements.

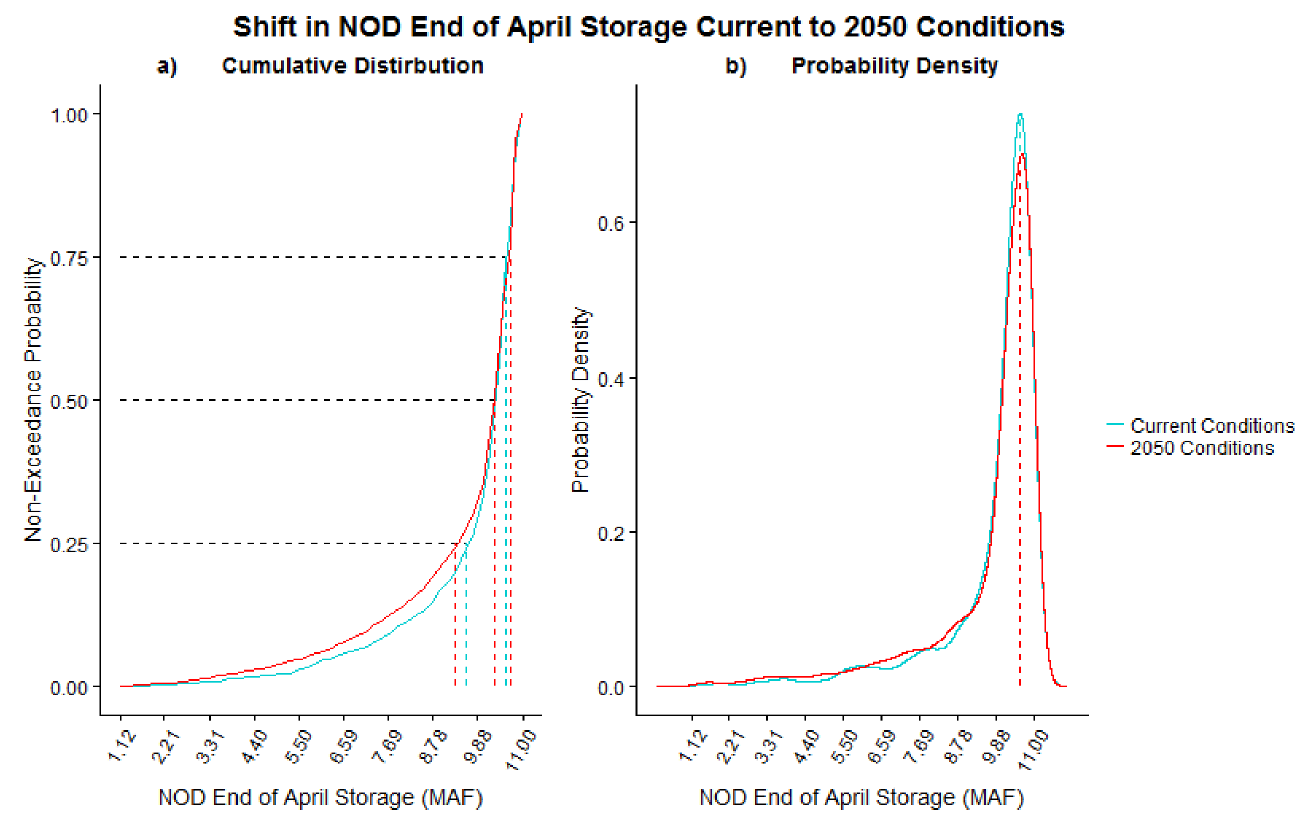


Notes: NOD = north of Delta
Solid black lines show historical storage levels. Two degrees C of warming alone, with no change precipitation (approximately the centroid of the GCM bivariate pdf) would result in a 5 percent decrease in April 1 NOD storage, and a 20 percent decrease in NOD carryover storage.

Figure 6: Response Surface – End of April (left) and End of September (right) NOD Storage

The cdf (Figure 7a) and pdf (Figure 7b) of end of April NOD storage shows that nearly all of the shift in annual April NOD storage occurs in the driest years (below the 25th percentile), indicating beginning of irrigation season storage in years that are already water stressed will likely become more stressed. There would be a small change, or no change, in beginning of irrigation season storage in wetter, less stressful years.

NOD carryover storage shows much more significant annual changes. Figure 8a presents the cdf for NOD carryover reservoir storage. The cdf shows a downward shift of more than 1 maf (15 percent) in median NOD carryover storage by mid-century. The decrease in future NOD carryover storage is similarly significant at the 75th percentile and 25th percentile, meaning that nearly all year types, from dry to wet, will see similar decreases in storage values. Below the 25th percentile the losses of carryover storage in NOD reservoirs are less severe. This is because of reservoirs reaching minimum storage targets (a relatively high priority in the operations model), resulting in other water uses in the model being reduced to avoid the reservoirs falling below targeted levels. Figure 8b shows a nearly 2 maf (25 percent) decrease in the mode of the pdf of future NOD carryover storage relative to current conditions.

