Feasibility Report
Appendix F – Climate Change Risk and Uncertainty Analysis

Los Vaqueros Reservoir Expansion Investigation
Final Feasibility Report

U.S. Department of the Interior

February 2020

Mission Statements

The Department of the Interior (DOI) conserves and manages the Nation's natural resources and cultural heritage for the benefit and enjoyment of the American people, provides scientific and other information about natural resources and natural hazards to address societal challenges and create opportunities for the American people, and honors the Nation's trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities to help them prosper.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Feasibility Report
Appendix F – Climate Change Risk and Uncertainty Analysis

Los Vaqueros Reservoir Expansion Investigation, California
Interior Region 10 • California-Great Basin

prepared for Reclamation by Stantec under Contract No. R12PC20255, GS-00F-0040L

Cover Photo: A full Los Vaqueros Reservoir in the spring (Contra Costa Water District)

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Abbreviations and Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
µS/cm	micro-Siemens per centimeter
Basin Study	Sacramento and San Joaquin Rivers Basin Study
Bay Area	San Francisco Bay Area
CalEPA	California Environmental Protection Agency
CALFED	CALFED Bay-Delta Program
CCWD Board	CCWD Board of Directors
CCWD	Contra Costa Water District
CEN	Central Tendency
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
Commission	California Water Commission
Delta	Sacramento-San Joaquin Delta
DEW	drier, extreme warming
DWR CCTAG	DWR's Climate Change Advisory Group
DWR	California Department of Water Resources
EC	electrical conductivity
EIR	Environmental Impact Report
EIS	Environmental Impact Statement
HD	Hot-Dry
HW	Hot-Wet
in/yr	inches per year
Investigation	Los Vaqueros Reservoir Expansion Investigation
Local Agency Partners	Prospective Bay Area partner water agencies including CCWD; Alameda County Water District; Alameda County Flood Control and Water

	Conservation District, Zone 7; Bay Area Water Supply and Conservation Agency; Byron-Bethany Irrigation District; City of Brentwood; Del Puerto Water District; East Bay Municipal Utility District; East Contra Costa Irrigation District; San Francisco Public Utilities Commission; San Luis Water District; San Luis & Delta-Mendota Water Authority; Santa Clara Valley Water District; and Westlands Water District.
MAF	million acre-feet
MAF/yr	million acre-feet per year
mg/L	milligrams per liter
mm/yr	millimeters per year
NRC	National Research Council
NOD	North-of-Delta
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
Refuges	SOD CVPIA-designated wildlife refuges
RF	Reference-No-Climate-Change
SOD	South-of-Delta
SWP	State Water Project
TAF	thousand acre-feet
USACE	U.S. Army Corps of Engineers
WD	Warm-Dry
WEAP-CV	Water Evaluation and Planning Model of the Central Valley
WMW	wetter, moderate warming
WSIP	Water Storage Investment Program
WW	Warm-Wet

Chapter 1 Introduction

This technical appendix to the Feasibility Report for the Los Vaqueros Reservoir Expansion Investigation (Investigation) documents the climate change analyses. The Investigation is a feasibility study evaluating alternatives to develop environmental water supplies and improve the reliability and quality of San Francisco Bay Area (Bay Area) water supplies, primarily through the expansion of Los Vaqueros Reservoir in Contra Costa County, California.

Background

Los Vaqueros Reservoir is located in the coastal foothills west of the Sacramento-San Joaquin Delta (Delta) in the eastern Bay Area. Contra Costa Water District (CCWD), owner and operator of the reservoir, provides water for 500,000 customers throughout central and eastern Contra Costa County as one of the largest urban water districts in California (CCWD 2017). CCWD completed construction of the original 100-thousand-acre-foot (TAF) Los Vaqueros Project in 1997. CCWD stores water in Los Vaqueros Reservoir that is diverted from the Delta when water quality is favorable, for later release and blending when Delta water quality is degraded. An initial expansion, Phase 1, to 160 TAF was completed in 2012. The primary purposes of both phases of the project is to address seasonal water quality degradation associated with CCWD's Delta water supplies and CCWD's dry year water supply reliability. The 160 TAF reservoir also provides important emergency water supply storage and, as secondary benefits, recreation and flood management.

Expansion of Los Vaqueros Reservoir was one of five potential surface water storage projects identified by the CALFED Bay-Delta Program (CALFED) as warranting further study. In 2001, the U.S. Department of the Interior, Bureau of Reclamation (Reclamation), California Department of Water Resources (DWR), and CCWD began appraisal-level studies of the potential to expand Los Vaqueros Reservoir to address regional water quality and supply reliability needs. The appraisal-level studies indicated that expanding the reservoir to as much as 500 TAF capacity was technically feasible and could provide water quality and supply reliability to agencies in the region, as well as providing potential benefits to fisheries sensitive to water management operations in the Delta.

Subsequently, Reclamation was directed in Public Law 108-7 (Omnibus Appropriations Act of 2003) to conduct a feasibility-level investigation of the potential expansion of Los Vaqueros Reservoir. In 2004, voters in CCWD's service area were asked to vote on whether CCWD should consider expanding the reservoir. The advisory ballot measure won approval, and as a result, the proposed expansion project was further developed and refined through preparation of environmental documentation in accordance with the National Environmental Policy Act and California Environmental Quality Act, and extensive public outreach.

After the Draft Environmental Impact Statement (EIS)/Environmental Impact Report (EIR) was published in 2009 by Reclamation and CCWD, a two-step approach was implemented for expanding

Los Vaqueros Reservoir. This was done in order for CCWD to move forward with addressing urgent water supply and quality needs, particularly during dry years, while the feasibility-level investigation was still in process. The initial expansion was completed as a local action by CCWD, without financial assistance from the Federal government. Because it was done without State or Federal assistance, this feasibility-level investigation was put on hold until after completion of the initial expansion. To implement the initial expansion, the CCWD Board of Directors (CCWD Board) certified the EIS/EIR (Reclamation 2010) and approved an expansion from 100 TAF to 160 TAF on March 31, 2010. Reclamation issued a Record of Decision in February 2011 to enter into an Integrated Operations Agreement with CCWD based on the 2010 EIS/EIR. Construction on the initial expansion began in early 2011 and was completed in 2012.

Reclamation, DWR, and CCWD continue to investigate the feasibility of larger expansion alternatives, as documented in this appendix, because the earlier appraisal-level studies indicated that an additional expansion of Los Vaqueros Reservoir beyond the initial 60 TAF would provide additional regional water supply reliability and statewide environmental benefits. This feasibility-level investigation includes updates to the project plans and studies previously performed to account for significant changes to existing conditions that have occurred since the 2010 EIS/EIR was released, as well as to account for changes that are anticipated to take place within the coming years. These changes include CCWD's initial expansion of Los Vaqueros Reservoir to 160 TAF and the operation of this expanded storage space, other local infrastructure changes (e.g., Contra Costa Canal Replacement Project), likely water management constraints resulting from regulatory actions in the Delta and large programs such as Bay Delta Conservation Plan, and new project beneficiaries participating in the Investigation.

Study Location

Los Vaqueros Reservoir is located in the Kellogg Creek watershed of Contra Costa County, California in the central and south Delta. The reservoir lies in the foothills west of the Delta in the eastern Bay Area. The study area for the Investigation includes the Los Vaqueros Reservoir watershed and associated facilities, central and south Delta, and service areas of potential local partner water agencies. The central and south Delta is roughly bound by the San Joaquin River on the north and the boundaries of the legal Delta to the south (as established in Section 12220 of the California Water Code).

Prospective Bay Area partner water agencies include CCWD; Alameda County Water District; Alameda County Flood Control and Water Conservation District, Zone 7; Bay Area Water Supply and Conservation Agency; Byron-Bethany Irrigation District; City of Brentwood; Del Puerto Water District; East Bay Municipal Utility District; East Contra Costa Irrigation District; San Francisco Public Utilities Commission; San Luis Water District; San Luis & Delta-Mendota Water

Authority[1];Santa Clara Valley Water District; and Westlands Water District. These are collectively referred to herein as Local Agency Partners.

Other potential partners include the managing agencies of South-of-Delta (SOD) Central Valley Project Improvement Act (CVPIA)-designated wildlife refuges (Refuges): California Department of Fish and Wildlife, the U.S. Fish and Wildlife Service, and Grassland Water District, in cooperation with Reclamation.

Due to the potential influence on other programs and projects, an extended study area was identified for the Investigation. The extended study area includes the Refuges, operational areas of the Central Valley Project (CVP) and State Water Project (SWP), and the service areas of other Bay Area water agencies that may be indirectly affected by project operations.

Project Objectives

The Investigation focuses on using an expanded Los Vaqueros Project to accomplish the following primary and secondary planning objectives:

Primary Planning Objectives

- Develop water supplies for environmental water management that supports fish protection, habitat management, and other environmental water needs.

- Increase water supply reliability for water providers within the Bay Area to help meet municipal and industrial water demands during drought periods and emergencies or to address shortages due to regulatory and environmental restrictions.

Secondary Planning Objective

- Improve the quality of water deliveries to municipal and industrial customers in the Bay Area, without impairing the project's ability to meet the environmental and water supply reliability objectives stated above.Final Alternatives Considered in the Feasibility Report

The No Action Alternative and four Action Alternatives are evaluated in this Feasibility Report. The physical features of the alternatives are summarized in Table 1-1. The Action Alternatives are refined versions of the alternatives evaluated in the 2010 Final EIS/EIR with the exception of Alternative 3, which was rejected in the 2010 Final EIS/EIR and was not further refined or evaluated herein. These alternatives account for changes to existing conditions that have occurred since the 2010

[1] The San Luis & Delta-Mendota Water Authority includes Banta-Carbona Irrigation District, Broadview Irrigation District, Byron-Bethany Irrigation District, Central California Irrigation District, the City of Tracy, Columbia Cana Company, Del Puerto Water District, Eagle Field Water District, Firebaugh Canal Water District, Fresno Slough Water District, Grassland Water District, Henry Miller Reclamation District #2131, James Irrigation District, Laguna Water District, Mercy Springs Water District, Oro Loma Water District, Pacheco Water District, Panoche Water District, Patterson Water District, Pleasant Valley Water District, Reclamation District #1606, San Benito County Water District, San Luis Water District, Santa Clara Valley Water District, Tranquility Water District, Turner Island Water District, West Side Irrigation District, West Stanislaus Irrigation District, and Westlands Water District.

EIS/EIR was released (e.g., expansion of Los Vaqueros Reservoir to 160 TAF, completion of other local projects). These alternatives are operated to provide varying levels of emphasis to the above project objectives.

Physical Features

Alternatives 1A, 1B, and 2A would expand Los Vaqueros Reservoir storage from 160 TAF to 275 TAF, build a new Delta-Transfer Pipeline, and relocate the existing Marina Complex and Los Vaqueros Watershed trails and access roads that would be inundated by the reservoir expansion. None of these would occur under Alternative 4A. All the action alternatives would upgrade the existing Transfer Facility, build a new Transfer-Bethany Pipeline, improve Pumping Plant #1, and add facilities to deliver water to the Transfer Facility from the Rock Slough Intake, which entails building a new Neroly High Lift Pump Station.

A list of the major components for all the alternatives is provided in Table 1-1 below. Alternatives 1A, 1B, and 2A differ from one another only in the proposed operational priorities of the facilities. Figure 1-1 shows the facilities associated with Alternatives 1A, 1B, and 2A. Figure 1-2 shows the facilities associated with Alternative 4A.

Table 1-1. Summary of Facilities and Operations for the Revised No-Action and Final Comprehensive Alternatives

	No Action	Alternatives 1A, 1B, 2A[1]	Alternative 4A
Existing Facilities (no change)			
Old River Intake	250 cfs	250 cfs	250 cfs
Middle River Intake	250 cfs	250 cfs	250 cfs
Old River Pipeline	320 cfs	320 cfs	320 cfs
Los Vaqueros Pipeline	400 cfs	400 cfs	400 cfs
Transfer Pipeline (Fill/Release)	200/400 cfs	200/400 cfs	200/400 cfs
EBMUD-CCWD Intertie	155 cfs	155 cfs	155 cfs
Transfer Reservoir	4 million gallons	4 million gallons	4 million gallons
Proposed Modifications to Existing Facilities			
Los Vaqueros Reservoir Capacity	160 TAF	275 TAF	160 TAF
Los Vaqueros Reservoir Maximum Water Surface Elevation	507 feet	560 feet	507 feet
Transfer Facility Pump Station Capacity	150 cfs	200 cfs	200 cfs

Table 1-1. Summary of Facilities and Operations for the Revised No-Action and Final Comprehensive Alternatives (contd.)

	No Action	Alternatives 1A, 1B, 2A[1]	Alternative 4A
Proposed New Facilities			
Transfer-Bethany Pipeline Capacity	None	300 cfs	300 cfs
Delta-Transfer Pipeline Capacity	None	180 cfs	None
Expanded Transfer Facility Pump Station Capacity	None	300 cfs	300 cfs
Expanded Transfer Facility Storage Reservoir Capacity	None	5 million gallons	5 million gallons
Neroly High Lift Pump Station Capacity	None	350 cfs	350 cfs
Pumping Plant #1 Capacity	200 cfs	350 cfs[2]	350 cfs[2]
Los Vaqueros Watershed Facilities			
Los Vaqueros Marina Complex	No change	Relocated upslope	No change
Los Vaqueros Watershed Trails	None	Expanded	None
Los Vaqueros Interpretive Center	No change	Improved	Improved
Los Vaqueros Watershed Office Barn	No change	Seismically upgraded and improved	Seismically upgraded and improved

Notes:

General: Local Agency Partners plan on constructing several projects related to the proposed Los Vaqueros Reservoir expansion. These include the Brentwood Pipeline, the EBMUD-CCWD Intertie Pump Station, the EBMUD Walnut Creek Pumping Plant Variable Frequency Drives, the EBMUD Mokelumne Aqueduct Relining, and the East Contra Costa Irrigation District Intertie. These associated local projects are not part of the Federal feasibility study but are important related improvements to Local Agency Partners' infrastructure that would be constructed in conjunction with this project.

[1] Alternatives 1A, 1B, and 2A differ from one another only in the proposed operational priorities of the facilities. Alternatives evaluated in the Investigation are refined versions of the alternatives evaluated in the 2010 Final EIS/EIR. Alternative 3 was rejected in the 2010 Final EIS/EIR and was not evaluated further in Phase 2 of the Investigation.

[2] Permitted capacity is 350 cfs as defined in the Supplement to the Final EIS/EIR. 300 cfs is the capacity modeled and designed under the Feasibility Study to reflect the current operation requirements. Capacity requires improvements to the existing Rock Slough Fish Screen's rake cleaning system, included under Pumping Plant #1 improvements in this Feasibility Report.

Key:
CCWD = Contra Costa Water District
cfs = cubic feet per second
EBMUD = East Bay Municipal Utility District
EIS = Environmental Impact Statement
EIR = Environmental Impact Report
Investigation = Los Vaqueros Reservoir Expansion Investigation
TAF = thousand acre-feet

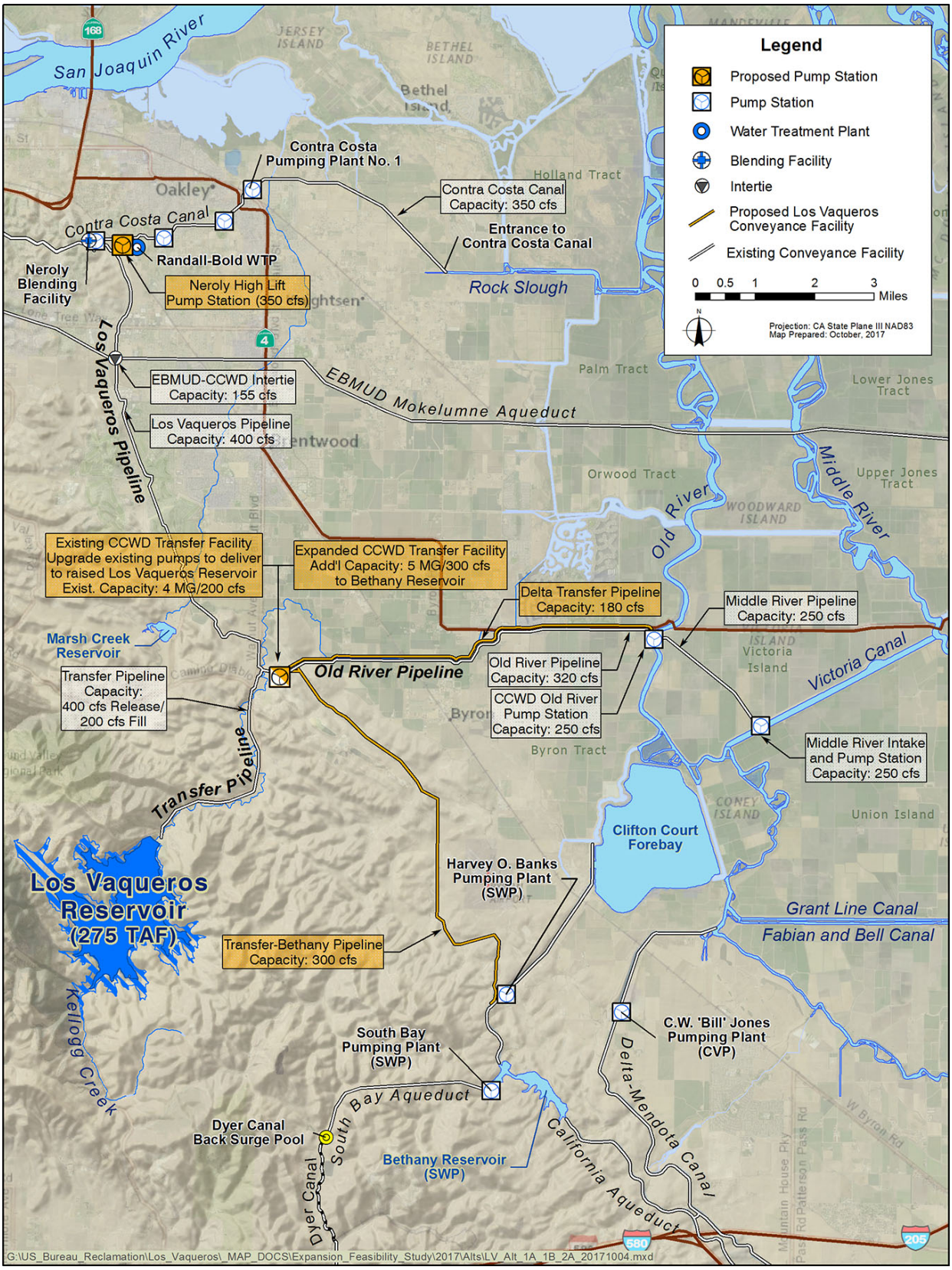

Figure 1-1. Major Components of Alternatives 1A, 1B, and 2A

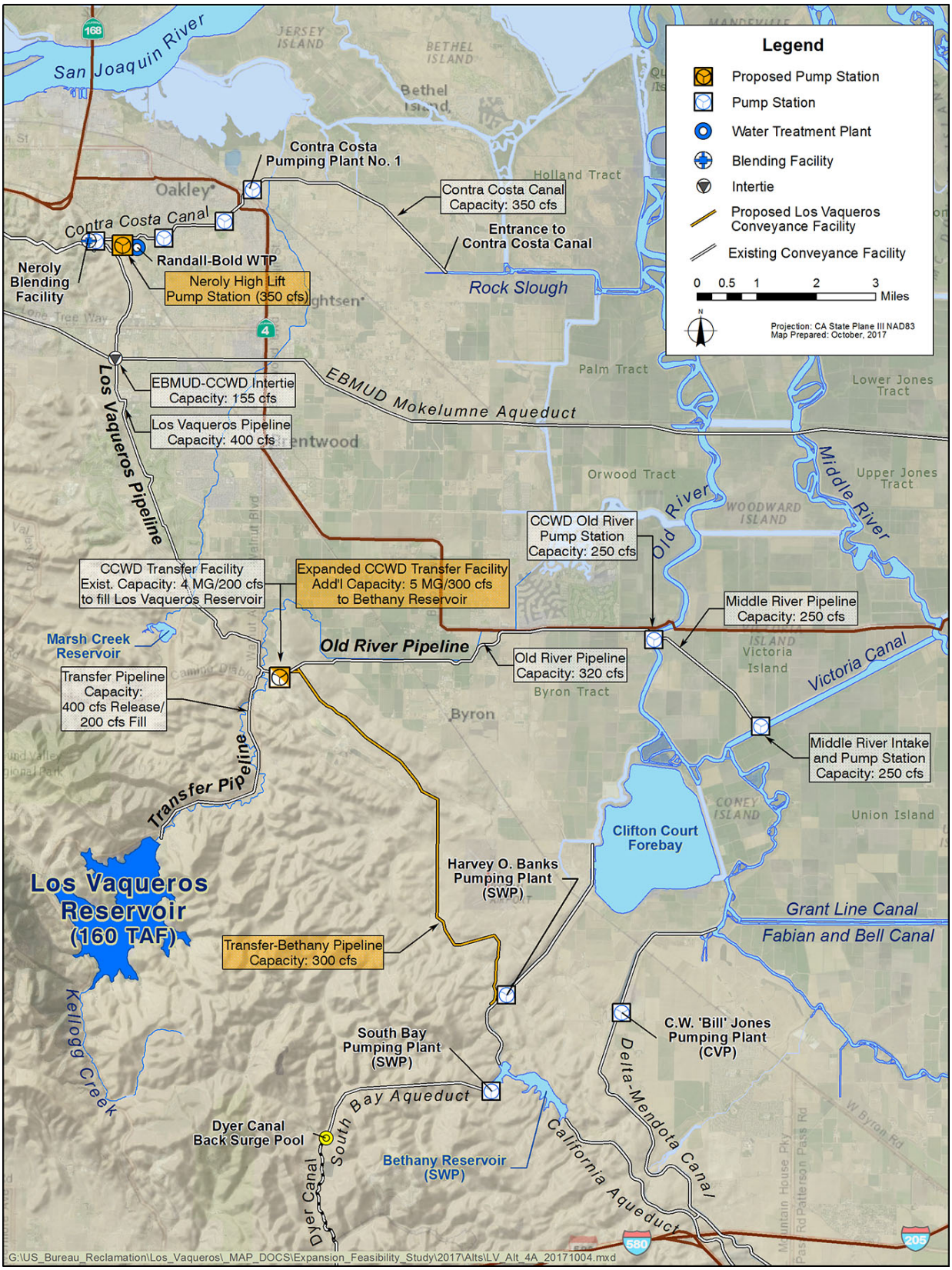

Figure 1-2. Major Components of Alternative 4A

Operational Priorities

All alternative plans would utilize CCWD's existing Delta intakes at Old River, Middle River, and Rock Slough to divert water from the Delta. In addition, CCWD, Local Agency Partners, and the Refuge Water Supply Program might (subject to obtaining the appropriate water rights modifications and other approvals) receive water diverted from the Freeport Intake on the Sacramento River via the EBMUD-CCWD Intertie. Water diverted at these four locations could be directly delivered to beneficiaries or stored in Los Vaqueros Reservoir for later use.

The Refuges would receive water delivered through the Transfer-Bethany Pipeline to the California Aqueduct. The delivered water would be either direct diversions or rediversions from the Delta, or releases from Los Vaqueros Reservoir storage, depending on the alternative plan. The water would be Delta Surplus Water[2] or water otherwise made available from CCWD or Local Agency Partner or the RWSP. The alternatives would not change the manner in which water is conveyed by the RWSP to the various Refuges.

Similarly, water delivered to Local Agency Partners would be direct diversions or rediversions from the Delta, or releases from Los Vaqueros Reservoir storage. The water would be Delta Surplus Water or water available from Local Agency Partner water rights and contracts. In addition, some alternatives include dedicated storage space in Los Vaqueros Reservoir for Local Agency Partner storage and withdrawal, including reserved drought and/or non-drought emergency storage.

All operations were formulated to meet the project objectives while minimizing impacts and avoiding harm to other water users. The operational differences and priorities for the Action Alternatives is summarized below.

- Alternative 1A is operated to maximize deliveries for water supply reliability to the Local Agency Partners, including drought and emergency supply reliability. The operations first seek to deliver Delta surplus and/or Local Agency Partner's water rights and contract supplies to meet current demands. Any available supplies above current demands are stored in Los Vaquero Reservoir for later use, including dry years. If additional system capacity is available after these operations, CVPIA Level 2 Refuge water is wheeled through CCWD facilities instead of C.W. Jones Pumping Plant, freeing up capacity to increase CVP SOD deliveries at C.W. Jones Pumping Plant. Last, remaining CCWD system capacity is then used to deliver water supplies south of the Delta to help meet Incremental Level 4 Refuge contract allocations. These operational priorities result in the highest water deliveries to Local Agency Partners and CVP contractors (via wheeling), and the lowest deliveries to Refuges, compared with the other alternative plans.

- Alternative 1B includes the same physical facilities as Alternative 1A but is operated to provide roughly equal water deliveries (long-term) to both Local Agency Partners and Refuges, thereby balancing the Investigation's two primary objectives. Level 2 Refuge supplies (which result in increased CVP operational flexibility) are only wheeled through

[2] "Delta Surplus Water" is water diverted when the Delta is in excess conditions as defined in the SWRCB's Decision 1641.

CCWD facilities once the operational priorities for Local Agency Partners and Refuges are met. In addition, SOD CVP contractor deliveries that would otherwise by limited by Delta conveyance constraints are rescheduled using Los Vaqueros Reservoir expanded storage, resulting in additional CVP operational flexibility. These operational priorities result in higher benefits to Local Agency Partners (M&I and agricultural water supplies), Refuges, and CVP contractors, compared with the other alternative plans.

- Alternative 2A includes the same facilities as Alternatives 1A and 1B but is operated to maximize potential Incremental Level 4 deliveries to the Refuges. Benefits to Refuges occur from both direct deliveries conveyed via CCWD facilities, as well as water supplies stored in Los Vaqueros Reservoir. These operational priorities result in the highest benefits to Refuges, compared with the other alternative plans.

- Alternative 4A uses similar operational priorities as Alternative 1B. Alternative 4A is formulated to maximize potential project deliveries to both the Local Agency Partners and Refuges, but without the benefit of expanded storage in Los Vaqueros Reservoir. These operations result in relatively low benefits to Local Agency Partners, Refuges, and CVP contractors, compared with the other alternative plans.

Organization of This Appendix

This appendix is organized as follows:

- **Chapter 1**, **Introduction**, provides an overview of the Investigation project and alternatives under consideration.

- **Chapter 2, Summary of Previous Climate Change Studies in the Study Area**, presents information on projected climate change and relevant research on climate change implications for California water resources, particularly those for Los Vaqueros Reservoir Study Area.

- **Chapter 3, Potential to Achieve Objectives under Future Climate Change,** presents modeling results comparing the performance of the project alternatives under future climate change.

- **Chapter 4, References**, lists the sources used in preparing this technical appendix.

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Chapter 2 Summary of Previous Climate Change Studies in the Study Area

This chapter provides a summary of climate projections and relevant research on climate change implications for California water resources, including a summary of key findings on the sensitivity of California water resources to climate changes, particularly those related to the Study Area of the Investigation.

Study Area Setting

The study area for the Investigation includes the Los Vaqueros Reservoir watershed and associated facilities, central and south Delta, service areas of potential Bay Area partner water agencies, as well as the operational areas of the potential affected programs, such as the Refuges in the Central Valley. These areas are heavily influenced by or located in two of the Central Valley's three hydrological regions: the Sacramento basin and the San Joaquin basin. Both the Sacramento and San Joaquin rivers flow into the Delta, which drains an area of approximately 59,000 square miles. However, the third region, the Tulare Lake basin, containing 17,050 square miles, is generally internally drained with no exports and has little impact on the Investigation.

The Central Valley is a large south trending alluvial basin extending over 450 miles from the southern Cascade Mountains near the City of Redding to the Tehachapi Mountains south of the City of Bakersfield. The basin is about 40 to 60 miles wide, bounded by the Coast Range to the west and the Sierra Nevada to the east. The Delta, approximately midway, drains the Sacramento Valley in the northern half of the Central Valley and the San Joaquin Valley in the southern half of the Central Valley.

The Sacramento River, north of the Delta, is the largest river in California with a historical mean annual flow of 18 million acre-feet (MAF). It drains an area of about 27,000 square miles and flows south to the Delta. The Sacramento River begins in Northern California where it is joined by the Pit River above Shasta Dam, a Reclamation facility. Below Shasta Dam, transmountain diversions from the Trinity River, a tributary to the Klamath River, along with many small- and moderate sized tributaries join the river as it flows south through the Sacramento Valley. Major tributaries join the river out of the Sierra Nevada range, including the Feather, Yuba, and American Rivers. Major facilities on these rivers include Oroville Dam operated by the State SWP on the Feather River and Folsom Dam operated by Reclamation on the American River. The Sacramento River flows 445 miles to the Delta.

