MEAN AND EXTREME CLIMATE CHANGE IMPACTS ON THE STATE WATER PROJECT

A Report for:

California's Fourth Climate Change Assessment

Prepared By:
Jianzhong Wang[1], Hongbing Yin[1], Jamie Anderson[1], Erik Reyes[1], Tara Smith[1], and Francis Chung[1]

1 Bay-Delta Office, Department of Water Resources

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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 advances the understanding of the mid-century vulnerability of the State Water Project to various climate change factors including extreme scenarios.

ABSTRACT

Warming temperatures, shifting hydrology, and rising sea levels will challenge management of California's water resources. This study quantifies climate change risks to California's State Water Project (SWP) and federal Central Valley Project (CVP). This study uses the California Department of Water Resources' (DWR's) newly developed water planning model, CalSim 3.0, as a risk assessment tool. Impacts were assessed for 20 climate change scenarios (10 global climate models and two emission scenarios, representative concentration pathway (RCP) 4.5 and RCP 8.5). Water supply and water quality metrics evaluated include Delta exports, North of Delta Carryover storage, reservoir dead storage (i.e. when reservoir levels fall below the lowest outlets), and Delta salinity. Results for the driest future scenario were also analyzed to examine future drought impacts. In addition, a series of sensitivity tests were implemented to assess individual impacts of four climate change factors: flow seasonal pattern shift, sea level rise, annual flow volume change, and water demand change on the State Water Project and Central Valley Project operations.

It was found that flow seasonal pattern shift will become a major climate change factor and sea level rise a secondary factor, leading to a half million-acre feet of Delta export reduction as well as a roughly 25% decrease of North-of-Delta carryover storage by around 2060. The results also indicate that the extra runoff from early snow melting and higher percentage of rain in the winter and early spring is not conserved in reservoirs and thus cannot be used to meet the higher summer demand in the current SWP/CVP system. This extra water is released as flood water in the winter and early spring to become Delta outflow.

Keywords: Climate Change Assessment, State Water Project, Delta Export, CalSim, and Sea Level Rise

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HIGHLIGHTS

Mid-century impacts of warming temperatures, shifting hydrology, and rising sea levels on California's State Water Project (SWP) and the federal Central Valley Project (CVP) were assessed for 20 climate change scenarios. The study utilizes a state of the art water resources planning model, CalSim 3.0, as a risk assessment tool. Key findings include:

- The SWP/CVP system would face significant stresses exerted by climate change in the middle of this century; Delta exports would reduce by half million-acre feet and north of Delta carryover storage would diminish by 1.5 million-acre feet. Reservoir dead storage would occur much more frequently.
- For the worst drought in the middle of this century, climate change would make the water supply situation much worse; Delta exports would reduce to half of those found in historical droughts while carryover storage would diminish to one-fifth of those found in historical droughts
- The primary culprit for these negative impacts on the SWP/CVP system is the flow seasonal pattern shifts due to earlier snow melting and more precipitation falling as rain due to warming. These extra flows occurring in the winter and early spring seasons cannot be conserved in reservoirs to meet high demand in the summer. The extra water is released as flood water in these seasons but most of the released water become Delta outflow.
- The green-house gas emission mitigation from RCP8.5 to RCP4.5 could cause 0.7° C less warming and then lessen the reduction of Delta export by one quarter million-acre-foot and lessen the diminishing of carryover storage by a half million-acre feet in the middle of this century.

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1: Introduction

After the new Coupled Model Intercomparison Project (CMIP5) climate model projections came into use in 2015, California initiated the Fourth Climate Change Assessment. One of the seven priorities in California's climate change-related research in the *California Fourth Climate Change Assessment* is to prepare for a changing climate. It includes incorporating new climate science into a risk assessment framework using probabilistic climate change and sea-level projections and identifying robust adaptation strategies that would fare well under multiple potential climate scenarios. Vulnerability to extreme events is a particularly critical research gap that should be explored at both local and statewide levels.

The California State Water Project (SWP) is a water storage and delivery system, consisting of reservoirs, aqueducts, powerplants, and pumping plants (Figure 1). Its main purpose is to store water and distribute it to 29 urban and agricultural water suppliers in Northern California, the San Francisco Bay Area, the San Joaquin Valley, the Central Coast, and Southern California.

The Central Valley Project (CVP) is a federal water management project in the U.S. state of California. It provides irrigation and municipal water to much of California's Central Valley by regulating and storing water in reservoirs in the water-rich northern half of the state, and transporting it to the water-poor San Joaquin Valley and its surroundings through a series of canals, aqueducts, and pump plants, some shared with the SWP (Figure 1).

The California Department of Water Resources (DWR) has more than 10 years of experience in developing ways to assesses climate change impact on the SWP. A major milestone in climate change analysis in California occurred in June 2005, when Governor Arnold Schwarzenegger issued Executive Order S-3-05, which requires biennial reports on climate change impacts in several areas, including water resources. In response to this executive order, DWR prepared two reports: *Progress on Incorporating Climate Change into Management of California's Water Resources* (California Department of Water Resources 2006), and *Using Future Climate Projections to Support Water Resources Decision Making in California* (California Department of Water Resources 2009).

DWR undertook additional climate change studies in 2010 as part of the Bay Delta Conservation Plan (BDCP), and later for California WaterFix (Bay Delta Conservation Plan 2013). Because climate change poses significant threats to the success of the BDCP's ecological and water supply goals, DWR implemented a climate change impact study on the BDCP.

DWR and the U.S. Bureau of Reclamation (Reclamation) have released other studies that include information on climate change impacts to the SWP and CVP. The list of studies includes *Operating Criteria and Plan Biological Assessment* (U.S. Bureau of Reclamation 2008), *California Water Plan Update 2013* (California Department of Water Resources 2013); and *Central Valley Project Integrated Resources Plan* (U.S. Bureau of Reclamation 2015).

All the above climate change impact studies are based on climate model projections from the third phase of the Coupled Model Intercomparing Project (CMIP3) (Meehl et al, 2007).

The California Water Commission recognizes that climate change poses an ever-growing threat to the well-being, public health, natural resources, economy, and environment of California. Even under the best scenario for global emission reductions, additional climate change impacts are inevitable. DWR and the commission have developed a new approach to the climate change requirements in the Proposition 1 Water Storage Investment Program (WSIP). DWR and the Commission have developed the future-conditions scenarios based on multiple CMIP5 global climate models as well as additional information related to future conditions (California Department of Water Resources, 2016). This is the first climate change adaptation strategy study conducted by DWR.

Almost all the above climate change impact studies were made using the DWR's water planning model, CalSim II (Draper *et al*, 2004). The primary differences among the CalSim II-based studies are the methods used to translate downscaled general circulation model (GCM) climate change information into stream flow and other input data for CalSim II (Appendix A-3).

This study used DWR's newly developed and released water-planning model, CalSim 3.0, as a risk assessment tool (California Department of Water Resources, 2017). The 20 CMIP5 climate model projections (10 climate models and two emission scenarios, representative concentration pathway [RCP] 4.5 and RCP 8.5) selected by DWR's Climate Change Technical Advisory Group (CCTAG), were incorporated into CalSim 3.0. It estimated climate change risk factors in the SWP and CVP. The factors include Sacramento-San Joaquin Delta (Delta) exports, carryover storage, dead storage, and Delta salinity under the ensemble mean of model outcomes and the driest climate model projection.

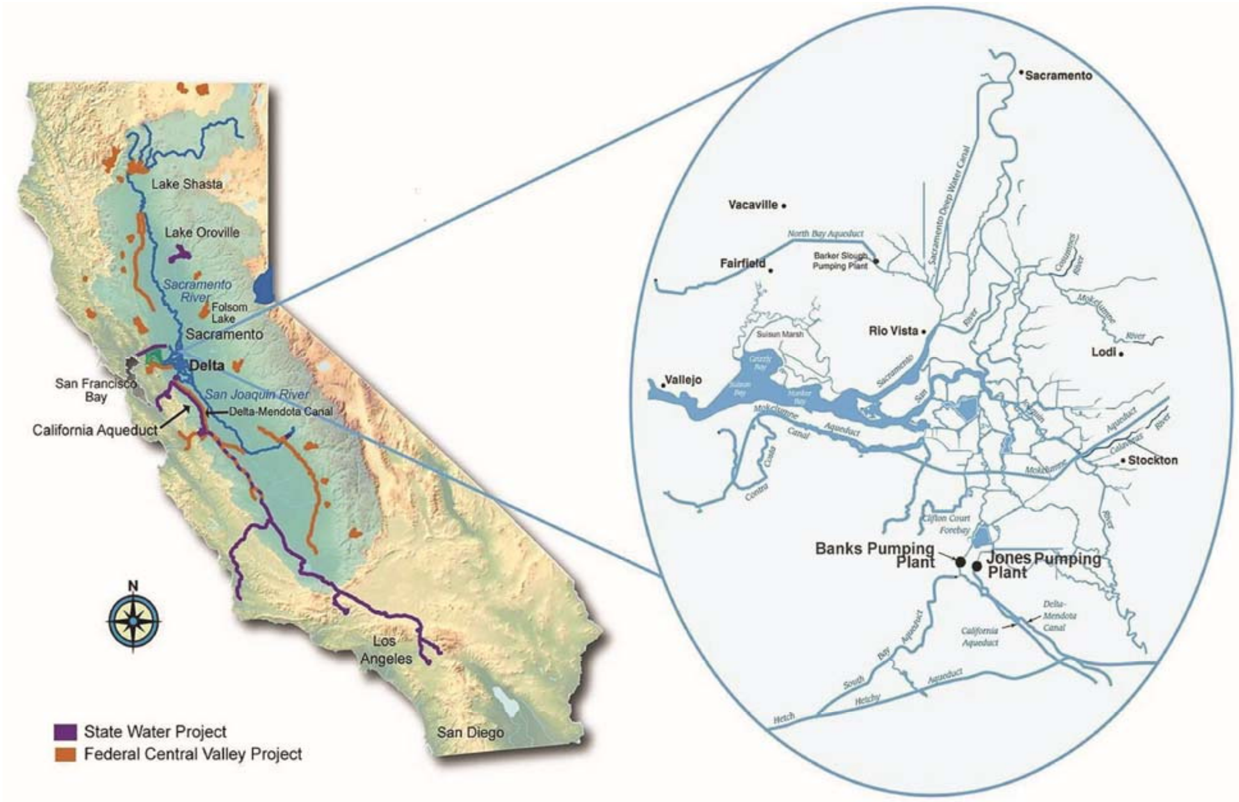


Figure 1: State Water Project and Central Valley Project in California (left), and Sacramento-San Joaquin Delta (right).

2: Approach and Data

This section describes the climate change analysis approach developed in this assessment to quantify climate change impacts on future CVP and SWP operations. The approach is scenario-based. A "base" scenario represents existing climate conditions and current level operational conditions including facilities, operations, and regulatory requirements, as assumed by *The State Water Project Delivery Capability Report 2015* (California Department of Water Resources 2015b). A set of 20 model runs represent a "mid-century" scenario consisting of an ensemble of future climate projections layered on to existing conditions. Mid-century refers to the period of 2045–2074, centered around 2060. This approach is generally composed of five steps:

- selection of GCM projections, including GCM models and emission scenarios;
- downscaling of GCM projections;
- generation of runoff and streamflow for concerned watersheds using downscaled data;
- incorporation of climate change information into the water planning model CalSim 3.0 including rim inflow, sea level rise, and applied water demand; and

- execution and analysis of CalSim 3.0 runs for climate change impact study.

One of major differences between this study and previous climate change impact studies on SWP/CVP is the utilization of CalSim 3.0. CalSim 3.0 is a new and improved water resources planning model, jointly developed by the California Department of Water Resources (DWR) and the Mid-Pacific Region of the U.S. Bureau of Reclamation (Reclamation), to simulate operations of SWP and CVP and much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region (California Department of Water Resources 2017). It is the next generation of the CalSim-II model. It has finer model spatial resolution, better water supply and demand estimation, and improved groundwater representation and simulation than CalSim II.

2.1 Selection of Climate Model Projections

New global climate projections have recently been released through the World Climate Research Programme's CMIP5. DWR's Climate Change Technical Advisory Group (CCTAG), which conducted the necessary analysis to identify the most applicable and appropriate future climate scenarios for water resource planning and analysis in California, has been developing an array of climatological metrics that have applicability and importance for water management planning and long-range decision making (California Department of Water Resources 2015a). These metrics will be used to cull GCMs from the CMIP5 database of GCMs. Among projections from 51 GCMs of CMIP5, CCTAG has chosen 20 climate model projections for potential climate change studies in California (Table 1). These 20 projections come from 10 GCMs with two greenhouse gas RCPs (RCP 4.5 and RCP 8.5). Half of the 20 climate model projections are for RCP 4.5; half are for RCP 8.5.

Table 1: Selected CMIP5 Climate Model Projections

Model	Institution	Ensemble Run	RCP		Number
ACCESS 1.0	Center for Australian Weather and Climate Research, Australia	r1p1i1	RCP 4.5	RCP 8.5	2
CMCC-CMS	Euro-Mediterranean Center, Italy	r1p1i1	RCP 4.5	RCP 8.5	2
CESM1_BGC	National Center for Atmospheric Research, USA	r1p1i1	RCP 4.5	RCP 8.5	2

CCSM4	National Center for Atmospheric Research, USA	r1p1i4	RCP 4.5	RCP 8.5	2
CNRM-CM5	National Center for Meteorological Research, France	r1p1i1	RCP 4.5	RCP 8.5	2
MIROC5	Center for Climate System Research, Japan	r1p1i1	RCP 4.5	RCP 8.5	2
GFDL-CM3	GFDL, USA	r1p1i1	RCP 4.5	RCP 8.5	2
HadGEM2-ES	Hadley Center, UK	r1p1i1	RCP 4.5	RCP 8.5	2
HadGEM2-CC	Hadley Center, UK	r1p1i1	RCP 4.5	RCP 8.5	2
CANESM2	Canadian Center for Climate Modelling and Analysis, Canada	r1p1i1	RCP 4.5	RCP 8.5	2
Total Projections					20

Note: CMIP5 = World Climate Research Programme's Coupled Model Intercomparison Project Phase 5, RCP = representative concentration pathway

Increasing computing capability and using batch processing techniques to run models simplifies the computational effort and allows for many individual GCM projections in an assessment analysis. This scenario-based approach, also known as ensemble-based or probability-based approach, maintains the spatial and temporal variability of each original GCM projection, and has the flexibility to evaluate the uncertainties caused by different GCMs, different emission scenarios, and different ensemble runs of some GCMs. This study used the 20 CCTAG-selected CMIP5 global climate model projections with this scenario-based approach as described in previous DWR studies (California Department of Water Resources 2006 and 2009) for climate change assessments.