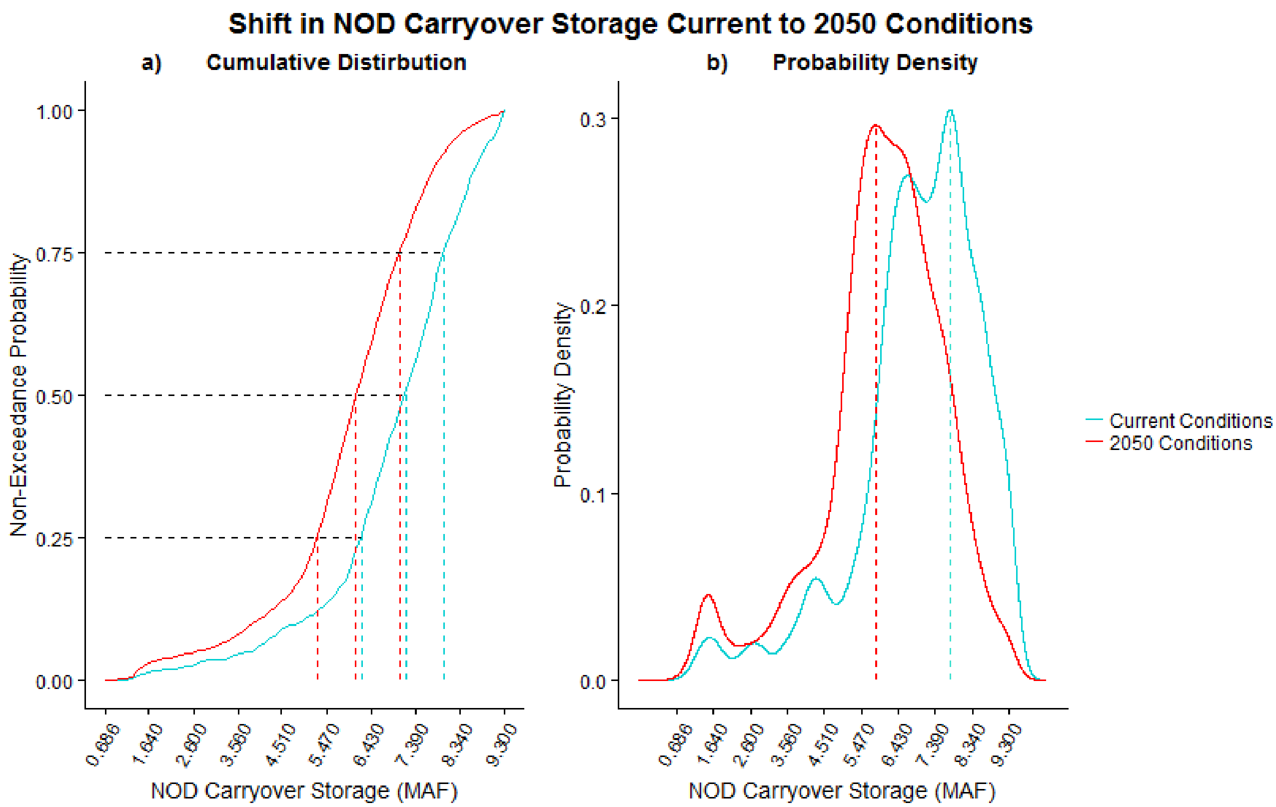


	P25	P50	P75
Current Conditions	9.62	10.3	10.6
2050 Conditions	9.35	10.3	10.7

	Mode
Current Conditions	10.6
2050 Conditions	10.6

Notes: NOD = north of Delta, MAF = million acre-feet

Figure 7: Shift in April 1 NOD storage, Current to Mid-Century Conditions



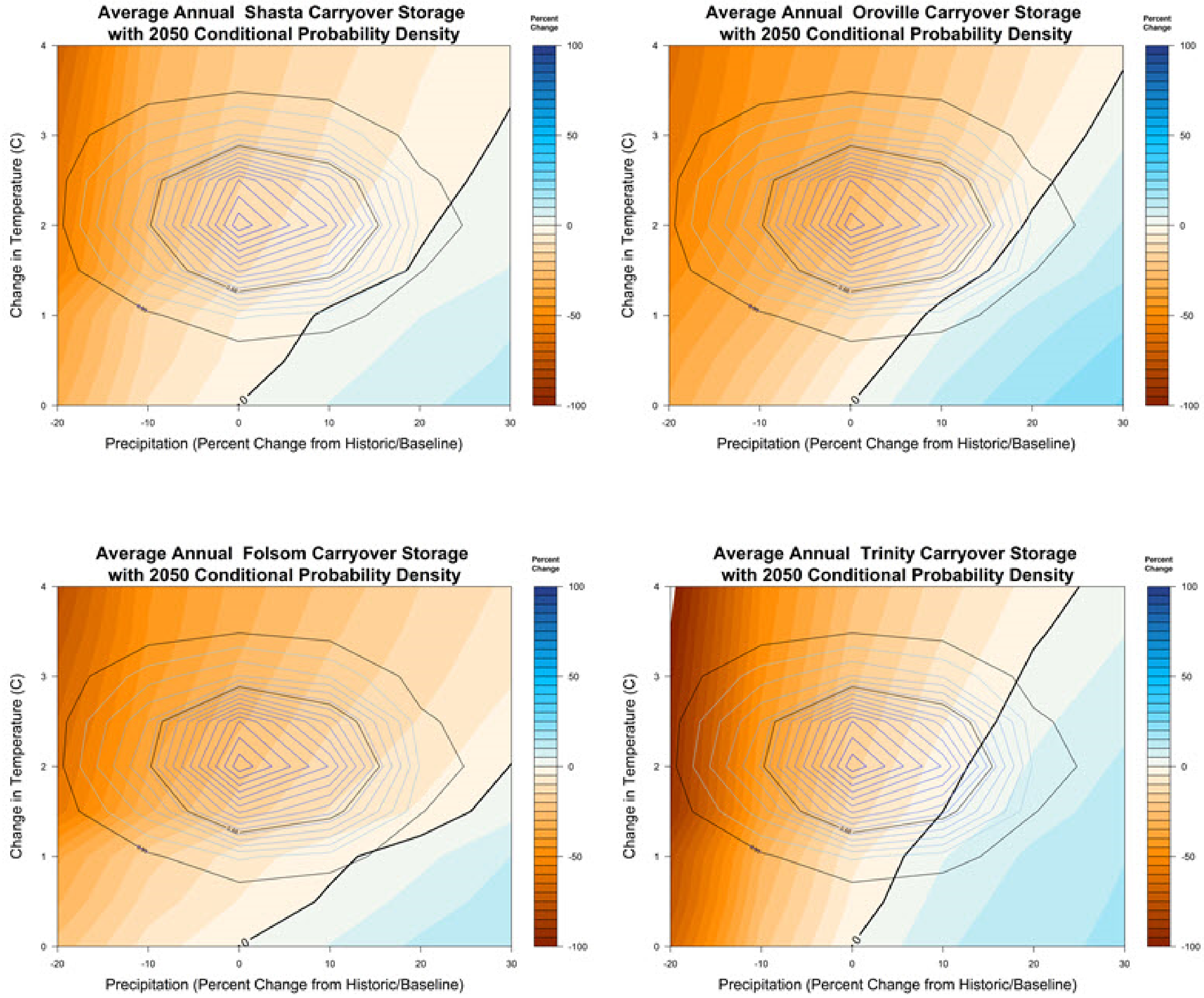
	P25	P50	P75
Current Conditions	6.23	7.18	8
2050 Conditions	5.29	6.11	7.06

	Mode
Current Conditions	7.77
2050 Conditions	5.84

Notes: NOD = north of Delta, MAF = million acre-feet
The cdf (left) shows a downward shift of 15 percent in median NOD carryover storage by mid-century, and a similarly significant decrease at the 25th and 75th percentiles. The pdf (right) shows a large (25 percent) downward shift in the mode of future NOD carryover storage relative to current conditions.

Figure 8: Shift in NOD carryover Storage, Current to Mid-Century Conditions

While NOD carryover storage provides an important systemwide metric, each of the four NOD reservoirs provide specific benefits to the system, warranting further investigation into the relative impacts on each of the reservoirs. Figure 9 shows the response surfaces for each of the four CCVS NOD reservoirs. From this comparison, Folsom reservoir is the most sensitive to changes in temperature, while Trinity reservoir is the least sensitive to changes in temperature. But for Folsom, Oroville, and Trinity, performance (level of storage at end of September) falls off rapidly at high temperatures and lower levels of precipitation as evidenced by the narrower performance (color) bands — each representing a 5 percent loss of storage. Shasta reservoir, while still acutely vulnerable to climate change, appears to be the most resilient of the four reservoirs, likely because it is mostly rain fed and relies less on snowmelt than the other reservoirs.



Note: Each sub-figure shows the relative sensitivity of each reservoir to changes in temperature and precipitation.

Figure 9: Response surfaces for Carryover Storage in Shasta, Oroville, Folsom, and Trinity Reservoirs

4.2 Performance Metric 2: Net Delta Outflow

Delta conditions dictate water project operations in summer and fall when maintenance of ecosystem conditions and water quality for Delta agricultural diverters is a critical aspect of CCVS operations. While there are a number of regulatory standards that must be met (and those standards change from month to month), net Delta outflow (NDO) provides a reasonable aggregate metric for Delta conditions.

Upstream conditions that influence NDO change throughout the year. Winter NDO is driven primarily by rainfall events and the resulting high flows in rivers flowing into the Delta. Spring NDO is driven by snowmelt and is sensitive to temperature changes that result in changes in spring snowpack conditions. Summer and fall NDO are driven primarily by regulatory and water quality requirements. Because these regulatory requirements are given high priority in real world water operations decisions, the water distribution algorithm used by CalLite 3.0 also gives them very high priority. CalLite 3.0 attempts to meet all regulatory requirements first, at the expense of other system water demands. The impacts of climate changes on summer and fall NDO conditions should be understood in this context as described in more detail below.