The San Joaquin River, south of the Delta, is the second largest river in California with a historical mean annual flow of 6 MAF. It drains an area of about 32,000 square miles and flows north to the Delta. The San Joaquin originates in the high Sierra Nevada Mountains in east-central California.

The river initially flows westwards into the Central Valley before reaching Friant Dam, a Reclamation facility, before entering the San Joaquin Valley. Diversions from Friant Dam enter the Tulare Lakes basin. Before implementation of the San Joaquin Restoration Program, flows below the dam were minimal except during flood conditions. Releases from the dam flow initially westward until reaching the Chowchilla Bypass (a constructed flood control facility) or the Mendota Pool (a managed irrigation water control facility). From there, the river turns northward and begins receiving return flows from agricultural and wildlife refuge areas as well as inflows from several eastside tributaries including the Merced, Stanislaus, Calaveras, and Mokelumne Rivers, each of which have major dams that store water and regulate flows. The San Joaquin flows 366 miles to the Delta, joining with the Sacramento River near Suisun Bay in the Delta.

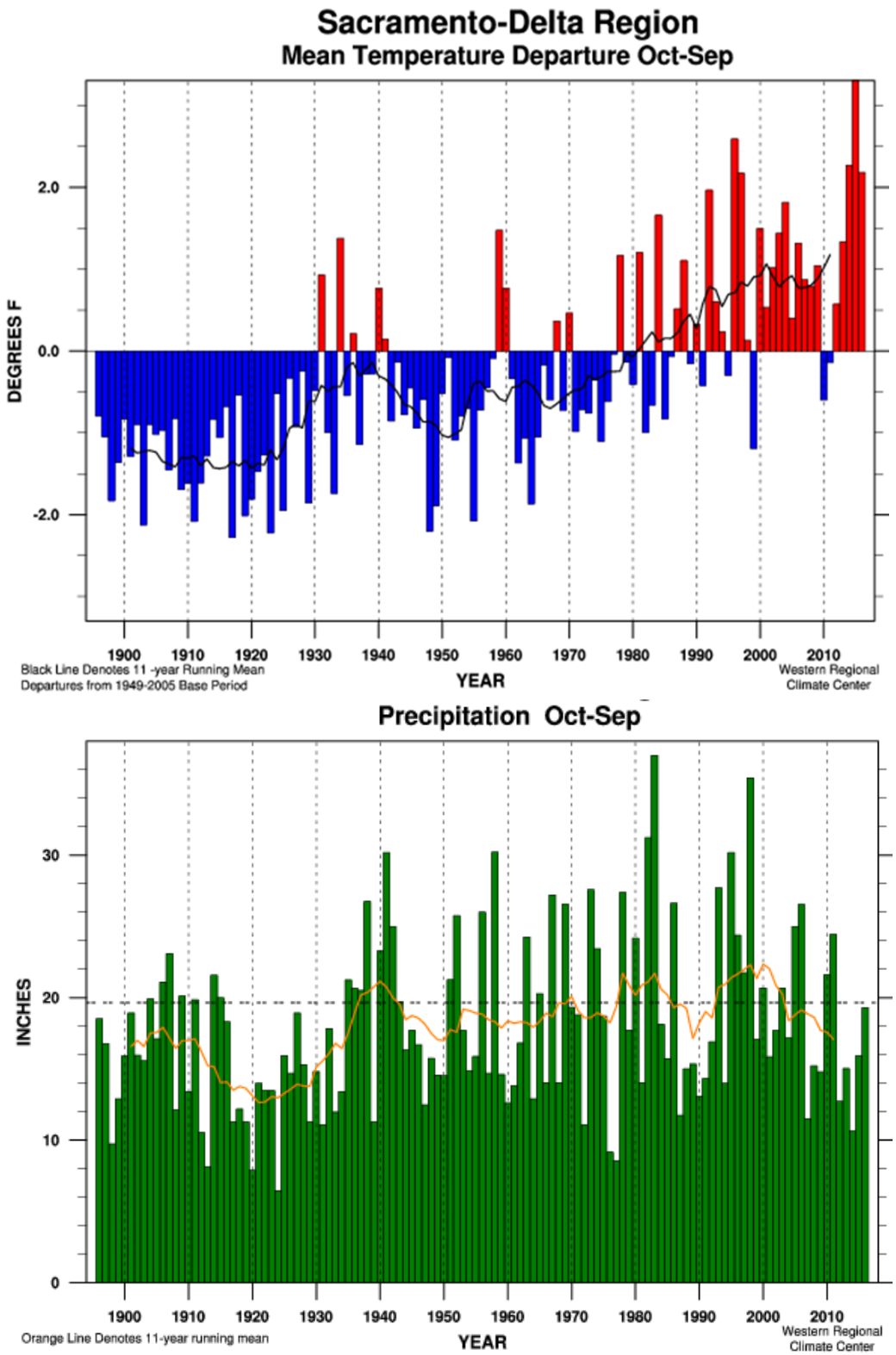
Reclamation's major role in the Central Valley resulted in the Central Valley Project which includes 20 dams, 11 power plants, and over 500 miles of canals. This multipurpose project provides, on average, 310 TAF per year of water for urban users and 5.4 MAF of water per year to irrigate approximately 3 million acres of land in the Sacramento, San Joaquin, and Tulare Lake basins. Additional flows also serve environmental purposes according to the 1992 Central Valley Project Improvement Act.

Historical Climate

The historical climate of the Central Valley is characterized by hot, dry summers and cool, damp winters. The northern Sacramento Valley of the Central Valley has a hot Mediterranean climate and receives greater precipitation, while the southern San Joaquin Valley is a drier, desert region. The majority of precipitation occurs from mid-autumn to mid-spring. Summer daytime temperatures can reach 90 degrees Fahrenheit (°F), with occasional heat waves resulting in temperatures over 110°F. In winter, temperatures below freezing may occur, but snow is rare in the valley lowlands. The Central Valley typically has a frost-free growing season ranging from 225 to 300 days. During the growing season, relative humidity is characteristically low; in the winter, values are usually moderate to high, and ground fog may form.

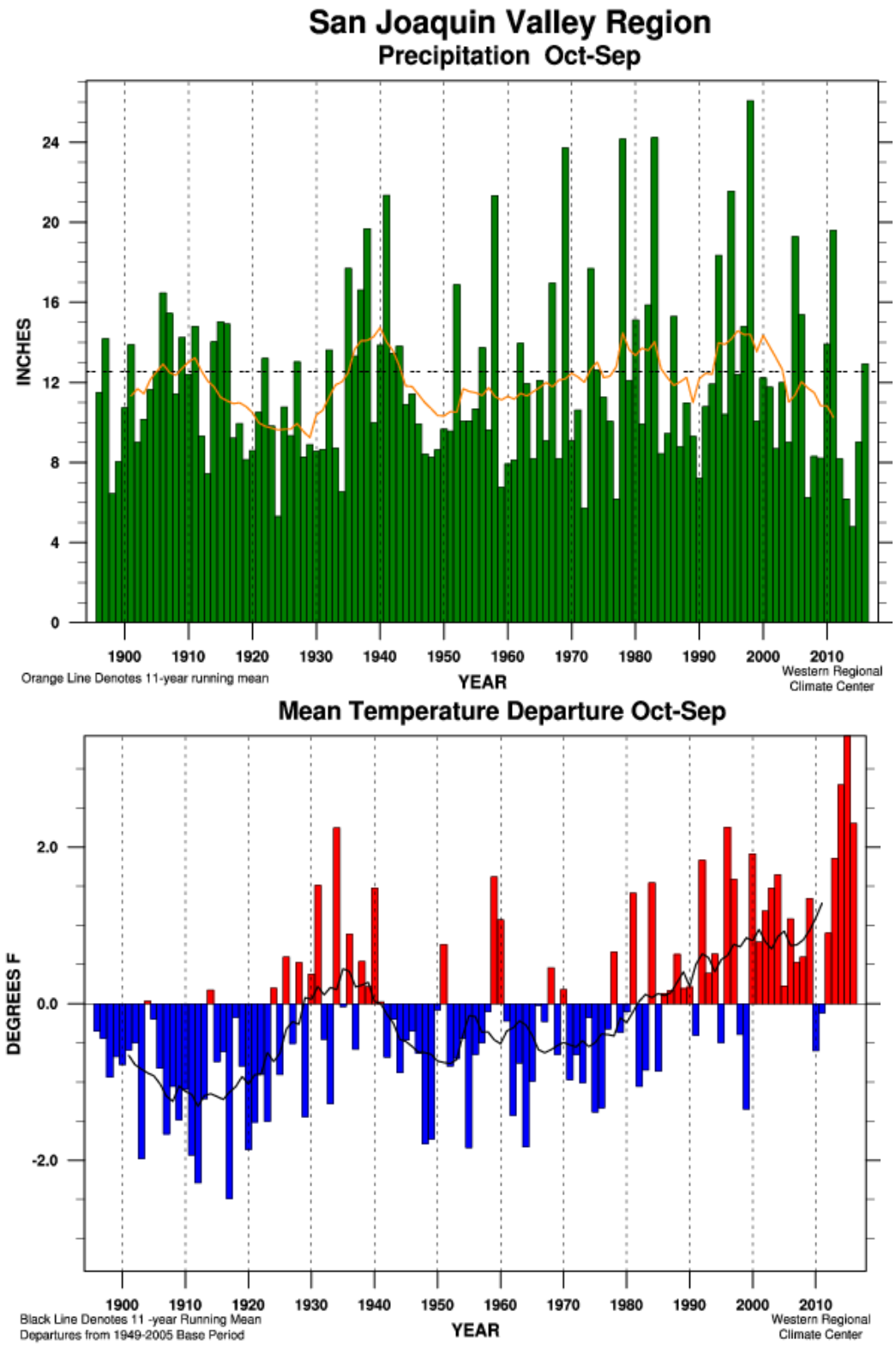
Over the course of the 20th century, warming has been prevalent over the Sacramento and San Joaquin River basins. The Sacramento and San Joaquin basins average mean-annual temperature has increased respectively by approximately 2.2°F and 1.7°F from 1895-2016, based on an 11-year running average (Figures 2-1 and 2-2).

Warming has not occurred steadily throughout the 20th century. Increases in air temperature occurred primarily between 1910 and 1935. Subsequently, renewed warming began again in the mid-1970's and has continued into the 21st century as seen in Figure 2-1 for the Sacramento Basin and Figure 2-2 for the San Joaquin Basin. Similar results have been found in other studies. Cayan et al. (2001) reported that Western United States spring temperatures have increased 1 to 3 degrees Celsius (°C) (1.8 to 5.4°F) since the 1970's. Dettinger and Cayan (1995) observed increased winter temperature trends in central California averaged about 0.5°C (0.9°F) per decade.



(Source: Western Regional Climate Center)

Figure 2-1. Observed Annual and 11-year Running Means of Mean Temperature Departure from 60.4°F and Precipitation, Averaged over the Sacramento-Delta Region



(Source: Western Regional Climate Center)

Figure 2-2. Observed Annual and 11-year Running Means of Mean Temperature Departure from 60.4°F and Precipitation, Averaged over the San Joaquin Region

Although the Sacramento basin has shown a slight increase in total precipitation over the 20th century, no such trend is evident in the San Joaquin basin. Other studies also show that precipitation trends are not as clear as temperature trends. Regonda et al. (2005) reported increased winter precipitation trends from 1950 to 1999 at many Western United States locations, including several in California's Sierra Nevada; but a consistent region-wide trend was not apparent. However, the variability in annual precipitation appears to have increased, as can be seen by comparing the range of differences in high and low values in Figures 2-1 and 2-2. These extremes have been especially frequent since the mid-1970s in both the Sacramento and San Joaquin basins.

The *Indicators of Climate Change in California* report produced by the California Environmental Protection Agency (CalEPA) (2013) combines scientific data on a series of indicators for climate change. The report provides a brief summary of key indicators of climate change in California including annual air temperature, extreme heat events, precipitation, annual Sierra Nevada snowmelt runoff, snow-water content, and sea level rise.

Since 1985, the CalEPA (2013) reports that annual average air temperatures in California have increased by 1.5°F. Most regions have experienced accelerated warming since the 1975. In the San Joaquin Valley region, the maximum temperature has not increased, although the minimum has increased by about 2.5°F and the average temperature by 1°F. However, the Sacramento Region has experienced stronger warmer trends. The maximum temperatures have increased by 1°F, the minimum temperatures by 3.5°F, and the average temperatures by 2°F. In addition, the number of nighttime extreme heat events has increased since 1950 in the Central Valley. For precipitation, the report agrees that although high variability is observed, no apparent overall trend can be observed (CalEPA 2013). The Sierra Nevada, from which many of the Sacramento and San Joaquin tributaries originate, has had both the wettest and driest winters on record in the past 35 years. The Sierra Nevada region receives an average of 40 inches per year of precipitation. The annual precipitation in California overall has ranged from 10.0 inches in 1924 to 39.6 inches in 1983, with an average of about 22 inches between 1895 and 2013 (CalEPA 2013).

Historical Hydrology

Streamflow in the Sacramento River and San Joaquin River basins varies both temporally and geographically. During any particular year, some portions of the basin may experience relatively greater runoff conditions while other areas experience relatively less runoff (e.g., more abundant runoff in the northern Sacramento Valley versus relatively drier conditions in southern San Joaquin Valley). On a monthly to seasonal basis, runoff is generally greater during the winter to early summer months, with winter runoff generally originating from rainfall-runoff events and spring to early summer runoff generally supported by snowmelt from the Cascade Mountains and Sierra Nevada.

The historical changes in climate described above have resulted in several important effects on Sacramento and San Joaquin basin hydrology. Among these is a change in the seasonal timing of runoff. In the Sacramento River basin, a decrease of about 10 percent in the fraction of total runoff occurring between April and July has been observed over the course of the 20th century (Roos 1991). Similar results were obtained from analyses of the combined basin runoffs for both the Sacramento and San Joaquin basins by Dettinger and Cayan (1995).

Along with the declining spring runoff, corresponding increases in winter runoff have been observed. Analysis of data for 18 Sierra Nevada river basins found earlier runoff trends (Peterson et al. 2008). Of the potential climatic factors that could produce such changes, analyses indicated that increasing spring temperatures rather than increased winter precipitation was the primary cause of the observed trends (Cayan 2001). Studies by these researchers and others showed that the magnitude of the decreases in April through July runoff was correlated with the altitude of the basin watershed. High altitude basins like the San Joaquin exhibited less decrease in spring runoff than lower elevation watersheds such as the Sacramento. However, it is noted that the appearance of runoff trends in the basins depends on location and period of record being assessed. For example, runoff trends were evaluated for this report during the last half of the 20th century; and although similar trend directions were found, they were found to be statistically weak.

However, possibly due to annual precipitation remaining relatively unchanged, no increases were observed in the mean annual runoff of the Sacramento and San Joaquin rivers (Dettinger and Cayan 1995). Other studies of the magnitude of spring snowpack changes during the 20th century found that snowpack as measured by April 1st Snow Water Equivalent showed a decreasing trend in the latter half of the 20th century (Mote 2005). Coincident with these trends, reduced snowpack and snowfall ratios were indicated by analyses Snow Water Equivalent measurements made from 1948 through 2001 at 173 Western United States stations (Knowles et al. 2007). Regonda et al. (2005) reported decreasing spring Snow Water Equivalent trends in 50 percent of Western United States locations evaluated. However, within the State, according to CalEPA (2013), the average total water stored in the snowpack on April 1 of each year has stayed roughly the same in recent decades for the State as a whole, but has declined in the northern Sierra Nevada and increased in the southern Sierra Nevada.

Historical Sea Level Rise

Sea level change also represents an important factor in assessing the effect of climate on California's water resources because of its effect on water quality in the Sacramento-San Joaquin Delta. Higher mean sea levels are associated with increasing salinity in the Delta, which influences the suitability of its water for agricultural, urban, and environmental uses. The rise in global sea level is attributed to thermal expansion of ocean water and the melting of polar ice sheets and mountain glaciers (CalEPA 2013). The global rate of mean sea level change was estimated by Intergovernmental Panel on Climate Change (2007) to be 1.8 +/- 0.5 millimeters per year (mm/yr) (0.07 +/- 0.02 inches per year (in/yr)) from 1961–2003 and 3.1 +/- 0.7 mm/yr (0.12 +/0.03 in/yr) during 1993–2003. Across California, sea levels have risen by an average of 7 inches in the same time period along the California Coast. Levels at the Golden Gate in San Francisco and at La Jolla near San Diego have increased by about 8 and 6 inches, respectively (CalEPA 2013). Anderson et al. (2008) observed an average rise of 2 mm/yr (0.08 in/yr) in mean sea level in San Francisco Bay during the 20th century. These rates of sea level rise appear to be accelerating based on tidal gauges and remote sensing measurements (Church and White 2006; Beckley et al. 2007). Total dissolved solids, one measurement of salinity, in drinking water taken from the Delta ranges from approximately 150 milligrams per liter (mg/L) to 300 mg/L, but can reach 500 mg/L (CALFED 2007b).

Projections of Future Changes in Climate and Hydrology

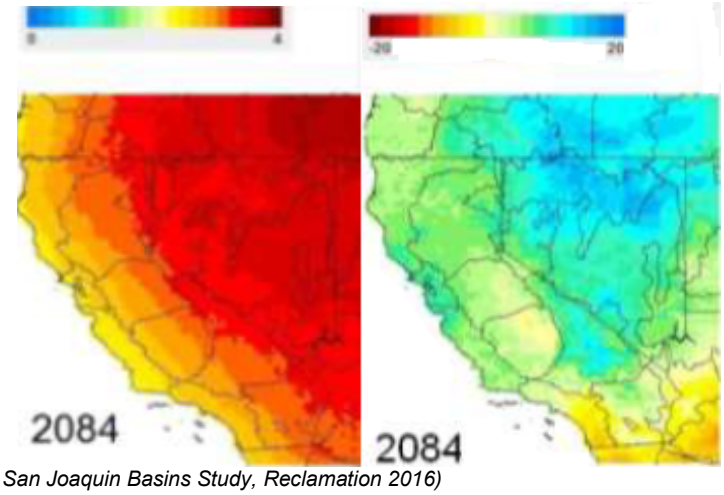
This section summarizes results from studies focused on future climate and hydrologic conditions within the Sacramento and San Joaquin River basins. It provides a brief overview of temperature and precipitation projections in California and changes to runoff in the Central Valley as well as a description of expected sea level rise in the Delta.

Projections of Future Temperature & Precipitation

Future changes in Central Valley climate and hydrology have been the subject of numerous studies. For the Central Valley watersheds, Moser et al (2009) reports on future climate possibilities over California and suggest that warmer temperatures are expected during the 21st century, with an end-of-century increase of 3°F to 10.5°F. For mean annual precipitation in northern California, the study indicates a generally decreasing trend of between 10 percent and 15 percent by the end of the century.

Reclamation's 2016 *Sacramento and San Joaquin Rivers Basin Study* (Basin Study) provides temperature and precipitation projections under climate change, using new climate change projections from the Coupled Model Intercomparison Project Phase 5. The central tendency climate scenario used in this study projects steadily increasing temperatures. Throughout the Sacramento and San Joaquin basins, temperatures are projected to increase steadily during the 21st century by 1°C (1.6 °F) every 30 years, to reach an increase of almost 3°C (4.8°F) by the late (2084) 21st century. The study finds that trends in precipitation are not as apparent, due high levels of variability. Trends show slight increases in the northern Sacramento Valley (2 percent by mid-century (2055)) and in the San Joaquin Basin (1 percent by mid-century (2055)).

The projections also suggest that annual precipitation in the Sacramento and San Joaquin basins should remain quite variable over the next century. Despite these statements about the Central Tendency scenario examined in the Basin Study, significant uncertainty exists among the climate projections regarding change in annual precipitation over the region.



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-3. Projected Median Temperature (°C) and Precipitation (%) Changes at the End of 21st Century (2084) Relative to Historic Conditions (1981-2010)

Projections of Future Hydrology and Runoff

The effects of projected changes in future climate were assessed by Maurer (2007) for four river basins in the western Sierra Nevada contributing to runoff in the Central Valley. These results indicate a tendency towards increased winter precipitation; this was quite variable among the models, while temperature increases and associated Snow Water Equivalent projections were more consistent. The effect of increased temperature was shown by Kapnick and Hall (2009) to result in a shift in the date of peak of snowpack accumulation from 4 and 14 days earlier in the winter season by the end of the century. Null et al. (2010) reported on climate change impacts for 15 western-slope watersheds in the Sierra Nevada under warming scenarios of 2°C, 4°C, and 6°C increase in mean-annual air temperature relative to historical conditions. Under these scenarios, total runoff decreased; earlier runoff was projected in all watersheds relative to increasing temperature scenarios; and decreased runoff was most severe in the northern part of the Central Valley. This study also indicated that the high elevation southern-central region was more susceptible to earlier runoff, and the central region was more vulnerable to longer low flow periods.

The more recent Basin Study, which considered less extreme warming scenarios, also found a considerable decline in snowpack. April 1st Snow Water Equivalent decreased by 10 percent at higher elevations and by 70 percent at lower elevations in the Sacramento Valley, with similar effects in the San Joaquin basin. The Basin Study predicts overall runoff will be reduced due to 5 to 10 percent decreases in runoff from the northern and central Sierra Nevada, despite slight increases in the Coast Ranges. In addition, a seasonal shift in runoff will occur from the spring months to the late fall and winter months (Reclamation 2016).

Projections of Future Sea Level Rise

Sea level changes have also been projected to occur during the 21st century due to increasing air temperatures causing thermal expansion of the oceans and additional melting of the land-based Greenland and Antarctic ice sheets (IPCC 2007). A Working Group of the California Ocean Protection Council Science Advisory Team have estimated projections of sea level rise, accompanied by their relative likelihood under several emission scenarios. At the Golden Gate, there exists a 67 percent probability of sea level rise between 12 inches and 28.8 inches under a low-emissions pathway (Representative Climate Pathway 2.6) and between 19.2 to 40.8 inches under a high-emissions pathway (Representative Climate Pathway 8.5) by the end of the century. Approximately 10.8 inches could occur in the next 50 years under both scenarios (Griggs et al. 2017). The CALFED Independent Science Board estimated a range of sea level rise at Golden Gate of 19 inches to 55 inches by the end of the century, 6 inches of which could occur in the next 50 years (CALFED 2007a). DWR used 12 future climate projections to estimate future sea levels. Their estimates indicate sea level rise by mid-century ranges from 9.6 inches to 12 inches with an uncertainty range spanning from 6 inches to 16 inches. By the end of the century, sea level was projected to rise between 21 inches and 37 inches, with an uncertainty range spanning from 12 inches to 47 inches. National Research Council (NRC) projections, which are given for 2030, 2050, and 2100 with upper and lower bounds, of sea level rise for San Francisco Bay by 2100 is projected to range from 42 to 166 centimeters (16.5 to 65.4 inches), with a mean of 90 centimeters (35.4 inches).

Continuing sea level rise will lead to increased salinity levels in Delta water according to studies by the CALFED Science Program, NRC, and others (Healey 2007, NRC 2012). These studies indicate that as sea level rise progresses during the century, the hydrodynamics of the San Francisco Bay–Sacramento-San Joaquin Delta estuary will change causing the salinity of water in the Delta estuary to increase. Although these increases in sea level have a reasonable potential to inundate many Delta islands, such large-scale levee failures are not modelled since this would require difficult assumptions on levee hardening adaptations. Even without modeling levee failures that would pull in additional saline water into the Delta, all of the climate scenarios explored in the Basin Study showed increases in Delta salinity levels from a low 2 percent increase in a Warm-Wet scenario to a high of 38 percent in a hot-dry scenario relative to a Reference-No-Climate-Change scenario.

Analytical Approaches & Tools for Assessing Effects of Future Climate Change in the Central Valley

Two sets of approaches and tools, described in this section, are available to assess the effects of projected future changes in climate on water management in the Central Valley.

Transient-Change Climate Analysis Approach

The transient-change approach simulates the gradual changes in climate conditions and other factors over time. The Basin Study builds on this approach, first developed in the Central Valley Project Integrated Resource Plan and the Sacramento and San Joaquin Basin's Climate Risk Assessment Report (Reclamation 2014) for assessing effects on climate change in the Central Valley. These studies have developed an integrated suite of tools that uses the CalLite-CV model and a series of scenarios to represent uncertainties in climate change and socioeconomic growth. In the Basin Study, the model is used to represent operations for the CVP/SWP system using 18 scenarios that combine 6 ensemble climate scenarios and 3 socioeconomic growth scenarios. Each scenario was analyzed over the period from October 2014 to September 2099 using a transient approach where factors gradually changed as the simulation moved through time.

The first ensemble climate scenario represents a reference, projecting historical conditions into simulations of future conditions-- the Reference-No-Climate-Change scenario. The other five ensemble climate scenarios were developed using a quantile mapping technique, to adjust the historical observed climate records by the climate shifts projected to occur in the future. Additional climate scenarios were also included in the study's analysis from the DWR Climate Change Technical Advisory Group (DWR CCTAG). Further information can be found in Appendix 3A of the Basin Study.

To develop transient projections of sea level rise, the Basin Study assumed a gradual increase in sea level rise correlated with increasing temperatures. An artificial neural network embedded in the CalLite-CV model was used to simulate salinity requirements and conditions in the Delta. This artificial neural network included adjustments to reflect changes in Delta conditions from sea level rise. To simulate the effects of the projected sea level rise on the Bay-Delta system, relationships between flow and salinity were developed and incorporated into the CalLite-CV model.

The transient climate projections were used in the Water Evaluation and Planning Model of the Central Valley (WEAP-CV) hydrologic and crop evapotranspiration and yield modeling. The WEAP-CV obtains the climate data at discrete nodes, including data on solar radiation, atmospheric humidity, wind speed, and carbon dioxide. The WEAP-CV provides simulated stream flows throughout the basins, along with information about groundwater pumping, local deliveries, local runoff, agricultural and urban return flows, water demands, and upper watershed runoff. The hydrologic process indicators of runoff, evapotranspiration, Snow Water Equivalent, and soil moisture were derived for future climate projections using WEAP-CV simulations under future climate conditions.

This information, along with water supply demands, regulatory requirements, local actions, and environmental flow enhancement actions, are included in CalLite-CV to determine project deliveries, river flows, reservoir storage, delta salinity, and ecosystem indicators under the climate change scenarios. The CalLite-CV model incorporates CVP/SWP system operations and supply/demand analysis. The results provided by the model include monthly flows in major Californian rivers, applied water demands, storage at major reservoirs, Delta salinity levels at Emmaton, Jersey Point, Rock Slough, and Vernalis, and CVP/SWP export pumping and Delta outflows– all under different climate change scenarios.

The entire process provides a baseline condition analysis which can be used to analyze the impacts of various actions on the system. The methods, tools, and assumptions used to develop the projections presented by Reclamation 2016 in the Basin Study are described in detail within appendices to the Technical Report.

Delta-Change Climate Analysis Approach

Unlike the transient-change approach, the delta-change approach evaluates the effects of future climate changes at pre-set points in the future. The "delta-change" from the baseline conditions reflects the potential effects of climate change. This approach, in comparison to the transient-change approach, may not capture important information about the timing of critical changes or effects. This approach does not include data on carbon dioxide, atmospheric humidity, wind speed, or solar radiation, which impacts its projections of crop yields and agricultural water demands. However, the delta-change approach is useful in conducting a comparative analysis of potential future actions.

The Investigation is pursuing State funding through the California Water Commission's (Commission) Water Storage Investment Program (WSIP), which is funded through California's Proposition 1 initiative. The WSIP developed analytical tools that use the delta-approach to analyze and compare proposed storage projects for funding. The Commission requires that applicants evaluate their storage project under two specific climate change scenarios for "near-future" (year 2030) and "far-future" (year 2070) conditions. CalSim II models were developed to provide the baseline conditions under climate change and to analyze, in detail, impacts of added reservoirs to the system. In addition, two more scenarios, a wetter, moderate warming (WMW) 2070 scenario and a drier, extreme warming (DEW) 2070 scenario were developed for the purpose of sensitivity analyses. The methods, tools, and assumptions used to develop the projections are documented in the *WSIP Technical Reference Document* (Commission 2016).

The Commission selected 20 climate model and Representative Climate Pathway combinations recommended by the DWR CCTAG as the most appropriate for California water resource planning. The 20-climate model and Representative Climate Pathway combinations were composed of 10 general circulation models run with two Representative Climate Pathways: one representing low-emissions (Representative Climate Pathway 4.5) and one representing high-emissions (Representative Climate Pathway 8.5). The results were downscaled to a 1/16th degree (approximately 3.75 miles) spatial resolution by Scripps Institution of Oceanography using localized constructed analog methods (Commission 2016).