2.2 Downscaled Precipitation, Temperature and Simulated Flow

Starting in 2015, Pierce et al. developed a new statistical downscaling technique, called localized constructed analogs (LOCA), and spatially downscaled projections of 32 CMIP5 global climate models (Pierce et al., 2015). The resulting dataset included daily maximum and minimum surface air temperature and precipitation projections from 1950 through 2099 on a 1/16-degree grid.

LOCA is a statistical scheme that produces downscaled estimates suitable for hydrological simulations using a multi-scale spatial matching scheme to pick appropriate analog days from observations.

These downscaled daily data were used by the Scripps Institute of Oceanography (SIC) as input to the calibrated variable infiltration capacity (VIC) surface hydrologic model to generate rim inflows at 12 major streamflow locations (Appendix A-2) in the Sacramento and San Joaquin river basins. The grid-based macro-scale surface hydrologic model, VIC, has long been used and is well suited for climate change study (Liang et al, 1994.). The simulated monthly rim inflows were further bias-corrected using an improved quantile-mapping approach (Pierce et al, 2015).

2.3 Incorporation of Climate Change Information into CalSim 3.0

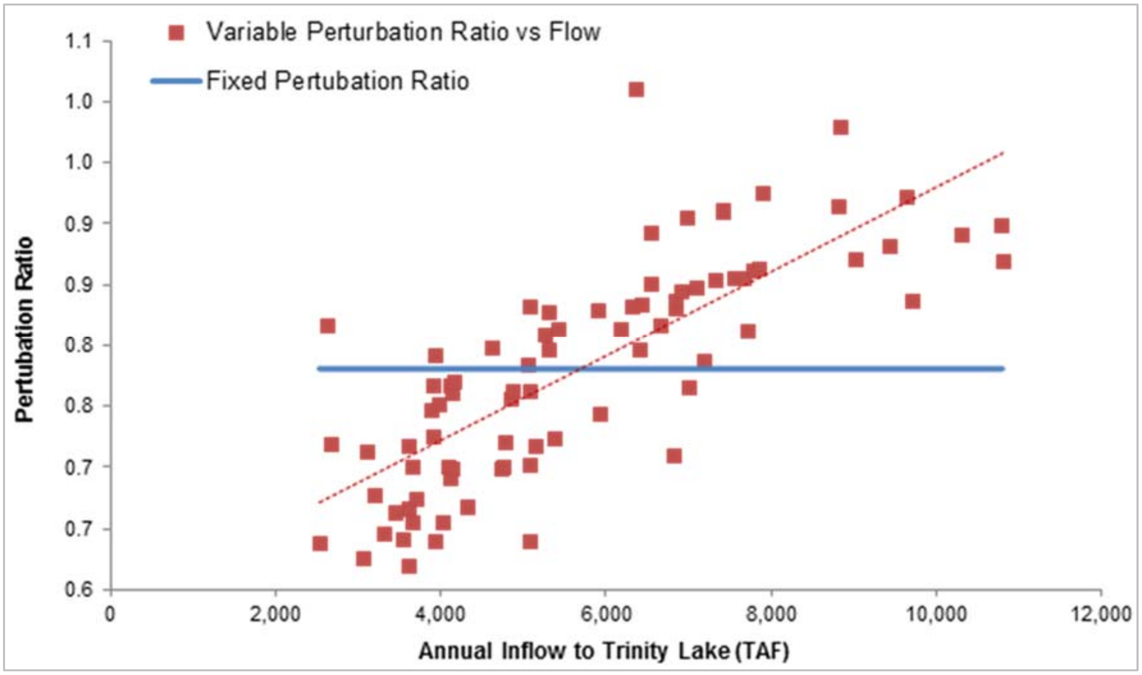
Various CalSim 3.0 inputs, including rim inflows, flow-related parameter tables, reservoir evaporation, water demands, and water use are modified for the mid-century scenario (see Appendix A-1). Additionally, the Delta flow-salinity relationships in the model are modified to account for the effects of sea level rise. Detailed descriptions are provided below for development of climate change affected rim inflow, water demand, and Delta flow-salinity relationships.

2.3.1 Rim Inflow

Inputs to CalSim 3.0 included unimpaired and impaired streamflows from 63 rim watersheds (rim inflow) in the Sacramento River Hydrologic Region and other rim watersheds in the San Joaquin Hydrologic Region (California Department of Water Resources 2017).

VIC-model-simulated streamflow, using downscaled GCM projections as its input, are not directly used as rim inflows in CalSim 3.0 because (1) current GCM projections and the VIC-simulated streamflow from projections are not able to reproduce the observed interannual variability of precipitation and streamflow in California (Wang et al., 2014); and (2) not all CalSim 3.0 rim watersheds are simulated by the VIC model. Instead, a three-step perturbation ratio method (Wang et al. 2011, Bay Delta Conservation Plan 2013) is modified to generate climate change rim inflow. This method is capable of keeping the observed interannual variability and incorporating climate change information into historical rim inflow time sequences in CalSim 3.0.

Climate change may have different effects in drought years than in wet years or in normal years. As a result, a fixed perturbation method (Wang et al., 2011) using the same monthly and annual perturbation ratios for different water years would underestimate the effect of more extreme flows in the future. In the Fourth Assessment, a variable perturbation ratio approach, applying different monthly and annual perturbation ratios for different water years to CalSim 3.0 historical rim inflow time sequences, is adopted to generate rim inflows under climate change scenarios (e.g., climate change rim inflow). Figure 2 shows potential improvements in generating climate change rim inflows to Trinity Lake if a variable perturbation ratio method (Bay Delta Conservation Plan 2013) is used, rather than a fixed perturbation method (see Appendix B).



Note: TAF = thousand acre-feet

Figure 2: Variable Perturbation Ratio for Inflows to Trinity Reservoir under the Bay Delta Conservation Plan Climate Change Scenario Q2

In this CalSim 3.0 application, the variable perturbation ratio approach is implemented to generate rim watershed streamflows under climate change scenarios. The procedure is described in Appendix B in detail.

2.3.2 Water Demands and Water Use

In previous climate change assessment studies (California Department of Water Resources 2006, 2009), DWR did not account for climate change effects on agricultural water demands and water use. However, given the magnitude of agricultural water use within the Central Valley, it is important that potential climate change impacts on agricultural water use be considered in CalSim 3.0 climate change studies.

This assessment used CalSimHydro with downscaled precipitation and air temperature to estimate applied water demands for agriculture and wildlife refuges, surface runoff, and deep percolation under each of the 20 climate change projections. Applied water demand means the water necessary to irrigate a crop. CalSimHydro is the valley floor surface hydrology modeling system of CalSim 3.0 (California Department of Water Resources, 2017). Historical daily precipitation at each water budget area and monthly potential crop evapotranspiration rate for crops were adjusted in a manner similar to the generation of climate change rim inflows. This was done to generate climate change impacted daily precipitation and monthly evapotranspiration rates as inputs to CalSimHydro in order to assess applied water demands for each climate projection. No consideration was given to possible changes in planting dates, length of growing seasons, or changes in evapotranspiration caused by increased carbon dioxide concentrations.

In CalSimHydro and associated input models, actual crop evapotranspiration ($ET_{historical}$) rate under non-standard conditions is the product of a water stress coefficient (Ks), crop coefficients (Kc), and reference crop evapotranspiration (ETo). Daily reference crop evapotranspiration is estimated using an adjusted Hargreaves-Samani equation (Samani 2000) that is calibrated to ETo through an estimate by the California Irrigation Management Information System (CIMIS). Because downscaled climate model projections provide daily mean, maximum, and minimum temperature, it is possible to estimate the climate change impacts on water demands caused by changes in evapotranspiration.

Actual crop evapotranspiration under climate change scenarios (ET_{future}) can be estimated as:

$$ET_{future} = ET_{historical} * (T_{future}+17.8)/ (T_{historical}+17.8) * ((T_{max}-T_{min})_{future}/ (T_{max}-T_{min})_{historical})^{0.5}$$

where:

ET_{future} = crop evapotranspiration under climate change [L/T]

$ET_{historical}$ = crop evapotranspiration under historical climate conditions [L/T]

T_{future} = 30-year average monthly projected temperature, 2045–2074 [°C]

$T_{historical}$ = 30-year average monthly historical temperature, 1976–2005 [°C]

T_{max} = 30-year average maximum monthly temperature [°C]

T_{min} = 30-year average minimum monthly temperature [°C]

Outdoor urban water demands are adjusted in a similar manner. It is assumed that urban indoor water use is not affected by climate change. The effect of population growth on indoor water use is not considered here for it is not a climate change factor.

2.3.3 Sea Level Rise and Delta Salinity

Determination of flow-salinity relationships in the Delta is critical to the correct simulation of CVP and SWP operations. The two projects share responsibility for meeting Delta water quality standards specified by the State Water Board in Water Right Decision 1641 (D-1641). However, Delta salinity cannot be simulated accurately by the simple mass balance routing and coarse time step (monthly) used in CalSim 3.0. As a result, DWR has developed an artificial neural network (ANN) to determine Delta salinity for a given set of Delta flows (Sandhu 1995, Wilbur and Munévar 2001). The ANN is trained to mimic the flow-salinity relationships of DWR's hydrodynamic and water quality model, DSM2, and to rapidly transform this information into a form usable by CalSim 3.0 (Sandhu et al. 1999, Wilbur and Munévar 2001).

The ANN developed by DWR (Sandhu et al. 1999, Seneviratne and Wu 2007) statistically correlates the salinity results from a particular DSM2 model run to the stage at Martinez, peripheral flows (Delta inflows, exports, and diversions), gate operations, and an indicator of tidal energy. The ANN is trained using DSM2 results that may represent historical or future conditions. For example, future sea level rise will significantly affect the hydrodynamics of the Delta. The ANN is able to represent this new condition by being retrained using the results from the DSM2 model representing Delta conditions with the sea level rise. DWR has developed specific sea-level-rise ANNs for different sea-level-rise projections.

In previous impact studies of sea level rise conducted by DWR and Reclamation, the same value for sea level rise was associated with all selected GCM projections. For example, a 2-foot sea level rise was assigned to 12 GCM projections under the *Special Report on Emissions Scenarios* A2 or B1 scenarios for the end of this century (SRES data, 2000), although the sea level rise predicted from these 12 projections ranged from 1.0 foot (35.5cm) to 3.9 feet (118.9 cm) (California Department of Water Resources 2009).

For the Fourth Assessment, each of the 20 climate change scenarios is assigned a sea-level-rise value for the middle of this century (2045–2074) according to projected surface air temperature changes at San Francisco Bay, based on work conducted by the National Research Council (National Research Council 2012). If the projected air temperature change is less than 0.75°C (1.35 °F), the scenario is assigned no sea level rise; a value of 0.5 feet (15.2 cm) is assigned for 0.75°C–1.5°C (1.35°F -2.5°F) warming; 1.0 foot (30.5 cm) assigned for 1.5°C–2.25°C (2.5°F -4.05°F) warming; and 1.5 feet (45.7 cm) sea level rise assigned for air temperature changes greater than 2.25°C. Subsequently, for the Fourth Assessment, each climate scenario uses a particular sea-level-rise ANN, based on the surface air temperature projected from the individual GCM projection. As a result, 11 climate change scenarios are assigned 1-foot (30.5 cm) sea level rise, four are assigned 0.5-foot (15.2 cm) sea level rise, and five are assigned 1.5-feet sea level rise (45.7 cm) (Table 2). In doing so, the average sea level rise in the San Francisco Bay for the period of 2045–2074 is about 1 foot (30.5 cm).

For the moderate emission scenario RCP 4.5, the surface air temperature would increase by 1.6 °C and the mean sea level rise is 0.8 foot (24.4 cm) in 2060, for the highest emission scenario, RCP 8.5, the warming is 2.3°C and the sea level rise is 1.25 feet (38.1 cm) in 2060.

In contrast to previous DWR studies (California Department of Water Resources 2009), the Fourth Assessment assumes no explicit tidal amplitude increase on the effect of sea level rise in this. In DWR's 2009 study, a 1.0-foot sea level rise combined with an explicit 9 percent tidal amplitude increase was assumed for the middle of this century.