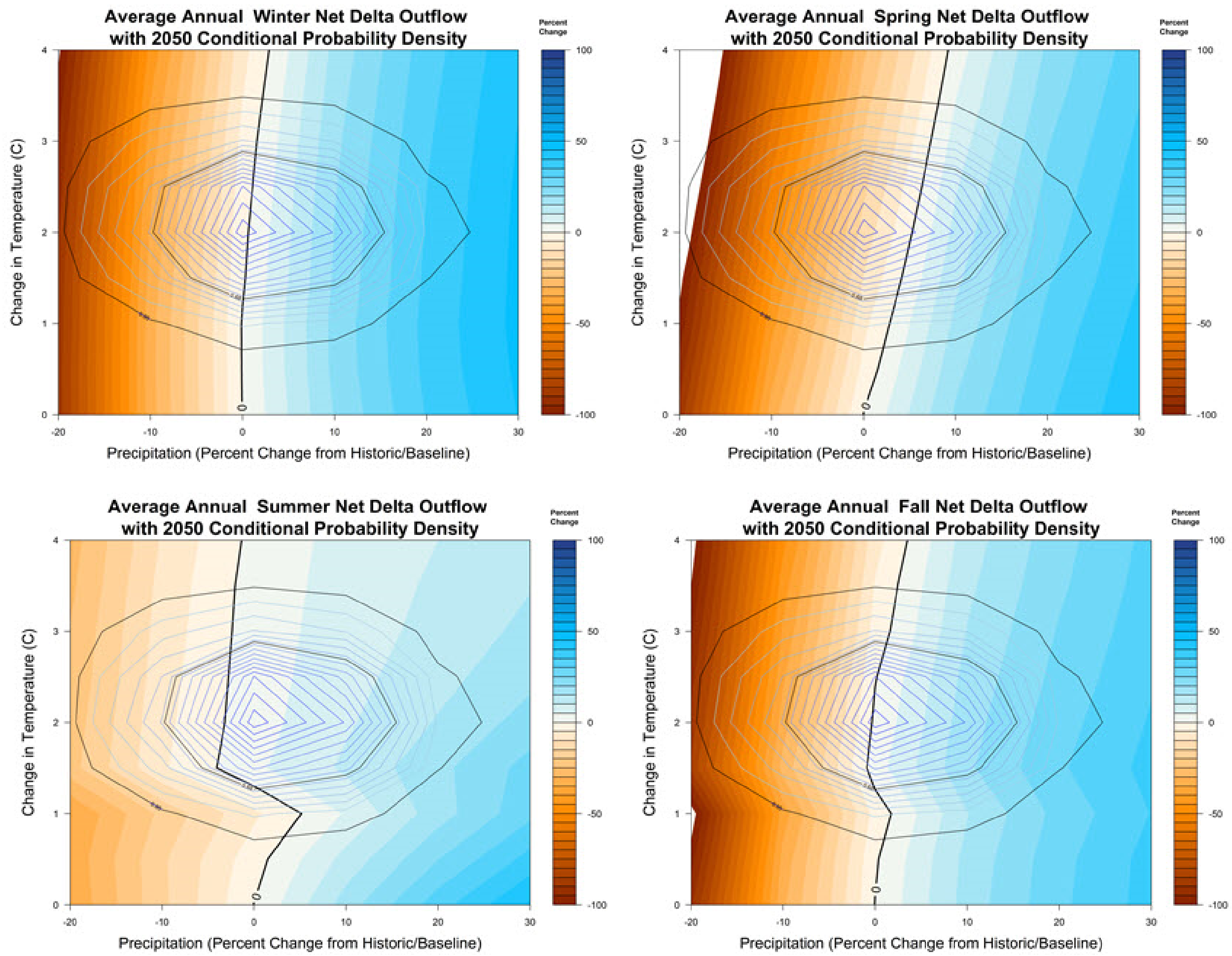
The climate response surfaces below for each seasonal NDO condition indicate that temperature changes have little effect on winter and fall NDO and a relatively weak influence on spring NDO. Summer NDO exhibits unique behavior, indicating that NDO would be likely to increase under future climate conditions. In the summer NDO response surface (Figure 10, bottom left) and, to a lesser extent, in the fall NDO response surface (Figure 10, bottom right), discontinuities in the system performance at 0.5 °C, 1.0 °C, and 1.5 °C (0.9 °F, 1.8 °F, and 2.7 °F) are evident. These are caused by the implementation of sea level increases discussed in the methodology section and Table 2. The significant discontinuity between 1.0 °C and 1.5 °C is the result of the shift from the 15 cm sea level rise parameterization of CalLite to the 45 cm sea level rise parameterization. Sea level increases the hydrostatic pressure of sea water pushing into the Delta, requiring more fresh water to be released (resulting in more NDO) to repel the sea water and maintain required salinity conditions in the Delta. In the case of summer NDO, (Figure 10, bottom left) the sea level increase results in NDO levels that exceed historical levels.