All twenty scenarios are combined into single ensemble projections for 2030 and 2070. These ensembles are described by temperature and precipitation change with respect to a 1995 reference for each watershed. Temperature, precipitation, evaporation, and potential runoff is derived for California for a time series of 96 water years. This 96-year time series was developed by adjusting observed historical meteorology data from Livneh et al. (2013) over a period from 1915 to 2011 with the amount of climate change expected to occur at the reference climate period i.e., 2030 or 2070 (Commission 2016). The adjustment to develop the time series of temperature and precipitation was done through quantile mapping methods similar to those used by the Bureau. Starting with the climate model simulation results, statistical relationships, such as cumulative distribution functions, are developed and adjusted through quantile mapping. In addition, the Commission provides additional extreme bounding conditions from two of the twenty scenarios that can be used to test the resiliency of a project's benefit.

Sea level rise was selected to fit the NRC's projections, incorporating advice from the U.S. Army Corps of Engineers (USACE). The sea level rise amounts used in the Commission modeling are 15 centimeters by 2030 and 45 centimeters by 2070 at the Golden Gate Bridge in San Francisco. In addition, the Commission followed previous work by the Reclamation to develop an artificial neural network to incorporate the effects of sea level rise into the CalSim II. The artificial neural network simulates conditions provided by the DSM2 model, DWR's one-dimensional model for hydrodynamics and water quality. The DSM2 model provides flow-salinity relationships for the Delta. The Commission developed model conditions for 2030 and 2070.

The Variable Infiltration Capacity model is used by the Commission to simulate hydrologic indicators and process, including runoff, base flow, soil moisture, evapotranspiration, and snowmelt and depletion. The model provides results for grid cells in California for both 2030 and 2070 conditions. The model uses the adjusted temperature and precipitation time series data developed through quantile mapping. The Variable Infiltration Capacity model provides the stream flows, which after being adjusted as needed for model bias and impairments, are provided to the CalSim II model to simulate the effects of these 2030 or 2070 conditions or of unadjusted baseline conditions over the entire period for which the model is run.

The CalSim II model, developed by DWR and Reclamation, incorporates historical hydrology, regulatory requirements, and land use to simulate the CVP/SWP operations. Through a linked network of nodes and arcs, the model represents 24 surface water reservoirs and interconnected flow systems. The model's optimization techniques routes water based on the optimal decision sets for a given time based on priority inputs and system constraints. The model is run on monthly time

steps for water years 1922 to 2003. The historical stream flow data is updated with projected values and the developed artificial neural network provide the effects of sea level rise on Delta flow-salinity conditions. Changes in water and land use that have occurred or may occur under future conditions are also simulated. However, the model assumes a fixed level of development for projected conditions, wherein facilities, water supply contracts, and regulatory requirements remain constant as described in detail in the Commission's WSIP Technical Reference.

Demands, preprocessed to reflect changes in the level of development and hydrologic conditions in the scenarios, are input to the model on a monthly time step and include CVP, SWP, local project, and non-project demands. The CVP and SWP demands integrate water delivery rules, shortage criteria, water right priorities, refuge deliveries, and delivery contracts. Environmental requirements are also included as appropriate. Adjustment of demand due to climate change can be provided to the model.

This approach adopted by the Commission for evaluating climate change and the performance of the CVP and SWP differs from the approach used by the Basin Study (Reclamation 2016). The Basin Study evaluated three social-economic scenarios in combination with five future ensemble-informed climate scenarios and one scenario without climate change. One of the three social-economic scenarios was also analyzed in combination with twelve DWR CCTAG climate projections. The Commission created a single ensemble projection which indicated California could be warmer and wetter on average. Therefore, the Basin Study evaluated a wider range of climate projections than required by the Commission. The Commission provides two additional "extreme" scenarios to evaluate the wider range of projections.

Effects of Future Climate Change on the Central Valley Hydrology and Water Management

In this section, the results of the Commission modeling are compared to those of the 2016 Basin Study to provide context and highlight the potential uncertainty of the ensemble future projections developed by the Commission.

Summary of Basin Study Future Projections

The Basin Study (Reclamation 2016) performed a scenario-based CVP-Division specific supply and demand analysis incorporating the potential impacts of climate and socioeconomic changes and other factors through the year 2100. The study analyzed 18 scenarios based from three future socioeconomic conditions (current trends, slow growth, and expansive growth) in combination with six future climate conditions. The first climate condition, labelled Reference-No-Climate-Change (RF), reflects a reference climate with no climate change from historical conditions. Table 2-1 describes each of the following four climate conditions, which were selected to reflect the results of the 10 projections nearest each of 10th and 90th joint temperature-precipitation change percentiles in each of the quadrants: Warm-Dry (WD), Hot-Dry (HD), Hot-Wet (HW), and Warm-Wet (WW). The Central Tendency (CEN) scenario is bounded by the 25th and 75th percentile of joint temperature precipitation change.

Table 2-1. Climate Conditions with respect to Central Tendency

Temperature Change	Precipitation Change	
	Dry (D)	Wet (W)
Warm (W)	WD	WW
Hot (H)	HD	HW

During the modeling process, the Water Evaluation and Planning Model of the Central Valley was used to determine the hydrology (precipitation, inflows from local streams and upper watersheds, and local deliveries) as well as urban and agricultural demands based on each of the 18 socioeconomic-climate ensemble scenarios. These results were then used as inputs to the CalLite-CV model to simulate the expected CVP/SWP operations, including, but not limited to, reservoir storage, expected groundwater pumping, CVP/SWP/Non-Project deliveries, and urban and agricultural consumptive use.

The results of the Basin Study included impacts of climate change on water deliveries, water quality, hydropower, flood control, recreation, and ecological resources. These resource categories were represented through indicators, including end-of-September storage, CVP/SWP exports, delta salinity, end-of-May storage, CVP net generation of hydropower, and reservoir flood control.

Runoff and Hydrology

The Basin Study analyzed average annual streamflows for the Sacramento River System, the Eastside Streams and Delta, and the San Joaquin River System as well as average monthly runoff into major CVP/SWP reservoirs. These changes were computed over four periods: 2015-2039, 2040-2069, 2070-2099, and 2015-2099.

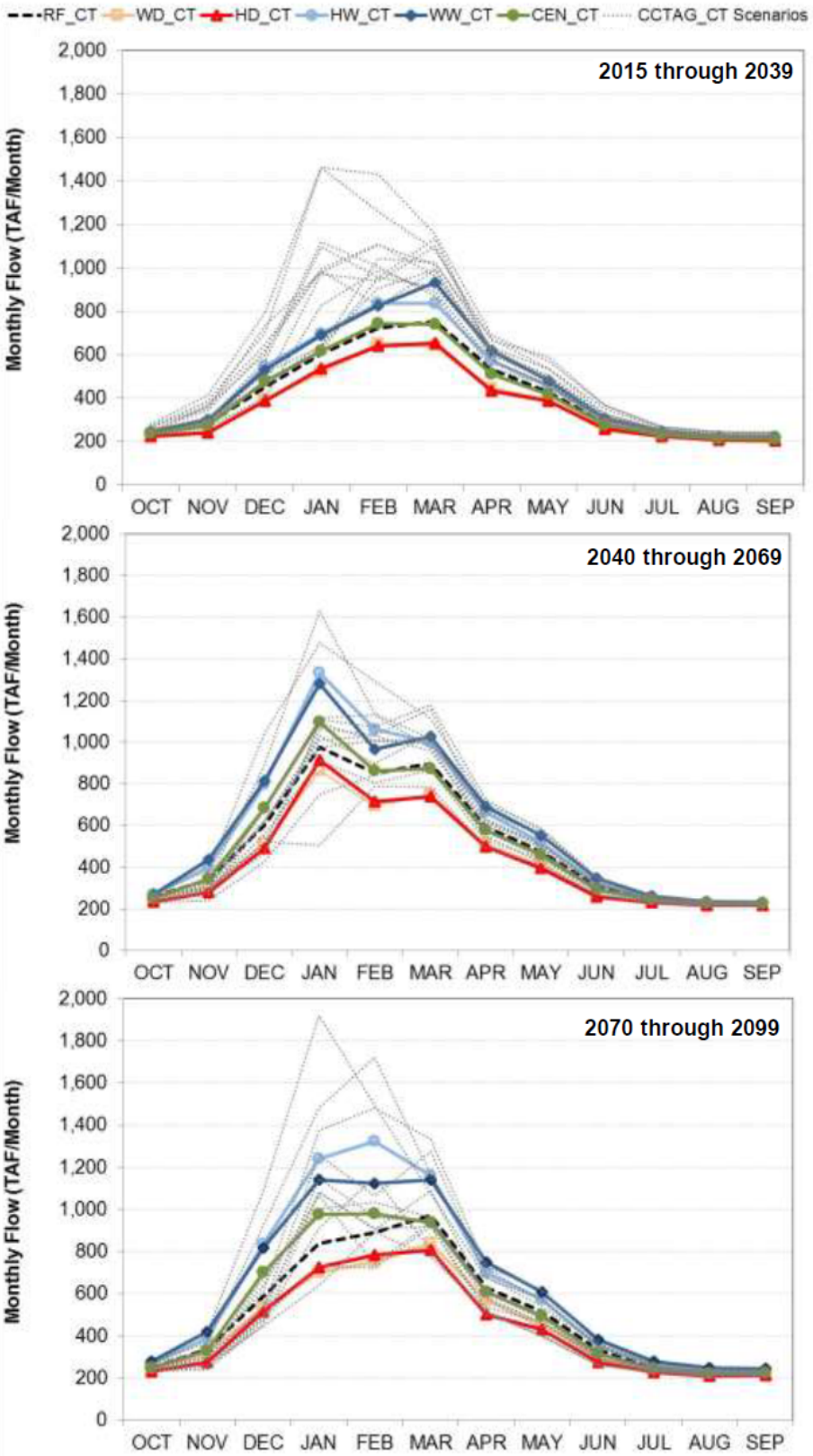
Table 2-2 shows the average annual runoff in the Sacramento River System, the Eastside Streams and Delta, and the San Joaquin River System for each of the ensemble climate scenarios under the current trends socioeconomic scenario. Under the reference climate scenario, average annual runoff was about 21.6 million acre-feet per year (MAF/yr) in the Sacramento River system, 0.9 MAF/yr in the East Side streams and the Delta, and 6.4 MAF/yr in the San Joaquin River system. In the Central Tendency climate scenario, average annual runoff in each region was within a few percentage points of the reference scenario. However, the dry climate scenarios, HD and WD, had average annual runoff over the 2015-2099 period that was substantially lower than the RF scenario (ranging from a-15.5 to a -26.6 percent change), and the wet climate scenarios, HW and WW, had average runoff over the 2015-2099 period that was substantially higher than the RF scenario (ranging from a 25.6 to a 47.9 percent change). The changes in each climate scenario were generally stronger in the later time periods reflecting the nature of transient climate change projections.

Table 2-2. Summary of Annual Streamflow (TAF/year) and Changes (%) in the Sacramento River System, Eastside Streams and Delta, and San Joaquin River System for the Ensemble Climate Scenarios under the Current Trends Socioeconomic Scenario

Period	Reference	Warm-Dry	Hot-Dry	Hot-Wet	Warm-Wet	Central
Sacramento River System						
2015-2039	18,535	-13.8	-13.7	15.2	18.9	-0.3
2040-2069	22,617	-16.4	-16.7	26.4	26.2	3.1
2070-2099	23,277	-15.8	-16.9	32.3	29.6	4.9
2015-2099	21,649	-15.5	-16.0	25.8	25.6	2.9
Eastside Streams and Delta						
2015-2039	789	-23.8	-23.6	32.8	28.7	-1.7
2040-2069	920	-27.4	-25.5	42.3	47.9	2.6
2070-2099	1,005	-26.3	-29.6	53.5	60.3	6.0
2015-2099	911	-26.0	-26.6	44.2	47.9	2.8
San Joaquin River System						
2015-2039	5,883	-14.7	-15.3	21.4	19.7	0.1
2040-2069	6,471	-23.1	-25.8	22.1	28.2	-0.9
2070-2099	6,700	-21.3	-25.4	35.0	38.8	1.4
2015-2099	6,379	-20.2	-22.8	26.7	29.8	0.2

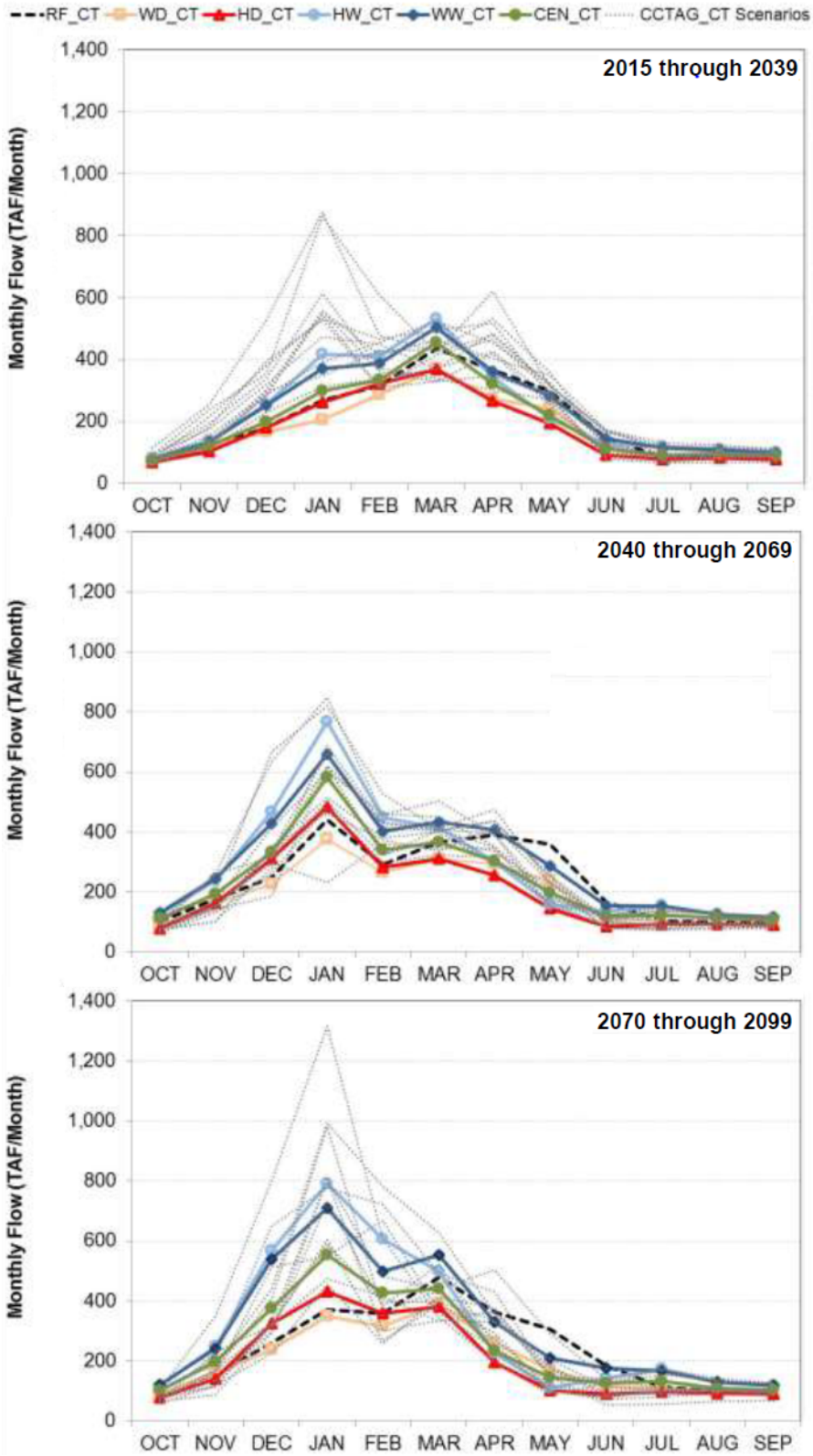
Source: Sacramento and San Joaquin Basins Study, Reclamation 2016
Key:
Delta = Sacramento-San Joaquin Delta
TAF = thousand acre-feet

Figures 2-4 through 2-8 show the impacts of seasonal runoff shifts affecting inflow into Lake Shasta, Folsom Lake, Lake Oroville, New Melones Lake, and Millerton Lake (Friant Reservoir). Each basin has a different monthly pattern reflecting the difference in hydroclimate and terrestrial conditions within the basin. In each basin, the climate scenarios exhibited a shift in runoff from the spring months to the winter months due to higher winter temperatures. This seasonal shift is greater in basins where the elevations of the historical snowpack areas are lower and, therefore, more susceptible to warming-induced changes in precipitation from snow to rain.



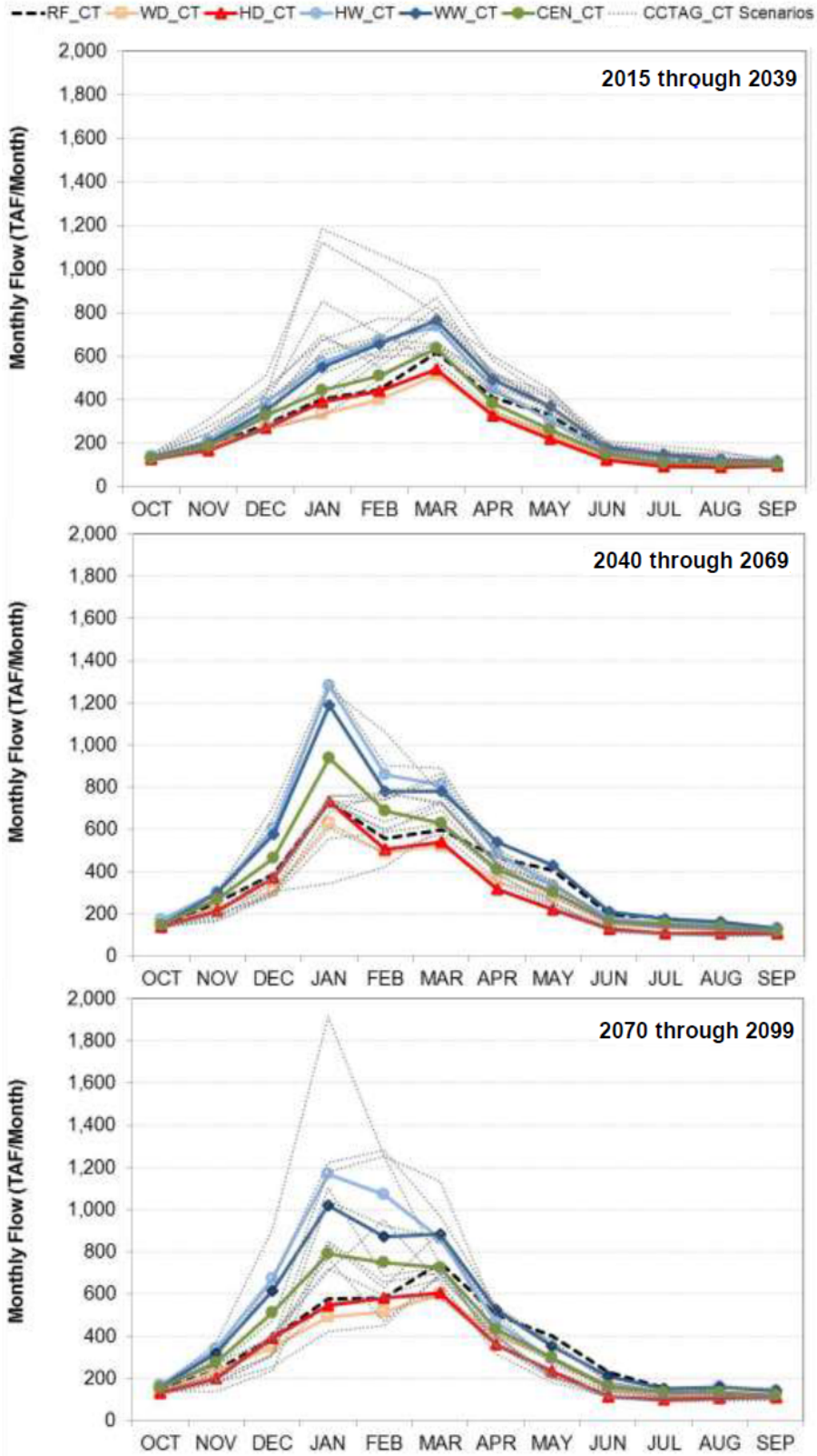
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-4. Average Runoff in Each Month into Lake Shasta in Each Scenario



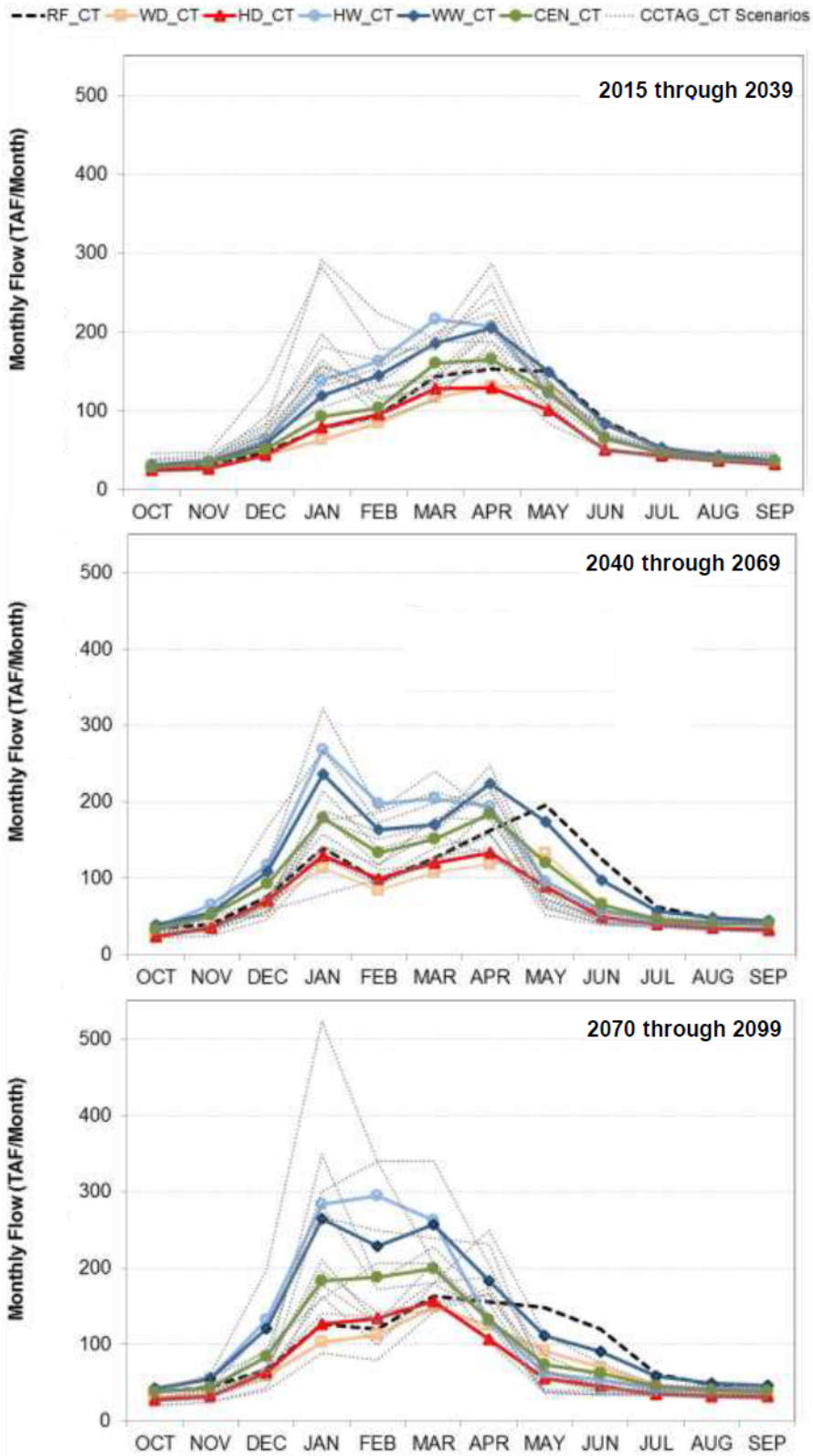
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-5. Average Runoff in Each Month into Folsom Lake in Each Scenario



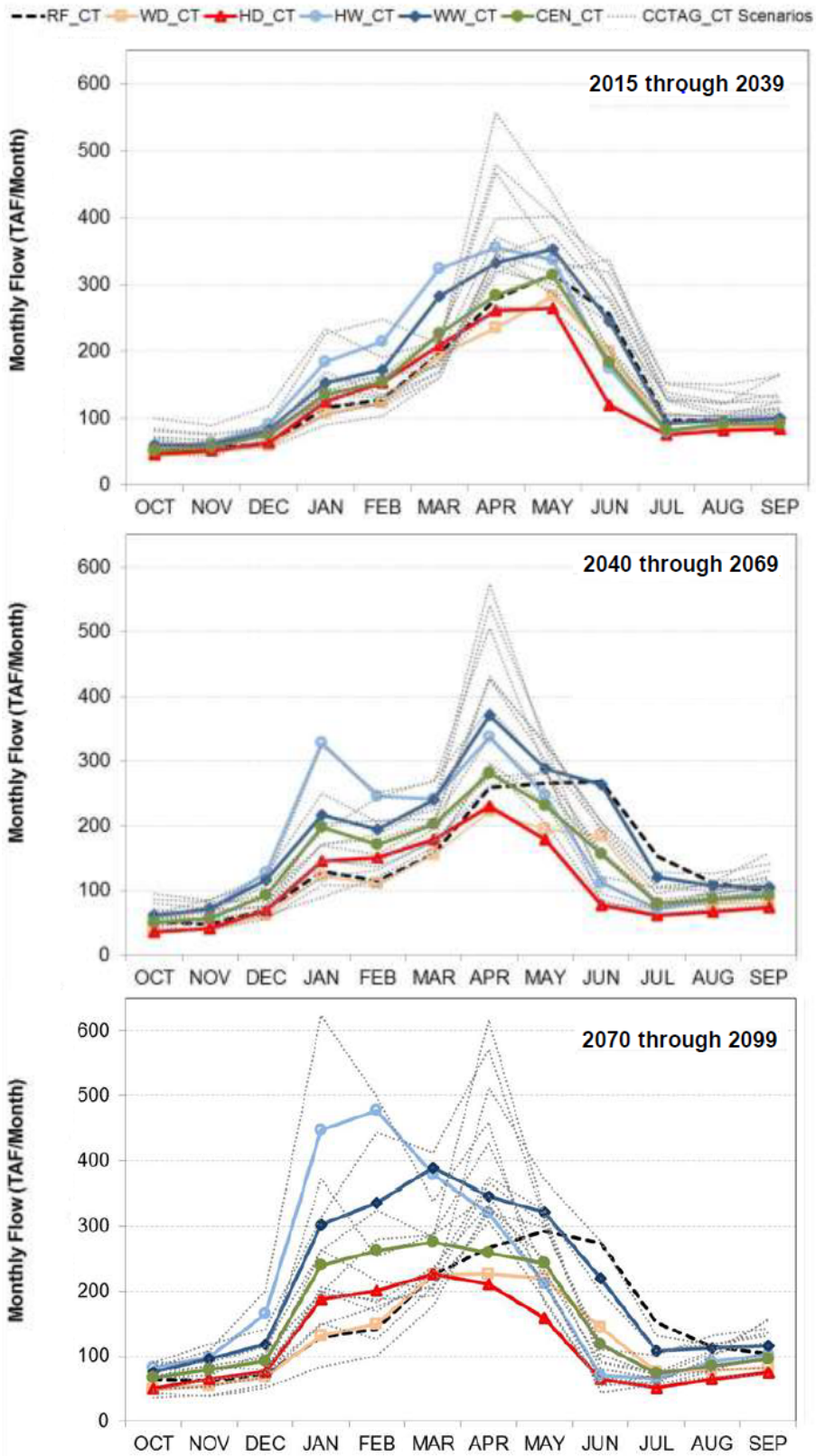
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-6. Average Runoff in Each Month into Lake Oroville in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