Table 2: Projected Mid-Century (2045–2074) Surface Air Temperature Change and Sea Level Rise at San Francisco Bay

CCTAG CMIP5 GCM Projection	Temperature Change (°C)	Sea Level Rise (feet)
CESM1-BGC_rcp45	1.1	0.5
CNRM-CM5_r1p1i1_rcp45	1.1	0.5

CCSM4_r1p1i4_rcp45	1.2	0.5
MIROC5_rcp45	1.4	0.5
HadGEM2-CC_rcp45	1.6	1
CMCC-CMS_rcp45	1.6	1
ACCESS1_0_rcp45	1.7	1
CCSM4_r1p1i5_rcp85	1.8	1
CESM1-BGC_rcp85	1.8	1
MIROC5_rcp85	1.9	1
CNRM-CM5_r1p1i1_rcp85	1.9	1
GFDL-CM3_rcp45	2.0	1
CANESM2_r1p1i1_rcp45	2.1	1
HadGEM2-ES_r1p1i1_rcp45	2.2	1
CMCC-CMS_rcp85	2.2	1
ACCESS1_0_rcp85	2.3	1.5
GFDL-CM3_rcp85	2.6	1.5
HadGEM2-CC_rcp85	2.7	1.5
CANESM2_r1p1i1_rcp85	3.0	1.5
HadGEM2-ES_r1p1i1_rcp85	3.0	1.5

RCP 4.5	1.6	0.8
RCP 8.5	2.3	1.25
Mean	2.0	1

Note: CCTAG = California Department of Water Resources' Climate Change Technical Advisory Group, CMIP5 = Coupled Model Intercomparison Project Phase 5, GCM = general circulation model,
RCP = representative concentration pathway

3: Mean Climate Change Impact

The ensemble means of the selected 20 climate model projections and the 20 corresponding CalSim 3.0 runs are used to assess mean climate change impacts to hydroclimate in the concerned regions and to operations of the CVP/SWP system.

3.1 Precipitation and Surface Air Temperature

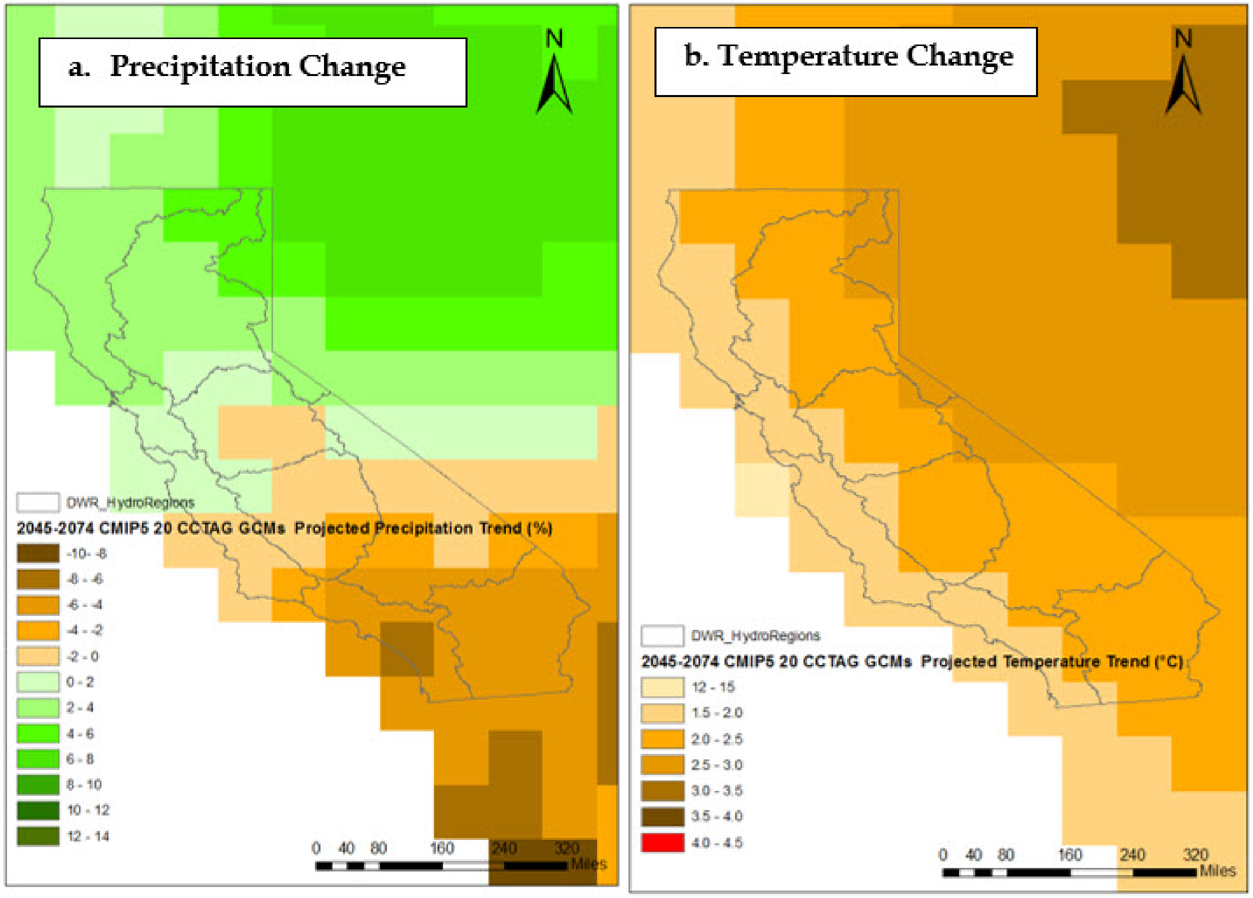
Figure 3 shows the precipitation change and temperature change relative to the historical period 1976-2005 for years 2045–2074 derived from the 20 CCTAG climate model projections. The precipitation and temperature data used for this calculation is 1°×1° re-gridded GCM projection, not the LOCA downscaled data. The years 1976-2005 are used for the historical period because CMIP5 model historical simulations end at 2005.

The average of 20 CCTAG CMIP5 climate model projections shows a wetting trend in Northern California and part of Central California, while a drying trend is projected in most of Central California and Southern California in 2060, ranging from a 6 percent increase to an 8 percent decrease (Figure 3a). Figure 3b shows that the projected ensembles mean temperature in the middle of this century in inland and mountainous regions increases by 2.0°C to 2.5°C and 1.5°C to 2.0°C in coastal regions.

For the highest emission scenario, RCP 8.5, the average precipitation in the Sacramento River basin would increase 3.43% in 2060 (not shown). For the moderate emission scenario, RCP4.5, it would increase 3.35% in 2060, a slight difference from the precipitation increase for RCP 8.5. The average surface temperature in the basin would increase by 2.7 °C for RCP 8.5 and 2.0°C in 2060. The 0.7 °C warming difference may cause impacts of variable severity on water supply in CVP/SWP.

Precipitation in the Sacramento River basin provides most of the water supply to the Central Valley. Among 20 GCM model projections, precipitation change in the basin ranges from -12%

to 29% and 6 GCM projections shows precipitation decrease in 2060. Surface temperature increase in the basin in 2060 ranges from 1.5°C to 3.4 °C.



Note: CCTAG = California Department of Water Resources' Climate Change Technical Advisory Group, CMIP5 = Coupled Model Intercomparison Project Phase 5, GCM = general circulation model

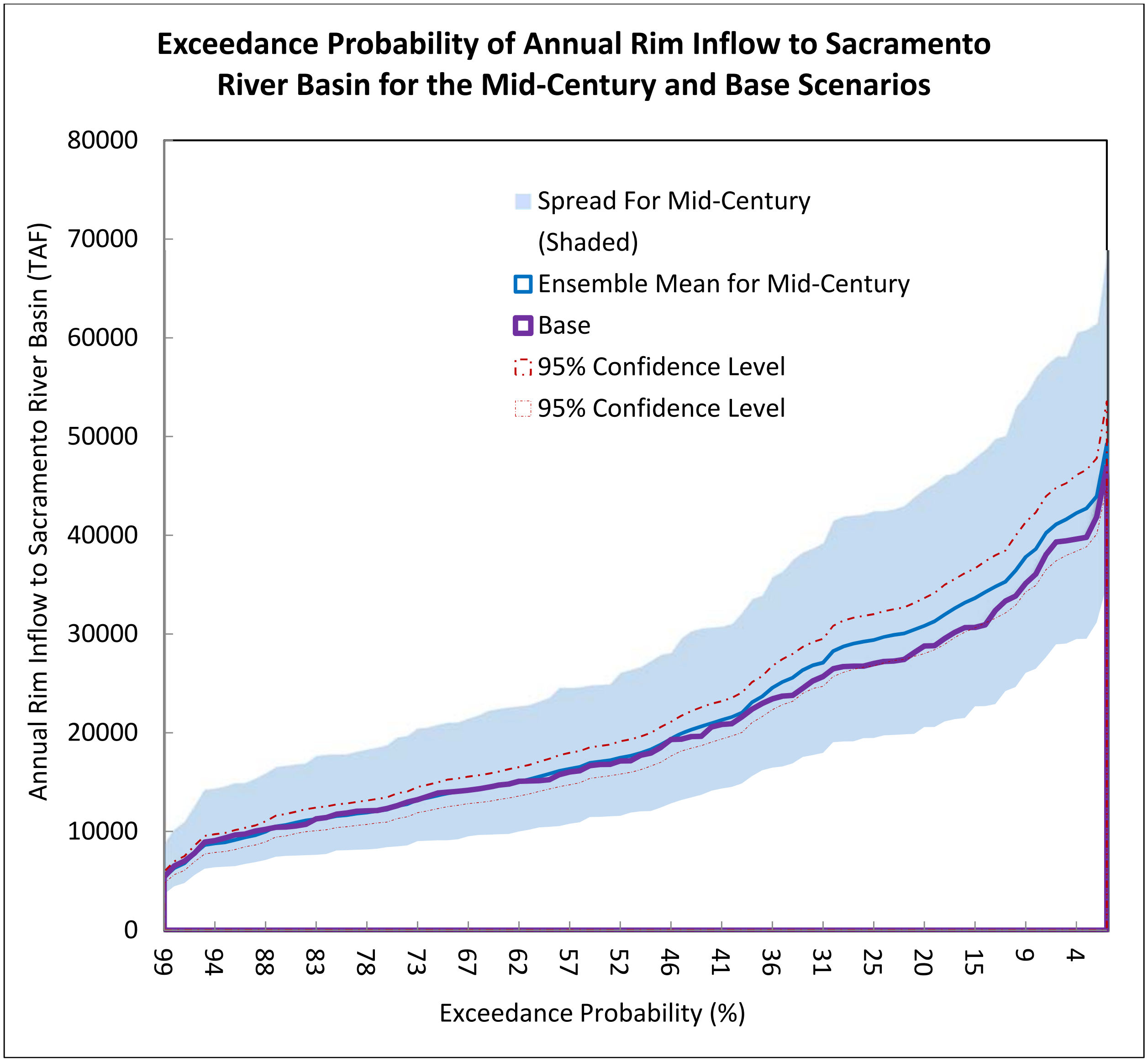
Figure 3: Projected Precipitation and Surface Air Temperature Change, 2045–2074, by 20 CCTAG Climate Model Projections, based on 1°×1° re-gridded GCM Projections

3.2 Rim inflow

With precipitation in Northern California projected to increase in the middle of this century, mean annual streamflow to the Sacramento River basin would increase accordingly. Rim inflows to the Sacramento River are the principal source of water for the CVP and SWP. Based on the ensemble of 20 CCTAG CMIP5 climate model projections (mid-century scenario), the annual volume of rim inflows is expected to increase 4.4 percent with respect to the current climate (base scenario), as shown in Figure 4. Most of streamflow increase occurs in high-flow periods, with flow exceedance probability lower than 40 percent. Because the two 95% confidence level curves encompass the flow exceedance curve for the base scenario, the total annual rim flow in the middle of this century is not statistically significant compared to annual rim flow for the current climate. The spread of flow at each exceedance level is broad (Figure 4).

For the highest emission scenario RCP8.5, the ensemble mean annual rim inflow would increase by 4.6%, slightly higher than the increase for the moderate emission scenario RCP4.5 (4.2%).

The mid-century scenario shows a shift in the monthly rim inflow hydrograph compared to the base scenario (Figure 5). The peak of the inflow hydrograph occurs in February, one month earlier than the current climate. Additionally, monthly rim inflows decline rapidly from their peak so that, beginning in April, mid-century flows are less than corresponding monthly flows for the current climate. These phenomena are the result of the warming trend causing earlier and more rapid snow melt and precipitation with a smaller snow-to-rain ratio. **The shifted water resulting from only the warming is approximately 2,100 thousand acre-feet (taf). That would be approximately twice as much as the storage capacity (977 taf) of the Folsom Lake**.



Notes: TAF = thousand acre-feet
The base scenario represents existing land use and climate conditions. The mid-century scenario represents an ensemble of future climate projections layered on to existing land use, facilities, and regulatory requirements. Also shown are two 95 percent confidence bands (dash lines) and the spread of results from 20 GCM projections (shaded) (same as in Figure 6-8)

Figure 4: Exceedance Probability of Rim Inflows to Sacramento River Basin for Base (purple) and Mid-Century (blue) Scenarios.