Sea level rise is not the only influence on summer and fall NDO. The requirements for minimum NDO (as defined by California Water Resources Control Board Decision 1641) and minimum average monthly Delta outflow at Chipps Island (as defined by California Water Resources Control Board Decision 1485) both scale as a function of various wetness indices in the watersheds that feed the Delta. Under wetter future climate conditions, these indices would become wetter resulting in increases in required Delta outflows, while drier future conditions result in these indices becoming drier, resulting in relaxation or reduction of Delta outflow conditions. This effect is evident in the slight left to right tilt of the performance (color) bands on the response surface.

The changes in summer and fall NDO shown in Figure 10 (bottom right and bottom left) are largely a reflection of how the regulatory outflow requirements change, and consequently, how the operation of the system changes to meet those regulatory requirements. The shift to greater summer NDO to repel sea level rise and maintain currently required Delta salinity and water quality conditions means that additional water is being released to achieve this higher NDO. Water releases to meet these requirements come at the expense of other important system functions such as carryover storage, cold-water storage for aquatic resources, water deliveries, and instream flows later in the year. At the time of this study, 45 cm (18 in.) of sea level rise was the highest parameterization available. At a temperature increase of more than 2.5 °C (4.5 °F), higher sea levels would be expected, but were not modeled here. As a result, it would be expected that higher levels of NDO would be required during the summer if sea levels rise more than 45 cm (18 in.).

Cdfs and pdfs of seasonal NDO conditions show only slight changes from historical conditions, making them difficult to draw significant insights. For that reason, they have not been included.

Figure 10 Response Surfaces – Average annual Net Delta Outflow by season



Note: Winter (upper left), Spring (upper right), Summer (lower left), Fall (lower right). Solid black lines show historical values.

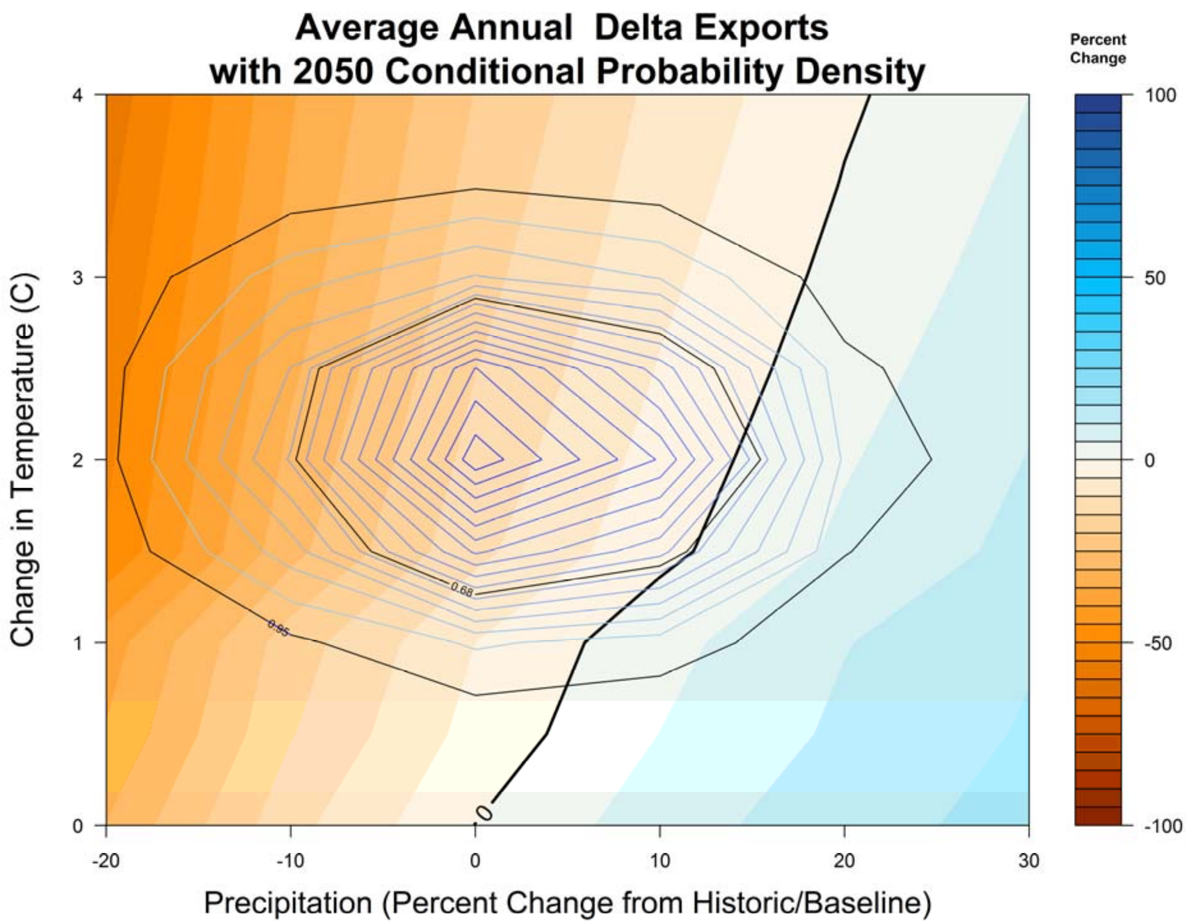
Figure 10: Response Surfaces – Average annual Net Delta Outflow by season