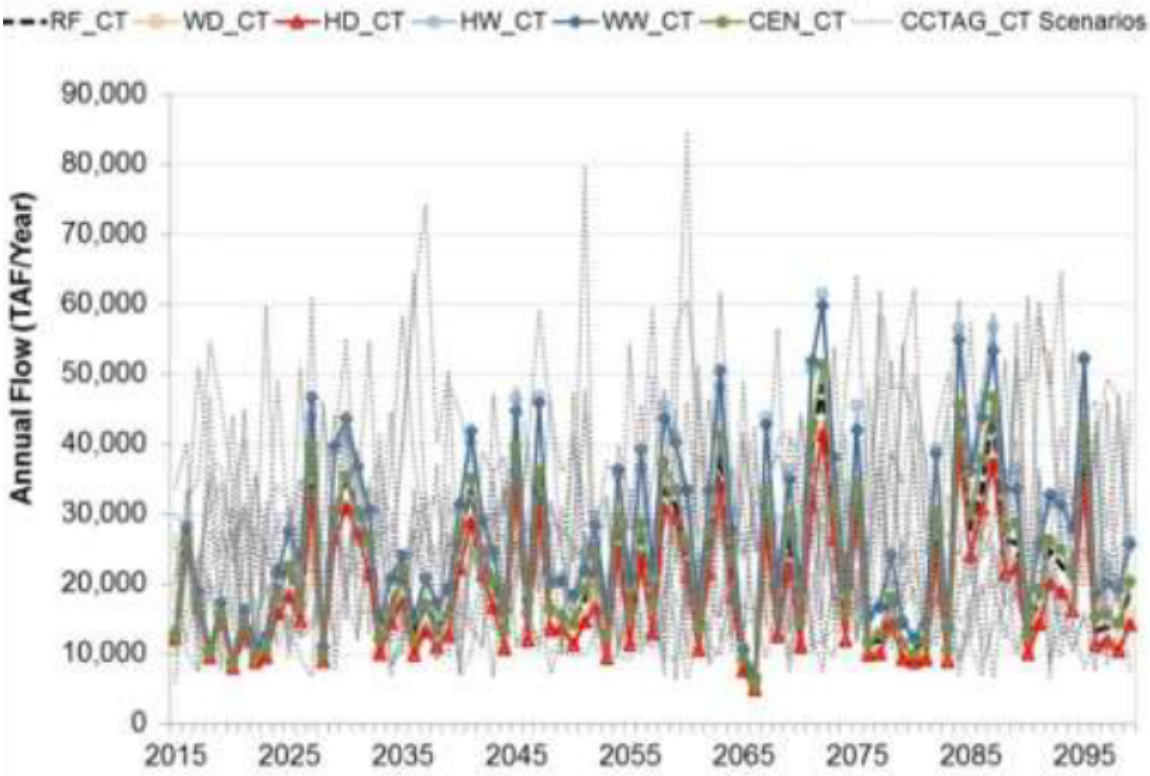
Figure 2-7. Average Runoff in Each Month into New Melones Reservoir in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

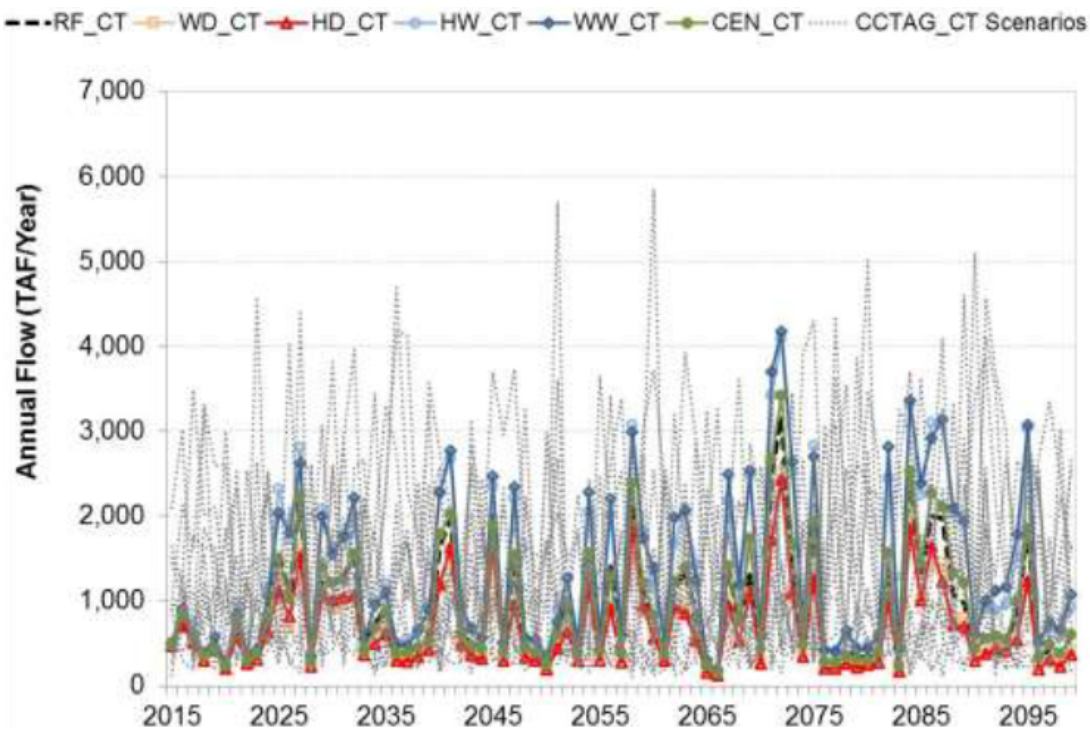
Figure 2-8. Average Runoff in Each Month into Millerton Lake in Each Scenario

Figures 2-9 through 2-11 show the annual time series of runoff in the Sacramento River system, the East Side streams and the Delta, and the San Joaquin River system under each of Current Trends scenarios from water years 2012 through 2099. These future time series reflect the same inter-annual sequence as the historical period because of the methodology used in developing the projections, with extended drought periods of lower runoff values from 2025–2030 (corresponding to the 1929–1934 dry period) and from 2083–2088 (corresponding to the 1987–1992 drought), and a very substantial dry period from 2072–2073 (corresponding to the 1976–1977 low precipitation years). However, as can be observed on the figures, the magnitude of the events differs from historical conditions.



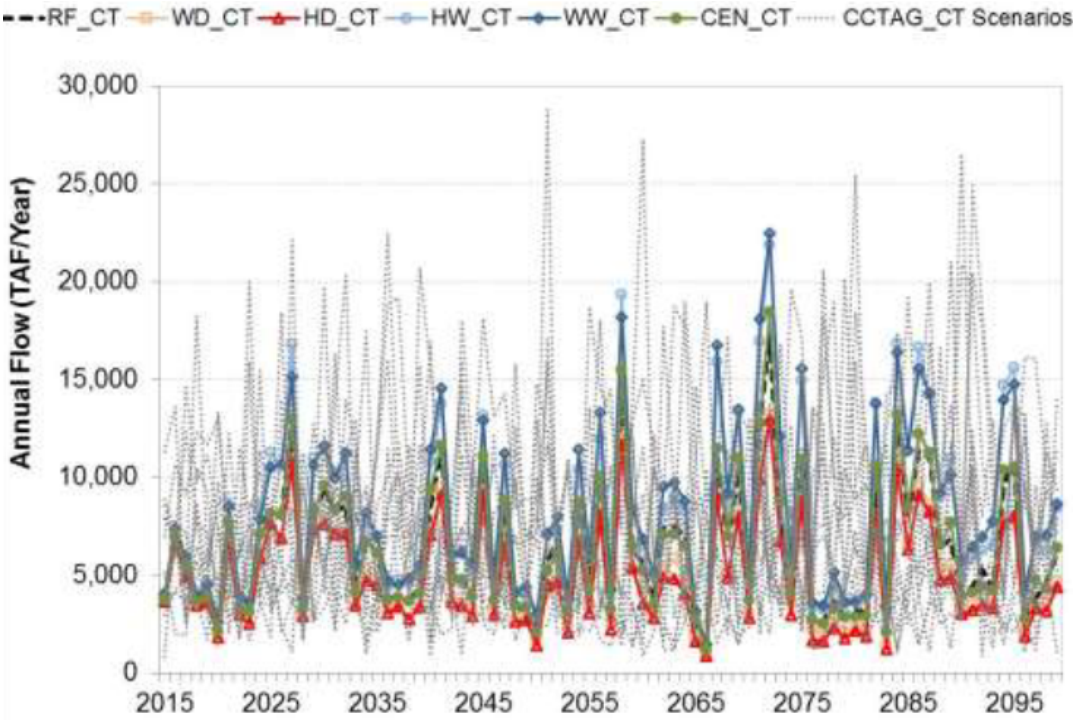
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-9. Annual Time Series of Runoff in the Sacramento River System in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-10. Annual Time Series of Runoff in the East Side Streams and Delta in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-11. Annual Time Series of Runoff in the San Joaquin River System in Each Scenario

Water Demands for CVP, SWP, and Non-Project Water Users

The Basin Study characterized the average annual agricultural and urban applied water demands for CVP, SWP, and non-project water users for each scenario and in each system. In the Reference-No-Climate Change climate/Current Trends socioeconomic scenarios, the average Central Valley agricultural demand from 2015 to 2099 was 20.2 MAF/yr. Across the full range of scenarios analyzed by the Basin Study, this demand averaged 19.5 MAF/yr, with a range from 18.1 MAF/yr to 20.8 MAF/yr. Overall, agricultural demands are projected to remain fairly constant, with possible declines, throughout the 21st century. In the Reference-No-Climate Change climate/Current Trends socioeconomic scenarios, the average Central Valley urban demand from 2015 to 2099 was 3.0 MAF/yr. Across the full range of scenarios analyzed by the Basin Study, this demand averaged 3.2 MAF/yr, with a range from 2.5 MAF/yr to 4.2 MAF/yr. The variation in projected urban demands results from varied levels of growth due to the socioeconomic conditions used in the Basin Study. Consequently, the Expansive Growth scenario had the largest urban demands and the Slow Growth scenario the least.

Performance of the CVP and SWP

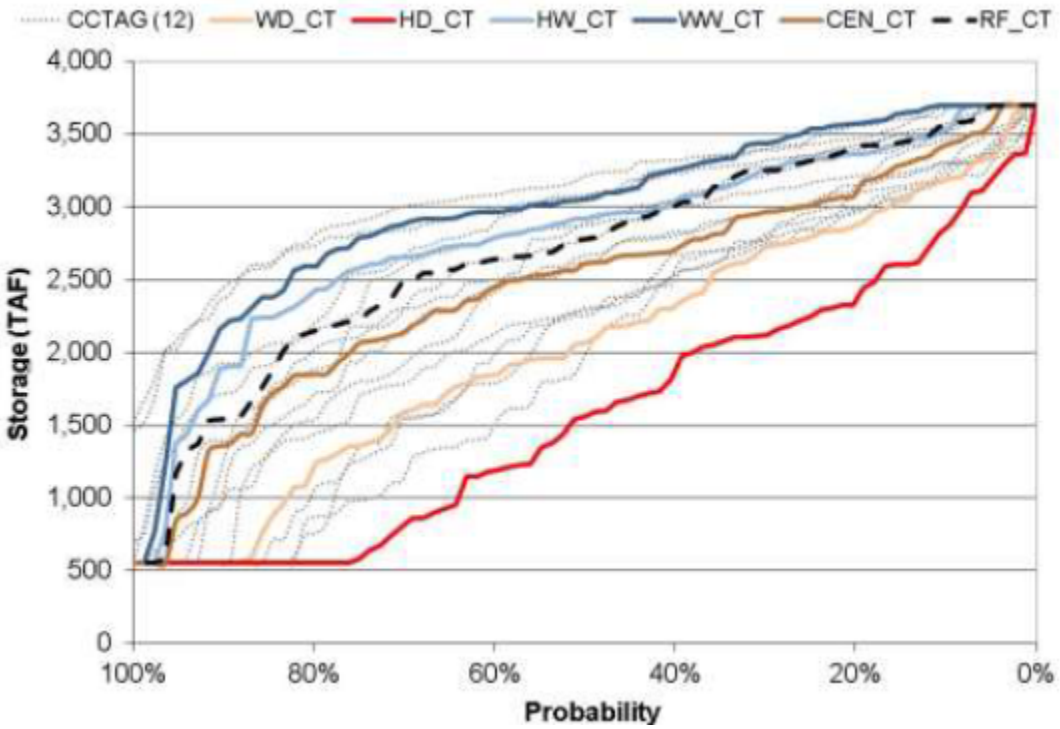
Figures 2-12 through 2-17 are exceedance plots of end-of-September storage in Shasta, Folsom, Oroville, New Melones, CVP San Luis, and SWP San Luis Reservoirs for each of the socioeconomic-climate scenarios. For example, the 50 percent probability of exceedance may be interpreted as the median storage volume over the entire twenty-first century period. The end-of-September storage is an indicator of the "carryover" storage that is reserved to meet demands in subsequent years.

In some of the dry climate projections, HD and WD, reservoir storage reached a minimum volume (dead pool) below which releases cannot be made. Typically, the CVP and SWP systems are operated to maintain sufficient carryover storage to meet demand requirements during drought periods of several years. In the CalLite-CV simulations, the reservoir operating rules were not adjusted to account for the projected hydrologic conditions under climate change. Therefore, the dead pool results presented in these figures do not reflect how the CVP and SWP systems would actually be operated under future changes in climate but, rather, may be viewed as indicators of the potential need for adaptation under some of the projected future climates should such conditions actually occur.

Although the storage trends for the scenarios were very similar in the first few years of the simulation, the variability among scenarios grew greater as the transient simulation moved toward the latter part of the century. Figure 2-18 shows the 10-year moving average of end-of-September storage at all the reservoirs in the Current Trends scenarios.

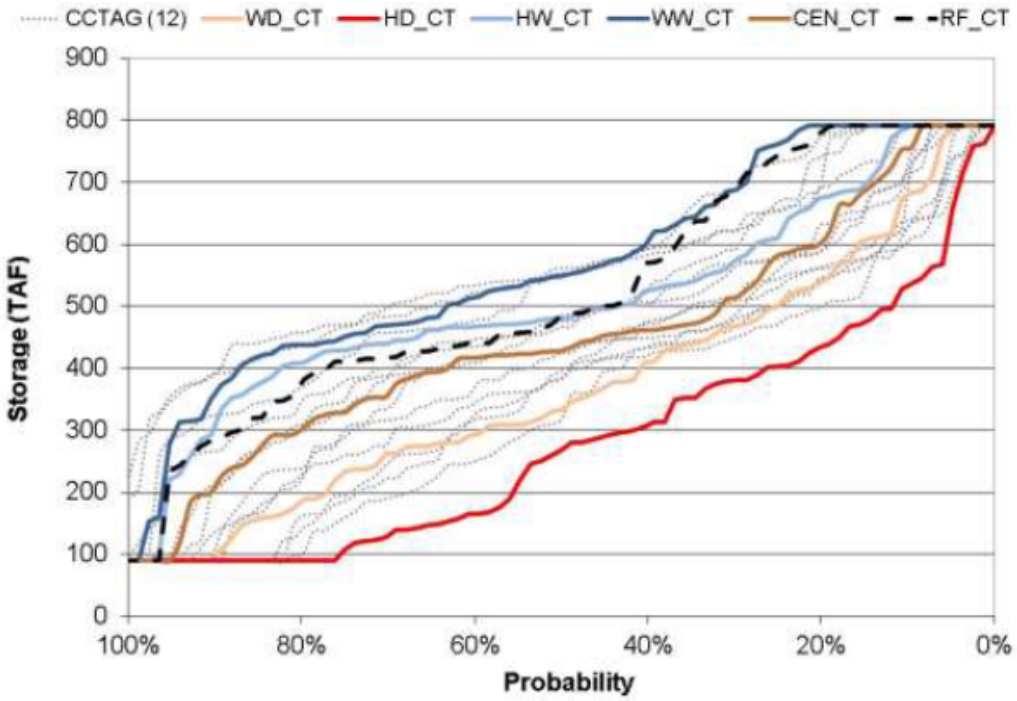
The Central Tendency climate scenario had storage levels very close to the Reference-No-Climate-Change scenarios in Lake Oroville and New Melones Reservoir, but a moderate amount lower in Shasta and Folsom reservoirs. In all the upstream reservoirs, the storage levels in September were higher under the wetter climate scenarios, HW and WW, than under the RF scenarios, with the highest storage levels in the WW scenario. Conversely, the storage levels in September were lower under the dry climate scenarios, HD and WD, than under the RF scenarios, with the lowest storage levels in the HD scenario. All five reservoirs were at dead storage in some proportion of years at the

end of September under the HD, WD, and CEN climate scenario. Lake Shasta reached dead storage in about 25 percent of all years under the HD climate scenario. In most of these reservoirs, under the WD and CEN scenarios, less frequent dead storage conditions occurred. As noted previously, the actual operation of these reservoirs in the dry scenarios would more than likely be adapted to maintain end-of-September carry-over storage greater than the amounts simulated here.



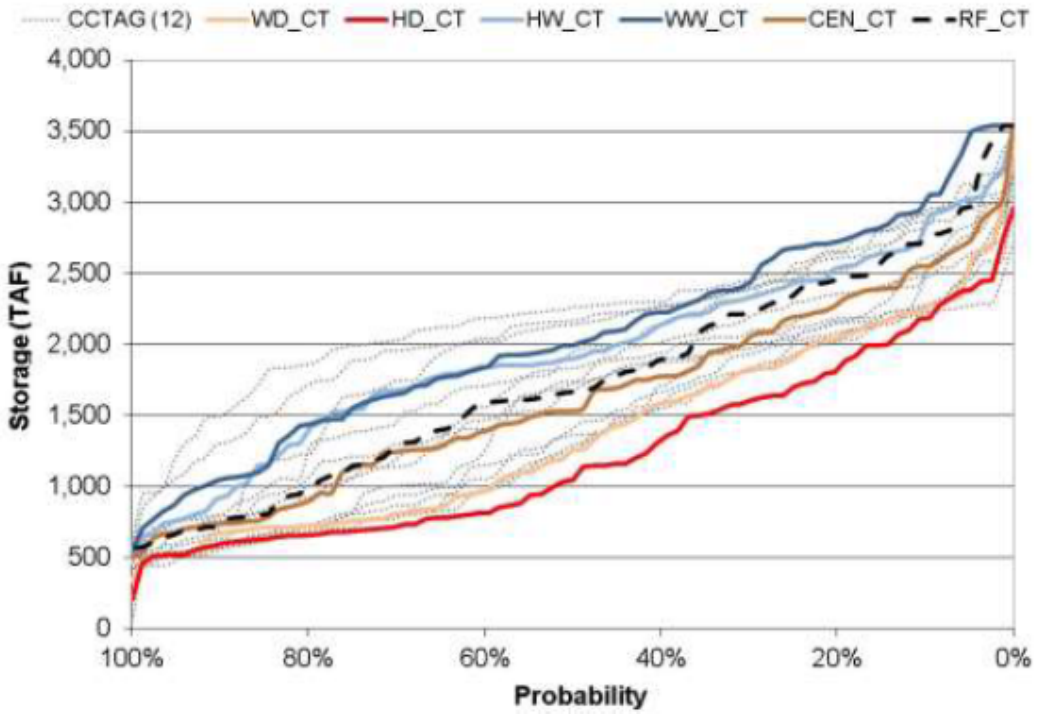
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-12. Exceedance of Lake Shasta End-of-September Storage in Each Scenario



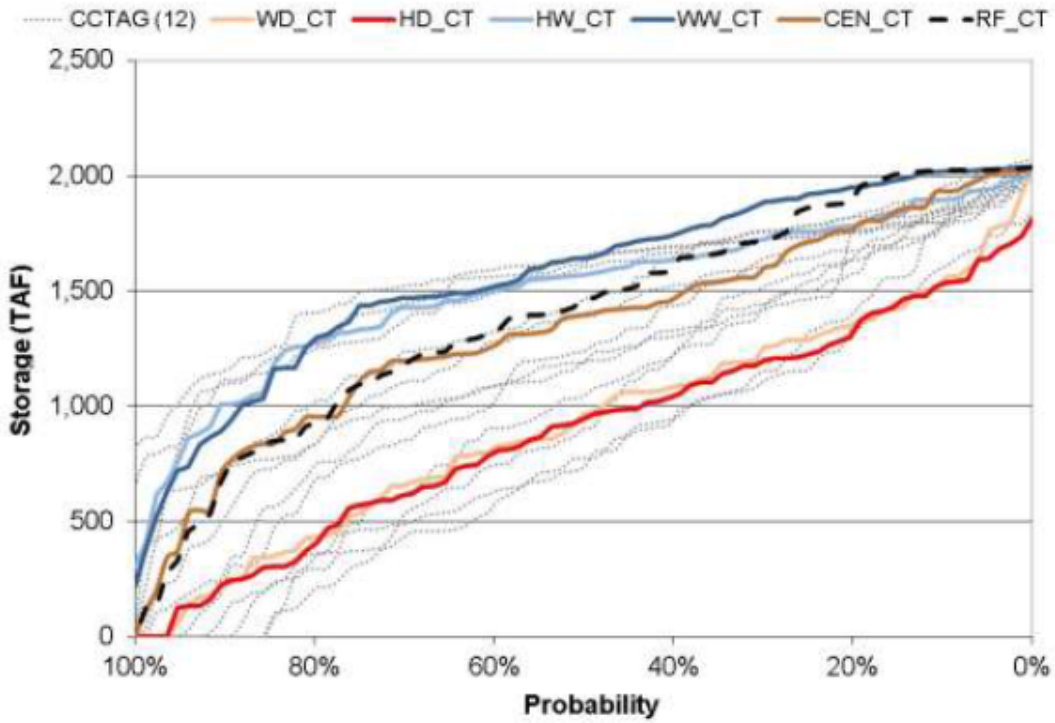
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-13. Exceedance of Folsom Lake End-of-September Storage in Each Scenario



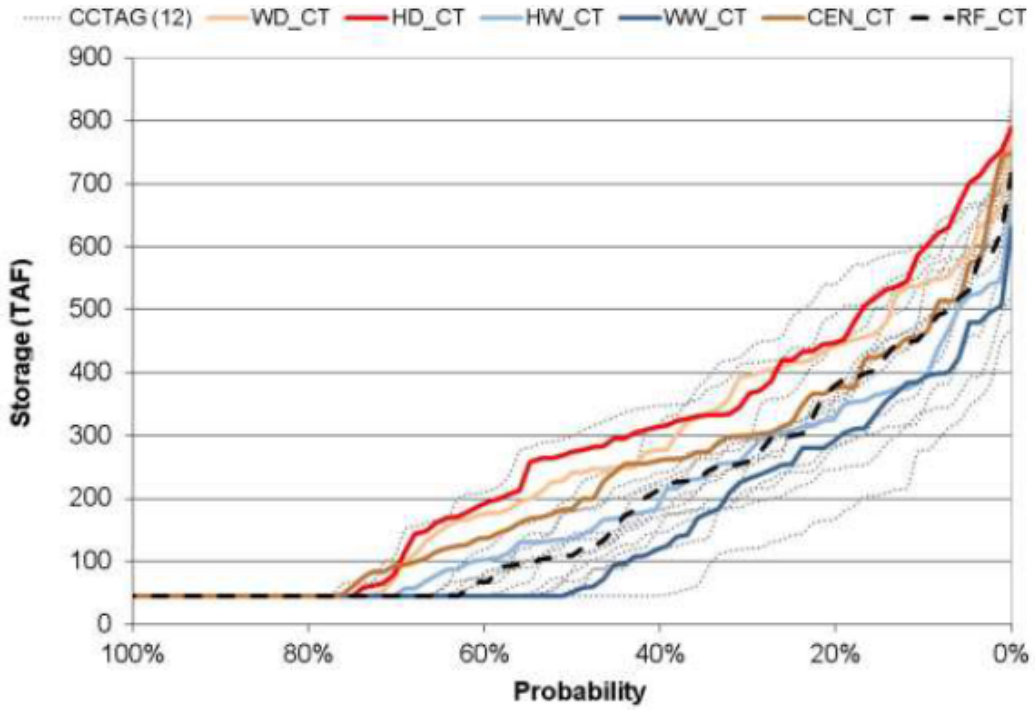
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-14. Exceedance of Lake Oroville End-of-September Storage in Each Scenario



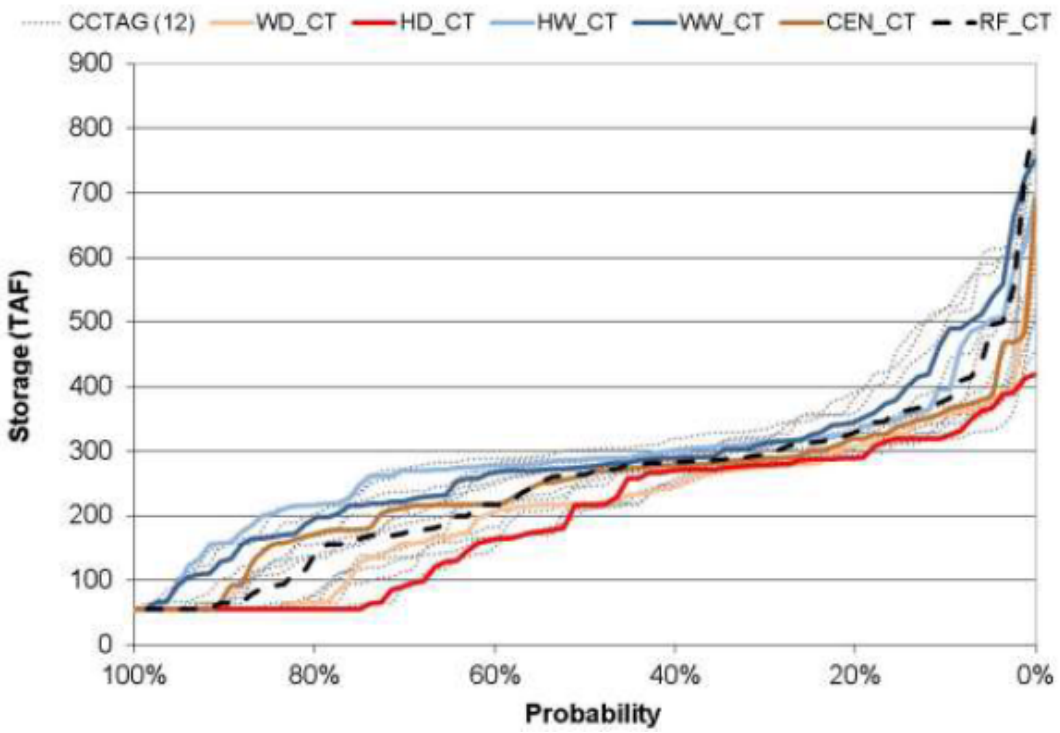
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-15. Exceedance of New Melones End-of-September Storage in Each Scenario



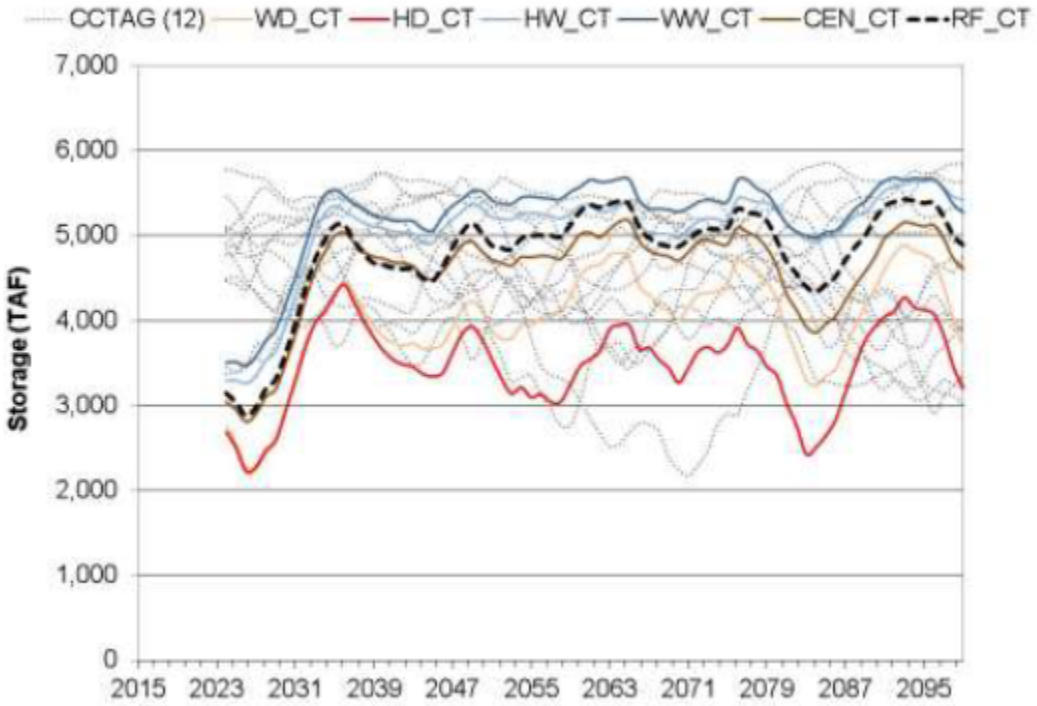
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-16. Exceedance of CVP San Luis End-of-September Storage in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-17. Exceedance of SWP San Luis End-of-September Storage in Each Scenario