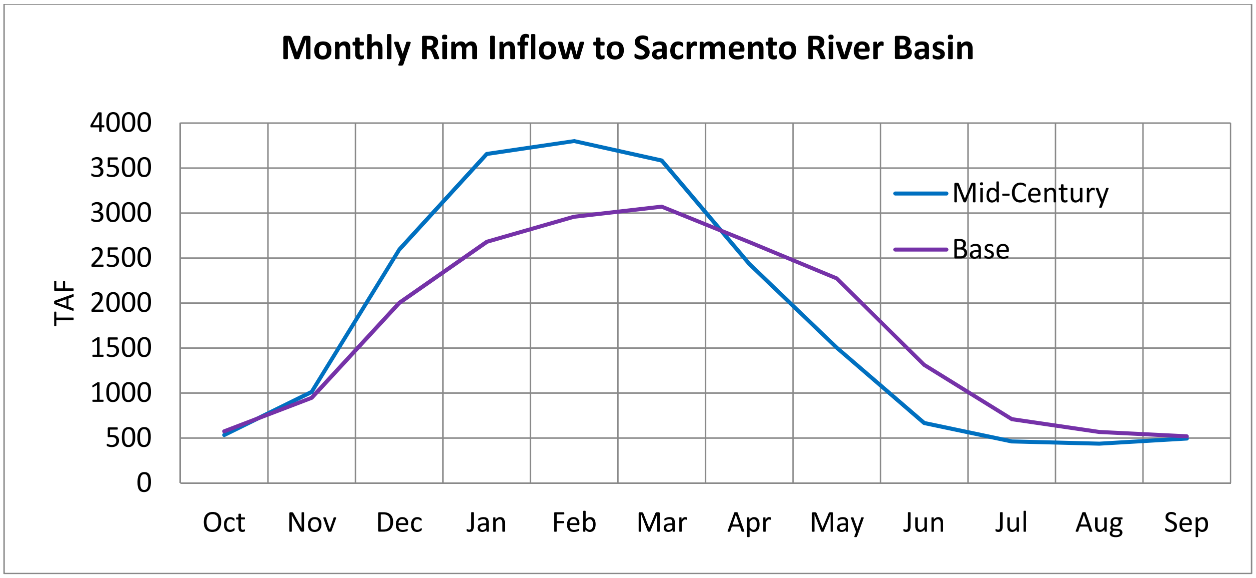


Figure 5: Average Monthly Rim Inflows to Sacramento River Basin for Base and Mid-Century Scenarios

3.3 Applied Water Demand

Potential changes in agricultural water use are presented in Figure 6. The agricultural applied water annual demand in the Sacramento Valley and the San Joaquin Valley may increase by 8 percent, approximately 1,400 taf, by the middle of this century. This would result from the increased rate of evapotranspiration and valley floor precipitation change stemming from climate change. Applied water demand in the Sacramento Valley may increase by 6.5 percent, approximately 527 taf, in the middle of this century. The increase in applied water demand in 2060 is statistically significant at a 95% confidence level, indicating that agricultural water demand is extremely sensitive to warming under the current estimated approach. The demands from 20 GCM projections all increase in 2060 despite the wide demand range (shaded area).

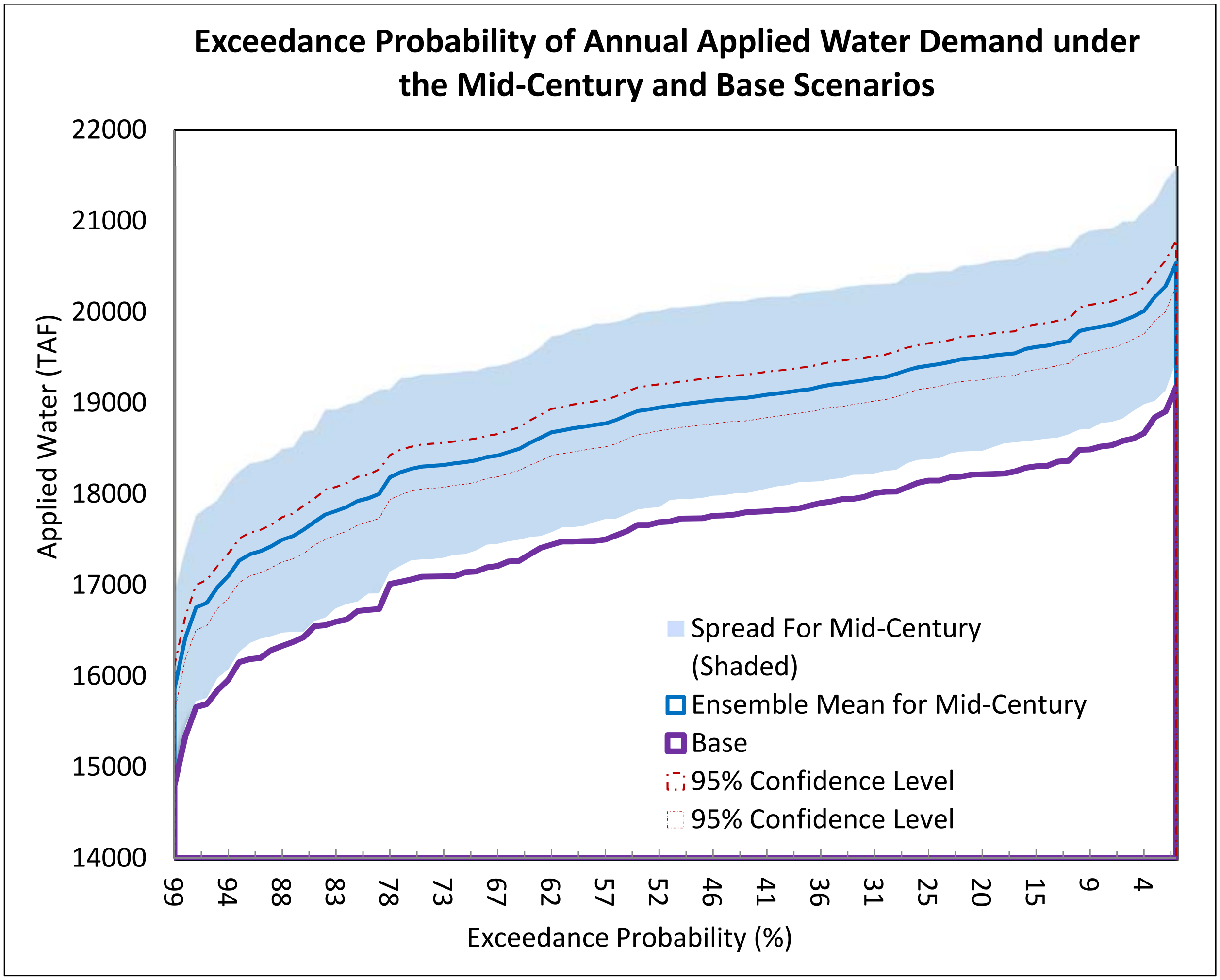


Figure 6: Sacramento and San Joaquin Valley Annual Applied Water Demand for Base and Mid-Century Scenarios

Applied water demand change in the Delta from climate change is estimated using DWR's Delta Island Consumptive Use (DICU) model in a fashion similar to that described for the valley floor (California Department of Water Resources, 2017).

The evaporation rate of lakes and reservoirs simulated in CalSim 3.0 are modified in a similar manner to model/project crop evapotranspiration rates. The percentage change in reservoir evaporation because of climate change is similar to that of crop evapotranspiration.

3.4 Climate Change Effects on the SWP and CVP Operations

Summarized CalSim 3.0 model results are presented for a base scenario and a mid-century scenario. Results presented for the mid-century scenario are the average values of 20 CalSim 3.0 simulations. Each simulation is based on one of 20 CCTAG CMIP5 climate model projections. Equal weight is given to the projections.

Several metrics are evaluated to determine the potential effects of climate change on CVP and SWP operations. These metrics include Delta exports, north-of-Delta carryover storage, X2 (the distance from the Golden Gate Bridge to the point where daily average salinity is 2 parts per thousand (ppt) at 1 meter from the channel bottom) and Delta outflow, and occurrence of north-of-Delta dead storage.

3.4.1 Delta Exports

For the purposes of this metric, Delta exports are defined as the combined flows through the Banks and Jones pumping plants in the south Delta (Figure 1). Delta exports for the base and climate change scenarios are presented in Figure 7. **Average annual Delta exports decrease by 521 taf in the middle of the century based on the ensemble mean of 20 CCTAG CMIP5 climate model projections; this is equivalent to a 10 percent reduction compared to the base scenario**. The exports show significant reduction at 95 percent confidence level over almost the entire export range, except during drought years (defined by an exceedance probability of more than 90 percent). The estimate of 95 percent confidence interval for the mean of Delta export is based the sample of 20 climate model projections comprising 10 climate models and two representative concentration paths (RCPs). The sample size of 20 is not large enough and the actual uncertainty for the mean of Delta export is still unknown. Delta export in 2060 shows a very large spread, with only a small portion of GCM projections projecting export increase in 2060. It should be noted that the uncertainties in GCM projected rim inflow change and the resulting Delta export change are high.

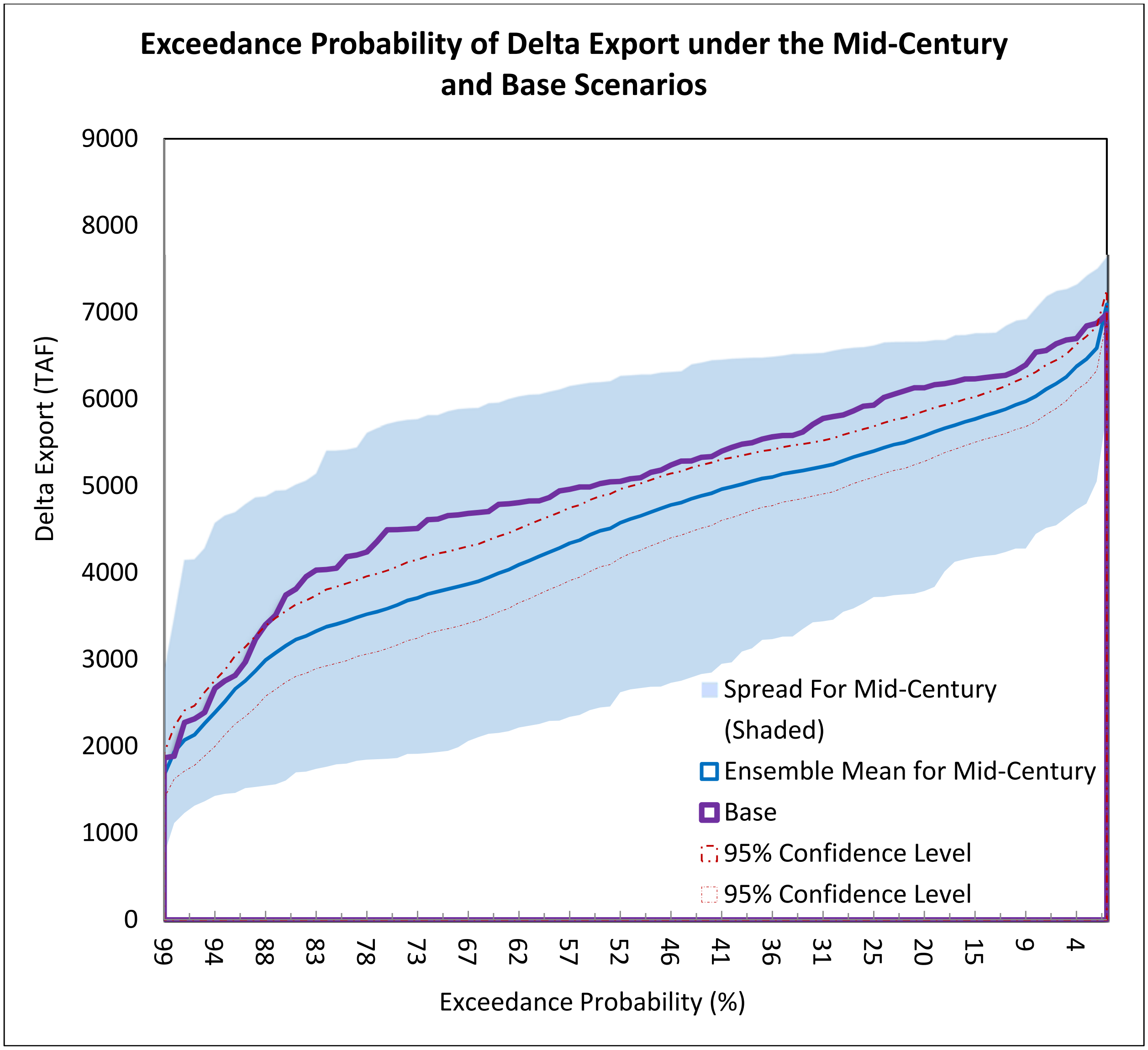


Figure 7: Exceedance Probability of Annual Delta Exports for Base and Mid-Century Scenarios

One might expect that the mean Delta Export would increase in 2060 because of an increase of 887 taf per year in total rim inflows to Sacramento river basin on the average. In fact, **increased rim inflow under climate change scenarios principally occur during winter months (Figure 5), and much of this extra water may be released for purposes of flood control and subsequently not be realized as exported water**. In addition, Delta exports are also negatively affected by rim inflow seasonal shifting, sea level rise, and increasing agricultural applied water demand in the future. Further sensitivity tests are necessary to quantify effects from these different factors.

On the ensemble mean of 10 projections for the highest emission scenario RCP 8.5, the Delta export would reduce by 13%, about 250 taf more than the reduction for RCP 4.5 (8%).

3.4.2 North of Delta Carryover Storage

For the purposes of this metric, north of Delta carryover storage is defined as the sum of end-of-September storage in four project reservoirs north of the Delta: Lake Shasta, Trinity Lake, Oroville Reservoir, and Folsom Lake. Higher values of carryover storage provide a more resilient and reliable CVP/SWP water supply system. **From the ensemble mean of the 20 climate model projections, the mid-century carryover storage is 24 percent less than the base scenario.** The carryover storage reduction is significant at the 95 percent confidence level over almost the entire range of carryover storage (Figure 8**). During drought years (defined by an exceedance probability above 90 percent), the carryover storage would be reduced more significantly, by half.** There are very large spreads in the projected carryover storage in 2060 at each exceedance probability level but only a tiny portion of GCM projections show the increase in carryover storage in 2060.

On the ensemble mean of 10 projections for the highest emission scenario RCP 8.5, the north of Delta Carryover storage would diminish by 29%, about half million-acre- foot more than the diminishing for RCP 4.5 (21%).