4.3 Performance Metric 3: Annual Delta Exports

Delta exports represent the combined SWP and CVP water exports from the south Delta pumping plants operated by DWR and Reclamation. These exports are delivered to SWP and CVP contractors who, in turn, deliver the water to millions of Californian households, businesses, and farms. Long-term average Delta exports are estimated to be approximately 5.1 maf.

At 2 °C (3.6 °F) warming and no change in precipitation, average annual Delta exports would be expected to be approximately 15 percent less than current conditions (Figure 11). The response surface shows sensitivity to changes in temperature, precipitation, and sea level rise. Sea level rise changes are clearly evident in the response surface as inflection points.

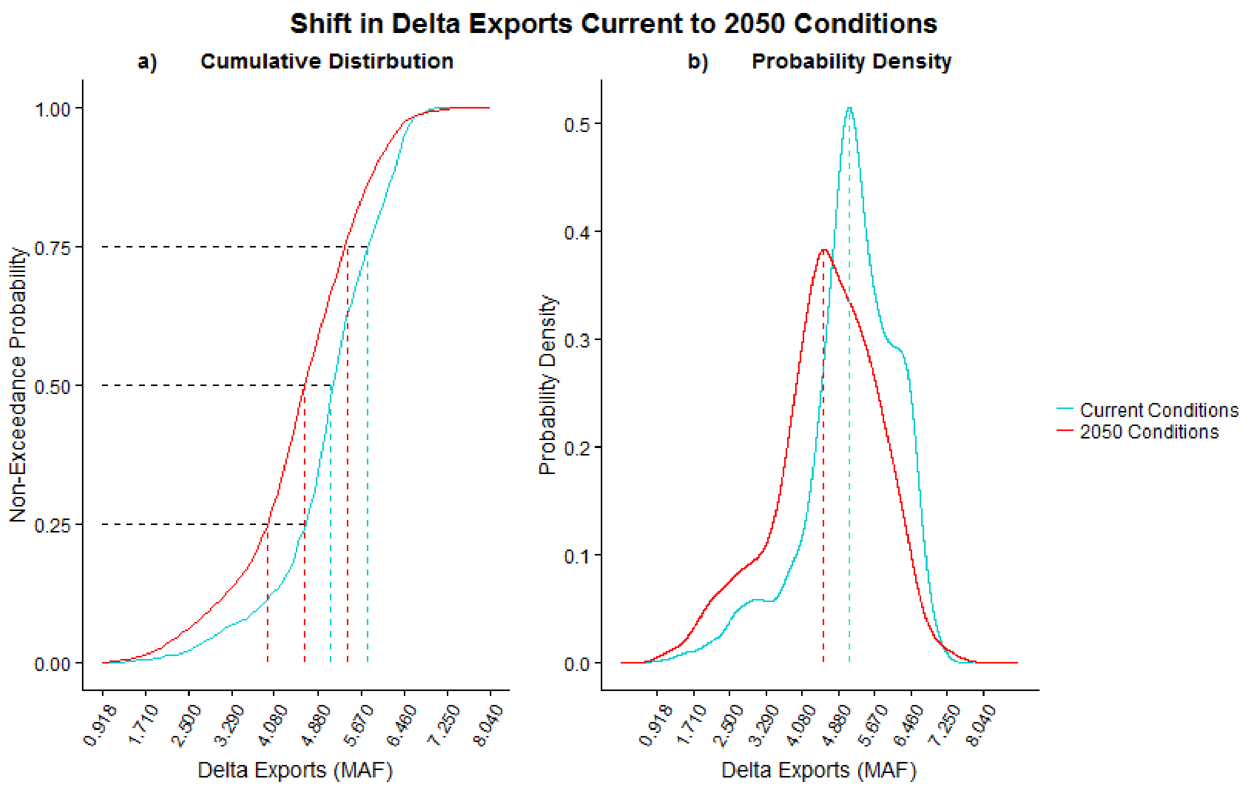
The GCM-based pdf superimposed on Figure 11 informs the likelihood of change in Delta exports. The results indicate that Delta exports are much more likely to decrease than increase (though an increase is plausible even at 2 °C [3.6 °F] warming, if average annual precipitation increases by 15 percent or more), and it is reasonable to expect a substantial decrease in Delta exports were temperature to increase 2 °C (3.6 °F) and precipitation decrease. The 95 percent confidence interval for average annual Delta exports ranges from -50 percent to +10 percent.



Note: At 2 °C (3.6 °F) warming and no change in precipitation, average annual Delta exports would be expected to be 15 percent less than current conditions.