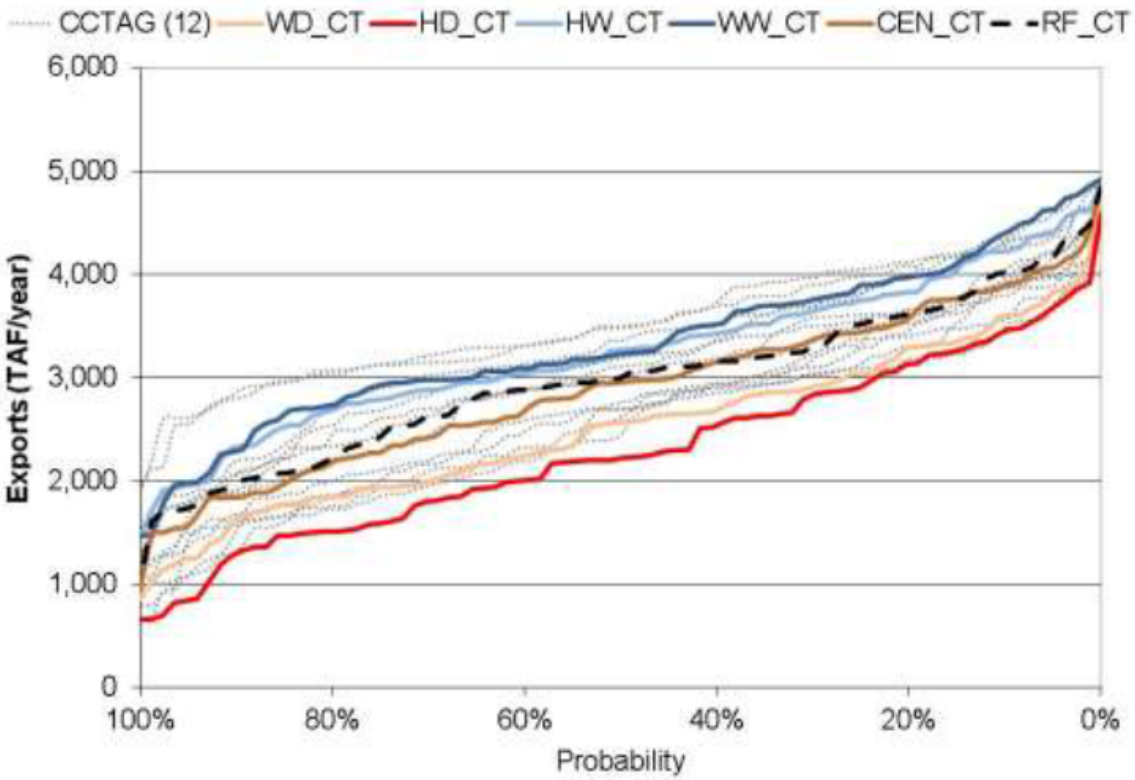
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-18. End-of-September Storage: 10-year Moving Average

CVP/SWP Delta Exports and Pumping

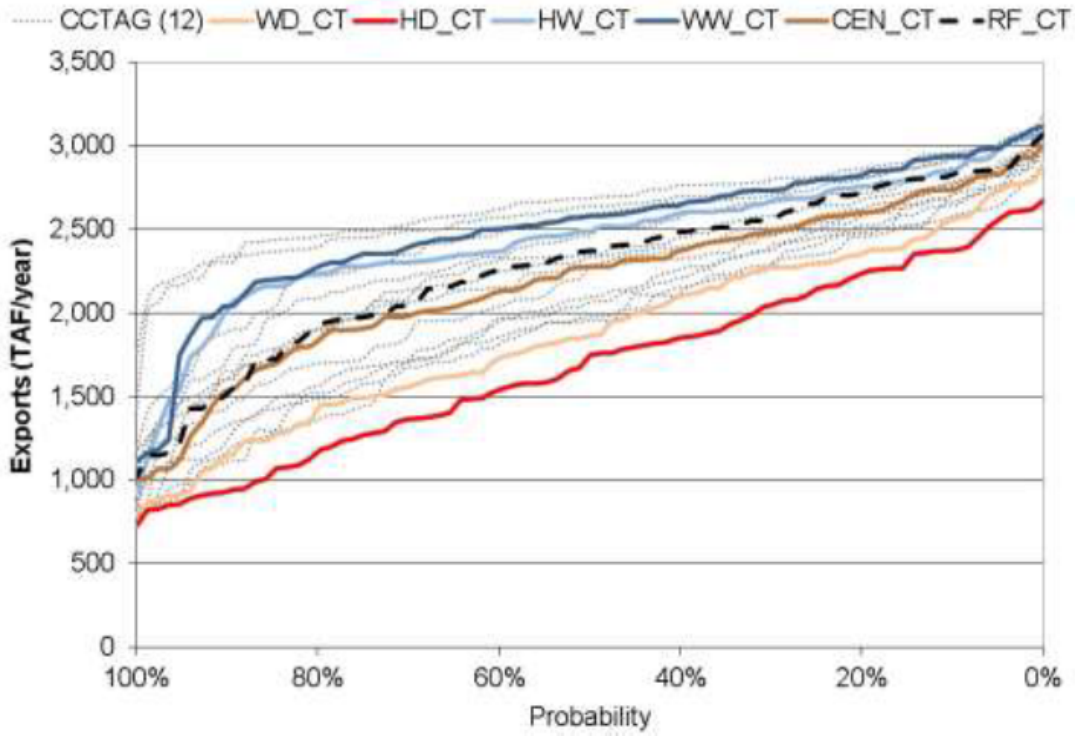
Figures 2-19 through 2-20 are annual exceedance plots of CVP/SWP exports at Banks Pumping Plant and C.W. Jones Pumping Plant, and of total Delta exports. These results differed significantly among the different climate scenarios. Banks Pumping Plant (SWP) and C.W. Jones Pumping Plant (CVP) pumping were both lower under climate scenarios CEN, WD, and HD than under the corresponding RF scenarios, with the lowest flows occurring in the HD scenario. Conversely, the annual flows at all three locations were greater under climate scenarios WW and HW than under their corresponding RF scenarios, with the highest flows occurring in the WW scenario. The dry climate scenarios, WD and HD, showed a greater difference in Delta exports relative to the RF scenarios than did the wet climate scenarios, WW and HW, because exports in the wet climate scenarios were frequently limited by CVP SWP conveyance capacities and Delta regulatory requirements. Under the RF scenario, the total average annual export was 5,252 TAF/year from 2015 to 2099. Across the range of all socioeconomic-climate scenarios, the average annual total export was 5,121 TAF/year, or 2.5 percent lower than the RF scenario.

Figure 2-22 shows a 10-year moving average time series of annual Delta exports to show the increasing differences amongst the projections as the simulation moved through the twenty-first century.



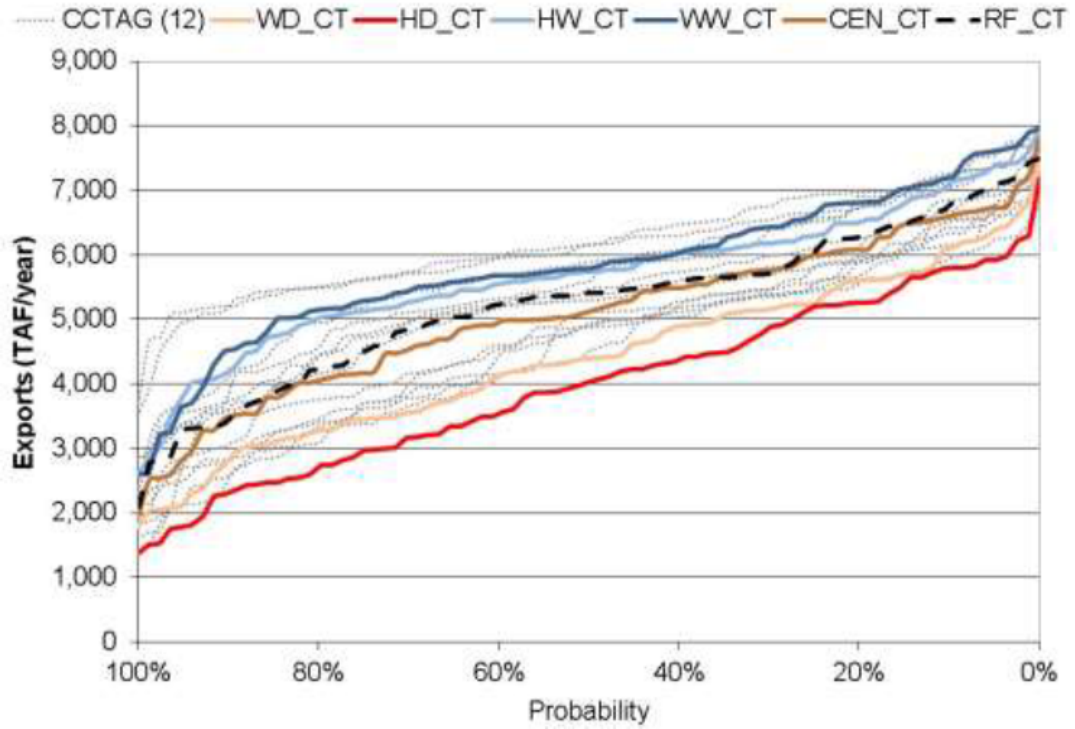
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-19. Annual Exceedance of Banks Pumping Plant Pumping in Each Scenario



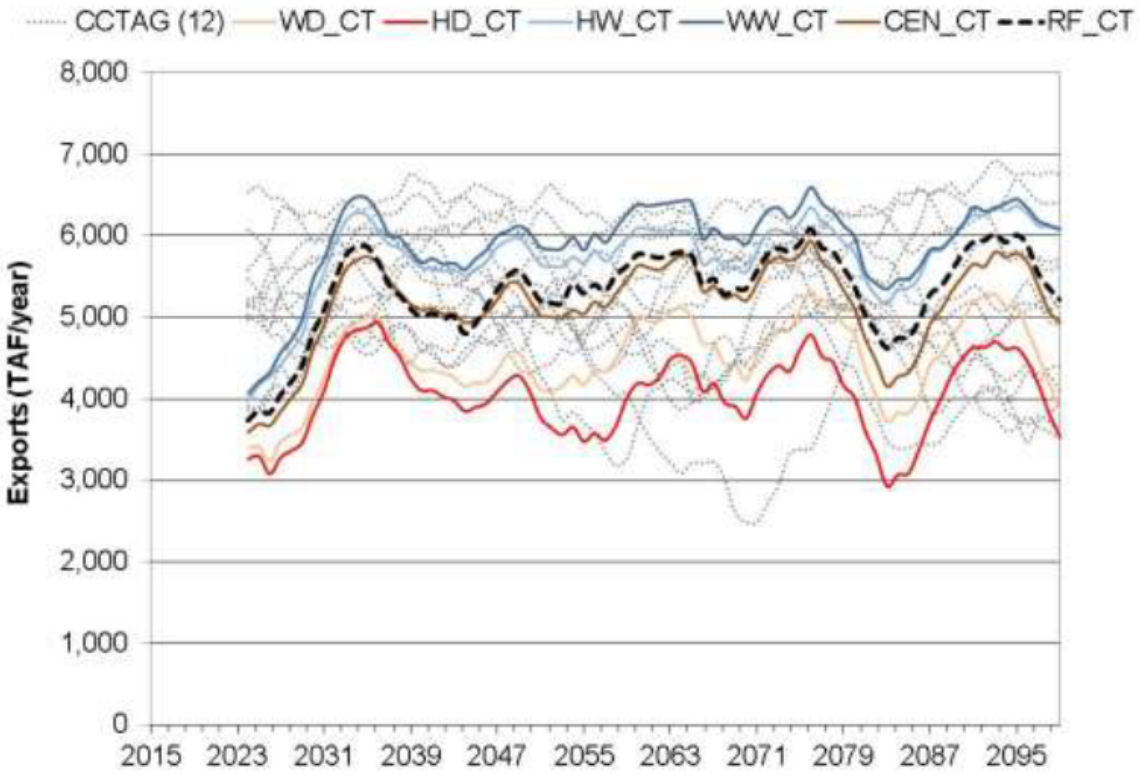
(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-20. Annual Exceedance of C.W. Jones Pumping Plant Pumping in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-21. Annual Exceedance of Total Delta Exports in Each Scenario



(Source: Sacramento and San Joaquin Basins Study, Reclamation 2016)

Figure 2-22. Delta Exports: 10-year Moving Average of Annual Total Delta Exports

Delta Water Quality – Salinity

Table 2-3 shows the average electrical conductivity (EC) expressed as micro-Siemens per centimeter (µS/cm) at four Delta compliance locations, including Emmaton, Jersey Point, Vernalis, and Rock Slough. The EC at these locations increases during the latter half of the twenty-first century due to the effects of sea level rise on Delta salinity. Among the climate change scenarios, the EC levels are highest under the HD scenarios and lowest under the WW scenario.

Table 2-3. Average April-August WC (µS/cm) at Emmaton and Jersey Point and Average EC (µS/cm) at Vernalis and Rock Slough in the Ensemble Climate Scenarios for the Current Trends Socioeconomic Scenario over the Period from 2015-2090

Location	Warm-Dry	Hot-Dry	Hot-Wet	Warm-Wet	Central
Emmaton	595	713	841	717	591
Jersey Point	512	619	707	606	522
Vernalis	579	671	669	498	478
Rock Slough	362	421	464	406	366

Source: Sacramento and San Joaquin Basins Study, Reclamation 2016
Key:
µS/cm = micro-Siemens per centimeter
EC = electrical conductivity

Summary of California Water Commission WSIP Future Projections

This section summarizes the without-project future conditions simulated using the two CalSim II models for the years 2030 and 2070 developed by the Commission. These results are compared to those developed by the Basin Study.

Temperature and Precipitation

The climate change scenarios generated by the Commission generally indicate that temperatures would be warmer across the state; on average, temperatures are projected to increase by 2.3 degrees and by 5.3°F by 2030 and 2070 respectively. Projections predict an overall increase in total precipitation in the northern part of the state. More of this precipitation would fall as rain rather than snow. On average, precipitation is projected to increase by 2.4 percent and by 4.6 percent by 2030 and 2070 respectively. The results of the temperature and precipitation projections are summarized in Table 2-4. The watersheds used by the Commission in this table are shown in Figure 2-23.

Table 2-4. Projected Changes in Climate Conditions for 2030 and 2070 Conditions with Respect to the 1995 Reference

Basin	2030 Future		2070 Future	
Watershed Name (USGS HUC-6)	Average Precipitation Change (%)	Average Temperature Change (°F)	Average Precipitation Change (%)	Average Temperature Change (°F)
Statewide				
Statewide	2.9%	2.4	5.3%	5.4
Central Valley Regions				
Central Valley	3.2%	2.6	5.6%	5.9
Upper Sacramento	3.4%	2.5	5.9%	5.7
Lower Sacramento	3.8%	2.4	7.0%	5.3
San Joaquin	3.1%	2.4	5.2%	5.4
Tulare-Buena Vista Lakes	1.8%	2.3	2.6%	5.2

Source: Commission 2016 WSIP Technical Reference

Note:

Regions are shown in Figure 2-23.

Key:

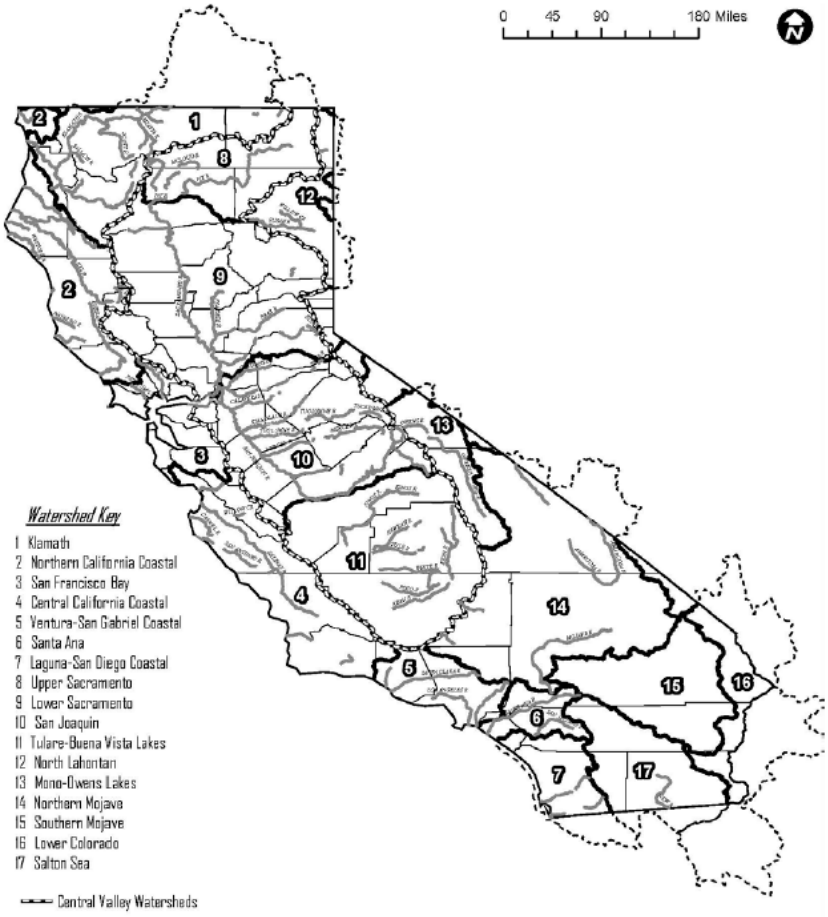
°F = degrees Fahrenheit

HUC = hydrologic unit code

USGS = United States Geological Survey

Figures 2-24 and 2-25 compare late-century projections developed by the Commission and in the Basin Study for the Sacramento and San Joaquin Basins, respectively. These figures show how the Central Tendency scenario used by the Basin Study is similar to the 2070 Future ensemble scenario developed by the Commission in terms of expected precipitation and temperature changes. In addition, the 2070 WMW and DEW scenarios provided by the Commission for sensitivity analyses help span the range of uncertainty shown in the Basin Study. Although the Commission lacks

scenarios similar to the Warm-Dry and Hot-Wet scenarios explored in the Basin Study, these scenarios usually produced results in the range of Hot-Dry and Warm-Wet scenarios, which are matched by the Commission extreme scenarios.



(Source: Commission 2016 WSIP Technical Reference)

Figure 2-23. Watershed Boundaries in California used by the California Water Commission

In the Basin Study, the projected increase in annual average temperature in the Central Valley basins relative to the historical period ranged from approximately 0.1 to 1.3°C during the period from 2015 to 2039 and from approximately 1 to 4.5°C from 2070-2099. The ensemble Commission temperature projections are within the range of those evaluated in the Basin Study. In the Basin Study, the projected changes in precipitation due to climate change reflect considerable uncertainty. The Commission precipitation projections do not reflect this same uncertainty due to the ensemble nature of the projections. The Commission precipitation projections are wetter than those found in the central tendency precipitation changes examined in the Basin Study. For example, in the San Joaquin region, the Commission projects a 3.1 percent increase in precipitation by 2030. The Basin Study's CEN scenario projects a -0.2 percent decrease during the period from 2015-2039. The other four climate ensemble scenarios range from a -9.2 percent decrease to a 10 percent increase for the

region over the same period. The Commission precipitation ensemble projections lie well within the range provided by the Basin Study, despite being slightly wetter than the Central Tendency scenario.

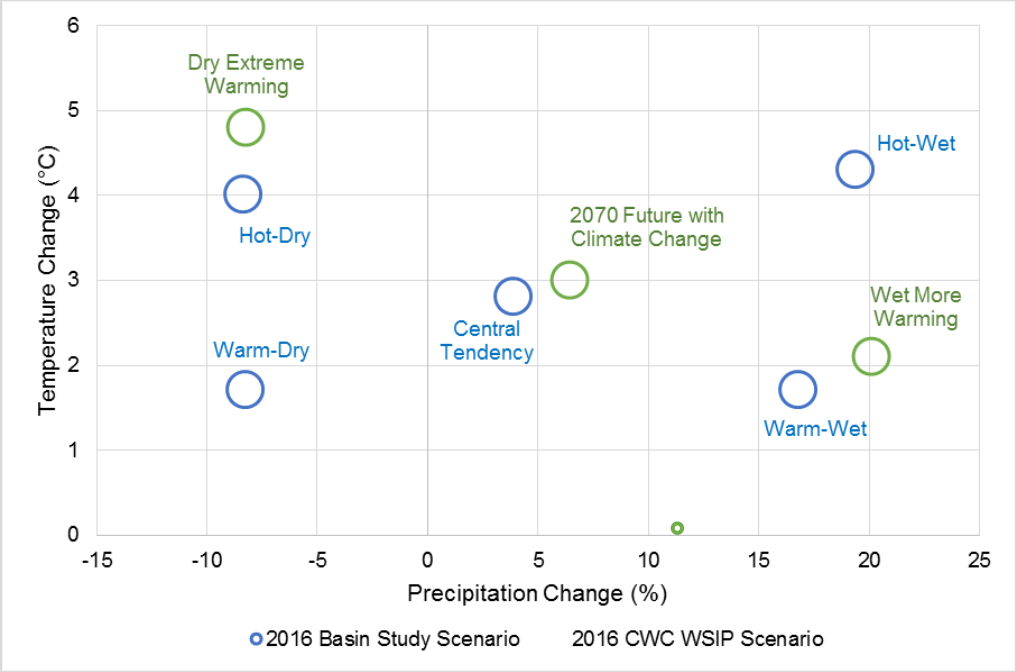


Figure 2-24. Comparison of 2016 Basin Study and the 2016 California Water Commission Water Storage Investment Program Climate Scenarios for the Sacramento River Basin

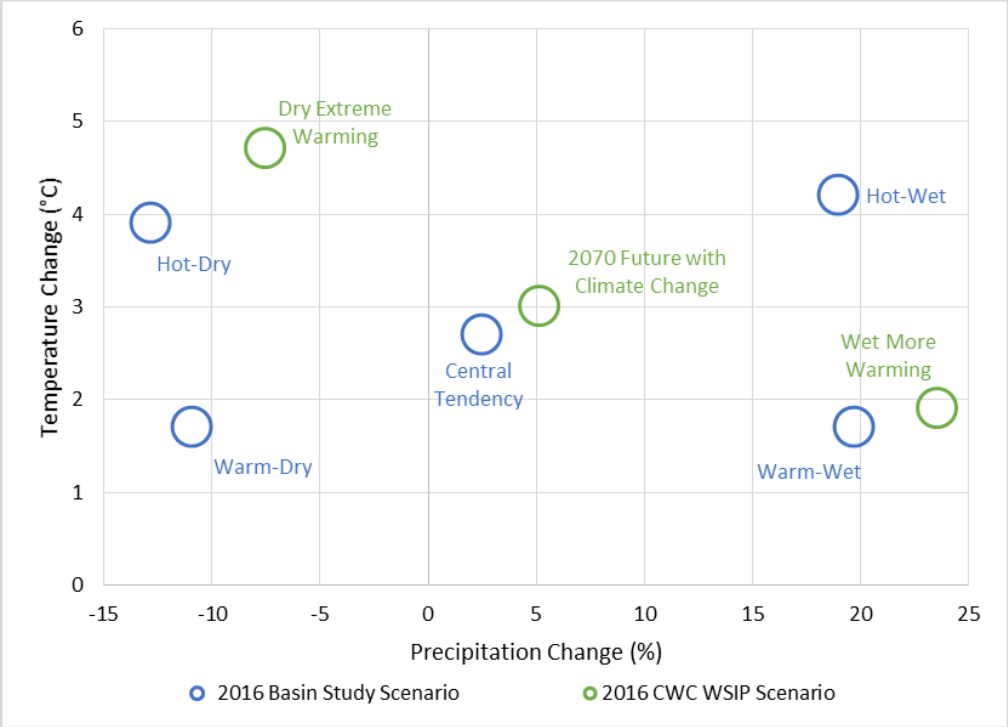


Figure 2-25. Comparison of 2016 Basin Study and the 2016 California Water Commission Water Storage Investment Program Climate Scenarios for the San Joaquin River Basin

Sea Level Rise

Sea level rise, due to a combination of melting glaciers and ice sheets and thermal expansion of seawater as it warms in response to rising global temperatures, has been projected by multiple parties. The transient sea level rise projections used by Reclamation (2016) and the levels chosen by the Commission (2016) are informed by projections furnished by the National Research Council and further evaluated by the U.S. Army Corps of Engineers. The sea level rise projections are input into CalSim II and DSM2 models to model changes in flow-salinity in the Delta.

The Commission used 15 centimeter (5.9 inch) and 45 centimeter (17.7 inch) increases for the years 2030 and 2070, respectively. These sea level rise projections are within the range evaluated in the Basin Study. In addition, the mean projections in 2030 are similar.

Runoff and Hydrology

Snow is projected to melt earlier in the year in the Commission climate change scenarios, shifting the timing of peak runoff flows into reservoirs. In addition, despite the increase in precipitation in the Commission scenarios, more of this precipitation would fall as rain, not snow, in winter. The change would require additional flood releases during winter, reducing the reservoir storage levels the rest of the year. As a result of these changes, the reservoirs achieve a peak level of storage almost a month earlier on average, as shown below for Shasta Lake and Lake Oroville in Figure 2-26 and Figure 2-27, respectively.

Similar to the Commission scenarios, the Basin Study found that runoff into reservoirs would occur earlier in the winter and would be reduced later in the spring and summer. The changes in annual stream flow presented by the Basin Study show a high variability amidst the ensemble climate scenarios. In the CEN scenario, average stream flow was only slightly higher than the RF condition. The Commission scenarios show a change in runoff that would be slightly decreased overall, well within the projection ranges of the Basin Study.

