RECLAMATION

Managing Water in the West

West-Wide Climate Risk Assessment

Sacramento and San Joaquin Basins
Climate Impact Assessment

U.S. Department of the Interior
Bureau of Reclamation

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

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.

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Sacramento and San Joaquin Basins
Climate Impact Assessment

Prepared for Reclamation by CH2M HILL under
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Bureau of Reclamation
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Abbreviations and Acronyms

°C	degrees Centigrade
°F	degrees Fahrenheit
µS/cm	microSiemens per centimeter
AET	actual evapotranspiration
AMJ	April, May, and June
AMO	Atlantic Multi-decadal Oscillation
ANN	artificial neural network
AR4	Fourth Assessment Report (IPCC's 2007 Climate Change 2007: The Physical Science Basis)
Banks PP	Harvey O. Banks Pumping Plant
Bay-Delta	San Francisco Bay–Sacramento-San Joaquin Delta Commission
BDCP	Bay Delta Conservation Plan
BiOp	biological opinion
CAT	California Climate Action Team
CCSM	Community Climate System Model
CDEC	California Data Exchange Center
CDF	cumulative distribution function
cfs	cubic feet per second
cm	centimeter
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CNRM	National Centre for Meteorological Research (transposition from French)
CO2	carbon dioxide
CT	Current Trends
CT_noCC	Current Trends NoCC
CT_Q5	Current Trends – central tendency
CVP	Central Valley Project
CVP IRP	Central Valley Project Integrated Resource Plan
CVP IRP CalLite	CVP IRP Central Valley Water Management Screening Model
CWP	California Water Plan Update 2009
D1641	Decision 1641
Delta	Sacramento-San Joaquin Delta
DOF	California Department of Finance
DRMS	Delta Risk Management Strategy
DWR	California Department of Water Resources
EC	electroconductivity
EG	Expansive Growth
EG-Q2	Expansive Growth – warmer and drier
EI5	five ensemble-informed

ENSO	El Nino Southern Oscillation
ET	evapotranspiration
GCM	global climate model
GHG	greenhouse gas
GWh/year	gigawatt hours per year
Impact Assessment	West-wide Climate Risk Assessment for the Sacramento and San Joaquin Basins
IPCC	Intergovernmental Panel on Climate Change
JAS	July-August-September
JFM	January-February-March
Jones PP	C. W. Jones Pumping Plant
km	kilometer
MAF	million acre-feet
MPI	Max Planck Institute for Meteorology
mTCO2e	metric tons of CO2 equivalents
mTCO2e/GWH	metric tons of CO2 equivalents per gigawatt hour
NCAR	National Center for Atmospheric Research
NOAA	National Oceanographic and Atmospheric Administration
NoCC	No Climate Change scenario
NRC	National Research Council
OMR	Old and Middle Rivers
OND	October-November-December
PCM	Parallel Climate Model
PDO	Pacific Decadal Oscillation
Q1	drier, less warming
Q2	drier, more warming
Q3	wetter, more warming
Q4	wetter, less warming
Q5	ensemble median
Reclamation	Bureau of Reclamation
SG	Slow Growth
SG-Q4	Slow Growth – less warming and wetter
SRES	Special Report on Emission Scenarios
SSJBS	Sacramento and San Joaquin Basins Study
SSJIA	Sacramento and San Joaquin Basins Study Climate Impact Assessment
SWE	snow water equivalent

SWP	State Water Project
SWRCB	State Water Resources Control Board
TAF	thousand acre-feet
TAF/year	thousand acre-feet per year
USACE	U.S. Army Corps of Engineers
USFWS	U.S. Fish and Wildlife Service
VIC	Variable Infiltration Capacity
WCRP	World Climate Research Program
WEAP-CV	Water Evaluation and Planning model of the Central Valley
WWCRA	West-wide Climate Risk Assessment
X2	2 parts per thousand salinity concentration

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Chapter 1 – Executive Summary

Introduction

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009) (SWA), authorizes the Bureau of Reclamation (Reclamation) to evaluate the risks and impacts of climate change in each of the eight major Reclamation river basins identified in the Act, and to work with stakeholders to identify climate adaptation strategies. Reclamation implements Section 9503 of the SWA through the Basin Study Program, part of the Department of Interior's WaterSMART Program, which is working to achieve a sustainable water strategy to meet the Nation's water needs now and for the future. Through West-Wide Climate Risk Assessments (WWCRAs) conducted under that program, Reclamation is conducting reconnaissance-level assessments of risks to water supplies and related resources in eight major Reclamation river basins in the Western United States.

This report presents the results of the Sacramento and San Joaquin Climate Impact Assessment (SSJIA), which addresses impacts in two of these major basins in California. The SSJIA also includes the Tulare Lake Basin in the southern part of the Central Valley of California; part of the Trinity River watershed from which some water is diverted into the Central Valley; and a portion of California's central coast region where Central Valley Project (CVP) and State Water Project (SWP) water supplies are delivered. The water supplies and demands analyzed in the SSJIA include CVP water users, SWP water users, and the other non-project water users in the study area.

Included in the report is an overview of the current climate and hydrology of California's Central Valley (Sacramento, San Joaquin and Tulare Lake Basins), an analysis of observed trends in temperature and precipitation over historical record, and a comparison of these trends to future water operation projections not considering climate change. The report then presents hydrologic projections developed from global climate models to evaluate the ways that projected climatic and hydrologic changes could impact water availability and management and water demands within the Sacramento, San Joaquin and Tulare Lake basins. The SSJIA analyzes potential impacts of climate change under a current trends projection of future urban growth considering the conversion of agricultural to urban land use and assuming the continuation of current crop types in the Central Valley. Finally, the SSJIA assesses risks to the eight major resource categories identified in the SWA by looking at a range of climate futures and attempting to book-end future uncertainties.

The SSJIA complements and builds on several previous climate change impact studies performed by Reclamation. In 2011, Reclamation completed its first climate change and impact assessment report under the SWA (Reclamation 2011). The 2011 SWA report was based on 112 climate change projections developed for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment report (IPCC 2007) as part of the World Climate Research Program's Coupled Model Intercomparison Project phase 3 (CMIP3). The primary focus of the 2011 SWA report was on 21st century changes in temperature, precipitation and their impact on "unimpaired" flows in the eight major Reclamation river basins, including the

Sacramento and San Joaquin rivers. These flows were simulated to represent what would occur without current infrastructure, reservoir and project operations and regulatory requirements. The report also contained qualitative estimates of impacts on other SWA resource categories.

The Central Valley Project Integrated Resource Plan (CVP IRP), completed by Reclamation in 2013, employed the same climate change projections as the 2011 SWA report, with the addition of sea level rise, and expanded the study area to include the entire CVP Service Area. The CVP IRP also used different methods and models to characterize future climate and socioeconomic uncertainties and their impact on water supply, demand, and some related resources. Most significant was the inclusion of current reservoir and conveyance infrastructure, CVP/SWP operational criteria, and regulatory requirements. The SSJIA leverages the methodologies and tools developed for the CVP IRP – expanding the analysis to include all water users in the Sacramento, San Joaquin, and Tulare Lake basins, and completing a more comprehensive assessment of impacts in all the resource categories identified by the SWA.

Reclamation is also currently working with five non-federal cost-share partners on a Sacramento and San Joaquin Basins Study (SSJBS), a collaborative evaluation of potential climate impacts and formulation of adaptation strategies. The SSJBS, conducted under Reclamation's Basin Study Program as a complement to the SSJIA, is scheduled to be completed in 2015 and is not included in this report. Currently, the SSJBS study partners are updating the climate impact assessments using the new IPCC CMIP phase 5 climate projections and the latest California Water Plan Update 2013 socioeconomic projections.

Study Approach

Reclamation employed a scenario based approach in the SSJIA to evaluate the impacts of potential climate change to water and related resources in the 21st century. The two major uncertainties affecting future impacts included climate and socioeconomic conditions. Future socioeconomic assumptions used in the SSJIA were based on population projections to 2050 as developed by the State of California's Department of Finance (DOF) and assumptions about the effects of urban growth on agricultural lands. The DOF projections were extended from 2050 to 2100 using projections developed by the Public Policy Institute of California. Climate uncertainties were addressed by including multiple 21st century projections using Global Climate Model (GCM) simulations to represent a wide range of potential future climate conditions.

A total of 18 socioeconomic-climate scenarios were developed for the SSJIA. A single socioeconomic projection representing a continuation of "Current Trends" in population and land use changes was employed. In this projection, California's Central Valley population was assumed to increase from the 2005 base levels by 8 million in 2050 and 19 million in 2100. The Current Trends scenario also assumed that as population increased in California's Central Valley, the expansion of urban regions would encroach into surrounding agricultural areas and would result in a projected loss of 500,000 irrigated acres by 2050 and 1.7 million acres by 2100.