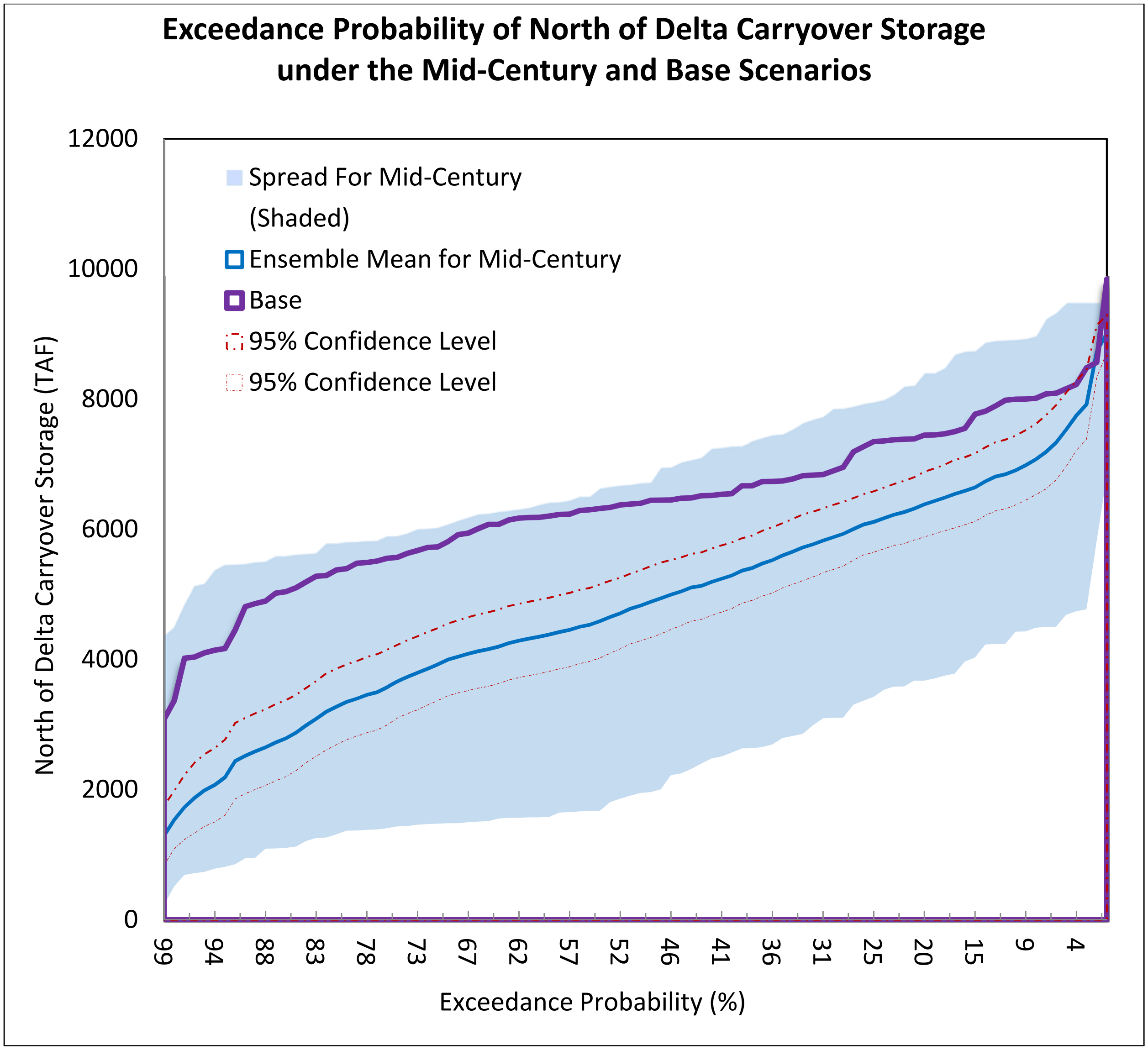


Figure 8: Exceedance Probability of North of Delta Carryover Storage for Base and Mid-Century Scenarios

3.4.3 System Reliability: Dead Storage

Under extreme hydrologic and operational conditions, such that there is not enough surface water supply to meet all requirements, a series of operating rules are applied in CalSim 3.0 to reach a solution to allow for the continuation of the simulation. These operating rules are a simplified version of the complex decision processes that SWP and CVP operators would use in actual extreme conditions. Despite these, in very dry years, the model will still sometimes show dead pool conditions that may result in instances in which flow conditions fall short of minimum flow criteria, salinity conditions may exceed salinity standards, diversion conditions fall short of allocated diversion amounts, or operating agreements are not met. Such model results are anomalies that reflect the inability of the model to make real-time policy decisions (e.g. curtailment) under extreme circumstances, as the actual operators must do. Thus, any operations simulated due to reservoir storage conditions being near dead pool should only be considered an indicator of stressed water supply conditions under that scenario.

Because dead storage occurs in the summer and fall of a drought year, counting the occurrence of dead storage (i.e., number of months) reflects the extent of drought in the middle of this century and the extent of major problems for CVP/SWP water supply reliability. The occurrence of dead storage is presented in Figure 9**.** The water planning model CalSim 3.0 use historical monthly flow data from 1922 to 2015 (94 years) as input and then has 94*12 (1128) simulation months for the base scenario. Because climate change flow time series for the middle of this century is generated by perturbing historic monthly flow data they have the same length of flow data and simulation months as the base scenario. The dead storage criteria for Shasta, Oroville, Trinity, and Folsom reservoirs are 550, 30, 240, and 90 TAF. **In the base scenario, dead storage occurs in 44 months. The occurrence of dead storage in the climate change scenario is 228 months on the ensemble mean** (Figure 9), approximately a 420 percent increase. Shasta and Trinity reservoirs are the most susceptible to climate change in terms of dead storage occurrence. Oroville reservoir only have a one dead storage month in 2060 on the ensemble mean because of its capacity to release water at very low water levels.

As a measure of system reliability, a year with at least one dead storage month occurring at any of the four reservoirs is defined as a "dead storage" year. Reliability of CVP/SWP water supply is defined as the ratio of non-dead storage years to total simulation years (94 years). The system reliability for the base scenario is approximately 92.5 percent. Among the 20 CCATG climate model projections, 16 projections show worsening system reliability by mid-century. Four predict improved reliability (Table 3). **The median of reliability predicted by the 20 projections is approximately 80 percent, worse than that for the base scenario, by 12 percent**. The worst system reliability scenario comes from ACCESS1_0_rcp85, in which reliability is only 24 percent (Table 3).

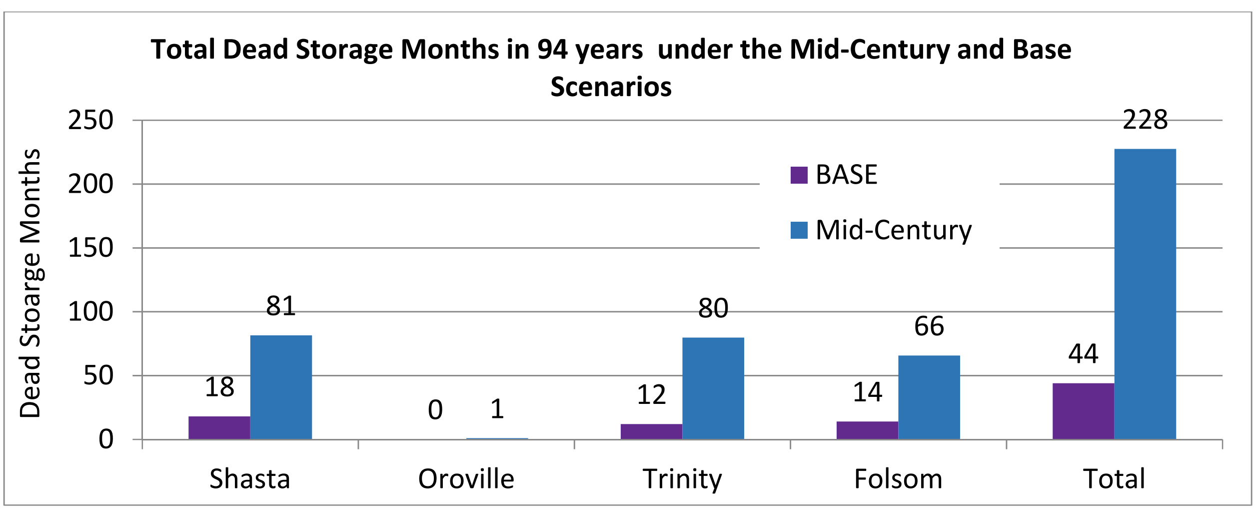


Figure 9: Dead Storage Occurrence for the Base and Mid-Century Scenarios

Table 3: Change in Value of Performance Metrics for 20 CCTAG CMIP5 GCM Projections Compared to Base Scenario

CCTAG CMIP5 GCM Projection	Change in Performance Metric: Climate Change Scenario minus Base Scenario			
	Delta Export Change	Carryover Storage Change	Rim Inflow Change	Reliability Change*
ACCESS1_0_rcp45	-9%	-25%	-2%	-3%
ACCESS1_0_rcp85	-44%	-62%	-29%	-74%
CANESM2_r1p1i1_RCP45	12%	7%	31%	8%
CANESM2_r1p1i1_RCP85	21%	7%	52%	7%
CCSM4_r1p1i4_rcp45	-8%	-23%	4%	-9%
CCSM4_r1p1i4_rcp85	-4%	-20%	13%	-3%
CESM1-BGC_rcp45	-4%	-17%	-3%	-6%
CESM1-BGC_rcp85	-15%	-32%	-5%	-23%
CMCC-CMS_rcp45	-23%	-33%	-15%	-29%
CMCC-CMS_rcp85	-18%	-31%	-6%	-22%
CNRM-CM5_r1p1i1_rcp45	10%	-2%	36%	4%
CNRM-CM5_r1p1i1_rcp85	13%	-2%	45%	6%
GFDL-CM3_rcp45	-12%	-25%	-4%	-8%
GFDL-CM3_rcp85	-7%	-21%	3%	-3%
HadGEM2-CC_rcp45	-9%	-25%	7%	-16%
HadGEM2-CC_rcp85	-10%	-29%	2%	-13%
HadGEM2-ES_r1p1i1_rcp45	-16%	-30%	-5%	-26%
HadGEM2-ES_r1p1i1_rcp85	-37%	-55%	-19%	-68%
MIROC5_rcp45	-20%	-34%	-9%	-22%
MIROC5_rcp85	-27%	-41%	-12%	-32%
RCP8.5	-13%	-29%	4.6%	-22%

RCP4.5	-8%	-21%	4.2%	-11%

Notes: Note: CCTAG = California Department of Water Resources' Climate Change Technical Advisory Group, CMIP5 = Coupled Model Intercomparison Project Phase 5, RCP = representative concentration pathway

*A year with at least one dead storage month occurring. The system reliability for the base scenario is approximately 92.5 percent. A change of 0 percent indicates a reliability of 92.5 percent

3.4.4 X2 Location and Net Delta Outflow

Climate change may affect not only water quantity but also Delta water quality. X2 is the point identified by its distance from the Golden Gate Bridge where salinity measured one meter from the channel bottom is approximately 2 ppt. X2 is the basis for standards to protect aquatic life (seawater salinity is about 35 ppt).

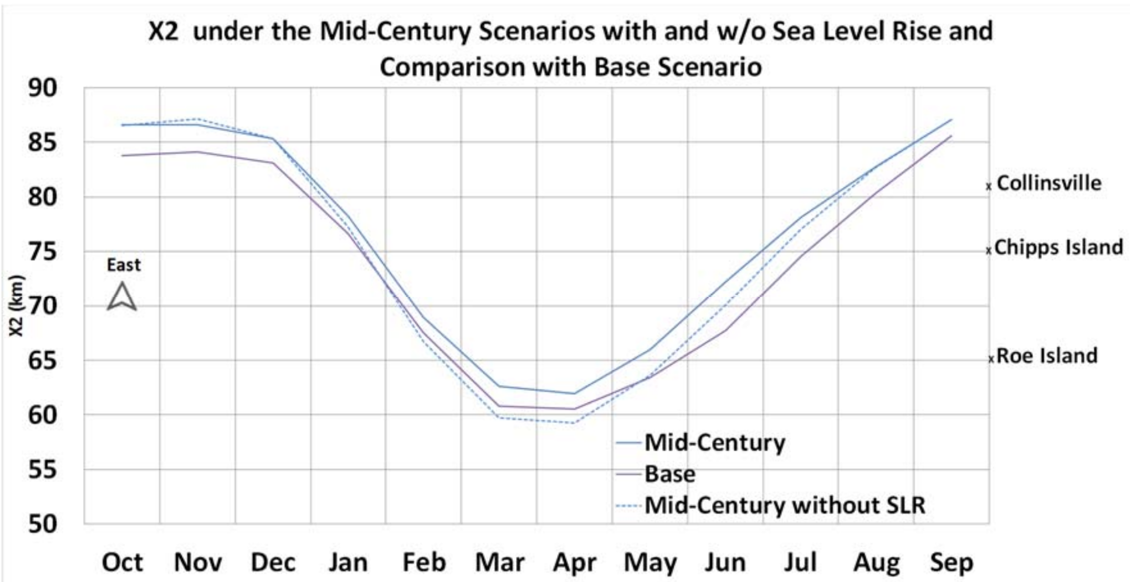
In 1995, the State Water Resources Control Board adopted X2 as an objective for the protection of fish and wildlife and to help restore the relationship between springtime precipitation and the geographic location and extent of estuarine habitat. The regulatory requirements for the springtime (February through June) objective mandates water managers to position X2 farther downstream in wet months than in dry months. That can be accomplished by increasing reservoir releases or, more commonly, decreasing exports from the Delta.

To help quantify the effects of sea level rise on the X2 location, and separate these effects from other climate change-induced effects, each of the 20 CMIP5 climate change scenarios were run using a zero and a designated sea-level-rise ANN (Table 2). Figure 10 presents the average monthly simulated location of X2 for the base and these two mid-century scenarios (with sea level rise and without sea level rise). Figure 11 presents the simulated average monthly net Delta outflow index (NDOI), a key determinant of X2. NDOI increases in the climate change scenarios both with and without sea level rise (solid and dash blue lines) from December through March (Figure 11).