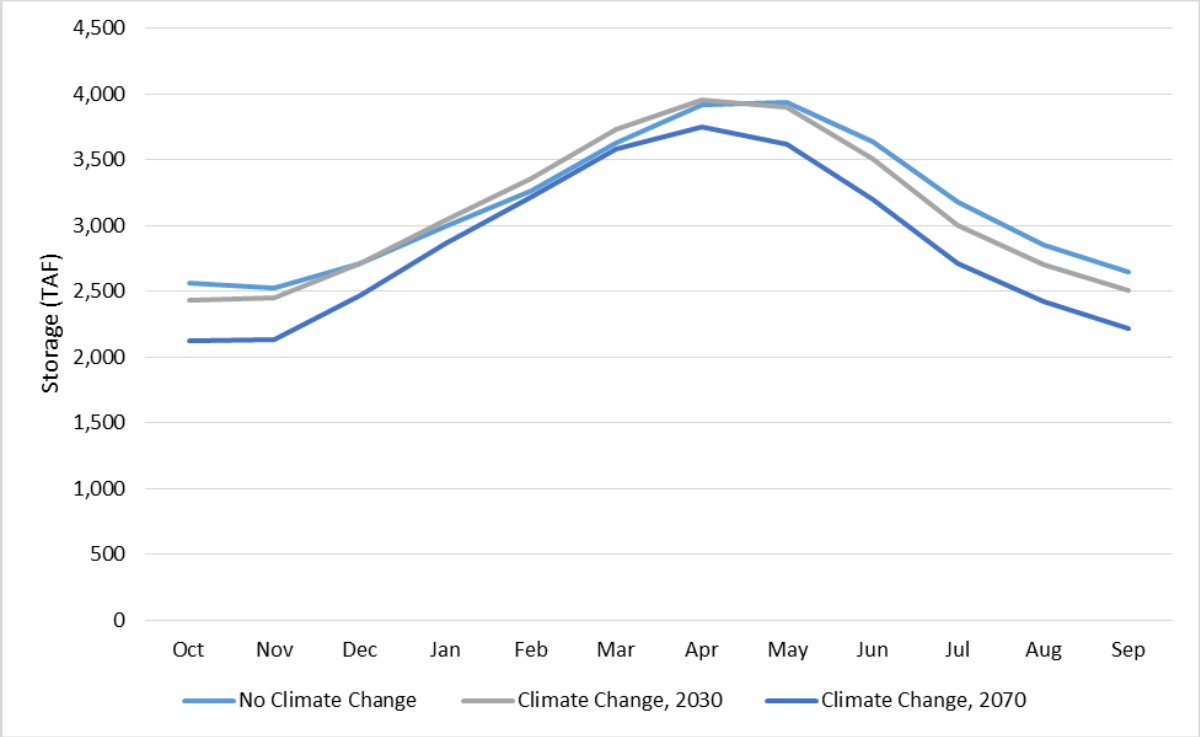


Figure 2-26. Time Series of Average Storage in Shasta Lake in Each Commission Scenario

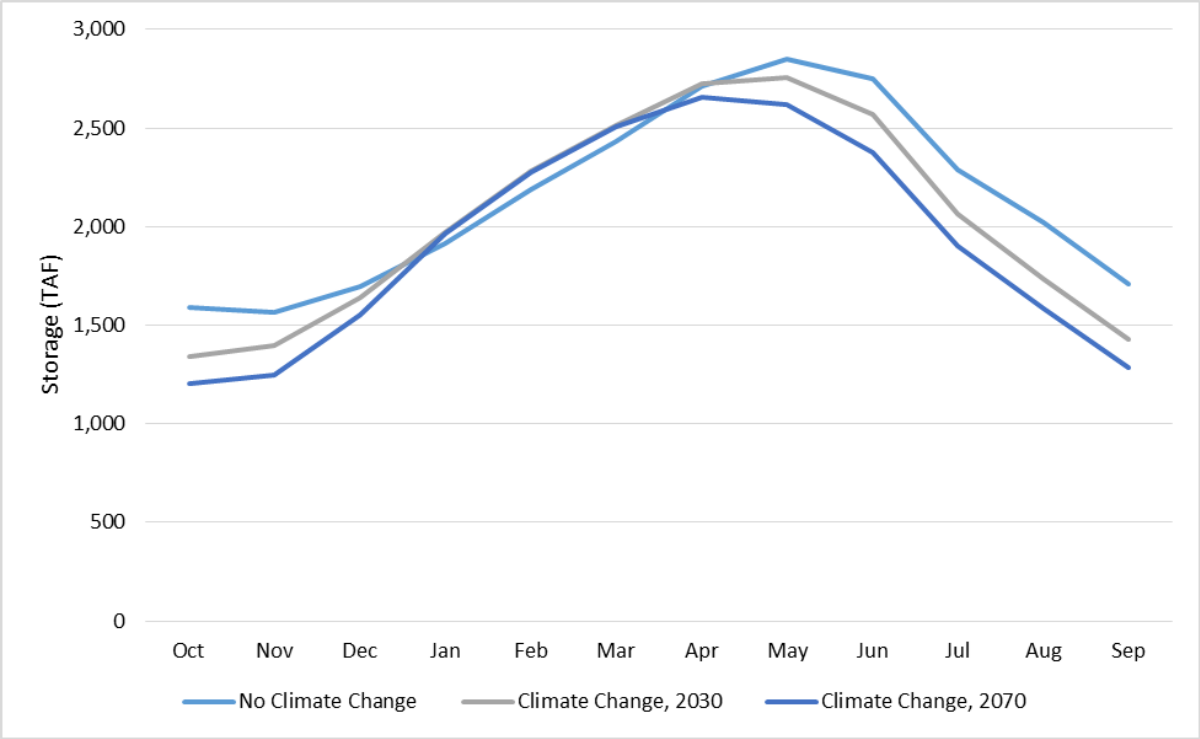


Figure 2-27. Time Series of Average Storage in Lake Oroville in Each Commission Scenario

Performance of the CVP and SWP

Table 2-5 shows a summary of the deliveries and carryover storage for the SWP and CVP. As follows from Figure 2-28, the combined amount of CVP and SWP carryover storage is decreased. Climate change also decreases both CVP and SWP annual deliveries. The far future conditions exacerbate this effect. In comparison with a future with no climate change, annual CVP deliveries decrease by approximately 3.4 percent by 2030 and 10.7 percent by 2070. Similarly, annual SWP deliveries decrease by 1.5 percent by 2030 and by 7.3 percent by 2070, when compared to a future without climate change.

Table 2-5. Summary of CVP and SWP Performance in Each Commission Scenario

	Annual CVP Deliveries[1] (TAF)	Annual SWP Deliveries[2] (TAF)	CVP and SWP Carryover Storage[3] (TAF)
Future, without climate change	4,688	3,771	6,741
Near Future, with Climate Change (2030)	4,527	3,707	6,156
Far Future, with Climate Change (2070)	4,184	3,492	5,477

Notes:
[1] Total CVP Deliveries include total agricultural, refuge, municipal, and industrial deliveries.
[2] Total SWP Deliveries include Table A, Article 56, and Article 21
[3] CVP and SWP Carryover Storage includes end-of-September storage for Shasta, Trinity, Oroville, Folsom, and San Luis reservoirs
Key:
CVP = Central Valley Project
Commission = California Water Commission
SWP = State Water Project
TAF = thousand acre-feet

Figure 2-28 examines the impact of climate change on the carryover storage of the individual reservoirs for each Commission scenario of climate change as compared to a future without climate change. In almost all the reservoirs, climate change decreases the carryover storage. Only San Luis, off-stream and therefore less dependent on the seasonal timing of runoff, avoids this decrease in carryover storage. The overall amount of carryover storage decreases by approximately 8.7 percent by 2030 and 18.8 percent by 2070, when compared to a future without climate change.

The decrease in carryover storage is also seen in the results from the Basin Study when considering the central tendency scenario. The average end-of-September reservoir storage is projected to decrease by 9 percent. The dry scenarios were more likely to have low storage than the wet scenarios. The HD scenario resulted in reservoir levels under the 10th percentile of storage in the RF scenario in 30-50 percent of all years between 2015-2099 at most major reservoirs. However, unlike the Commission results, the Basin Study found the reservoirs were more likely to have low carryover storage from 2015-2039 than during the second half of the twenty-first century.

Figures 2-29 through 2-34 are exceedance plots of storage at the end of September for Shasta, Folsom, Oroville, Trinity, CVP San Luis, and SWP San Luis Reservoirs for each of the Commission climate scenarios. Although the 2030 climate conditions result in similar exceedance plots for each of the reservoirs, the 2070 conditions generally reflect lower reservoir storage levels. The results of the Basin Study and the results of the Commission CalSim II model also show similar performance of the CVP/SWP under future climate conditions. For example, exceedance plots for the major reservoirs in both systems can be compared (Figures 2-12 and 2-29, Figures 2-13and 2-30, Figures 2-14 and 2-31, Figures 2-16 and 2-33, Figures 2-17 and 2-34). Storage at Lake Shasta, as modelled with Commission modeling tools, follows the wet and CEN scenario projections of the Basin Study. Another example, SWP San Luis storage shows the same lack of variability between different climate conditions, with generally low end-of-September storage in most years under both Basin Study and Commission projections. The exceedance plots show the results of both sets of tools provide similar projections, although the Basin Study provides a greater range of scenarios and of results.

Figures 2-35 and 2-36 show the annual time series of storage in Shasta Lake and Lake Oroville, respectively, under each Commission climate scenario. The future time series reflect the same inter-annual variability as the historical period due to the methodology in developing the projections. Both Lake Shasta and Lake Oroville show similar responses to major droughts as seen in results from the Basin Study.

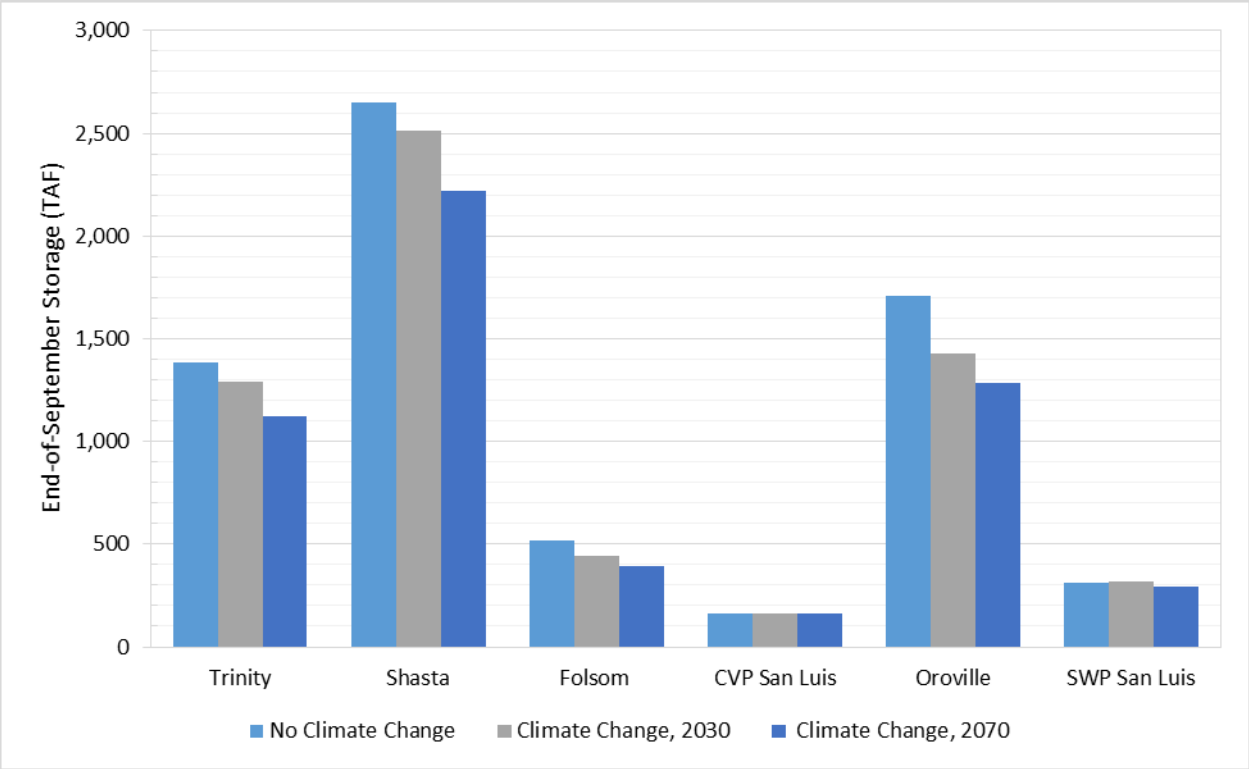


Figure 2-28. Average End-of-September Storage by Reservoir in Each Commission Scenario

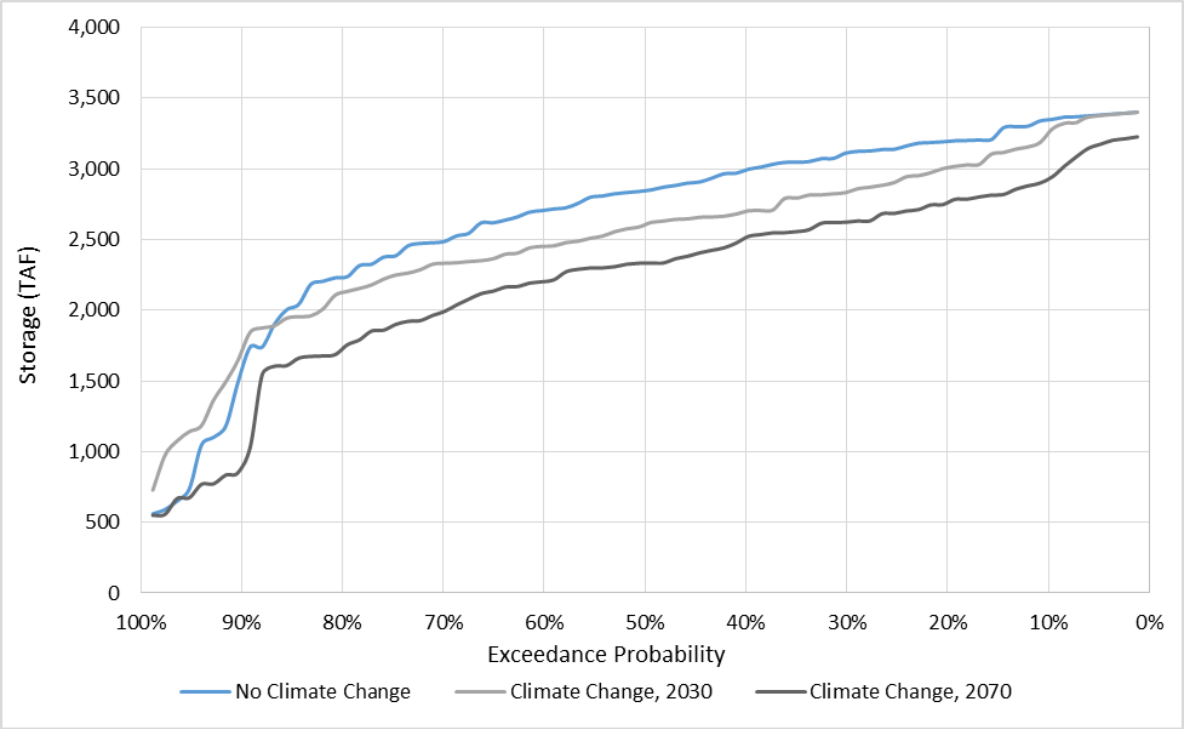


Figure 2-29. Exceedance of Lake Shasta End-of-September Storage in Each Commission Scenario

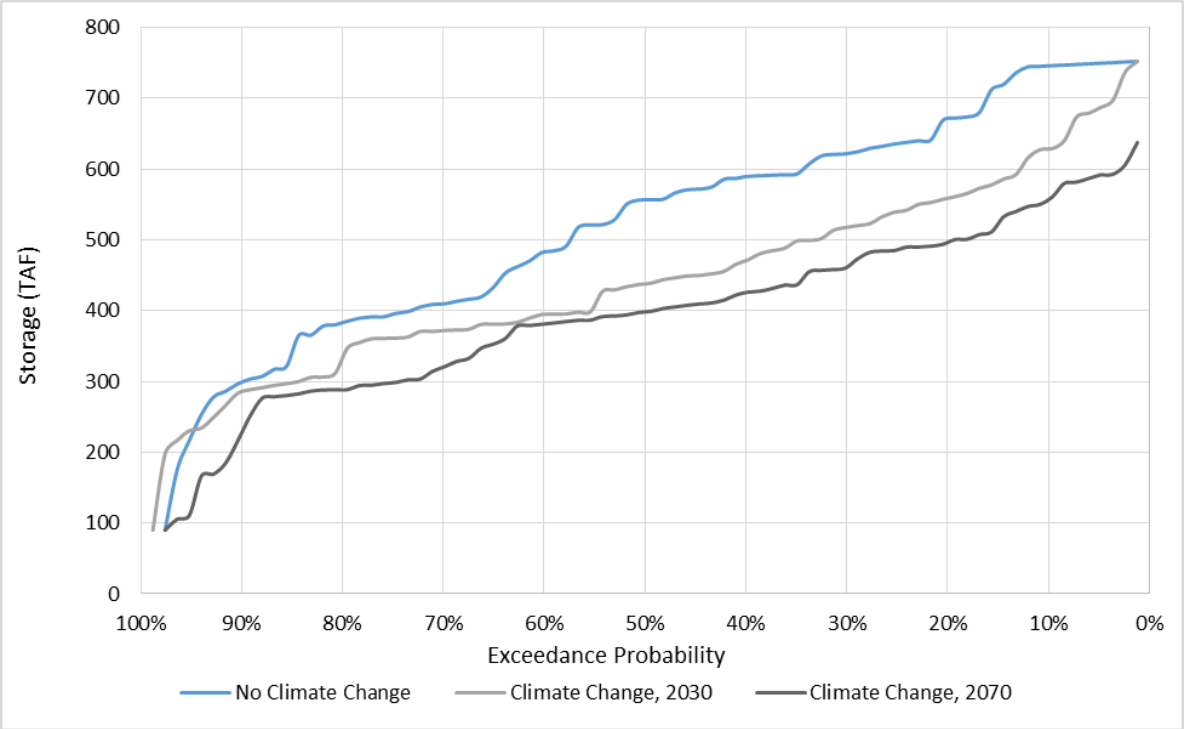


Figure 2-30. Exceedance of Folsom Lake End-of-September Storage in Each Commission Scenario

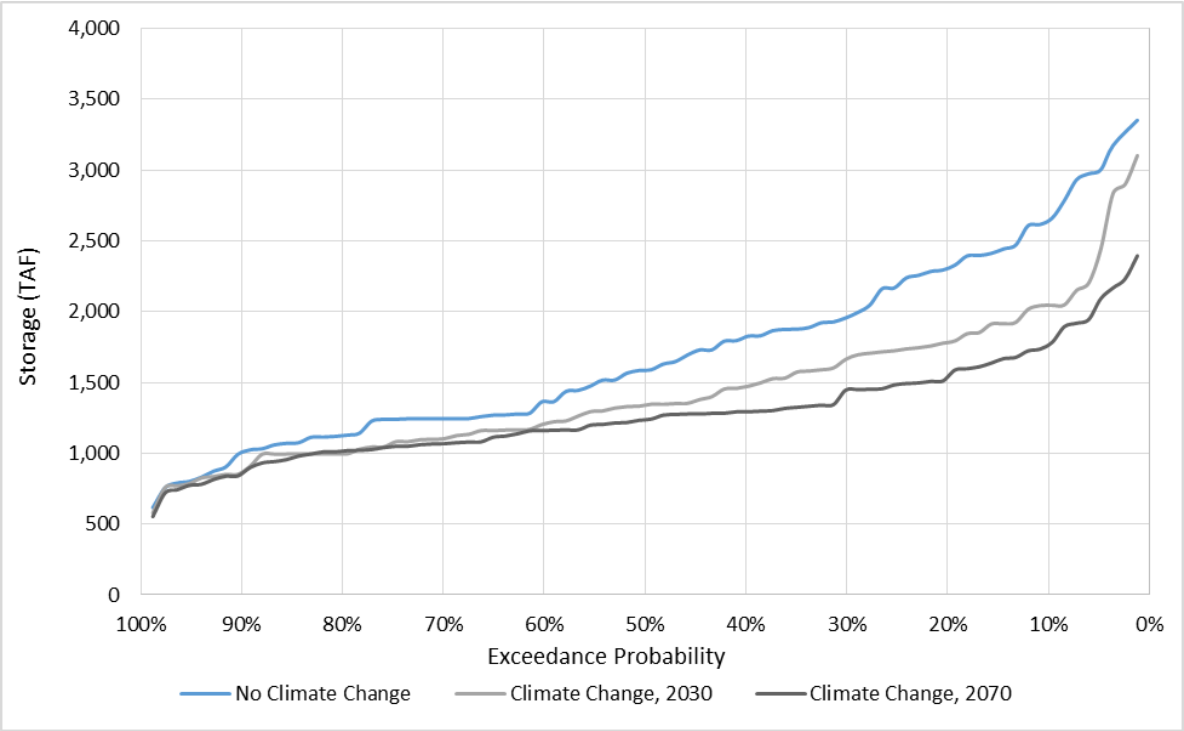


Figure 2-31. Exceedance of Lake Oroville End-of-September Storage in Each Commission Scenario

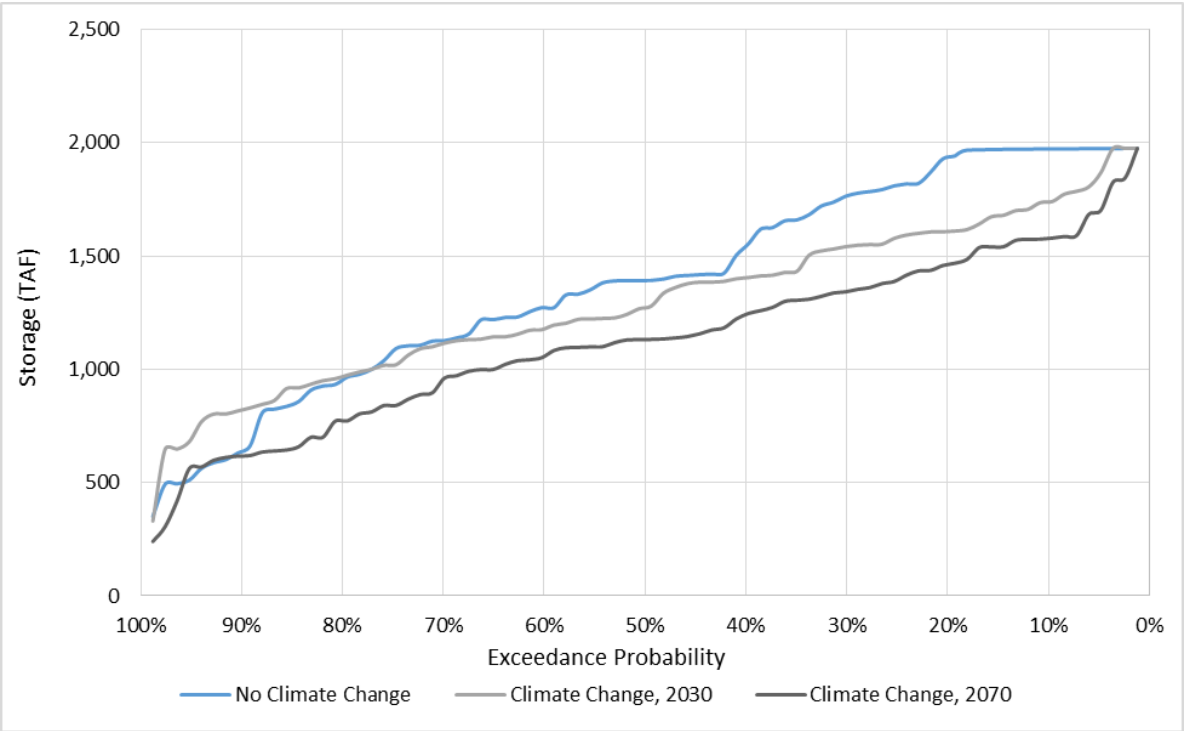


Figure 2-32. Exceedance of Trinity Lake End-of-September Storage in Each Commission Scenario

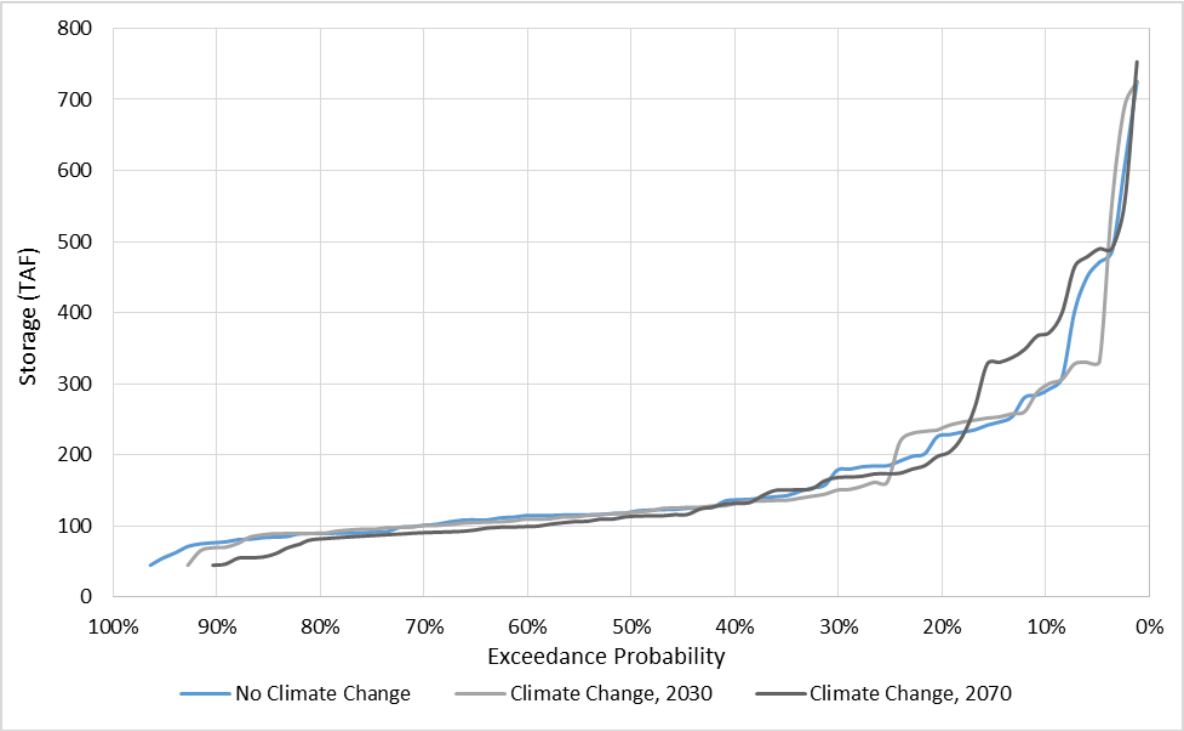


Figure 2-33. Exceedance of CVP San Luis End-of-September Storage in Each Commission Scenario

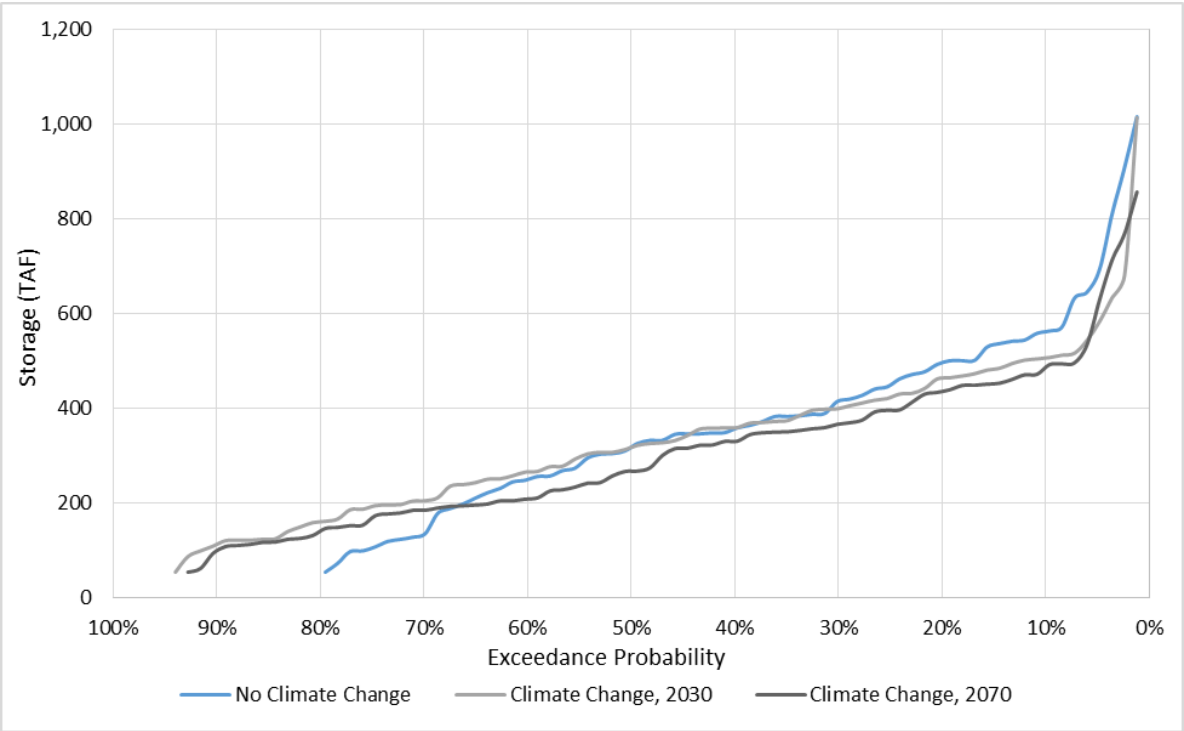


Figure 2-34. Exceedance of SWP San Luis End-of-September Storage in Each Commission Scenario