The Current Trends socioeconomic projection of water demands was combined with 18 projections of potential future climate (temperature, precipitation and carbon dioxide) changes. These transient projections included one which assumed no climate change and 17 GCM-based projections. Of these projections, five future climates were developed using ensembles of multiple climate projections to characterize the central tendency and four bounding potential climates relative to the central tendency. In addition, six GCMs considered to be especially relevant to California hydrology were included and climate projections were developed based on both high and low greenhouse gas (GHG) emissions scenarios to represent a wide range of potential future climate conditions.

The SSJIA also included one projection of sea level rise. This transient projection was the mean estimate developed by the National Research Council (NRC 2012). This sea level rise projection was simulated to estimate the salinity changes of the Sacramento-San Joaquin Delta (Delta). These simulations assumed that Delta levees would remain intact despite rising sea levels in the 21st century.

The modeling of the impacts of potential climate changes on water and the related resources was accomplished by using the suite of decision support tools developed for the CVP IRP study. These models use the 18 socioeconomic-climate projections as inputs to quantify water supplies and demands. Current reservoir and conveyance infrastructure, CVP/SWP operations and regulatory requirements are assumed to remain in place throughout the 21st century. In addition to climate impacts to water supplies and demands, the modeling tools estimate impacts to river and Delta flows, reservoir storage, CVP/SWP exports, groundwater pumping, water quality (river water temperatures and Delta salinity), CVP/SWP hydropower generation and associated GHG emissions. The relative effects of socioeconomic-climate changes on SWA resource categories can also be observed by comparing the model results with various performance metrics which are presented in greater detail in the body of the SSJIA.

Summary of Results

Climate Changes

The central tendency projected changes in annual average temperature in the Central Valley basins relative to the 1970 – 2000 historical period range from approximately 1 °C in the early 21st century to slightly less than 2 °C by mid-century. In the late 21st century, annual average temperatures are projected to increase in excess of 3 °C. A significant west to east geographic trend exists with greater change in temperatures projected in the interior Central Valley and Sierra regions as the distance from the cooling effect of Pacific Ocean increases.

The projected changes in annual average precipitation in the Central Valley basins show a clear north to south trend of decreasing precipitation, similar to historical conditions. This trend is projected to occur throughout the 21st century. In the northern part of the Sacramento Valley, projections indicate a slight increase of a few percent in precipitation around the mid-century period. A slight decrease in precipitation was projected to occur in both the San Joaquin and Tulare Lake basins. In these basins, the reductions tend to increase throughout the 21st century from a few percent to nearly 10 percent in the southern parts of the Central Valley.

Sea level, relative to levels in 2000 at the Golden Gate Bridge in San Francisco, could rise by 92 centimeters by the end of the century with a potential range from 42 to 166 centimeters.

Water Supplies and Demands

The potential climate change impacts on water supply and demand were assessed for each major hydrologic region in the study area. In each region, the climate scenarios exhibit a shift to more runoff in the winter and less in the spring months. This projected shift occurs because higher temperatures during winter cause more precipitation to occur as rainfall, which increases runoff and reduces snowpack. The projected annual runoff into major Central Valley reservoirs is similar to the historical period with a north to south geographical trend toward slightly reduced runoff reflecting a similar trend in precipitation.

Under current reservoir operational criteria, the seasonal shift in runoff has a negative impact on the ability to store water for later use. With earlier runoff and more precipitation occurring as rainfall, reservoirs may fill earlier and excess runoff may have to be released downstream to ensure adequate capacity for flood control purposes.

Water demands were impacted by both changes in climate and socioeconomics. The projected increases in population resulted in a steady increase in urban water use during the 21st century. Agricultural demands were also impacted by the assumed decrease in irrigated acreage and the changing climate. Unlike urban demands, agricultural demands have considerable inter-annual variability. In low precipitation years, demand is higher while in high precipitation years, agricultural water demands decrease. During the 21st century, the average annual agricultural demands are projected to decrease because of reduced irrigated acreage and to a lesser extent the effects of increasing carbon dioxide on decreasing water use by some crops despite increased temperatures in the latter half of the 21st century.

System Risk and Reliability

The SWA mandates the analysis of impacts that changes in water supply may have on eight specific resource categories. The summary presented in Table 1 provides a generalized assessment of the SWA Resource category impacts. The overall 21st century projected impacts are evaluated by changes in performance metrics with contributing factors described. The evaluation is based on current CVP/SWP operations, infrastructure and regulatory requirements without the implementation of adaptation strategies.

It is important to recognize that there are limitations to the interpretation of the impacts presented in Table 1. First, the resource impacts represent overall 21st century average conditions. However, there exists considerable variability during this period. Second, other limitations exist because of uncertainties in the socioeconomic-climate scenarios, the use of performance-based change metrics, and in the models employed for the impact evaluations. The column titled "Overall 21st Century Projects Impacts" shows an average of the central tendency range of impacts and is a representation of one of several possibilities examined. Please see Chapter 8 of this report for a more in-depth discussion of the projected impacts for each resource category.

Table 1. Summary of Projected Impacts by SWA Resource Category

SWA Resource Category	Change Metrics	Overall 21st Century Projected Impacts	Contributing Factors
Water Deliveries	Unmet Demands, End of September Storage, CVP/SWP Delta Exports	Unmet demands - Projected to increase by 3% End of September Storage – Projected to decrease by 2% CVP/SWP Delta Exports – Projected to decrease by 3%	Projected earlier seasonal runoff would cause reservoirs to fill earlier, leading to the release of excess runoff and limiting overall storage capability and reducing water supply; Sea level rise and associated increased salinity would result in more water needed for Delta outflow standards with less water available to deliver to water contractors
Water Quality	Delta Salinity and End of May storage	Delta Salinity – Projected to increase by 33% End of May Storage – Projected to decrease by 2%	Projected sea level rise would contribute to increased salinity in the Delta; climate warming and reduced reservoir storage would contribute to increased river water temperatures
Fish and Wildlife Habitats	Pelagic Species Habitats, Food Web Productivity	Pelagic Species Habitats – Projected to decrease by 12% Food Web Productivity – Projected to decrease by 8%	Increasing Delta salinity would contribute to declining pelagic habitat quality; reduced Delta flows in summer would contribute to declining food web productivity
ESA Species	Adult Salmonid Migration, Cold Water Pool	Adult Salmonid Migration – Projected to decrease by 1% Cold Water Pool – Projected to decrease by 4%	Projected reduced Delta flows in summer would contribute to declining salmonid migration; reduced reservoir storage would contribute to reduced cold water pool
Flow Dependent Ecological Resiliency	Floodplain Processes	Projected to decrease by 1%	Projected reduced reservoir storage and reduced spring runoff due to decreasing snowpack would contribute reduced river flows
Hydropower	Net Power Generation	CVP Net Generation - Projected to decrease by 2% SWP Net Generation – Projected to increase by 8%	Projected decreased in CVP reservoir storage would contribute to less power generation; projected decreased SWP water supply would result in reduced power use for pumping and conveyance
Recreation	Reservoir Surface Area	Projected to decrease by 17%	Projected lower reservoir levels would impact the surface area available for recreation
Flood Control	Reservoir Storage below Flood Control Pool	Projected to increase by 7%	Projected increases in early season runoff would contribute to releases earlier in the flood control period providing more flood storage.

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Chapter 2 – Introduction

Section 9503 of the SECURE Water Act, Subtitle F of Title IX of P.L. 111-11 (2009), authorizes Reclamation to evaluate the risks and impacts of climate change in each of the eight major Reclamation river basins identified in the Act, and to work with stakeholders to identify climate adaptation strategies. Reclamation implements Section 9503 of the SECURE Water Act through the Basin Study Program, part of the Department of Interior's Sustain and Manage America's Resources for Tomorrow (WaterSMART) Program, which is working to achieve a sustainable water strategy to meet the Nation's water needs now and for the future. To learn more about WaterSMART, please visit http://www.usbr.gov/WaterSMART/.

The Basin Study Program includes WWCRA, Basin Studies, and Landscape Conservation Cooperatives. These activities are complementary and represent a multi-faceted approach to address climate change. The WWCRA represents Reclamation's reconnaissance-level assessment of the hydrologic impacts of climate change, including risks to water supplies and demands. The WWCRA includes three separate activities:

1. Consistent, west-wide assessment of climate-change impacts to water supplies
2. Consistent, west-wide assessment of climate-change impacts to water demands
3. Impact assessments for individual basins or sub-basins

This report, conducted under the third WWCRA activity listed above for the SSJIA, provides baseline information about the potential risks of climate change, including projected impacts on water supplies and demands to Reclamation facilities and operations, including water and power delivery, recreation, flood control, and ecological resources. Additionally, this report provides information about the current Sacramento and San Joaquin Basins water management system under different potential future climate conditions.

The SSJIA is conducted to provide:

- A baseline analysis of potential climate change impacts that can be used to support the SSJBS where possible adaptation and mitigation strategies are developed and assessed.
- A more in-depth analysis of climate change impacts as they relate to Reclamation facilities and operations.