Figure 11: Response Surface – Annual Delta Exports

Figures 12a and b show in more detail how the climate-likelihood-weighted impacts would be born out on an annual basis. Figure 12a shows a decrease in median future Delta exports of approximately 9 percent relative to current conditions, with greater (approximately 15 percent) decreases at low flow conditions and relatively lower (approximately 7 percent) decreases at high flow conditions. Figure 12b indicates a decrease in the mode of the pdf of Delta exports of about 11 percent (560 thousand acre-feet per year).



	P25	P50	P75
Current Conditions	4.63	5.11	5.8
2050 Conditions	3.94	4.63	5.41

	Mode
Current Conditions	5.11
2050 Conditions	4.56

Note: MAF = million acre-feet, taf = thousand acre-feet
The cdf (left) indicates a decrease in median future Delta exports of approximately 500 taf (9 percent) relative to current conditions, with greater (approximately 700 taf or 15 percent) decreases at low flow conditions and relatively lower (approximately 400 taf or 7 percent) decreases at high flow conditions, and the pdf (right) indicates a decrease in the mode of Delta exports of approximately 560 taf or 11 percent.

Figure 12: Shift in Annual Delta Exports, Current to Mid-Century Conditions

5: Summary

The results of this analysis provide a summary of the water supply sensitivity of the CCVS to climate change by 2050. The details include specific climate changes that cause performance of the system to decline below historical expectations, and an estimation of the GCM-based probability of this decline. Because the results of this study include a probabilistic assessment of potential future conditions, these results fit more easily into a more traditional risk management framework that would likely be more familiar to planners and decision-makers. Further, because the GCM-based probability calculation is conducted independently of the system stress test, questions of sensitivity to GCM selection or sampling can be easily tested. For this study, additional analysis was conducted to determine how sensitive the system is selection of the full CMIP5 model ensemble versus the subset of GCMs selected for use in CCCA4 studies. The results of this comparison indicated that the small differences in the GCM-based probability density functions of the two ensembles made only very small differences in vulnerability assessments of system performance, with most differences confined to aspects of system performance that were most sensitive to wetter winter season conditions.

Each of the 11 system performance metrics evaluated in this study provide important information about the potential of the CCVS to perform under the range of potential future conditions projected by the IPCC. The probabilistic results provided in this study show climate change risks to the California water system in a fundamentally different way than previous analyses of the system. For each system performance metric, the GCM-based pdf of projected future climate conditions is superimposed over the response surface of a system performance metric. For 9 of the 11 system performance metrics evaluated for this study, the majority of the GCM-based pdf indicates system performance at 2050 that is less than current levels. For 6 of the 11performance metrics, greater than 85 percent of the GCM-based pdf indicates 2050 performance that is worse than current performance. Carryover storage in the NOD reservoirs shows the greatest vulnerability to future climate changes (95 percent of GCM-based pdf indicating reduced performance by 2050) with Delta exports also exhibiting a high level of vulnerability (93 percent of GCM-based pdf indicating reduced performance by 2050).

Likelihoods aside, all 11-performance metrics demonstrated some level of loss in performance with increasing temperature. Though little agreement exists on the direction of change in projections of mid-century precipitation for the CCVS, there is near unanimity that temperatures will increase by at least 1 °C (1.8 °F) by 2050 (Figure 3 and 4). Increases in precipitation would be required to offset the performance losses that would occur with this level of warming. For all storage reservoirs and Delta exports, a 5 percent to 10 percent increase in precipitation would be required at 1 °C (1.8 °F). A 15 percent to 30 percent increase in precipitation would be required at 2 °C (3.6 °F). In addition to sensitivity to precipitation and temperature changes, Delta exports, summer NDO, and fall NDO show particular sensitivity to sea level rise impact. As the sea level rises, more NDO is required in order to maintain existing water quality and salinity requirements in the Delta. In order to increase NDO, additional water must be released from reservoirs, or Delta exports reduced, forcing additional tradeoffs throughout the system.

For each performance metric, a small portion of the GCM-based pdf indicates improved system performance (performance better than historical performance). This suggests that there are combinations of temperature change and precipitation change that yield climate outcomes that would improve the performance of the CCVS — generally combinations that involve only moderate warming and extreme (more than 15 percent) increase in precipitation. But, for most performance metrics, this GCM-based probability is diminishingly small and far outweighed by the GCM-based probability of very severe losses of performance should temperature increase be more extreme, precipitation decrease, or both.

Previous studies of climate change impacts on California's water system have reported possible impacts to the system in two ways: (1) as expected values, calculated by averaging across multiple different scenarios of future climate change (Huang et al., 2012; Harou et al., 2010; Medellin-Azuara et al., 2008), or (2) as a range of potential values derived from the most extreme outcomes of the scenarios studied (U.S. Bureau of Reclamation 2016; Groves and Bloom 2013; California Climate Change Center 2009). In the first case, inherent uncertainty in the findings is vastly under reported, providing users of the information with a false sense of certainty about the results and leaving a wide range of potential impacts unreported. In the second case, the range of results often span from positive outcomes (improved system performance) to severe losses of performance. For example, Reclamation (2016) reported Delta export impacts at the end of the 21st century ranging from -26 percent to +14 percent. While these impact estimates provide users of the information with an indication of the level of uncertainty involved in the estimates, they provide no indication of how likely any outcome might be. While empirical evidence for how and why decisions are made is difficult to disentangle, it is not difficult to see that these types of impact assessments provide insufficient information for making large adaptation investment decisions. Others have reached similar conclusions (e.g., Stakhiv 1998).