The mid-century climate change scenario with sea level rise (Figure 10, solid blue line) shows larger (as much as 4.5 kilometers farther eastward) X2 values that create greater salinity intrusion into the Delta during the entire year compared to the base scenario.

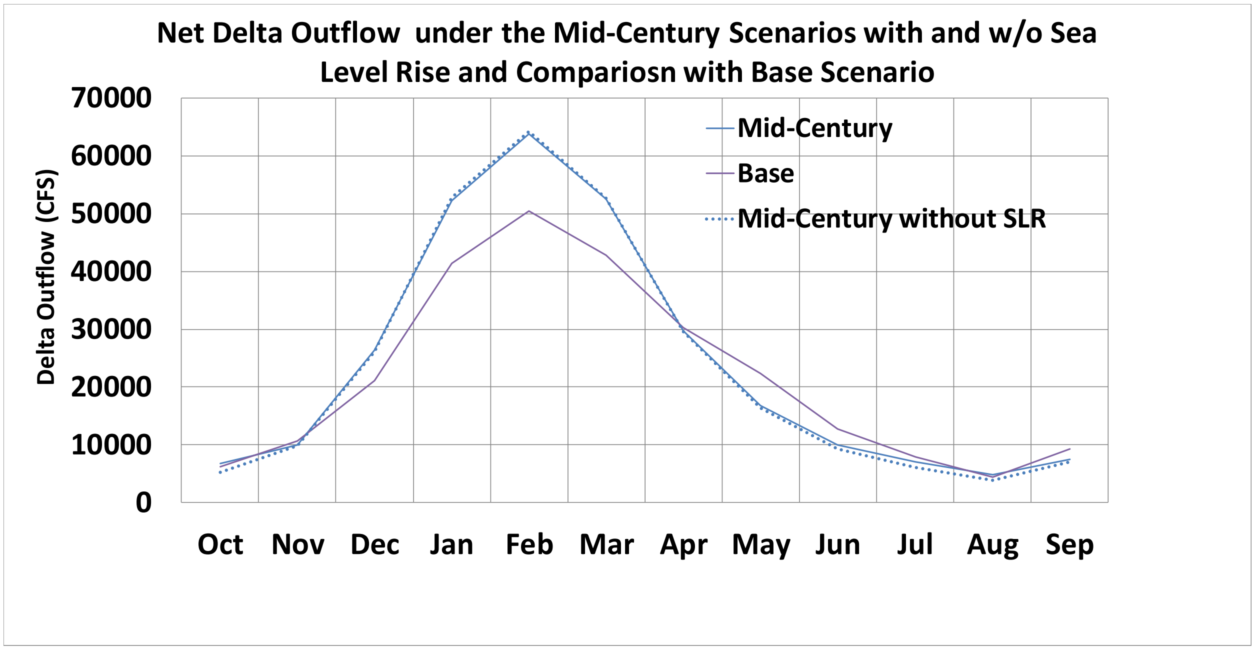
The X2 location under no sea level rise in the middle of this century (Figure 10, dash line) is as much as 1km farther westward from February to April (i.e. less Delta salinity) but as much as 3km farther eastward in other months compared to the base scenario. This is the result of higher precipitation combined with an increased rain-to-snow ratio and earlier snowmelt under climate change in the winter and early spring. All these factors increase runoff and NDOI from December to March, and decrease runoff in other months (Figure 10). Some time lag is expected for the X2 response to Delta outflow change.

Without sea level rise in the middle of this century (Figure 10, dash line), the X2 location is as much as 3 kilometers farther westward compared to that under the climate change scenario with sea level rise except for November. The average 1-foot sea level rise in the middle of this century will increase Delta salinity in terms of X2, leading to worse Delta water quality. This indicates that the negative impact of sea level rise overpowers the positive impact of increased Delta outflow in balancing X2 from February through April.



Notes: Collinsville, Chipps Island, and Roe Island are Delta salinity monitoring locations.
SLR = sea level rise, km = kilometer, X2 = the distance from the Golden Gate to the point where daily average salinity is 2 parts per thousand at 1 meter off the bottom.

Figure 10: X2 Location for the base scenario and Mid-Century Level Scenarios with and without Sea Level Rise



Notes: CFS = cubic feet per second, SLR = sea level rise.

Figure 11: Average Monthly Net Delta Outflow Index for the Base Scenario and the Mid-Century Scenarios with and without Sea Level Rise

4: Extreme Climate Change Impact

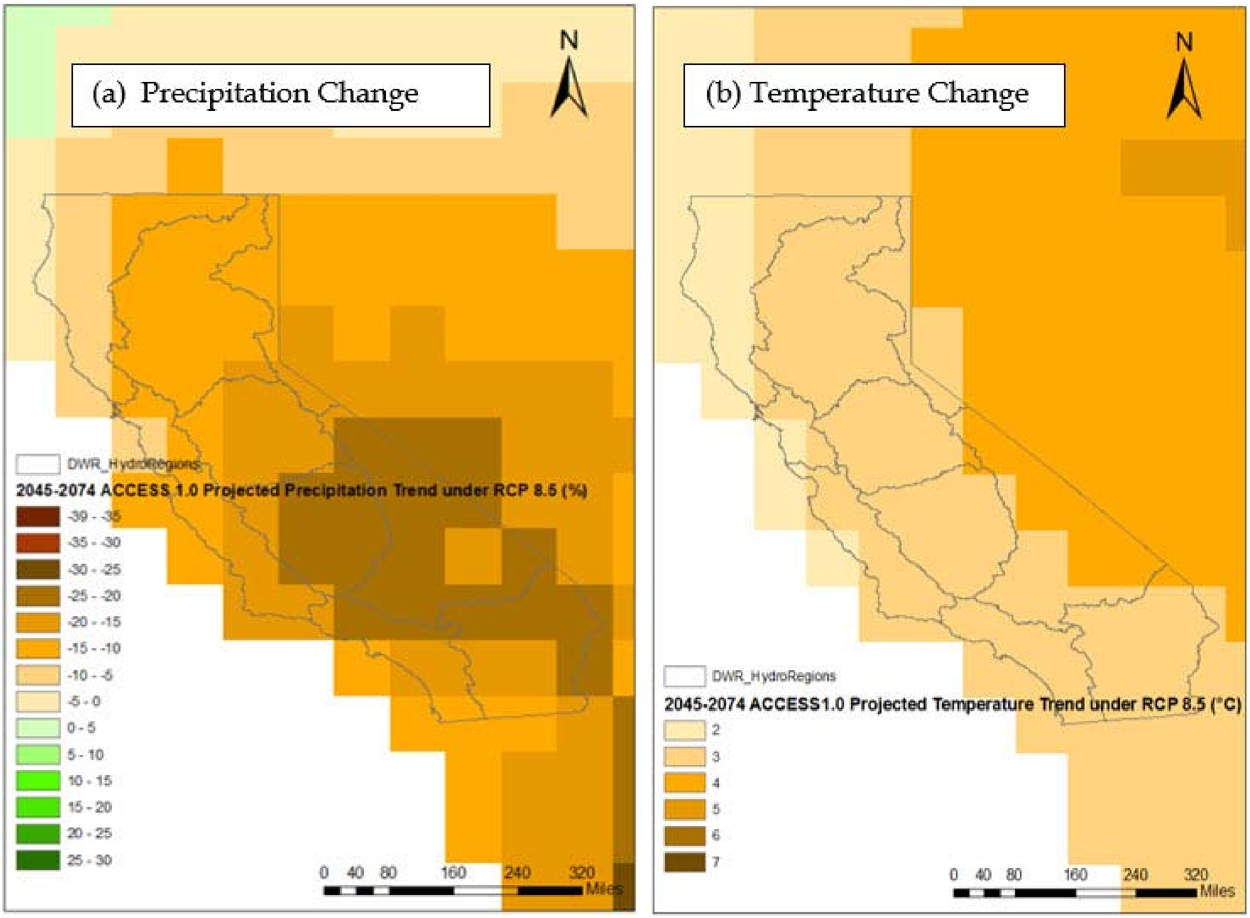
California's future climate may become more extreme due to climate change. More severe drought in California in the future would cause more severe stresses on the SWP and CVP systems. The recent five-year drought during Water Years 2012 to 2016 exerted tremendous stresses on the SWP and CVP and instigated an assessment of the potential impacts of the more extreme climactic conditions modeled by global climate projections.

In terms of the trend of total rim inflow to the Sacramento River basin in the middle of this century, the model from Australia, ACCESS 1.0, projects the most dismal water supply situation in the SWP and CVP areas under the highest emission scenario (RCP 8.5), with annual inflow volume reduced by about one-third (-29 percent). Projected precipitation change by this model in the middle of this century shows a drying trend throughout California (Figure 12a), with different severity in the Sacramento River basin (a decrease of 10 percent to 15 percent) and the San Joaquin River basin (a decrease of 15 percent to 20 percent). Temperatures in the Sacramento and San Joaquin valleys are projected to increase 3°C under the climate model projection (Figure 12b).

A CalSim 3.0 run result with this projection will be used to assess extreme climate change impact on water supply in the SWP and CVP during the middle of this century.

The climate-model-projected drought events in the future are not directly used by the CalSim model because of the issue of model projected interannual variability. Instead, the climate-model-projected trend of rim inflows in the middle of this century is used to perturb rim inflows during historical drought episodes to create future drought episodes for this assessment.

Two 6-year drought episodes (1929–1934 and 1987–1992) in the SWP and CVP areas are always cited in water supply reliability analysis and selected for climate change impact analysis on severe droughts.

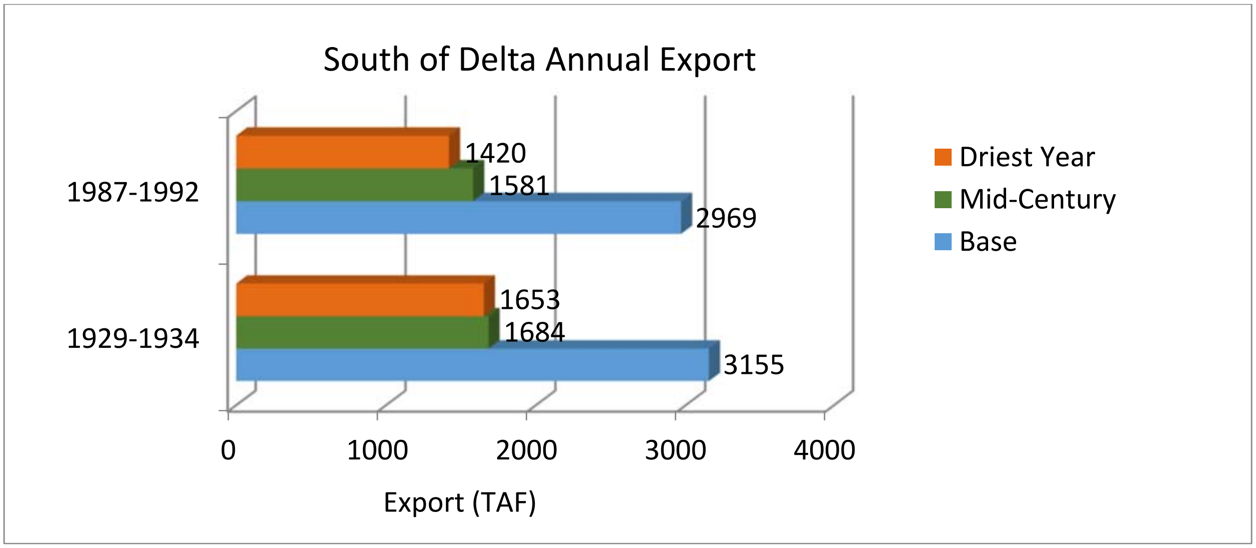


Note: Represented trends are under the Emission scenario representative concentration pathway (RCP) 8.5, based on 1°×1° re-gridded GCM Projections.

Figure 12: Projected (a) Precipitation and (b) Surface Air Temperature Change, 2045–2074, by the Climate Model ACCESS 1.0

4.1 Delta Exports

Climate change impact on Delta exports during droughts would be severe under the worst scenario (Figure 13). Compared to exports during two historical drought episodes (blue bars), exports would be reduced by about half during these types of drought episodes in the middle of this century (green bars). For the driest drought year during these future droughts (orange bars), the annual Delta export is reduced to 1,420 taf, less than one third of the Delta export normal (~5000 TAF).

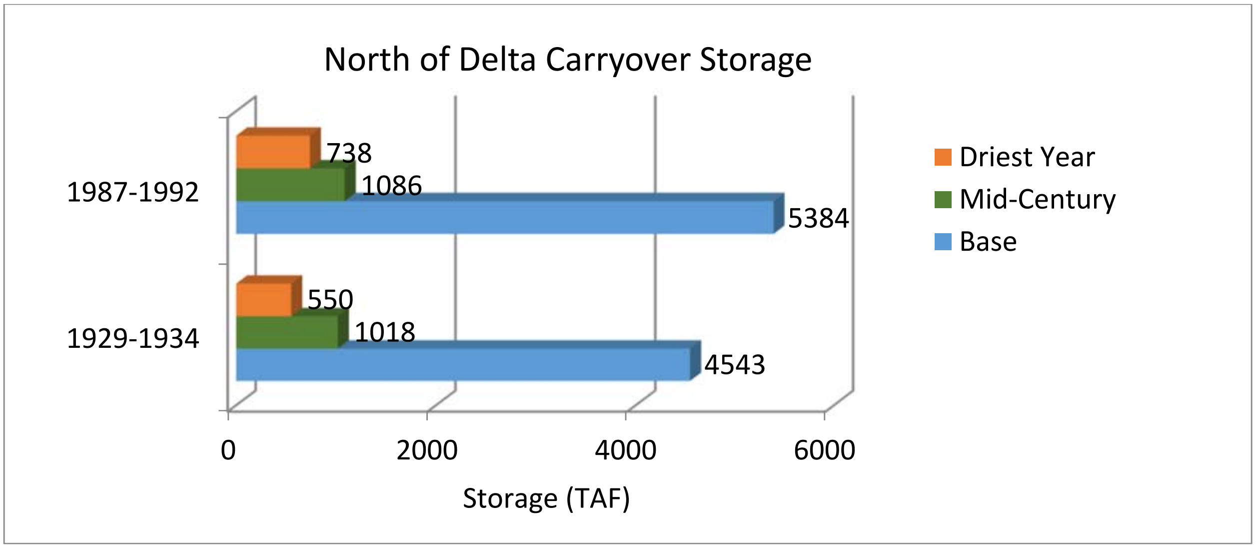


Note: The blue bars represent average annual exports during each historical drought. The green bars represent the anticipated exports if the same drought conditions occur in the middle of this century. The orange bars represent the anticipated exports during the driest years if the same drought conditions occur in the middle of this century.