Because the SSJIA is not focused on the development of adaptation strategies, Reclamation performed the study without direct involvement of non-Federal partners. This allows Reclamation to develop consistent baseline information in a time frame consistent with the reporting requirements of SWA 9503(c).

The SSJIA builds on an existing knowledge base that includes a variety of studies and reports. The information developed in the SSJIA will be used by the SSJBS as a foundation to work collaboratively with local cost-share partners and other stakeholders to evaluate existing and future supplies and demands, perform a risk and reliability assessment, and identify and analyze potential adaptation strategies.

Chapter 3 – Purpose and Background

Variability and uncertainty are the dominant characteristics of California's water resources. California's water resources vary dramatically across the state because of extreme differences in precipitation. The geographic variation and the unpredictability of precipitation make it challenging to manage the available runoff to meet urban and agricultural water needs. Most of California's precipitation occurs between November and April, yet most of the state's demand for water is in the hot, dry summer months. Additionally, most of the precipitation falls in the mountains in the northern half of the state, far from major population and agricultural centers.

To address location and timing differences among water supplies and water demands, Federal, State, and local water agencies constructed various water supply projects. DWR and Reclamation operate the SWP and the CVP, respectively, to divert, store, and convey water consistent with applicable water and environmental laws and contractual obligations in the northern portion of the state and divert water for the central and southern portions of the State from the Delta. The CVP includes major dams and associated reservoirs (Shasta, Trinity, Whiskeytown, and Folsom) located north of the Delta. The CVP also includes facilities (New Melones and Friant) south of the Delta that are operated to meet water supply and environmental demands in the San Joaquin River basin. Oroville Reservoir is the major SWP storage facility north of the Delta. After delivering water for local needs north of the Delta, water is transported via natural watercourses and canal systems to areas south and west of the Delta. San Luis Reservoir is a south-of-Delta offstream storage reservoir operated to store diversions from the Delta and provide both the CVP and SWP flexibility in delivering water on demand to the contractors of both projects.

The California water system is facing significant uncertainties associated with factors such as climate, agricultural and urban water demands, and ecosystem needs, as well as changing institutional conditions and regulatory requirements. The SSJIA analyzes the risk associated with climate uncertainties to water supply, water deliveries, hydropower generation, water quality, aquatic and terrestrial species, floods, recreation, and ecosystem resiliency within the California water system. An analytical framework has been developed that uses a suite of future climate scenarios to evaluate the effects of future changes on the water system on urban, agricultural, and environmental water needs and other water management goals under a broad range of potential future conditions.

Basin Description

This SSJIA study incorporates the three major hydrologic regions which comprise California's Central Valley. These regions are the Sacramento, the San Joaquin and the Tulare Lake basins. This study also includes other areas such as the Delta and central California coastal areas receiving water from the Reclamation's CVP. In addition to these areas, the study area also includes part of the Trinity River watershed which exports water from the Trinity River to the Sacramento River and the CVP. The entire area is shown on Figure 1.

Figure 1. SSJIA Study Area

The north portion of the Central Valley of California incorporates the Sacramento River basin. The Sacramento River is the largest river in California with a historical mean annual flow of 18 MAF. It drains an area of about 27,000 square miles and flows south to the Delta. Located south of the Delta, the San Joaquin River basin incorporates an area of about 32,000 square miles. The San Joaquin River flows north to the Delta and is the second largest river in California with an historical mean annual flow of 6 MAF. Both of these rivers flow into the Sacramento – San Joaquin Delta which is the largest estuary on the west coast of the United States. In the southern region of the Central Valley of California, the Tulare Lake basin incorporates about 17,050 square miles and incorporates the Kings, Kaweah, Tule, and Kern Rivers. All runoff in the Tulare Lake basin remains in the basin and there are no exports.

The two major water projects in this area are the CVP and the SWP. Reclamation began construction of the CVP in 1933. Today it consists of 20 dams, 11 powerplants and more than 500 miles of canals that serve many purposes including providing an average of 3.2 MAF of water per year to senior water right holders under settlement/stipulation agreement primarily for irrigation purposes, 2.2 MAF for CVP irrigation water contractors and approximately 310 TAF for CVP urban water users. The agricultural water deliveries irrigate about 3 million acres of land in the Sacramento, San Joaquin, and Tulare Lake basins. The 1992 Central Valley Project Improvement Act (CVPIA) dedicated about 1.2 MAF of annual supplies for environmental purposes. The State of California built and operates the SWP which provides up to about 3 MAF/year on average in water supplies from Lake Oroville on the Feather River to municipal and agricultural water users in the Central Valley as well as in central and southern coastal areas.

The historical climate of the Central Valley of California is characterized by hot and dry summers and cool and damp winters. Summer daytime temperatures can reach 90 °F with occasional heat waves with temperatures exceeding 110 °F. The majority of precipitation occurs from mid-autumn to mid-spring. The Sacramento Valley receives greater precipitation than the San Joaquin and Tulare Lake basins. During the 20th century, warming was prevalent over the Sacramento and San Joaquin River basins and has continued into the 21st century. Basin average mean-annual temperatures have increased by approximately 2 °F over the period that records have been kept. In the Sacramento basin, the warming trend also has been accompanied by a gradual trend starting in the 1930's toward increasing precipitation. Although annual precipitation may have slightly increased or remained relatively unchanged, corresponding increases in mean annual runoff in the Sacramento and San Joaquin Rivers did not occur (Dettinger and Cayan, 1995). However, a change in the timing of seasonal runoff has been observed (Roos, 1991). In the Sacramento River basin, a decrease of about 10 percent in fraction of total runoff occurring between April–July has occurred over the course of the 20th century.

Sea level change is also an important factor affecting California's water resources because of its potential effect on water quality in the Delta. Many of the Delta islands' land surfaces are below sea level and protected from flooding by non-engineered levees. Sea level rise threatens the integrity of these levees. Flooding of Delta islands would result in highly saline water being pulled in from the Bay thus degrading the Delta's water quality. During the 20th century, mean sea level in San Francisco Bay has risen by an average of 2mm/yr (0.08 in/yr) (Anderson et al., 2008) and its rate of rise appears to be increasing (Beckley et al., 2007).

Document Organization

This report begins with a discussion of the authorizations, purpose and description of the basins, followed by analysis methods, and then study results. The following list breaks down which information is presented in each chapter of this report.

- Chapters 2 & 3 introduce the SSJIA and describe the motivations for this work, objectives and scope, and programs supporting the study.
- Chapters 4 & 5 present the methods used for the analysis of current trends in climate and hydrology in the basin as well as the approach used to develop socioeconomic-climate future scenarios.
- Chapter 6 describes impacts to climate, hydrology, and water supply.
- Chapter 7 describes impacts to water demands.
- Chapter 8 describes system risk and reliability impacts to water management, including: water and power infrastructure/operations, water delivery, flood control operations, water quality, fish and wildlife habitat, critical habitat for species listed under the Federal ESA, flow and water-dependent ecological resiliency, and water-related recreation.
- Chapter 9 discusses study limitations and next steps.

Chapter 4 – Technical Approach

The technical approach employed in this SSJIA was designed to evaluate the impacts of climate change on water and related resources during the 21st century. An important aspect of the assessment is how to address the uncertainties involved in the analysis. Two major uncertainties affecting future impacts are climate and socioeconomic conditions. Although both involve significant degrees of uncertainty, it is clear that both climate and socioeconomic conditions are dynamic in nature. This aspect of the assessment was addressed by employing a transient analysis in which both climate and socioeconomic conditions are changing over time. The climate uncertainties were addressed by including multiple 21st century projections using Global Climate Model (GCM) simulations to represent a wide range of potential future climate conditions. Uncertainties in future socioeconomic conditions were based on population projections from present day to 2050 developed by the State of California's Department of Finance (DOF) and include assumptions about the effects of urban growth on agricultural lands. These socioeconomic projections are embedded in the 2009 California Water Plan. Additional information related to how the socioeconomic and climate projections were developed is provided in Chapter 5 of this report.

The modeling approach and tools employed in the SSJIA are shown on Figure 2 below. The modeling approach and tools were developed as part of the CVP IRP, which employed a scenario-based planning approach to evaluate the effectiveness of potential water management actions to increase supply and reduce demand under a range of potential future climate and socioeconomic conditions. Additional information on the modeling tools is available in the CVP IRP report (Reclamation, 2013)[1].

In the Critical Uncertainties and Scenario Development task (left side of figure), a current trends socioeconomic projection was combined with multiple GCM-based climate projections to form 18 future scenarios representing a wide range of potential 21st century socioeconomic-climate uncertainties. The scenarios were developed using data from climate projections used in the Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report (AR4) (IPCC 2007) and the World Climate Research Program's (WCRP) CMIP3.