In contrast to the approach taken by previous studies, this study adopted a stress-test strategy to explore the vulnerability of the system to a wide range of potential climate changes for the CCVS and grounded findings regarding system vulnerabilities in probabilities of change informed by RCPs 4.5 and 8.5 of the CMIP5 ensemble of GCMs. The use of CMIP5-based likelihoods also allowed discussion of the relative vulnerability of each performance metric on an annual basis at mid-century. Cdf and pdf plots of each performance metric explore the range of potential future climate shifts, weighted by relative likelihood, across all year types from the driest to the wettest, providing more detailed information about what types of years are likely to be impacted most significantly. Because the cdf and pdf provide annual likelihood information that considers the full range of potential climate shifts that the system could have to endure, the results of this study fit more easily into a more traditional risk management framework that would likely be more familiar to planners and decision-makers.

Further, by fully exploring the extremes of the vulnerability domain, decision-makers and planners are given a much more explicit depiction of the uncertainty of the impact assessment. And finally, the stress test approach, independent of assigning likelihood values using the GCM-based pdf, provides decision-makers and planners and all resource managers with a clearer recognition of some fundamental questions. How much climate change can the system withstand? What critical thresholds of climate change cause the system to fail expectations? What specific climate changes are problematic?

5.1 Limitations and Need for Further Research

It should be noted that the results presented in Table 4 do not account for the likely increase in climate variability (intensification of precipitation events and extended duration of droughts), which would likely further stress the system and worsen the performance shown.

There are many assumptions embedded in the analysis, changes to any of which would alter the system performance and probabilities presented. For example, the analysis assumes: 1) a continuation of long-term (1,100-year) historical variability in California; 2) a continuation of current policies and environmental regulations; 3) a continuation of current allocations and water-sharing practices; 4) continued full subscription to SWP and CVP water supplies; 4) no change to land use, agriculture, or industry; and 5) that current projections for future sea level rise, temperature, and precipitation are reasonably stable and not subject to large revision in the next generation.

However, the assumptions presented in the previous paragraph are mostly optimistic, and this report, though it presents findings of severe future consequences to California's water supply system, is therefore likely optimistic in its analysis. In addition, assumptions about regulatory, legal, or behavioral changes are more uncertain than the status quo assumptions made here and that such uncertainties are best explored as possible adaptation responses rather than baseline conditions.

The United States Bureau of Reclamation (USBR) 2016 Sacramento and San Joaquin Basin Study provides the only direct point of comparison for this study, though the climate conditions evaluated spanned a range smaller than that included in RCPs 4.5 and 8.5 of the CMIP5 ensemble, the possible changes were not sampled comprehensively, and the total number of evaluated changes was relatively small. USBR simulations showed an average decrease in 2015-2099 end-of-September reservoir storage of 9% relative to the Reference-No-Climate-Change scenario (where "reservoir storage" includes all system reservoirs), and an average decrease in Delta outflows of 3%. This study, by contrast, finds a 95% likelihood that September 1st /carryover North-of-Delta storage will be lower by mid-century than it has been historically, and highlights the risk of decreases (by 11-15%) in North-of-Delta storage reservoirs across all water year types. For comparison purposes, this study finds that a 9% decrease in September 1st /carryover storage in North-of-Delta reservoirs (i.e., the level of decrease found in the USBR study) corresponded to approximately the 31st percentile of potential decreases (69 percent probability that decreases would be more severe than 9% at mid-century). Regarding Net Delta Outflow (NDO), this study found a 65% likelihood of performance loss in spring, winter, and fall, and an 88% likelihood in summer. Spring NDO in low and median flow years was found to decrease 25-30% and in high flow years 15-20%. The downward shift in fall NDO was concentrated in already-at-risk low flow years. Because NDO is affected by different hydrological and regulatory conditions in different parts of the years, direct comparison of this study's seasonal impacts with the USBR study's annual impacts is not possible.

Useful future research would explore system response to increasing hydro-climatologic variability, though it is not clear at this moment how to ground such an analysis in likelihood constructs (e.g., what is the likelihood of the average number of atmospheric rivers delivering water to the California water system decreasing by 20%?). Additionally, future research into event-based flooding vulnerabilities to the system using a decision-scaling approach would provide complementary information upon which to make management decisions. It is well understood that the CCVS is managed for flood control and water supply, among other benefits, and that increasing flooding risks may further constrain water supply operations. Additional analysis of event-based flooding vulnerabilities would provide important information to decision-makers seeking to balance and improve these important system benefits.

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