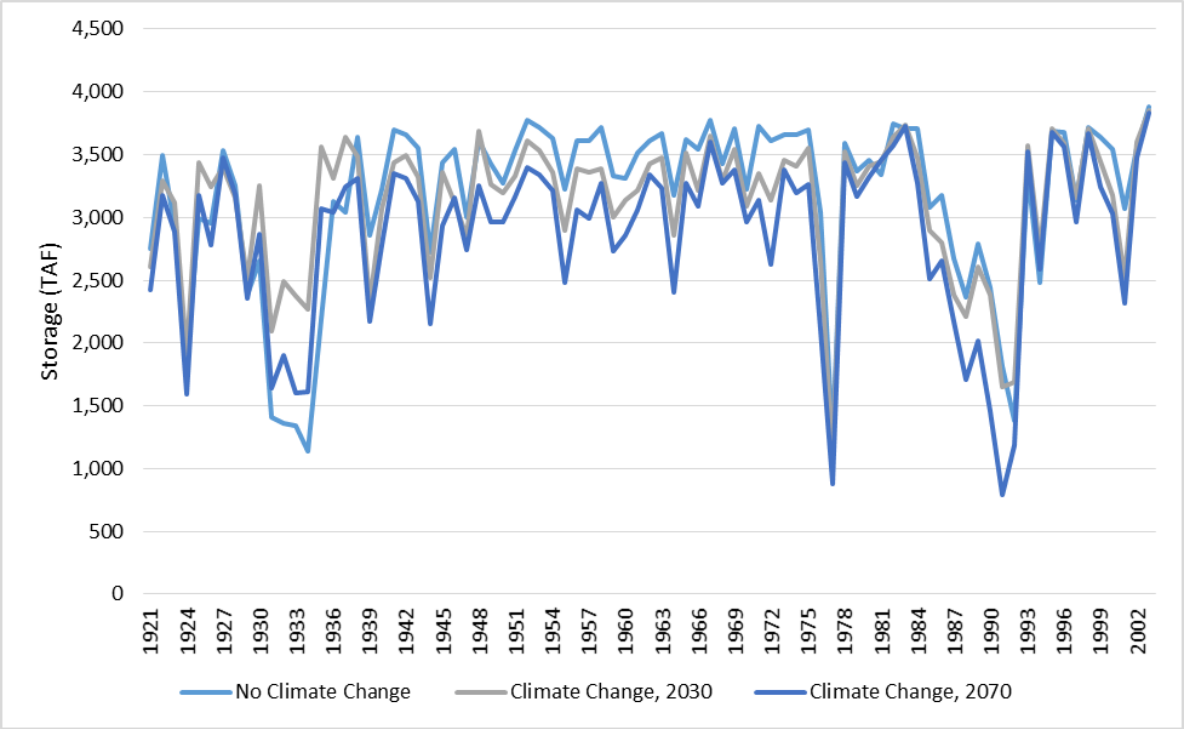


Figure 2-35. Time Series of Average Storage in Each Year in Lake Shasta in Each Commission Scenario

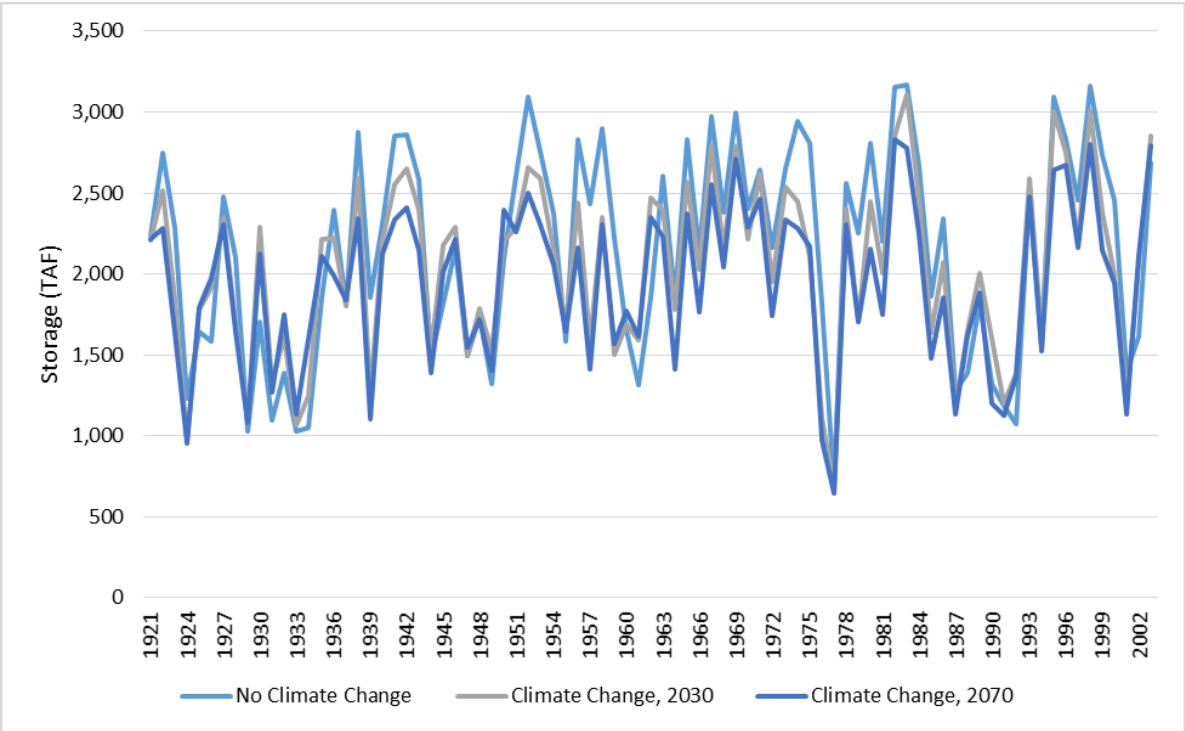


Figure 2-36. Time Series of Average Storage in Each Year in Lake Oroville in Each Commission Scenario

CVP/SWP Delta Exports and Pumping

Figures 2-37 through 2-38 are annual exceedance plots of CVP/SWP exports at Banks Pumping Plant and C.W. Jones Pumping Plant. The Commission climate change scenarios predict decreased pumping for both the Banks Pumping Plant (SWP) and C.W. Jones Pumping Plant (CVP) than under no climate change. This is consistent with a comparison of CEN and RF climate scenarios of the Basin Study. Pumping at Banks Pumping Plant is less effected by climate change than the pumping at C.W. Jones Pumping Plant. This relative sensitivity to climate change is also visible in the results of the Basin Study, as seen in Figures 2-19 and 2-20.

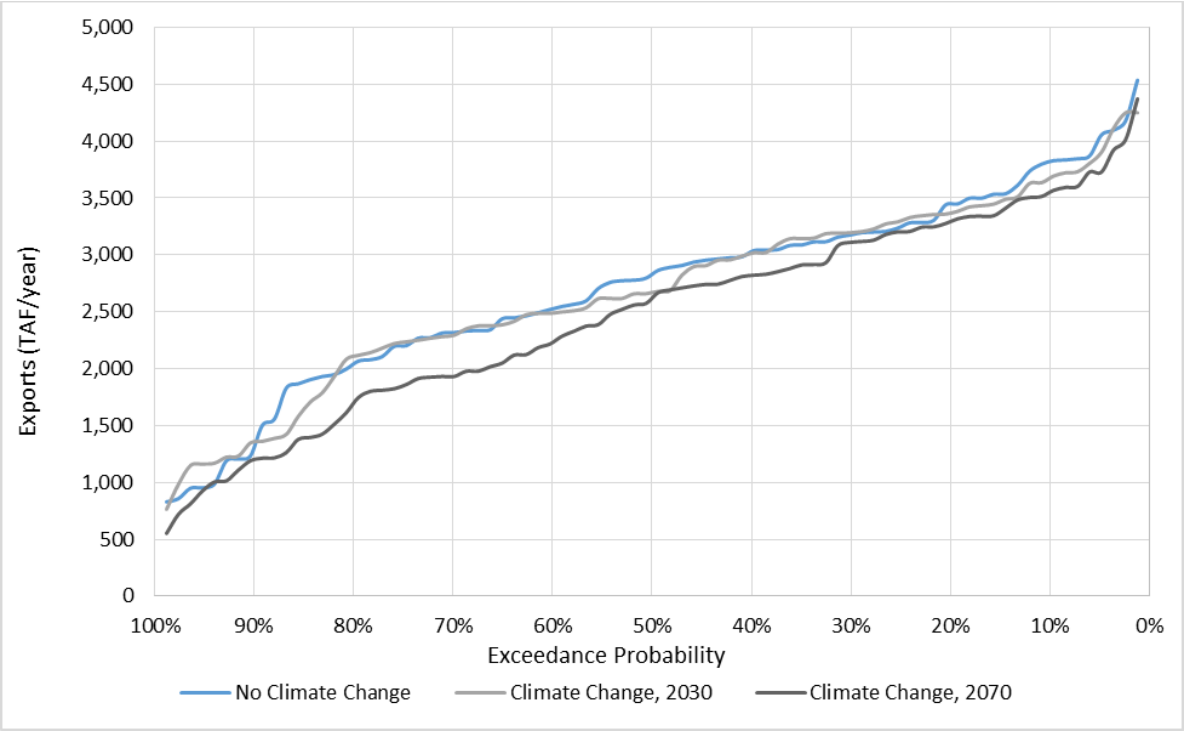


Figure 2-37. Annual Exceedance of Banks Pumping Plant Pumping in Each Commission Scenario

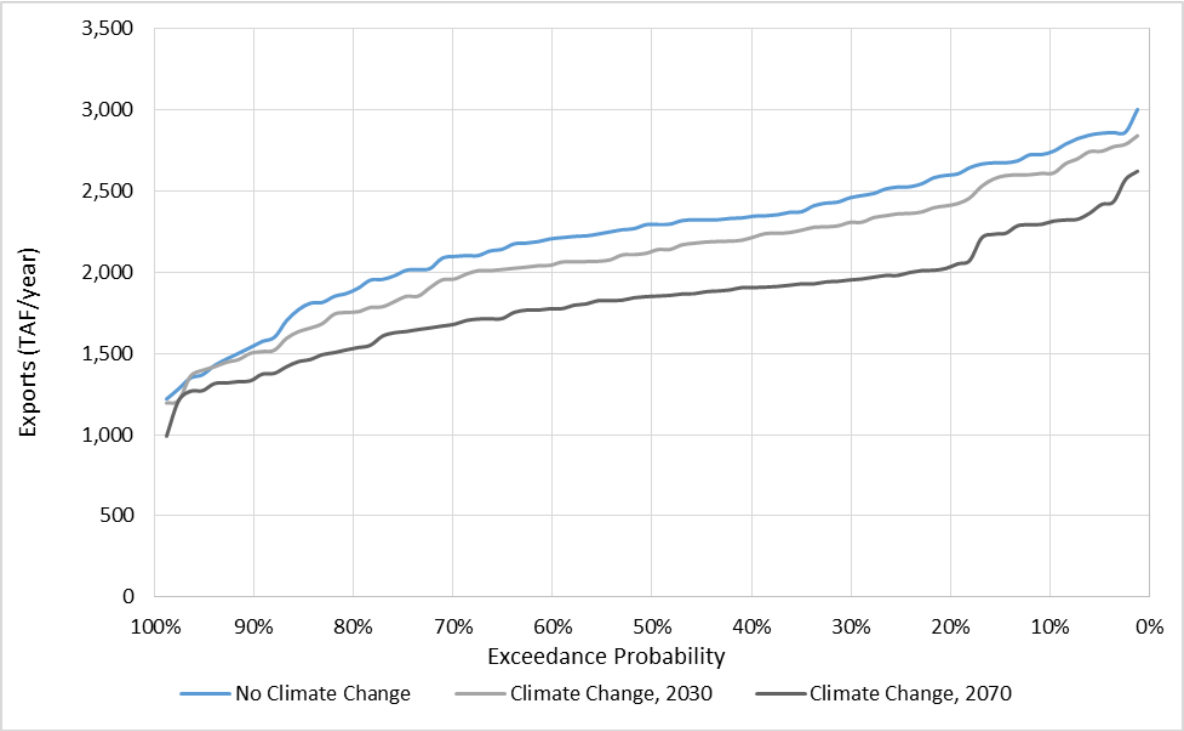


Figure 2-38. Annual Exceedance of C.W. Jones Pumping Plant Pumping in Each Commission Scenario

Delta Water Quality – Salinity

Table 2-3 shows the average EC expressed in micromhos per centimeter, equivalent to µS/cm at four Delta compliance locations, including Emmaton, Jersey Point, Vernalis, and Rock Slough. The EC at these locations is higher under climate change conditions than under no climate change conditions, consistent with 2016 Basin Study results. However, the salinity is generally lower in the Basin Study, especially under the central tendency scenario.

Table 2-6. Average April-August EC (µS/cm) at Emmaton and Jersey Point and Average EC (µS/cm) at Vernalis and Rock Slough in the Commission Climate Scenarios

Location	No Climate Change	Climate Change, 2030	Climate Change, 2070
Emmaton	211	658	745
Jersey Point	619	636	648
Vernalis	545	541	547
Rock Slough	431	449	438

Key:
µS/cm = micro-Siemens per centimeter
Commission = California Water Commission
EC = electrical conductivity

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Chapter 3 Potential to Achieve Objectives Under Future Climate Change

This chapter summarizes the likely impacts climate change would have on the achievability of the Investigation objectives using the modeling tools developed by the Commission, along with additional sensitivity analysis of how the impacts and benefits of Alternative 1B, the local preferred alternative and the EIS/EIR preferred alternative, would change given the ensemble scenarios of Commission "extreme" climate changes projected for the year 2070. The analysis of Alternative 1B showed small variations under "extreme" climate change, which are expected to be similar for the remaining alternatives since the impacts of the 2030 and 2070 Commission projections of climate change are similar between each alternative.

Performance of Alternatives Under Climate Change Conditions

The ensemble scenario developed by the Commission for the years 2030 and 2070 were used to evaluate the impacts and benefits of the Investigation proposed alternatives. These results are used to illustrate how the performance of the alternatives would be affected by future climate change.

Potential Changes in CVP/SWP Performance

None of the evaluated alternatives (Alternative 1A, 1B, 2A, and 4A) would change CVP or SWP deliveries under the climate changes scenarios evaluated. In addition, none of the alternatives would affect carryover storage at the major CVP and SWP reservoirs. Therefore, the alternatives would not adversely alter water deliveries to others under the 2030 and 2070 climate change scenarios. Table 3-1 shows changes in CVP and SWP deliveries and changes in carryover storage due to the implementation of any of the alternatives under consideration.

Table 3-1. Summary of Changes to CVP and SWP Performance in Each Commission Scenario due to the Alternatives

	Annual CVP Deliveries[1] (TAF)	Annual SWP Deliveries[2] (TAF)	CVP and SWP Carryover Storage[3] (TAF)
Near Future, with Climate Change (2030)	**4527**	**3707**	**6156**
Percent Change under Alt 1A	0.0%	0.0%	0.0%
Percent Change under Alt 1B	0.0%	0.0%	0.0%
Percent Change under Alt 2A	0.0%	0.0%	0.0%
Percent Change under Alt 4A	0.0%	0.0%	0.0%
Far Future, with Climate Change (2070)	**4184**	**3492**	**5477**
Percent Change under Alt 1A	0.0%	0.0%	0.0%
Percent Change under Alt 1B	0.0%	0.0%	0.0%
Percent Change under Alt 2A	0.0%	0.0%	0.0%
Percent Change under Alt 4A	0.0%	0.0%	0.0%

Notes:
[1] Total CVP Deliveries include total agricultural, refuge, municipal, and industrial deliveries.
[2] Total SWP Deliveries include Table A, Article 56, and Article 21.
[3] CVP and SWP Carryover Storage includes end-of-September storage for Shasta, Trinity, Oroville, Folsom, and San Luis reservoirs.
Key:
CVP = Central Valley Project
Commission = California Water Commission
SWP = State Water Project
TAF = thousand acre-feet

Potential Changes to Storage at Los Vaqueros

For each alternative, climate change creates a slight decrease in the amount of long-term average storage in Los Vaqueros Reservoir. Figure 3-1 shows how no climate change, 2030 climate change conditions, and 2070 climate change conditions would impact storage at Los Vaqueros Reservoir under each alternative.

Climate change also creates a slight decrease in the amount of storage during both wet and critically dry years as compared to no climate change conditions. However, operational decisions have a much greater effect than climate change, as seen in the differences between Alternatives 1A and 1B versus Alternative 2A. The impact of climate change on reservoir storage in wet years varies, but generally causes smaller changes than critically dry years.

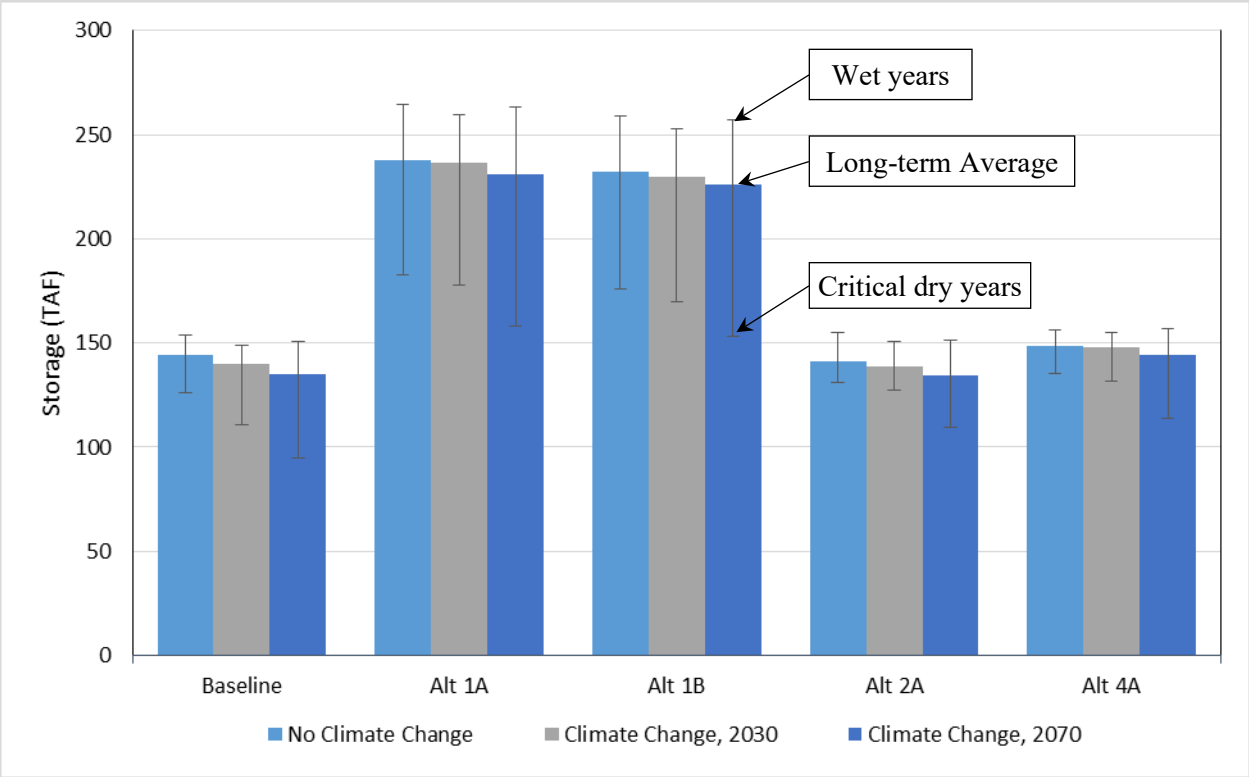

Figure 3-1. Los Vaqueros Reservoir Average Storage for Each Alternative in Each Commission Scenario

The percent change in storage from no climate change conditions to 2030 climate change conditions is reduced from -3 percent in the baseline to between -0.4 percent (Alternative 4A) and -1.6 percent (Alternative 2A) for the alternatives. The percent change in storage from no climate conditions to 2070 climate change conditions is reduced from -6 percent in the baseline to between -3 percent (Alternatives 1A, 1B, 4A) and -5 percent (Alternative 2A). Therefore, reservoir storage is more resilient to the impacts of climate change in the alternatives than in the baseline conditions.

Potential Changes to CCWD Deliveries and their Salinity

All project alternatives, including the baseline, deliver the same amount of water to Contra Costa Water District in a given water year type and climate change scenario. As seen in Table 3-2, CCWD deliveries increase in 2070 climate conditions in all scenarios due to increased CCWD demands in this future scenario.

Table 3-2. Contra Costa Water District Deliveries for Each Alternative in Each Commission Scenario

	Long-Term Average CCWD Deliveries (TAF)			Wet Year Average CCWD Deliveries (TAF)			Critically Dry Year Average CCWD Deliveries (TAF)		
	No Climate Change	Climate Change, 2030	Climate Change, 2070	No Climate Change	Climate Change, 2030	Climate Change, 2070	No Climate Change	Climate Change, 2030	Climate Change, 2070
Baseline	138	138	149	130	131	141	151	151	164
Alt 1A	138	138	149	130	131	141	151	151	164
Alt 1B	138	138	149	130	131	141	151	151	164
Alt 2A	138	138	149	130	131	141	151	151	164
Alt 4A	138	138	149	130	131	141	151	151	164

Key:
CCWD = Contra Costa Water District
Commission = California Water Commission
TAF = thousand acre-feet

In addition, despite slight changes in the salinity content of CCWD deliveries under the 2030 and 2070 climate conditions, the long-term average salinity of CCWD deliveries is relatively unchanged with climate change, as shown in Figure 3-2. Each alternative improves salinity when compared to baseline conditions, with the exception of Alternative 4A under no climate change conditions.

In critically dry years, only Alternative 1A remains relatively unaffected by climate change conditions, as shown in Figure 3-3. Under 2030 and 2070 conditions, increases in the salinity of CCWD deliveries occur for the project alternatives, likely due to increases in Delta water salinity due to sea level rise. In wet years, under 2030 and 2070 conditions, decreases in the salinity of CCWD deliveries occur for the project alternatives, despite increases in Delta salinity due to sea level rise. The effects of sea level rise are counteracted by increased runoff into the Delta due to precipitation shifts from snow to rain due to warmer temperatures and generally increased precipitation in the Commission climate scenarios. Climate change conditions increase the difference between critically dry and wet years' salinity levels.

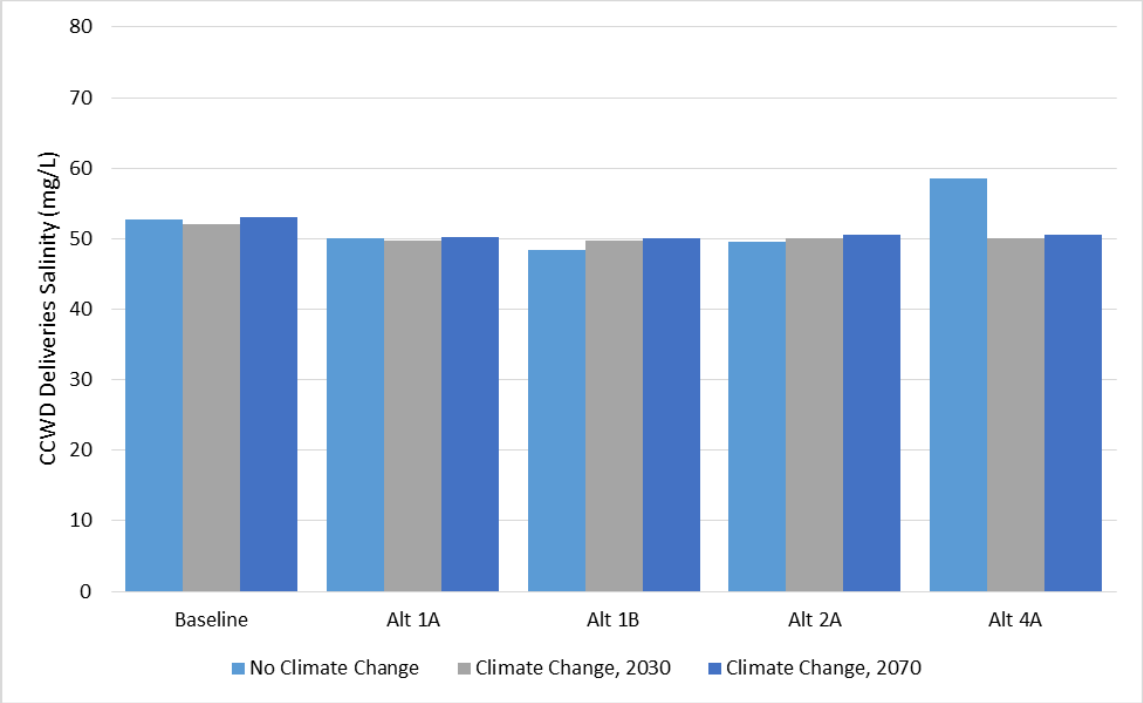

Figure 3-2. Long-Term Average of Salinity of CCWD Deliveries for Each Alternative in Each Commission Scenario

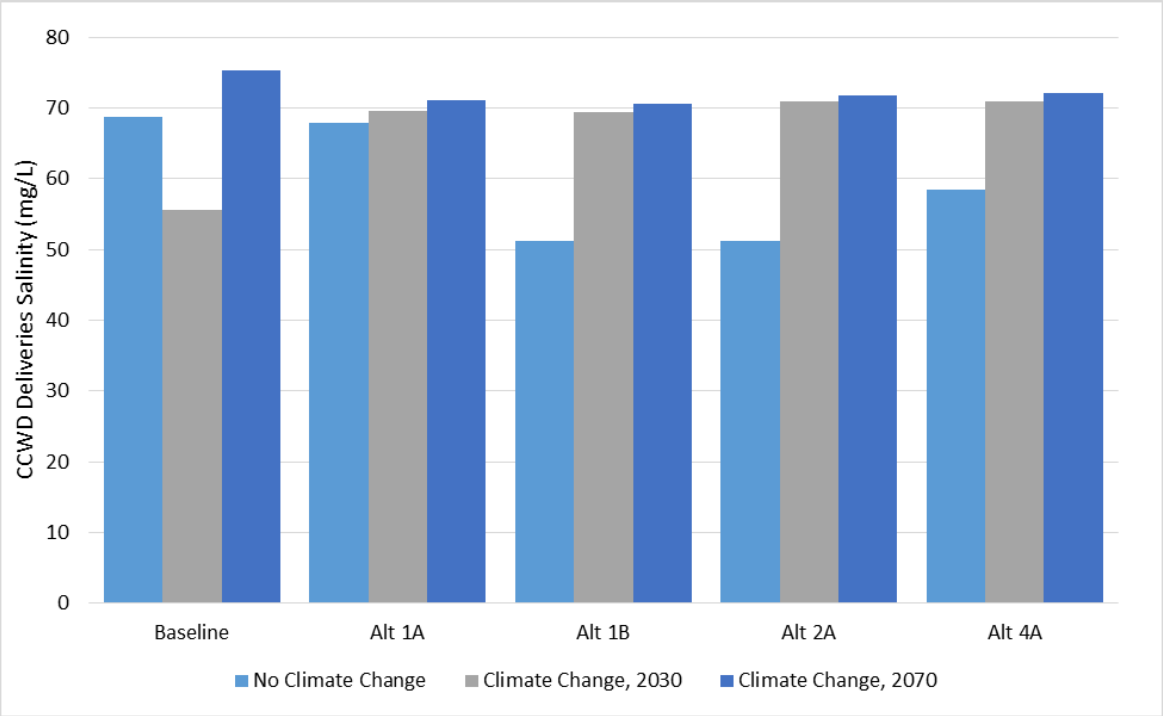

Figure 3-3. Salinity of CCWD Deliveries in Critically Dry Years for Each Alternative in Each Commission Scenario

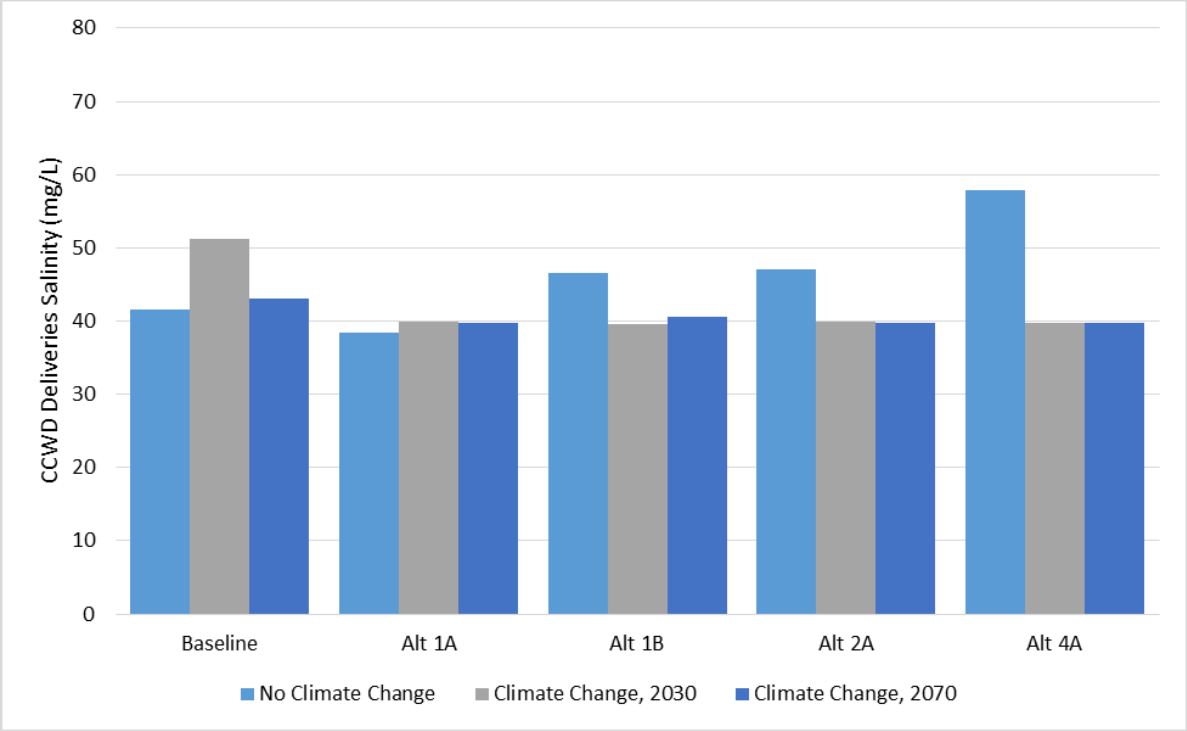

Figure 3-4. Salinity of CCWD Deliveries in Wet Years for Each Alternative in Each Commission Scenario

Potential Changes to Refuge Deliveries

Delta Mendota Canal and California Aqueduct refuge delivery benefits are resilient under the climate change scenarios, as shown in Figure 3-5. Under 2030 and 2070 climate change conditions, deliveries to the Refuges remain fairly stable in all alternatives.