The socioeconomic-climate scenarios developed for the SSJIA were used as inputs to the Water Evaluation and Planning model of the Central Valley (WEAP-CV) hydrology model (center left on figure) to simulate watershed runoff, reservoir inflows, river flows, groundwater recharge and demands for urban and agricultural water uses. These results were subsequently used as inputs to the CalLite model (center right on the figure) which simulates how the CVP, SWP and other water management infrastructure are operated to supply water to meet urban, agriculture, and environmental needs.

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[1] The CVP IRP report can be downloaded from the SSJBS website at http://www.usbr.gov/mp/SSJBasinStudy/documents.html

Results from the CalLite model were used as the basis for the Supply and Demand imbalance analysis and as inputs to other Performance Assessment Tools (lower left on figure) for evaluating impacts on water temperature, hydropower, greenhouse gas (GHG) emissions, as well as urban and agricultural economics. The final step was to assess the significance of the impacts by comparing the modeling results to Performance Metrics (lower center on figure) associated with a variety of resource categories important to the management of water resources in the study area. More detailed descriptions of the technical approach and assessment results are provided in the following sections for each resource category.

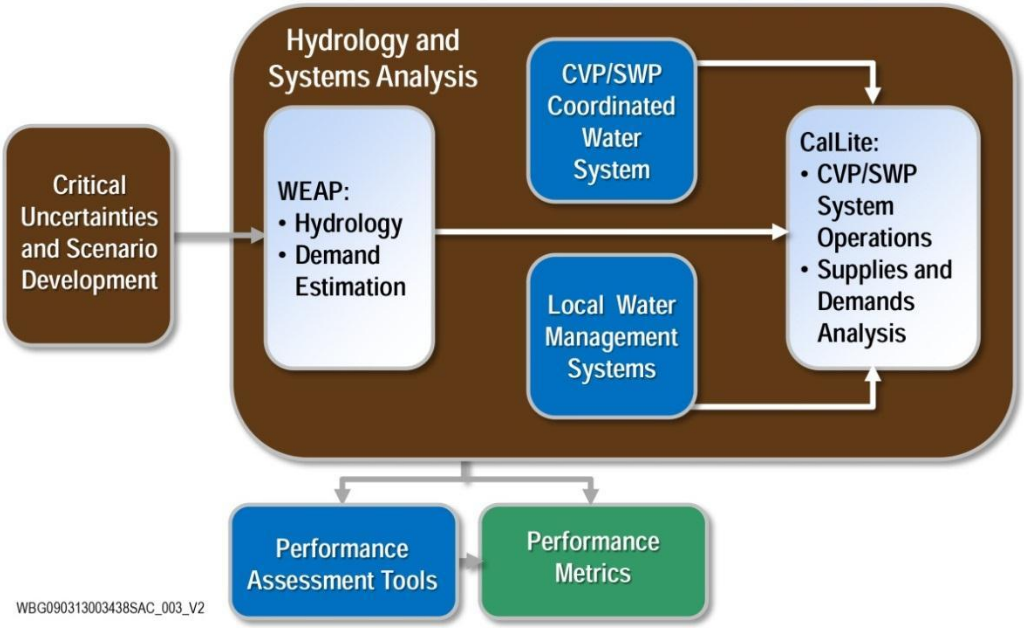


Figure 2. SSJIA Modeling Approach

Chapter 5 – Socioeconomic-Climate Future Scenarios

Water supplies and demands in the 21st century have uncertainties associated with both changing climate and evolving socioeconomic conditions. Climate is the most important factor influencing gross water supplies. Changes in the amount of precipitation directly affect water supplies. In addition, changes in the seasonality of precipitation or the amount of precipitation falling as snow versus rain will affect the ability to store water supplies, which in turn will affect water supply availability for particular needs. Temperature is one of several climate characteristics that can influence water supplies through its effect on reservoir evaporation and crop evapotranspiration. While increasing temperature tends to increase evapotranspiration by vegetation leading to a decrease in runoff, other climate changes such as increasing atmospheric carbon dioxide tend to reduce evapotranspiration, thereby offsetting some of the effects of increasing temperature. Similarly, these effects may tend to reduce water demands by some agricultural crops.

Socioeconomic conditions have a direct effect on water demands. As population increases, water demands for municipal, commercial, and industrial water supplies tend to increase. Furthermore, land-use changes also have important effects on water demands. How urban growth occurs has important influences on adjacent agricultural lands and the demand for agricultural water supplies.

Socioeconomic Futures

Because the focus of this report is on climate impact assessment, only a Current Trends (CT) projection of future socioeconomic conditions was used to represent changes in population and land use during the 21st century. This scenario was based on information developed by the California Water Plan Update 2009 (CWP) (DWR, 2009) and the CVP IRP. The CT projection was selected for use in the SSJIA because it represented an estimate of central tendency of future socioeconomic conditions which in combination with the 18 climate projections used, provided a reasonably wide range of future socioeconomic-climate uncertainties.

Figures 3-4 show the CT population and irrigated land projections for the Sacramento, San Joaquin and Tulare Lake hydrologic basins in the years 2005 (Base), 2050 and 2100. The CT projection was based on data developed by the California DOF (DOF, 2007). The DOF data included a single population projection for each county through 2050. These projections were extended from 2050 to 2100 using data from a study by the Public Policy Institute of California (Johnson, 2008) with some additional adjustments to make the projections more consistent with the DOF projections from 2010 to 2050. The projected changes in irrigated lands were developed from information used in the CWP Update 2009. These land use projections were extended from 2050 to 2100 by methods used for the CVP IRP (Reclamation, 2013). As shown on the figure, irrigated land acreages decline during the 21st century in all three hydrologic regions in proportion to the increase in population under the assumption that urban growth results in some loss of agricultural land.

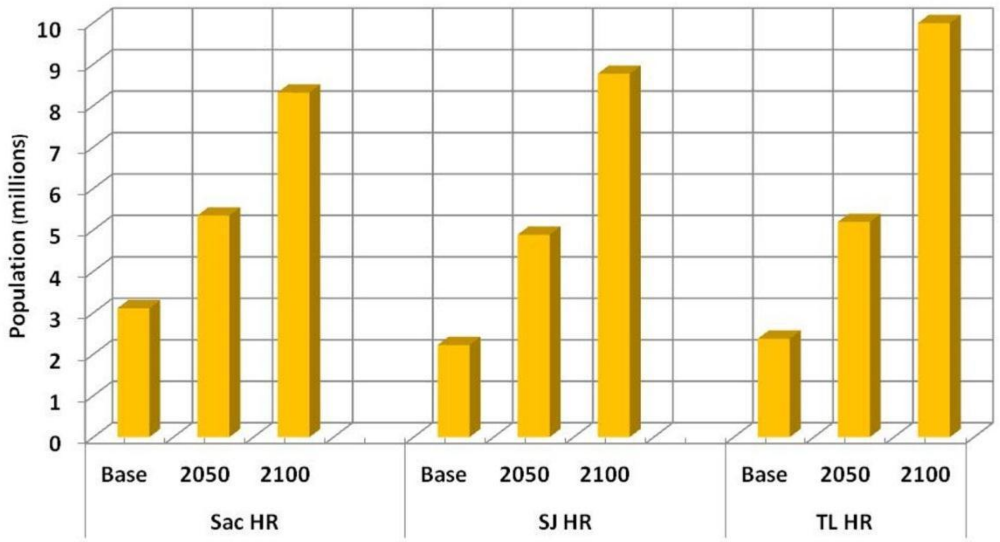


Figure 3. CT Population Projections for Hydrologic Regions: the Sacramento River, San Joaquin River, and Tulare Lake

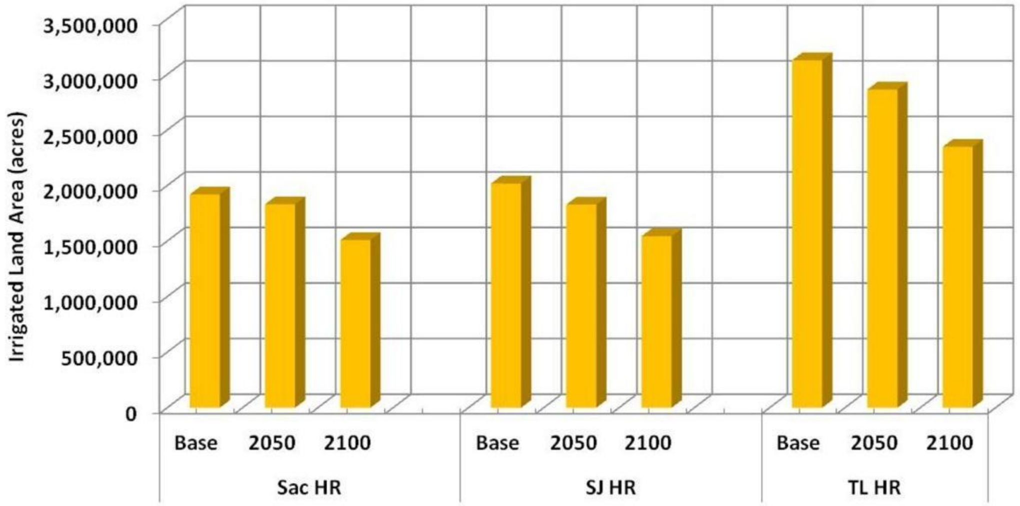


Figure 4. CT Irrigated Land Projections for Hydrologic Regions: the Sacramento River, San Joaquin River and Tulare Lake

Climate Futures

A total of 18 climate projections were used to characterize a wide range of future hydroclimate uncertainties. The following projections were included in the SSJIA:

- **No Climate Change (NoCC) Scenario**, which included simulations of hydroclimatic conditions under historical climate.