Figure 13: South of Delta Annual Export During Two Droughts

4.2 North of Delta Carryover Storage

The carryover storage tends to more sensitive to climate change than other SWP or CVP metrics, especially in drought years, because of its nature of "residual storage". For the driest climate model projection scenario, climate change could exert tremendous stresses on the SWP and CVP systems in terms of carryover storage reduction during future drought episodes. **The total carryover storage of four major reservoirs of the SWP and CVP could reduce to approximately 1,000 taf (Figure 14) in these two more extreme future drought episodes. This number represents only about one-fifth of the carryover storage in the two corresponding historical drought episodes**. Essentially, all four major reservoirs will reach below dead storage level in the future driest year, with total carryover storage only 550 taf. Some reservoirs, such as Trinity Lake, could dry up in the driest drought year (not shown).



The blue bars represent average annual carryover storage during each historical drought. The green bars represent the anticipated carryover storage if the same drought conditions occur in the middle of this century. The orange bars represent the anticipated carryover storage during the driest years if the same drought conditions occur in the middle of this century.

Figure 14: North of Delta Carryover Storage (End of September Storage) During Two Droughts

5: Ranges of Impact and Bottom-Line Estimate

There are different levels of uncertainty associated with every step of this climate change impact study on the SWP and CVP. For example, climate model projections give relatively consistent change of temperature in the future, less consistent sea level rise projections because of difficulties in predicting ice shelf melting in Antarctica and Greenland, and inconsistent projections in precipitation change. Climate model projections could give completely opposite measurements for change of precipitation in the future (drying versus wetting). As a result, the selection of different GCMs projections could affect climate change assessment results.

Future temperature change would affect snow melting and the ratio of snow to rain in the precipitation in the Sierra Nevada and Klamath mountains. This would result in changes of seasonal patterns of rim inflows, such as shifting of the peak flow month. Future global temperature change would also affect sea level rise in San Francisco Bay. Agriculture applied water demand would also be affected by future temperature change, but this effect is hard to quantify because of uncertainties in the response of crops to warming and raised carbon dioxide (CO_2) concentrations.

Future precipitation change would cause annual rim inflow volume change, resulting in changes to total water available for the SWP and CVP systems. It would also cause soil moisture change in the future, which would affect applied water demand of crops. However, because of the separation of precipitation season and cultivation season in the Central Valley, the effect of soil moisture change on demand would be minimal.

As a result, uncertainties in projecting future precipitation and temperature change would impact climate change assessment results on the SWP and CVP through the above paths.

In addition, extra uncertainties might be added on to assessment results during the process of the downscaling of GCM projections and the preparation of climate change affected rim inflow through the VIC model and the variable perturbation ratio approach.

5.1 Ranges of Impact

There are wide ranges of climate change assessment results among the 20 individual simulations that form the climate change scenario ensemble. Table 3 summarizes these results.

5.1.1 Rim Inflow

Among the 20 CCTAG CMIP5 climate model projections, the wettest climate model projection (CANESM2_r1i1p1_RCP85), results in an annual rim inflow increase of 52 percent. The driest climate model projection (ACCESS1_0_rcp85), results in an annual rim inflow reduction of 29 percent (Table 3).

The odds of annual rim inflow being reduced (increased) in 2060 is about 55% (45%). The wide range of GCM model projected total annual rim inflows to the Sacramento River might cause the impact on CVP/SWP to be highly uncertain.

5.1.2 South-of-Delta Delta Export

Among the 20 CCTAG CMIP5 climate model projections, 16 climate model projections show that Delta exports would reduce (from -4 percent to -44 percent). Four climate model projections predict an increase in Delta exports (from 10 percent to 21 percent). The odds of Delta export being reduced in 2060 is high, reaching 80%.

The most severe export reduction is from the model projection ACCESS1_0_rcp85 (i.e., the projection from the climate model ACCESS 1.0 under the RCP 8.5 scenario, which reduces exports by 44 percent (equivalent to approximately 2,200 taf). The most optimistic projection of Delta export results from the CANESM2_r1i1p1_RCP85 projection (i.e., the projection from the ensemble run r1i1p1 of the climate model CANESM2 under the RCP 8.5 scenario), which boosts exports by 21 percent (approximately 1,000 taf).

5.1.3 North-of-Delta Carryover Storage

Among the 20 CCATG climate model projections, 18 projections predict a carryover storage reduction. Only two projections predict a carryover storage increase by mid-century (Table 3). The probability of carryover storage being reduced in 2060 is very high, about 90%.

The most severe carryover storage reduction results from climate model projection ACCESS1_0_rcp85, which predicts a 62 percent decrease (Table 3). The climate model projection CANESM2_r1i1p1_RCP85 predicts the most favorable situation with the carryover storage boosted by 7 percent.

5.2 Separation Approach

One of approaches to deal with the wide range of impacts is to separate the previously mentioned climate change effects on the SWP and CVP, and then eliminate relatively highly uncertain effects, such as those from annual rim inflow volume change ranging from -29% to 52% and applied water demand change that is hard to quantify, from the assessment. At the same time, this approach keeps relatively less uncertain effects, such as those from flow seasonal pattern shifts and sea level rise of which all GCM projections have the similar trends, to form a "bottom-line" estimate of climate change impact on the SWP and CVP.

This approach to separating different climate changes effects on the CVP and SWP, and then making bottom-line climate change assessment, was described by Wang et al (2011).

Although temperature change affects seasonal inflows and sea level rise and applied water demand at the same time, these factors themselves are relatively independent in CalSim 3.0. Applied water demand is predetermined by crop types, acreage, and their actual evapotranspiration rate, while rim inflow and sea level rise would not affect the estimate of applied water demand. Conversely, applied water demand will not affect the estimate of rim inflow and the designation of sea level rise. And annual inflow volume change is predominantly caused by annual precipitation change and inflow monthly pattern shift is mainly induced by temperature change. These two climate change factors affecting rim flow can be separated through the three-step perturbation ratio method (See Appendix B). Secondly, the CalSim 3.0 model itself is based on the water balance between water use and water supply, with these four factors occurring as linear terms in the water balance formula. Thirdly, it is solved by linear programming, requiring the SWP/CVP simulation system at least linearized. Therefore, the effects of these climate change factors on CVP/SWP in CalSim 3.0 are linearly combined and then are separable. A comprehensive and strict test of this hypothesis is ongoing. For this report, it is assumed that the effects of seasonal inflow pattern shift, annual inflow change, sea level rise, and applied water demand change on water planning are independent. With this assumption, only five "cascading" sensitivity experiments with the CalSim 3.0 model are necessary to isolate these four climate change effects (Table 4):

1. Experiment 1: All four climate change factors considered.
2. Experiment 2: Only applied water demand change not considered
3. Experiment 3: Neither applied water demand change nor sea level rise considered
4. Experiment 4: The three climate change factors of sea level rise, applied water demand change, and annual inflow volume change not considered
5. Base run (i.e., base scenario): All four climate change factors not considered

The respective contributions of sea level rise, seasonal inflow pattern change, annual inflow change, and applied water demand change to climate change impacts on water operation are then separated as follows:

- Effects of applied water demand change = Experiment 1-Experiment 2.
- Effects of sea level rise = Experiment 2- Experiment 3.

- Effects of annual inflow change = Experiment 4 – Experiment 3.
- Effects of flow seasonal pattern shift = Experiment 4 – Base run.
- The bottom-line estimate of climate change impact on the SWP and CVP is defined as the sum of effects of flow seasonal pattern shift and effects of sea level rise.

Table 4: "Cascading" Sensitivity Experiments for the Separation of Effects of Four Climate Change Factors

Sensitivity Experiment	Four Climate Change Factors			
	Applied Water Demand	Sea Level Rise	Annual Rim Inflow Change	Flow Seasonal Pattern Change
Experiment 1	Yes	Yes	Yes	Yes
Experiment 2	No	Yes	Yes	Yes
Experiment 3	No	No	Yes	Yes
Experiment 4	No	No	No	Yes
Base Run	No	No	No	No

5.3 Four Climate Change Effects on SWP and CVP Operations

Eighty-One CalSim 3.0 simulations were made for separating the four climate change effects on the SWP and CVP, 20 for each of the four sensitivity runs, and one for the base run. Their individual effects on the performance metrics of the SWP and CVP are presented in this section.

5.3.1 Delta Export Reduction

The seasonal pattern of rim inflow shifts because of earlier snow melting and higher rain-to-snow ratio in precipitation, contributing to the greatest Delta export reduction in the middle of this century (Figure 15). This accounts for 42% (i.e. 269/ (269+229+150)) among the three export reduction terms. Georgakakos *et al* (2012) also pointed out that a seasonal shift of the wet season earlier in the year and other two climate change factors are bound to influence the ability of the Northern California reservoir system to meet its stated objectives. The shifted water from earlier melted snow and more runoff brought on by more rainwater in precipitation is either unable to be stored in reservoirs for later export because of flood space constraints in reservoirs, or is unable to be exported south of the Delta because of inadequate pump capacities or environmental regulations.

About 1-foot sea level rise in the middle of this century also contributes to the reduction of Delta exports significantly. It accounts for 35 percent% (i.e. 229/ (269+229+150)) among the three export reduction terms. Sea level rise increases Delta salinity, requiring extra Delta outflow to dilute more brackish Delta water to meet environmental standards. The extra Delta outflow is provided at the expense of Delta exports, especially in the summer.

Applier water demand increase (527 taf) in the Sacramento Valley in the middle of this century also contributes the reduction of Delta exports by 23 percent (i.e. 150/ (269+229+150)). But only part of the increased demand (150 taf) is met by sacrificing Delta exports. Other demand increases in the Sacramento Valley are met by extra groundwater pumping in the valley (not shown).

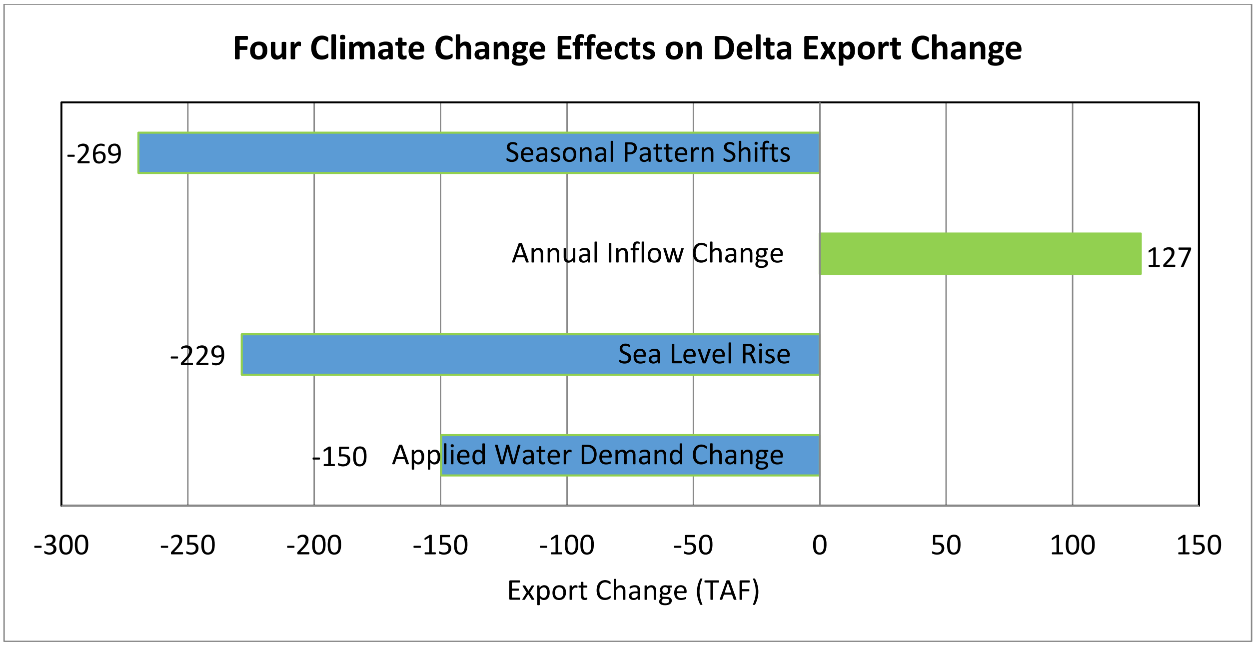


Figure 15: Contributions to Delta Exports Change from Four Climate Change Factors

Because of a model-projected wetting trend in the Sacramento river basin in the middle of this century, the rim inflow increase in the basin contributes 127 taf more to Delta exports. That amount is far from enough to compensate for the export loss brought by seasonal pattern shifts, sea level rise, and applied water demand change. **With rim inflow in the Sacramento River basin projected to increase approximately 900 taf in the middle of this century, only 15 percent of increased rim inflow is able to be transported south of the Delta. Another 15 percent of increased rim inflow is consumed to meet part of increased applied water demand in Sacramento Valley (not shown) and 17 percent of increased rim inflow is stored as carryover storage (Figure 16). The remaining 53 percent of increased rim inflow becomes Delta outflow and flows to Pacific Ocean.**

For the bottom-line estimate (i.e., excluding the effects of annual inflow change and applied water demand change), Delta exports in the middle of this century would reduce by approximately 500 taf, a 10 percent reduction from the number seen in the current climate and SWP and CVP systems.