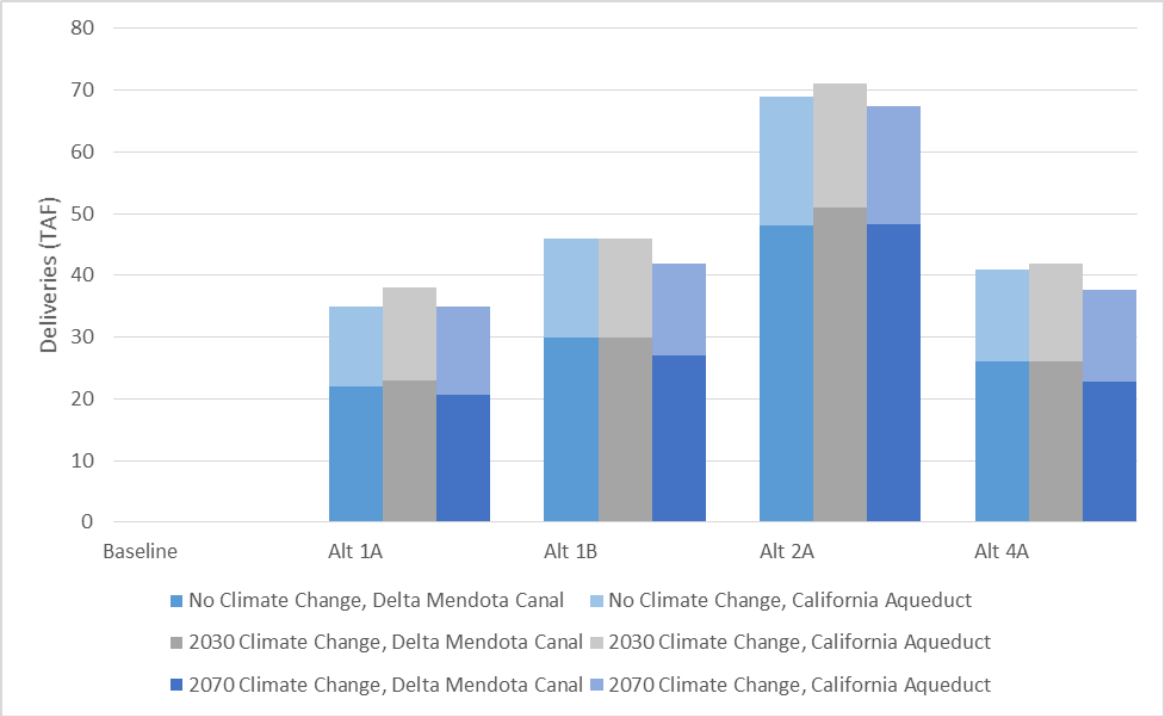

Figure 3-5. Long-Term Average Refuge Deliveries for Each Alternative in Each Commission Scenario

While the amount of water delivered to the Refuges changes drastically based on the water year categorization as wet, above normal, below normal, dry, and critical, the direction and magnitude of the change is inconsistent, as shown in Table 3-3 below. These deliveries represent a much smaller fraction of water than most of the flows considered in the model. Therefore, model operational decisions result in larger differences than the various climate change conditions, with no meaningful trends provided in the results.

Table 3-3. Comparison of Refuge Deliveries (TAF) in Wet, Above Normal, Below Normal, Dry, and Critical Water Years for Each Alternative

	Wet	Above Normal	Below Normal	Dry	Critical
Baseline					
No Climate Change	0	0	0	0	0
2030 Climate Change	0	0	0	0	0
2070 Climate Change	0	0	0	0	0
Alternative 1A					
No Climate Change	78	33	17	13	3
2030 Climate Change	75	44	26	13	3
2070 Climate Change	70	35	19	16	6
Alternative 1B					
No Climate Change	96	49	26	15	1
2030 Climate Change	92	62	32	12	0
2070 Climate Change	83	56	25	17	0
Alternative 2A					
No Climate Change	126	80	49	32	12
2030 Climate Change	128	91	59	26	7
2070 Climate Change	123	89	47	30	5
Alternative 4A					
No Climate Change	88	44	21	13	2
2030 Climate Change	80	59	29	12	0
2070 Climate Change	75	47	22	14	0

Key:
TAF = thousand acre-feet

Potential Changes to Municipal and Industrial Deliveries

The impact of climate change on municipal and industrial partners varies depending on the operational priorities chosen for an alternative, as shown in Figure 3-6. The differences due to operational decisions between Alternatives 1A and 1B and Alternative 2A are larger than those due to climate change. The changes in deliveries are small in magnitude when comparing 2030 or 2070 climate change conditions to the baseline. However, the deliveries remain fairly stable with climate change.

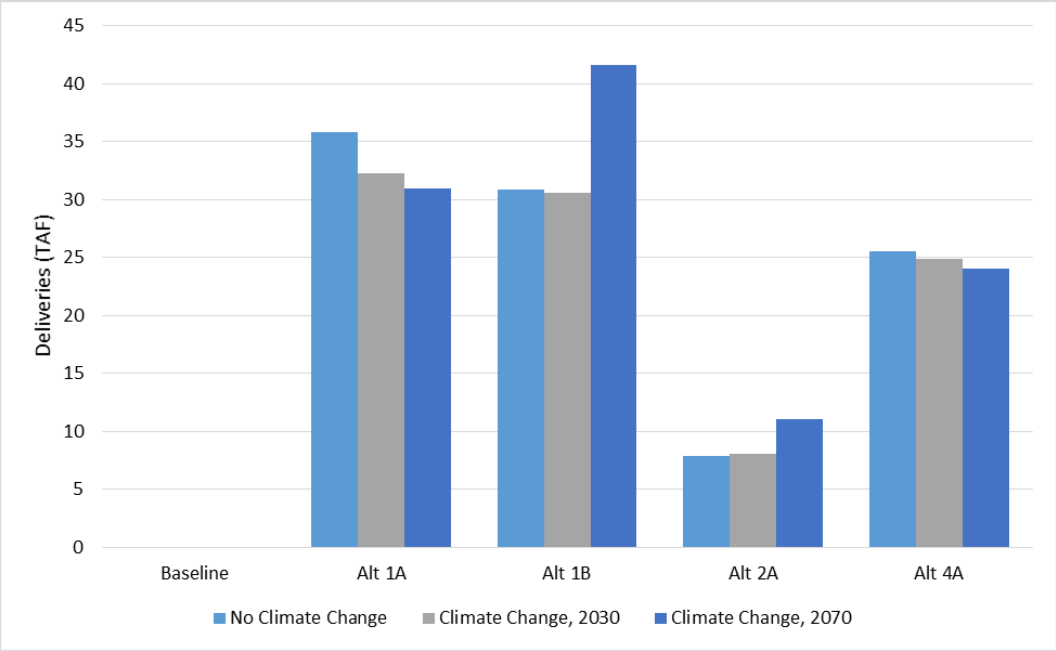

Figure 3-6. Long-Term Average Municipal and Industrial Deliveries for Each Alternative in Each Commission Scenario

Summary of the Performance of Alternatives Under Climate Change

The project's benefits remain resilient under the climate change scenarios examined. Table 3-4 summarizes the effects of climate change on the various benefits of the project.

Table 3-4. Summary of Climate Change Effects on Project Alternatives

Project Benefit/Impact	Effect of Climate Change
Water Deliveries to Others (SWP/CVP)	Decreased overall; no impact from project under the climate change scenarios
Los Vaqueros Reservoir Storage	Slightly decreased long-term average storage (less than 2% for all alternatives by 2030, less than 5% for all alternatives by 2070)
CCWD Deliveries	No significant impacts
CCWD Delivery Salinity	No significant impacts on the long-term average. Increased variation between wet and critically dry years.
Refuge Deliveries	No significant impacts
M&I Deliveries	No significant impacts

Key: CCWD = Contra Costa Water District
CVP = Central Valley Project
M&I = municipal and industrial
SWP = State Water Project

Sensitivity Analysis – Alternative 1B Performance Under "Extreme" Climate Change

The Commission provides "extreme" climate change projections for 2070 that are used to conduct this sensitivity analysis. These projections were used to model Alternative 1B. Changes in impacts and benefits associated with Alternative 1B are illustrative of the overall effect of "extreme" climate change on other alternatives. These "extremes" are similar to the boundary ensemble projections created by the Basin Study – a WW and HD Commission scenario.

The first extreme scenario has a statewide 7.1 percent decrease in precipitation and an 8.4°F increase in temperature by 2070, a DEW scenario. The second extreme scenario has a statewide 20.4 percent increase in precipitation and a 3.5°F increase in temperature, a WMW scenario by 2070. The changes of temperature and precipitation within the Central Valley are shown in Table 3-5 below.

Table 3-5. Projected Changes in Climate Conditions for 2070 "Extreme" Conditions with Respect to the 1995 Reference (Commission 2016)

Basin	2070 DEW Future		2070 WMW Future	
Watershed Name (USGS HUC-6)	Average Precipitation Change	Average Temperature Change (°F)	Average Precipitation Change	Average Temperature Change (°F)
Statewide				
Statewide	-7.1%	8.4	20.4%	5.4
Central Valley Regions				
Central Valley	-8.6%	9.2	21.1%	3.9
Upper Sacramento	-10.1%	9.0	16.1%	3.9
Lower Sacramento	-6.3%	8.2	24.2%	3.6
San Joaquin	-7.5%	8.4	23.6%	3.5
Tulare-Buena Vista Lakes	-12.9%	8.2	20.1%	3.2

Note:
Regions are shown in Figure 2-23.
Key:
°F = degrees Fahrenheit
Commission = California Water Commission
DEW = drier, extreme warming
HUC = hydrologic unit code
USGS = United States Geological Survey
WMW = wetter, moderate warming

Despite the "extreme" climate change conditions, no change in water deliveries to others results from the implementation of the project. No change occurs in annual CVP/SWP deliveries or carryover storage due to the implementation of the project as shown in Table 3-6.

Table 3-6. Summary of Changes to CVP and SWP Performance in Each "Extreme" Commission Scenario Due to the Alternative 1B

	Annual CVP Deliveries[1] (TAF)	Annual SWP Deliveries[2] (TAF)	CVP and SWP Carryover Storage[3] (TAF)
2070 WMW Future	**4440**	**3931**	**6308**
Percent Change under Alt 1B	0.0%	0.0%	0.0%
2070 DEW Future	**3854**	**3223**	**4751**
Percent Change under Alt 1B	0.0%	0.0%	0.0%

Notes:
[1] Total CVP Deliveries include total agricultural, refuge, municipal, and industrial deliveries.
[2] Total SWP Deliveries include Table A, Article 56, and Article 21.
[3] CVP and SWP Carryover Storage includes end-of-September storage for Shasta, Trinity, Oroville, Folsom, and San Luis reservoirs.
Key:
CVP = Central Valley Project
Commission = California Water Commission
DEW = drier, extreme warming
SWP = State Water Project
TAF = thousand acre-feet
WMW = wetter, moderate warming

As shown in Figure 3-7, storage in Los Vaqueros Reservoir is highly resilient to climate change, with the extreme scenarios only causing small changes in the overall storage of the reservoir.

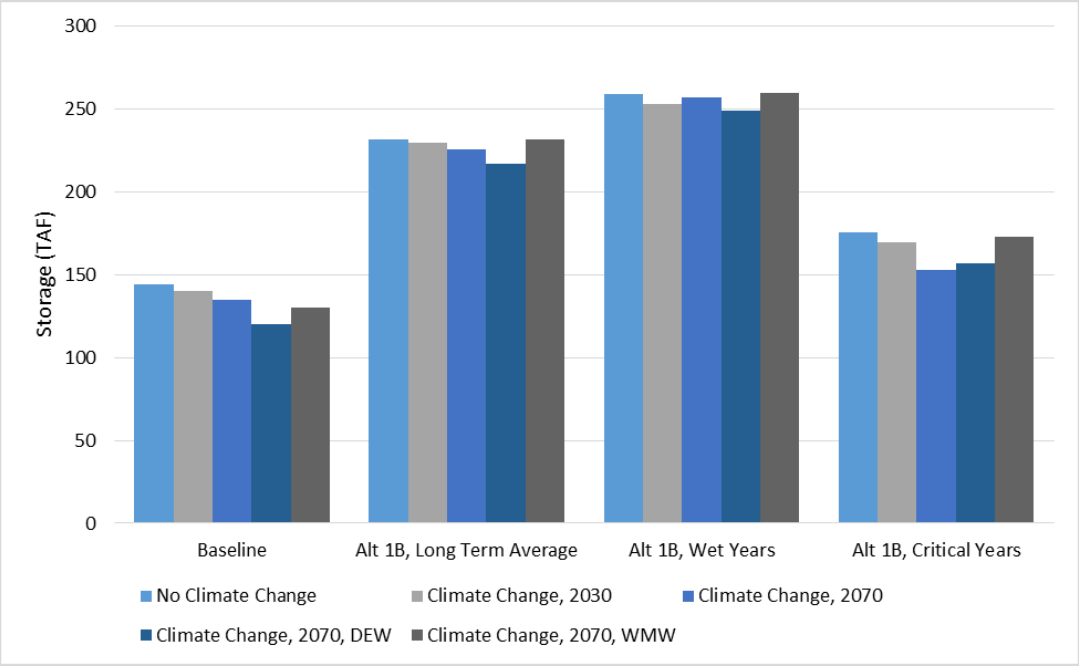

Figure 3-7. Los Vaqueros Reservoir Average Storage for Alternative 1B in Each Commission Scenario, Including Two Extreme Scenarios

The amount of water delivered to CCWD changes under the extreme climate scenarios for Alternative 1B. Under the DEW scenario, the long-term average delivery is 154 TAF, higher than under the 2070 ensemble conditions. CCWD would require more water under a dryer future to offset increases in salinity as lower runoff combined with sea level rise in the Delta result in increased salinity. Under the WMW scenario, the long-term average delivery is 143 TAF, lower than under the 2070 ensemble conditions. CCWD would require less water under a wetter future since additional runoff would combat increasing salinity due to sea level rise in the Delta. The deliveries follow a similar pattern between these two scenarios in both wet and critically dry years.

The salinity of the deliveries is shown in Figure 3-8. Under either the WMW or DEW scenarios, the salinity of the CCWD deliveries remains relatively unchanged from 2070 climate change conditions.

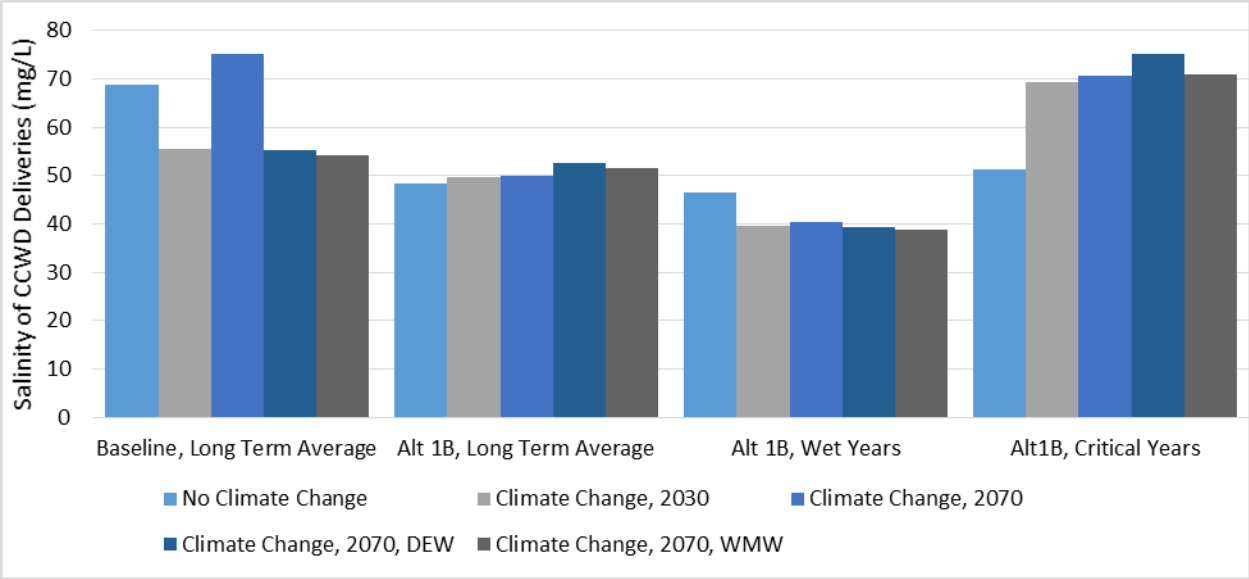

Figure 3-8. Salinity of CCWD Deliveries for Alternative 1B in Each Commission Scenario, Including Two Extreme Scenarios

Figure 3-9 shows that the extreme climate scenarios result in equal or greater refuge deliveries for Alternative 1B as in the 2070 ensemble climate change scenarios and greater deliveries than in the no climate change conditions. Figure 3-10 illustrates how the municipal and industrial deliveries depend more on policies than climate change with no discernible patterns due to the impact of climate change.

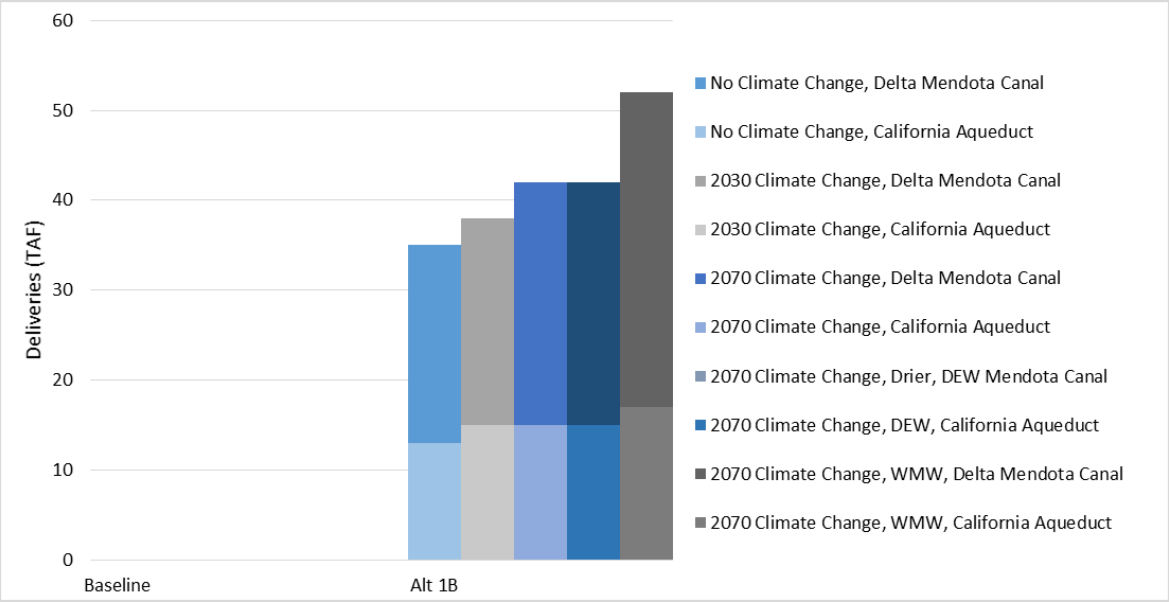

Figure 3-9. Long-Term Average Refuge Deliveries for Alternative 1B in Each Commission Scenario, Including Two Extreme Scenarios

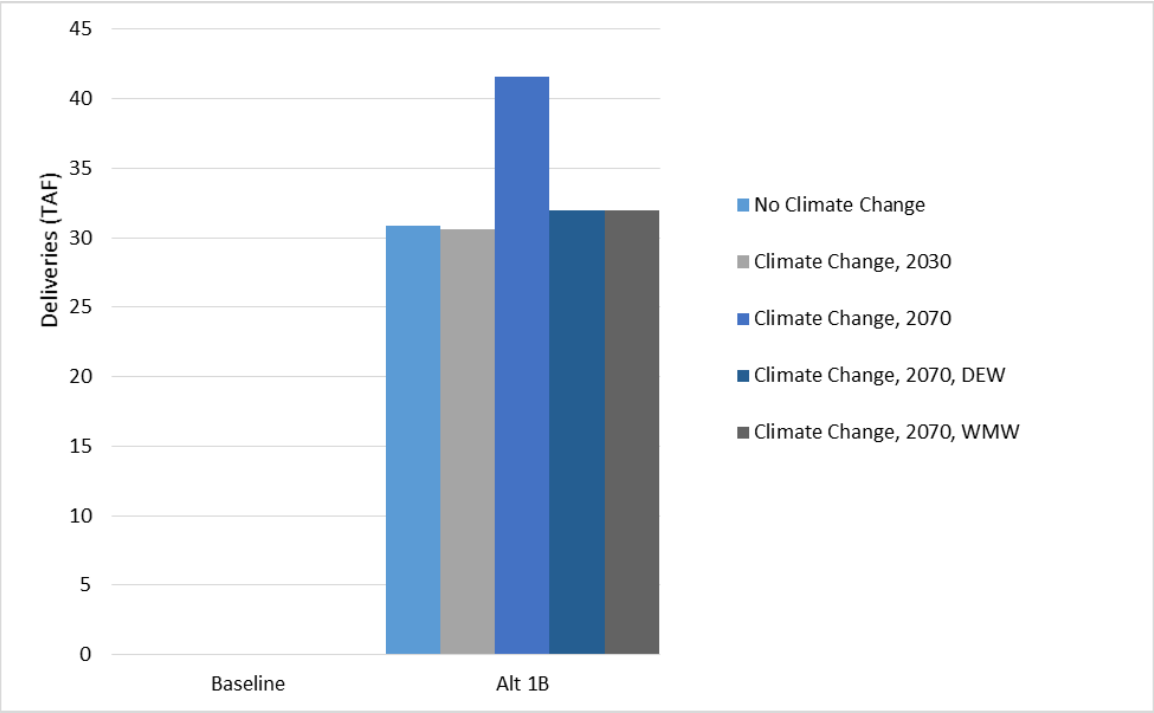

Figure 3-10. Long-Term Average Municipal and Industrial Deliveries for Alternative 1B in Each Commission Scenario, Including Two Extreme Scenarios

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Chapter 4 References

Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson, and R. Snyder. 2008. Progress on Incorporating Climate Change into Management of California's Water Resources. *Climactic Change*, Springer, Netherlands, Volume 69, Supplement 1, pp. 91-108. Published online 12-22-2007. ISSN: 0165-009 (Print) 1573-1480 (Online) DOI: 10.1007/s10584-007-9353-1.

Beckley, B.D., F.G. Lemoine, S.B. Luthcke, R.D. Ray, and N.P. Zelensky. 2007. A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits. *Geophysical Research Letters* 34:L14608.

CalEPA. *See* California Environmental Protection Agency.

CALFED. *See* CALFED Independent Science Board.

CALFED Independent Science Board. 2007. Sea Level Rise and Delta Planning. Memorandum to Michael Healey, Lead Scientist of the CALFED Bay-Delta Program. September 6, 2007.

_____. 2007. Conceptual Model for Salinity in the Central Valley and Sacramento-San Joaquin Delta. Prepared by CALFED Bay-Delta Program, Sacramento, California

Cayan, D.R., S.A. Kammerdiener, M.D. Dettinger, J.M. Caprio, and D.H. Peterson. 2001. Changes in the Onset of Spring in the Western United States. Bulletin of the American Meteorology Society 82(3):399-415.

California Environmental Protection Agency. 2013. Indicators of Climate Change in California. Prepared by the Office of Environmental Health Hazard Assessment (OEHHA). Available: <https://oehha.ca.gov/media/downloads/risk-assessment/document/climatechangeindicatorsreport2013.pdf> Last updated: August 2013. Accessed June 28, 2017.

CCWD. *See* Contra Costa Water District.

Church, J.A., and N.J. White. 2006. A 20th century acceleration in global sea-level rise. *Geophysical Research Letters* 33:L01602.

Contra Costa Water District. 2017. About Us. Contra Costa Water District. Available at: http://www.ccwater.com/27/About-Us. Accessed August 28, 2017.

Dettinger, M.D., and D.R. Cayan. 1995. Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California. *Journal of Climate*. Vol. 8(3).

Hoerling M., J. Eischeid and J. Perlwitz. 2010. Regional Precipitation Trends: Distinguishing National Variability from Anthropogenic Forcing. *Journal of Climate*. 23:2131–2145. DOI: 10.1175/2009JCLI3420.1.

Griggs, G., J. Árvai, D. Cayan, R. DeConto, J. Fox, H.A. Fricker, R.E. Kopp, C. Tebaldi, E.A. Whiteman (California Ocean Protection Council Science Advisory Team Working Group). 2017. Rising Seas in California: An Update on Sea-Level Rise Science. California Ocean Science Trust.

IPCC. 2007. The Physical Science Basis, contribution of Working Group I to The Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.).

Kapnick, S., and A. Hall. 2009. Observed Changes in the Sierra Nevada Snowpack: Potential Causes and Concerns. California Energy Commission CEC-500-2009-016-F.

Knowles, N., M. Dettinger, and D. Cayan. 2007. Trends in Snowfall Versus Rainfall in the Western United States, 1949-2001. Prepared for California Energy Commission Public Interest Energy Research Program, Project Report CEC-500-2007-032.

Maurer, E.P. 2007. Uncertainty in hydrological impacts of climate change in the Sierra Nevada, California under two emissions scenarios. *Climactic Change*, Vol. 82(3-4): 309-325. DOI: 10.1007/s10584-006-9180-9.

Moser. S., G. Franco, S. Pittiglio, W. Chou, D. Cayan. 2009. The Future is now: An Update on Climate Change Science Impacts and Response Options for California. California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2008-071.

Mote, P.W., A.F. Hamlet, M.P. Clark, and D.P. Lettenmaier. 2005. Declining mountain snowpack in western North America. Bull. Amer. Meteor. Soc., 86:39-49.

NRC. *See* National Research Council.

National Research Council. 2012. Sea-Level Rise of the Coasts of California, Oregon, and Washington: Past, Present, and Future. Committee on Sea Level Rise in California, Oregon, and Washington, Board on Earth Sciences and Resources, Ocean Studies Board, Division on Earth and Life Studies. The National Academies Press. Washington, D.C.

Null, S.E., J.H. Viers and J.F. Mount. 2010. Hydrologic Response and Watershed Sensitivity to Climate Warming in California's Sierra Nevada. *PLoS One*. Vol. 5(4):e9932. DOI:10.1371/journal.pone.0009932.

Ramstorf, S. 2007. A semi-empirical approach to projecting future sea level. *Science*. Vol. 315(5810): 368-370, DOI: 10.1126/science.1135456.

Reclamation. 2011. West-Wide Climate Risk Assessments: Bias Corrected and Spatially Downscaled Surface Water Projections, prepared by the U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado. March 2011.

_____. 2014a. Central Valley Project Integrated Resource Plan Technical Report. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, California.

_____. 2014b. Shasta Lake Water Resources Investigation: Climate Change Modeling Appendix. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, California.

_____. 2014c. West-Wide Climate Risk Assessment: Sacramento and San Joaquin Basins Climate Impact Assessment. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, California.

_____. 2016a. Reclamation Climate Change and Water SECURE Water Act Section 9503(c) Report 2016. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Policy and Administration, Denver, Colorado.

_____. 2016b. Sacramento and San Joaquin Rivers Basin Study: Basin Study Technical Report. Sacramento, California.

Regonda, S.K., B. Rajagopalan, M. Clark, and J. Pitlick. 2005. Seasonal Cycle Shifts in Hydroclimatology Over the Western United States. *Journal of Climate* 18(2):372-384.

Roos, M. 1991. A trend of decreasing snowmelt runoff in northern California. Proceedings of 59th Western Snow Conference, Juneau, Alaska, pp 29-36.

Vermeer, M., and S. Rahmstorf. 2009. Global Sea Level Linked to Global Temperatures. Proceedings of the National Academy of Sciences.

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