- **Future Climate – Ensemble-Informed (EI) Scenario** utilized five ensemble-informed (EI5) scenarios that were developed by the CVP IRP based on downscaled GCM projections.

- **Future Climate – Downscaled Climate Projections** utilized the 12 specific GCM projections identified by the State of California's Climate Action Team (CAT) for use in climate studies performed by DWR for the CWP **(i.e., 12 CAT Scenarios)**.

Table 2 summarizes the 18 climate scenarios: one reflecting no climate change (NoCC), 5 EI scenarios (Q1 through Q5) and 12 CAT scenarios. For each scenario, temperature and precipitation projections were developed for the period from 2011 through 2099. The methods used to develop each climate scenario are described below.

Table 2. Climate Scenarios Used in the SSJIA

Scenario	Description	Emmission Scenarios
NoCC	No Climate Change	Not applicable
Q1	Drier and less warming	Derived from mixtures of SRES A1B, A2, and B1
Q2	Drier and more warming	Derived from mixtures of SRES A1B, A2, and B1
Q3	Wetter and more warming	Derived from mixtures of SRES A1B, A2, and B1
Q4	Wetter and less warming	Derived from mixtures of SRES A1B, A2, and B1
Q5	Central tending climate scenario	Derived from mixtures of SRES A1B, A2, and B1
CAT Scenarios (12 Total CAT scenarios)	California's CAT scenarios were developed to be used in the 2009 update of the California Water Plan.	The A2 scenario represents the higher emission levels, while the B1 represents lower emission levels

For each of these 18 scenarios, temperature and precipitation projections were developed for the future period of 2011 through 2099. The NoCC scenario was developed by using the unadjusted historical climate sequence from 1915 through 2003 to simulate the same future period as the other 17 climate projections.

The EI climate projections were developed from 112 GCM simulations which had been bias-corrected spatially downscaled (BCSD) by Reclamation and others (Maurer et al., 2007). Using statistical techniques, the wide range of future temperature and precipitation uncertainties expressed in the full ensemble of 112 projections were represented in EI5 projections. Details of the methodology can be found in Reclamation (2013). One of the five EI projections include a central tendency projection (Q5) that is based on the BCSD projections near the median of changes in temperature and precipitation. The remaining four EI projections are based on ensembles of BCSD projections that differ from the central tendency by being drier with less warming (Q1); drier with more warming (Q2); wetter with more warming (Q3); and wetter with less warming than Q5. In addition, atmospheric carbon dioxide concentrations for each of the five climate projections were computed from the IPCC

(IPCC 2000) emission's scenarios associated with the individual GCM projections included in the ensemble.

The 12 CAT scenarios were developed as part of a series of reports released by California's CAT in 2009 that serve as a summary update of the latest climate change science and response options for decision makers in California (Cayan et al. 2008a, 2008b, and 2008c). This document included 12 CAT climate change scenarios (6 GCMs x 2 emission scenarios). The Special Report on Emission Scenarios (SRES) A2 (higher) and B1 (lower) emission scenarios was selected to represent a range of possible future global conditions (IPCC 2000). Approximately 80 percent of the range of emissions are between the A2 (higher emissions) and B1 (lower emissions). It should also be noted that the current GHG trajectory has been more closely following the A1Fi scenario.

Six GCMs were selected for use in the 2008–2009 update:

- National Center for Atmospheric Research's (NCAR) Parallel Climate Model
- National Oceanographic and Atmospheric Administration's GFDL version 2.1
- NCAR Community Climate System Model
- Max Planck Institute for Meteorology's (MPI) MPI ECHAM5
- Center for Climate System Research (The University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC), Japan MIROC 3.2 medium resolution model
- National Centre for Meteorological Research models used in the IPCC's AR4 and the WCRP's CMIP3

These GCM's were selected by the State's CAT based their ability to "reasonably" simulate historical climatic conditions including seasonal precipitation, temperature and variability of annual precipitation in California as well as important global climate conditions such as tropical Pacific Ocean sea surface temperatures associated with the El Nino Southern Oscillation. To bracket the range of future climatic uncertainties, high and low GHG emissions scenarios were simulated by each of the six models yielding the 12 CAT projections.

Figure 5 shows the central tendency (Q5) projected changes in annual average temperature in degrees centigrade (°C) relative to the average 1970 – 2000 historical period during the early (2025), middle (2055), and late (2084) 21st century for the Central Valley and surrounding areas.

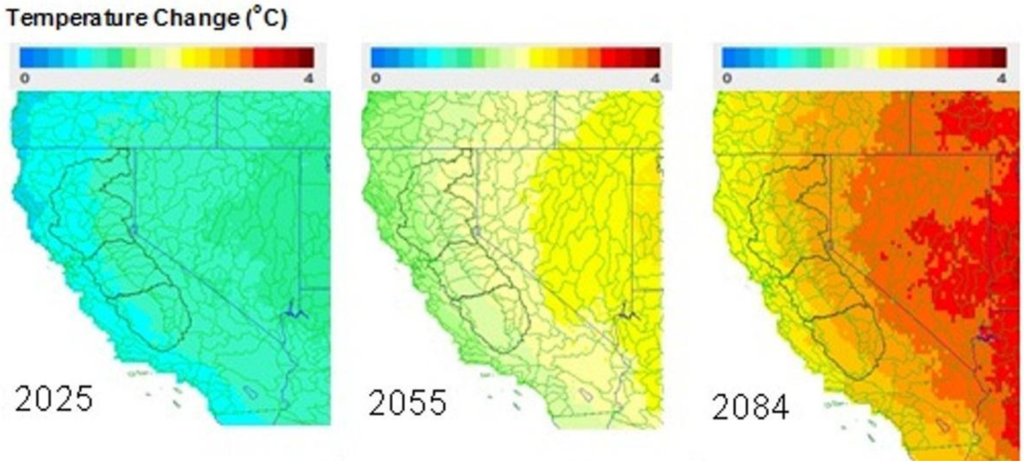


Figure 5. Projected Annual Average Temperature Changes (°C) in the early, mid, and late 21st century

As can be observed on the figure, there is a significant west to east trend with more warming in the interior regions as the distance from the cooling effect of Pacific Ocean increases. In the study area, warming increases from about 1 °C in the early 21st century to slightly less than 2 °C at mid-century and exceeds 3 °C in the eastern most regions by late in the 21st century.

Figure 6 shows the central tendency (Q5) projected changes in annual average precipitation expressed as a percentage relative to the average 1970 – 2000 historical period during the early (2025), middle (2055), and late (2084) 21st century for the Central Valley and surrounding areas.

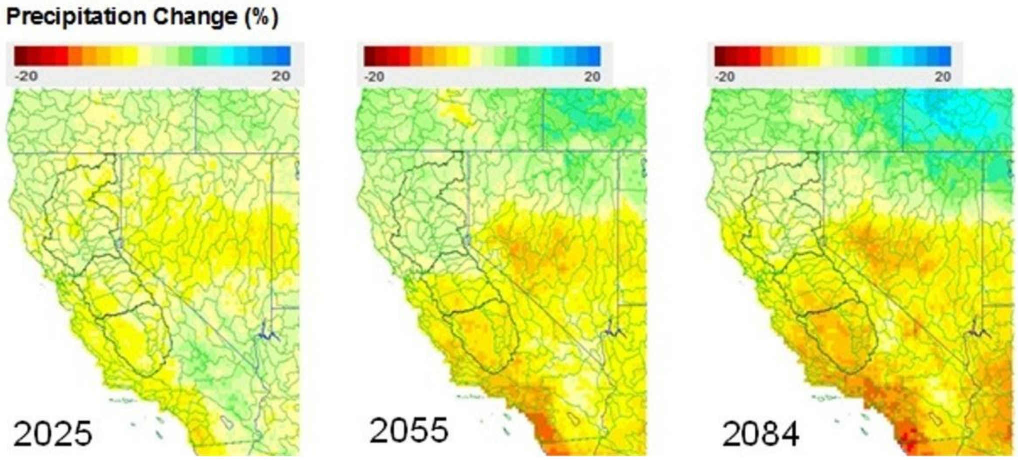


Figure 6. Projected Annual Average Precipitation Changes (percent) in the early, mid and late 21st century

A clear north to south trend of decreasing precipitation similar to historical conditions is projected to occur throughout the 21st century. There is an indication of a slight increase in precipitation in the northern most regions of the Sacramento Valley around the mid-century period. Slightly decreased precipitation is projected to occur in both the San Joaquin and Tulare Lake basins. In these basins, the projected reductions tend to increase throughout the 21st century. In the Sacramento Valley, precipitation changes range from mostly unchanged to slightly decreased in all periods.