5.3.2 Carryover Storage Decrease

Seasonal pattern shifts of rim inflow causes most of the total carryover storage decrease (approximately 1,300 taf) to occur in the middle of this century (Figure 16). It accounts for 75 percent (i.e. 1259/ (1259+183+242)) among the three carryover storage reduction terms. Two other factors, an approximate 1-foot sea level rise and an approximate 7 percent applied water demand increase in the Sacramento Valley, only reduces carryover storage by approximately 11 percent and 14 percent, respectively, among the three carryover storage reduction terms. This indicates that carryover storage reduction is extremely sensitive to approximately 2°C warming and that the function of reservoirs as storage space for the coming drought year would be severely damaged. This is to say, **extra runoff from early snow melting and higher percentage of rain in the precipitation in the winter and early spring cannot be conserved in reservoirs to meet higher demand in the summer**. **The extra water is released as flood water in the winter and early spring to become Delta outflow**.

A projected annual inflow increase of 887 taf in the Sacramento River basin during the middle of this century adds 157 taf of carryover storage. That amount is not significant enough to compensate carryover storage loss by the other three climate change factors.

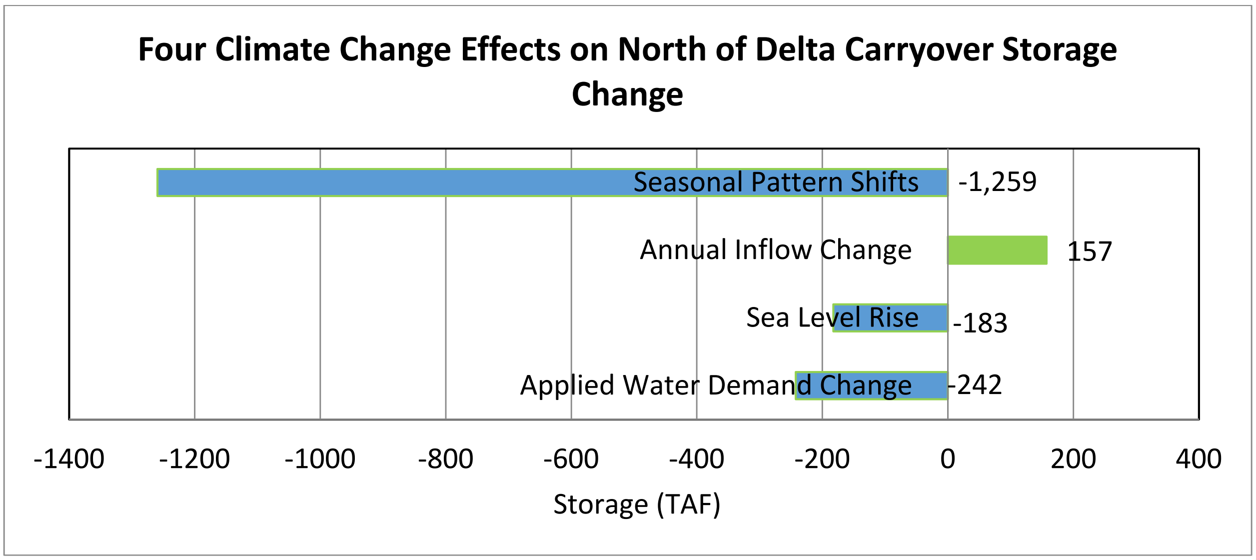


Figure 16: Contributions to North of Delta Carryover Storage Change from Four Climate Change Factors

The bottom-line carryover storage decrease for the SWP and CVP systems caused by climate change in the middle of this century is 1,442 taf, a reduction of approximately 23 percent from the current climate change (base scenario).

6: Findings and Future Directions

Although climate model projections, on average, show a 4 percent precipitation and then rim inflow increase in Northern California in the middle of this century, climate change would bring significant negative impacts on current SWP and CVP operations due to the warming.

The flow seasonal pattern shift in rim inflows from the Sierra Nevada and sea level rise in the San Francisco bay together would exert overwhelmingly negative effects on South of Delta export, leading to a half million-acre feet export reduction in the middle of this century.

The shifted seasonal flow due to earlier snow melting and more rain in the precipitation is about 2 million-acre feet, causing more reservoir flood release and then higher Delta outflow in winter and early spring. This means meeting demand in summer will consume more carryover storage. This results in north of Delta carryover storage diminishing by 1.5-million-acre feet in the middle of this century.

Besides reservoir carryover storage reduction, the occurrence of reservoir dead storage becomes potentially much more frequent due to higher variability of precipitation and flow, making the CVP/SWP system less reliable.

Exported water and environmental water quality in the Delta would also worsen throughout the year in terms of X2 extending eastward as much as 4.5 kilometers, a result caused not only by sea level rise but also by the flow seasonal pattern shift in the middle of this century.

Greenhouse gas emission mitigation from the highest emission scenario RCP 8.5 to the moderate emission scenario would lessen Delta export reduction by one quarter million-acre-foot and lessen the diminishing of carryover storage by half -million-acre-feet in the middle of this century.

During drought episodes in the middle of this century, climate change impacts on the SWP and CVP operations are much worse in the driest climate model projection scenario. Delta exports would reduce to half of that in historical droughts. Carryover storage would decrease to one-fifth of that in historical droughts.

In the future, improvements will be made to current study in the following aspects:

- A larger sample of GCM projections will be used to better evaluate the effects of GCM projection uncertainty on climate change impacts on CVP/SWP.
- Comprehensive sensitivity tests will be executed for the hypothesis of the independence of effects of four climate change factors on CVP/SWP.
- The impact study will expand to groundwater in Central Valley and extend to the end of this century.
- With the increasing certainty of negative impacts on the SWP and CVP brought by climate change in the future, various adaptive solutions to these impacts will be explored using the CalSim 3.0 model.

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APPENDIX A: Stream Flow and other Input Data for CalSim II

Table A-1: Modifications to CalSim 3.0 Input Parameters to Represent Climate Change

Parameter	Climate Change Representation
Rim Inflows	Use Variable Three-Step Perturbation Ratio Method to Modify Historical Inflow
Flow-Related Parameter Tables	Use Perturbed Inflow to Update Parameter tables
Reservoir Evaporation	Perturb Reference Evaporation Rate to Recalculate Evaporation
Water Demands and Water Use	Perturb Reference Evaporation Rate and Monthly Precipitation to Recalculate Applied Water Demand
Sea Level Rise	Use Variable Sea Level Rise (0.5-1.5 feet)

Table A-2: Simulated Stream-Flow Locations by VIC

Abbreviation	Name	Latitude	Longitude	VIC Latitude	VIC Longitude
SHAST	Sacramento River at Shasta Dam	40.7170	-122.4170	40.6875	-122.4375
SAC_B	Sacramento River at Bend Bridge	40.2890	-122.1860	40.3125	-122.1875
OROVI	Feather River at Oroville	39.5220	-121.5470	39.5625	-121.4375
SMART	Yuba River at Smartville	39.2350	-121.2730	39.1875	-121.3125
FOL_I	American River at Folsom Dam	38.6830	-121.1830	38.6875	-121.1875
PRD_C	Mokelumne River at Pardee	38.3130	-120.7190	38.3125	-120.8125

N_HOG	Calaveras River at New Hogan	38.1550	-120.8140	38.1875	-120.8125
N_MEL	Stanislaus River at New Melones Dam	37.8520	-120.6370	37.9375	-120.5625
DPR_I	Tuolumne River at New Don Pedro	37.6660	-120.4410	37.6875	-120.4375
LK_MC	Merced River at Lake McClure	37.5220	-120.3000	37.5625	-120.3125
MILLE	San Joaquin River at Millerton Lake	36.9840	-119.7230	36.9375	-119.6875
KINGS	Kings River - Pine Flat Dam	36.8310	-119.3350	37.1875	-119.4375

Note: VIC = variable infiltration capacity

Table A-3: Past Climate Change Impact Study on SWP/CVP

Study	Selection/Number of GCM Projections	Use of GCM projected streamflow
Progress on Incorporating Climate Change into Planning and Management of California's Water Resources (California Department of Water Resources 2006)	Scenario Based/4 CMIP3 Projections	Indirect Use: One-Step Perturbation Ratio Method
Using Future Climate Projections to Support Water Resources Decision Making in California (California Department of Water Resources 2009)	Scenario Based/12 CMIP3 Projections	Indirect Use: Three-Step Perturbation Ratio Method

California Water Plan, Update 2013 (California Department of Water Resources 2013)	Scenario Based/12 CMIP3 Projections	Direct Use
Operating Criteria and Plan Biological Assessment (U.S. Bureau of Reclamation 2008)	Scenario Based/4 CMIP3 Projections	Indirect Use: Two Step Perturbation Ratio Method
Modeling Technical Appendix 5A. Bay Delta Conservation Plan Public Draft EIR/EI (Bay Delta Conservation Plan 2013)	Ensemble Informed /112 CMIP3 Projections	Indirect Use: Variable Perturbation Ratio Method
Central Valley Project Integrated Resources Plan (U.S. Bureau of Reclamation 2015)	Ensemble Informed /112	Indirect Use: Variable Perturbation Ratio Method
Updated Climate Change Requirements for Proposition 1 Water Storage Investment Program (California Department of Water Resources 2016)	Scenario Based/3 CMIP5 Projections	Indirect Use: Quantile Mapping

APPENDIX B: Perturbation Ratio Method

The *fixed* three step perturbation ratio method is described below:

Step One: Monthly Perturbation Ratio

Assume that the 30-year climatologically mean (1976-2005) monthly inflow from a climate model projection is Qi, i=1,12 and the 30-year mean monthly inflow for the future (e.g., 2045-2074) from a climate model projection is Pi, i=1,12, then monthly perturbation ratio R_i

$$R_i = \frac{P_i}{Q_i} \qquad (1)$$

Assume the historical monthly inflow in one year is Tij, i=1, 12 for each month and j=1, 82 for each water year from 1922 to 2003 before the perturbation ratio is applied.

After the perturbation ratio is applied, the monthly inflow becomes

$$A_{ij} = R_i * T_{ij} \qquad (2)$$

Step Two: Annual Inflow Adjustment

The annual inflow after perturbation $\sum_{i=1}^{i=12} A_{ij}$ is probably not equal to the original annual inflow, which is $\sum_{i=1}^{i=12} T_{ij}$. Annual inflow adjustment aims to keep the annual inflow unchanged by multiplying the perturbed monthly inflow Aij by the ratio $\frac{\sum_{i=1}^{i=12} T_{ij}}{\sum_{i=1}^{i=12} A_{ij}}$ for each historical year. Thus, the perturbed and annual inflow adjusted monthly inflow, Bij,, i=1,12, becomes:

$$B_{ij} = A_{ij} * \frac{\sum_{i=1}^{i=12} T_{ij}}{\sum_{i=1}^{12} A_{ij}} \quad (3)$$

After doing this, only the shifting of inflow seasonal pattern due to early snow-melting and other factors is kept in the perturbed and annual inflow adjusted inflow. The trend of annual inflow due to climate change is left out in this step. Therefore, if this type of inflow is taken as input to CALSIM, the only remaining contribution to climate change impact is from inflow seasonal pattern change.

Step Three: Trend adjustment

Although different climate models have predicted a scattering trend of precipitation and then annual inflow in the future, keeping the annual inflow trend in water resource planning is desirable to account for the uncertainty of climate models in predicting annual inflow. To address this, we introduce the trend adjustment procedure. The trend ratio can be estimated by

$$Tr = \frac{\sum_{i=1}^{12} P_i}{\sum_{i=1}^{i=12} Q_i} \quad (4)$$

Through multiplying the perturbed and annual inflow adjusted monthly inflow by the trend ratio, we have the perturbed, annual inflow adjusted, and trend adjusted monthly flow, $\overline{T_{ij}}$, i=1,12, as follows

$$\overline{T}_{ij} = B_{ij} \times Tr \quad (5)$$

The *variable* three step perturbation ratio method is described below:

1. For each of the 12 calendar months during the future 30-year period (2045–2074), derive the (CDF) of GCM-projected monthly runoff values as estimated from daily simulation of the VIC model.

2. For each of the 12 calendar months during the historical 30-year period (1976–2005), determine the CDFs of GCM-simulated historical monthly runoff values.

3. For each of the 12 calendar months, develop a monthly quantile mapping between the CDF of the simulated historical monthly inflows and that of the projected monthly inflows.

4. For each observed/synthesized monthly inflow of a specific year in the historical period (1922–2015) find the above corresponding monthly quantile map, find the corresponding simulated historical monthly inflows, and then find the projected monthly inflows. Finally, calculate the monthly perturbation ratio between the projected and simulated historical flows. If the observed monthly inflow falls out of the range of the simulated historical flow, use the nearest simulated historical flow. This practice on flow saturation might underestimate future flood flow and its effects on water supply.

5. Apply this monthly perturbation ratio to the particular observed monthly inflow.

6. Calculate the perturbation (annual inflow trend) ratio between GCM-projected annual inflow and GCM-simulated historical annual inflow for the particular year, similar to the estimate of the monthly perturbation ratios (Steps 1–4).

7. Follow the three-step perturbation ratio method (Wang et al. 2011) to adjust each observed monthly inflow perturbed by the monthly perturbation ratio.

8. Repeat Steps 4–7 for all the years in the historical period (1922–2015)