Figures 7-8 show the transient climate departure with warming gradually increasing over time for the EI5 scenarios. All of the EI5 and CAT projections were consistent in the direction of the temperature change relative to the NoCC scenario, but varied in terms of climate sensitivity. Trends in the precipitation projections were less apparent because of naturally occurring decadal and multi-decadal precipitation variations.

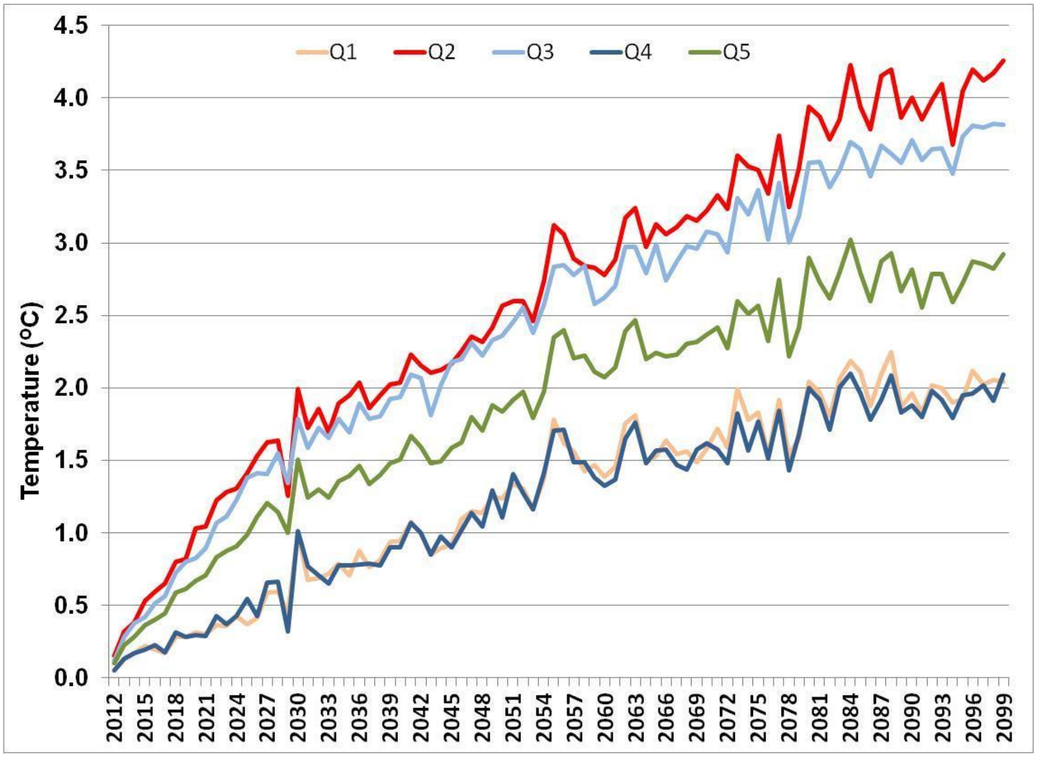


Figure 7. Projected Changes in Ensemble-informed Transient Climate Scenarios for a Representative Grid Cell in the American River Basin (Example) – Projected changes in temperature

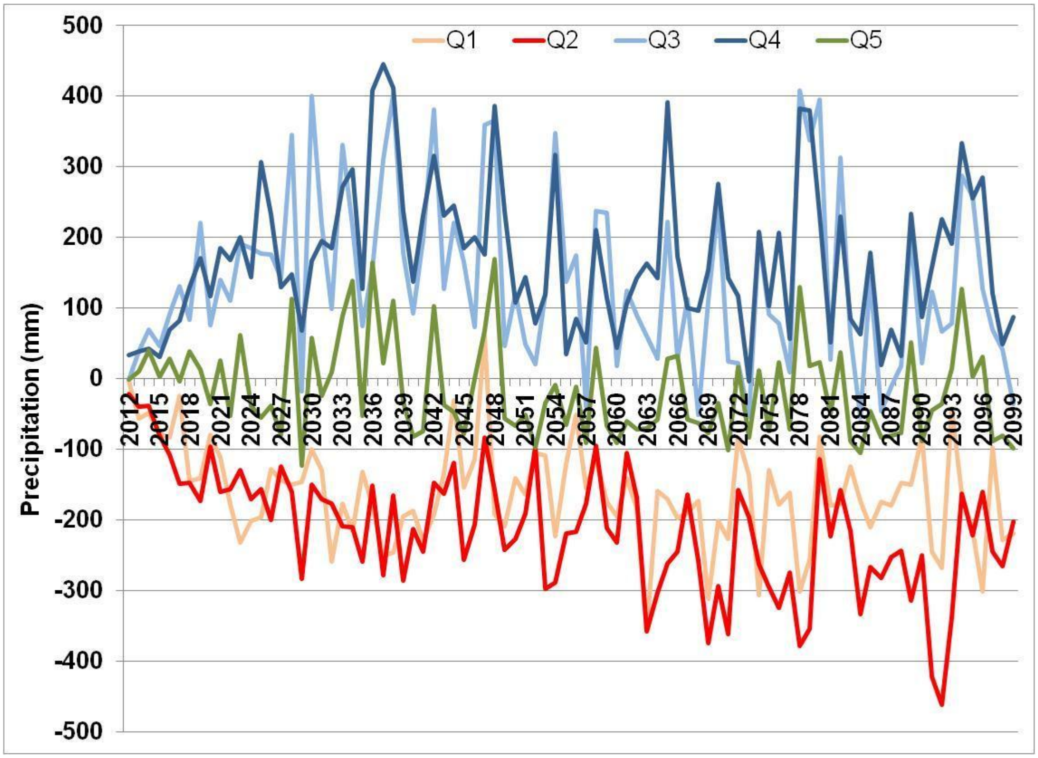


Figure 8. Projected Changes in Ensemble-informed Transient Climate Scenarios for a Representative Grid Cell in the American River Basin (Example) – Projected changes in annual precipitation

Sea Level Change

The National Research Council (NRC) study (NRC 2012) of west coast sea level rise relies on estimates of the individual components that contribute to sea level rise and then sums those to produce the projections. The NRC sea level rise projections for California are presented in Table 3 and displayed on Figure 9. For the SSJIA study, the transient median sea level rise projection was used for all simulations.

Table 3. Sea Level Rise Projections Relative to 2000 in San Francisco

Year	Mean Projection (in cm)	Lower Bound Projection (in cm)	Upper Bound Projection (in cm)
2000	0	0	0
2030	14.4	4.3	29.7
2050	28.0	12.3	60.8
2100	91.9	42.4	166.5

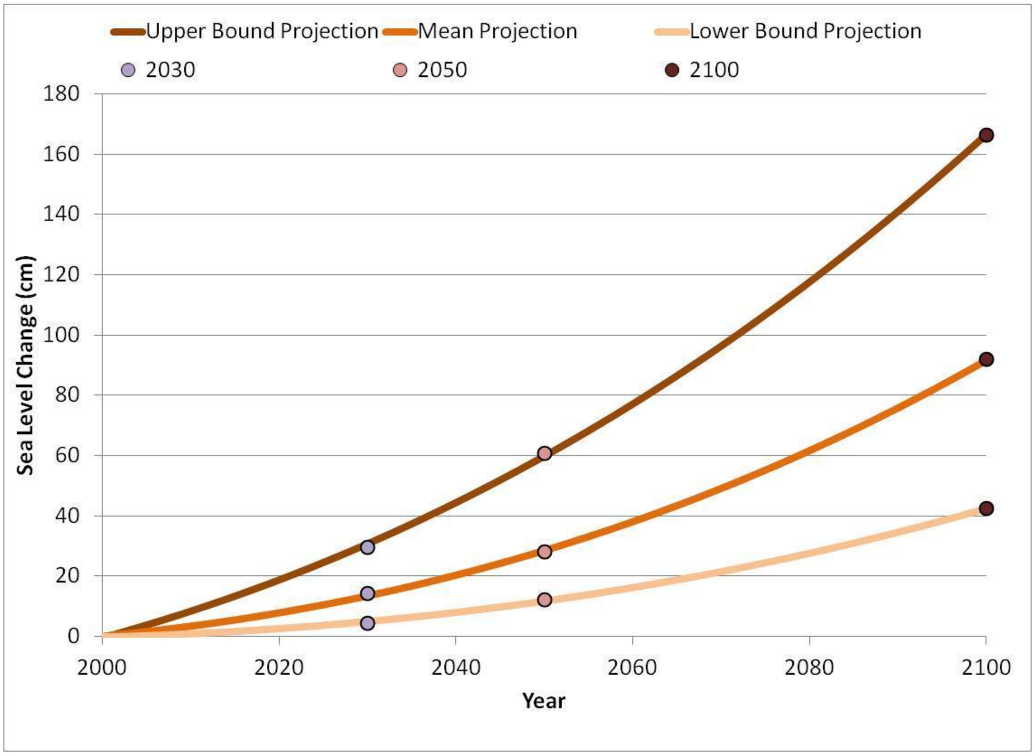


Figure 9. Projected Sea Level Rise Values Based on the NRC Study

Chapter 6 – Water Supply Assessment

The impacts of potential climate changes on water supplies were assessed for each of the three major hydrologic basins in the study area. These assessments included evaluating changes in the seasonality and volume of runoff due to the combined effects of temperature and precipitation. The full suite of 18 transient climate projections was simulated using the WEAP-CV hydrologic model to characterize the wide range of uncertainty associated with water supplies during the 21st century.

Figures 10-12 show the monthly pattern of runoff in the Sacramento, San Joaquin, and Tulare Lake hydrologic basins for each of the 18 socioeconomic-climate scenarios. Differences in the monthly pattern of runoff conditions between the basins reflect differences in latitude, watershed elevation, vegetation, and soil conditions. In each basin, the climate scenarios exhibit a pattern similar to the CT_NoCC scenario (dashed line), but with a shift to more runoff in the winter and less in the spring months. This projected shift occurs because higher temperatures during winter cause more precipitation to occur as rainfall which increases runoff and reduces snowpack. This shift in runoff is especially evident when comparing the approximately equivalent amounts of precipitation in the CT_Q5 and CT_NoCC scenarios. In the winter months (Dec, Jan, Feb) CT_Q5 has more runoff than CT_NoCC, but in the spring (Mar, Apr, May) CT_NoCC has greater runoff.

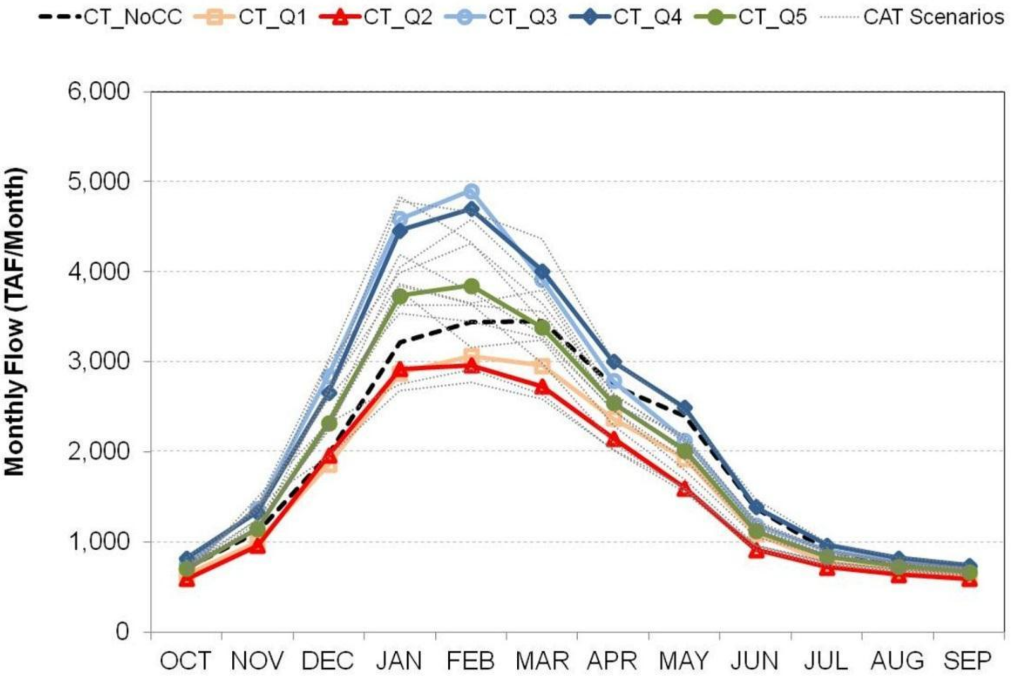


Figure 10. Average Runoff in Each Month in the Sacramento Basin in Each Climate Scenario

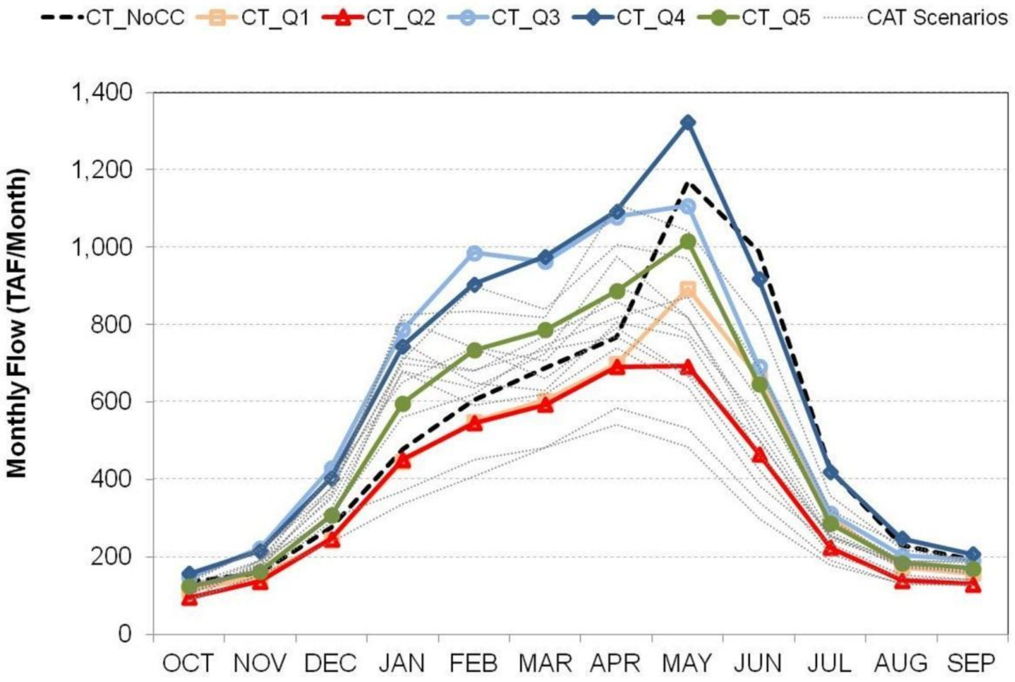


Figure 11. Average Runoff in Each Month in the San Joaquin Basin in Each Climate Scenario

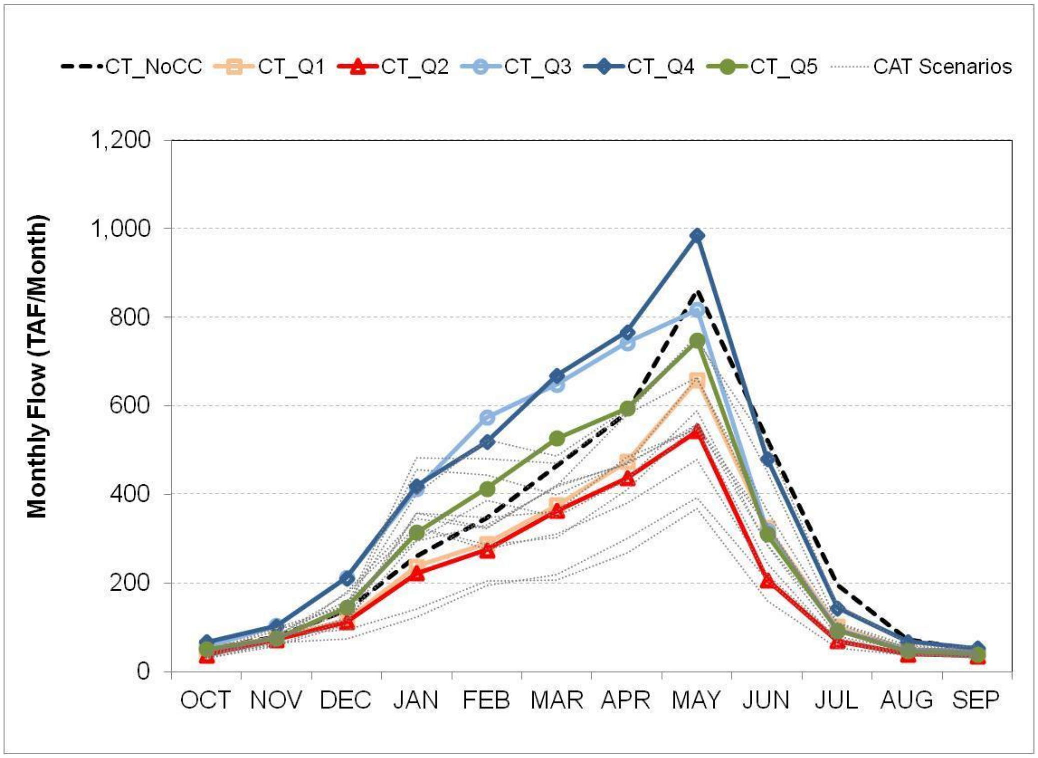


Figure 12. Average Runoff in Each Month in the Tulare Lake Region in Each Climate Scenario

This seasonal runoff shift is greater in the lower elevation Sacramento and San Joaquin basins than the higher Tulare Lake region watersheds because the lower elevation basins are more susceptible to warming-induced changes in precipitation from snow to rain. Figures 13-15 show time series of "unimpaired" annual runoff for each of the 18 socioeconomic-climate scenarios. Unimpaired runoff is the flow that would occur without development of the CVP, SWP and other water management systems in the study area.

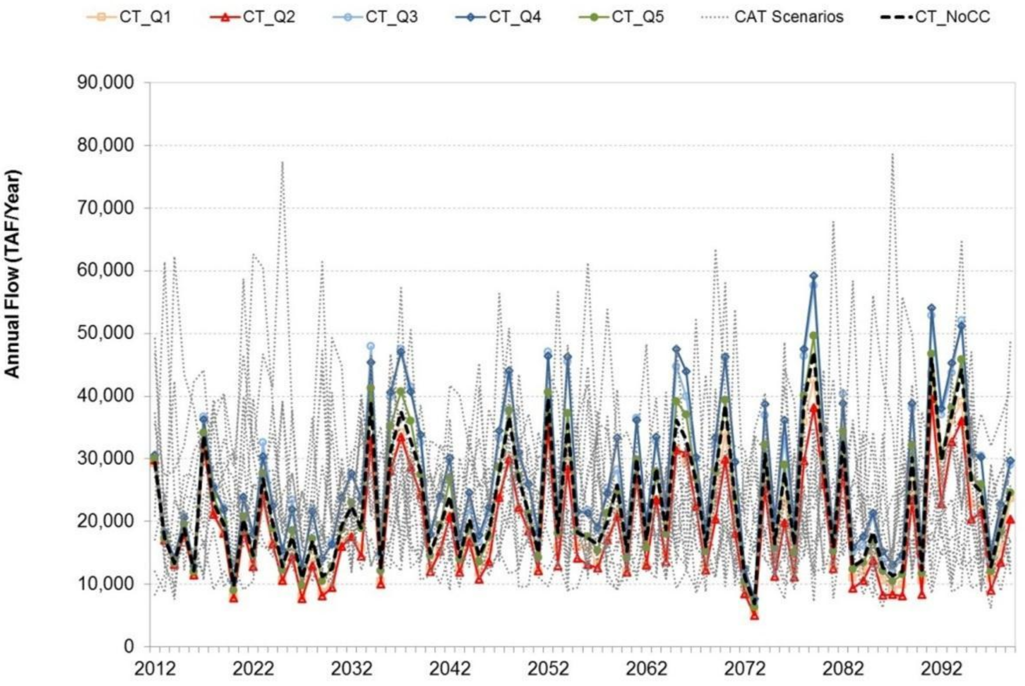


Figure 13. Annual Time Series of Unimpaired Runoff in the Sacramento River System in Each Climate Scenario

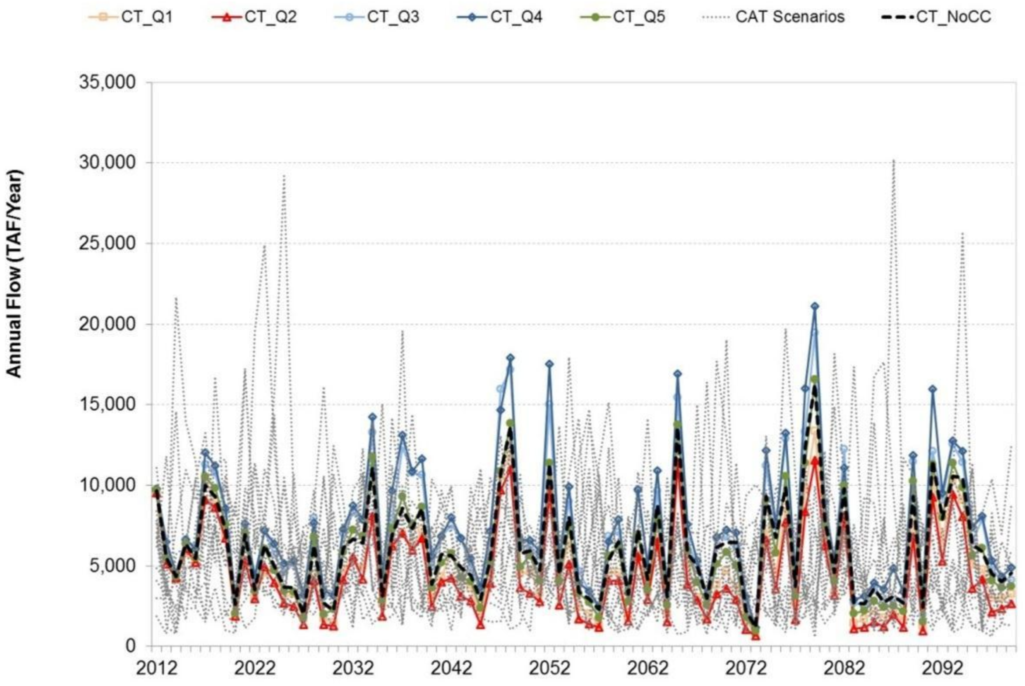


Figure 14. Annual Time Series of Unimpaired Runoff in the San Joaquin River System in Each Climate Scenario

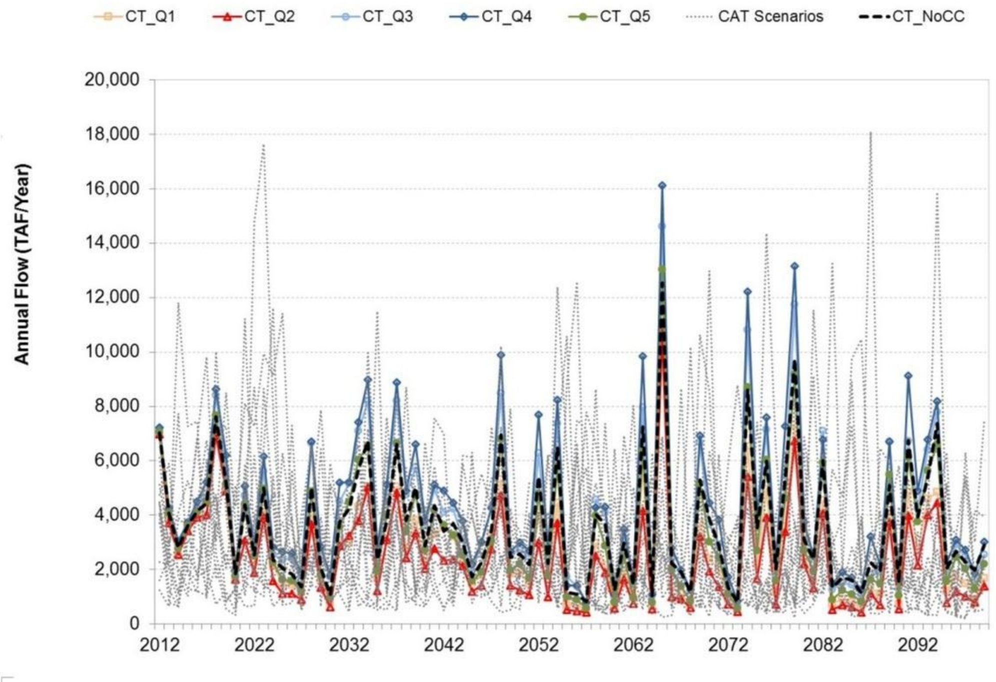


Figure 15. Annual Time Series of Unimpaired Runoff in the Tulare Lake Region in Each Climate Scenario

The methodology used to develop the EI projections was based on historical observations and consequently the projections have the same inter-annual variability. The details of the methodology are described in Reclamation (2013). The result is a direct correspondence between the occurrence of wet and dry periods in the future and historic time series. For example, the extended drought periods from 2025-2030 corresponds to the historic drought between 1929–1934. However, as shown on the figures, the magnitude of the projected unimpaired flows differs from historical flow (CT_NoCC).

The inter-annual variability in 12 CAT projections reflect differences between how the 6 CGMs simulate climate and the use of 2 different GHG emissions scenarios, 1 representing higher GHG emissions A2 and 1 with lower emissions (B1) (IPCC, 2000). These differences result in a different pattern of variability in the 12 CAT projections relative to each other and to the five EI projections.

In general, there is more overall variability present in 12 CAT projections than the five EI projections. In all three hydrologic basins, the magnitude of the CAT high runoff events is greater than the EI projections. This is especially true in the early 21st century period when the 12 CAT high-runoff events are notably greater than the EI projections. As shown on Figures 14 and 15, there is also an increased frequency and lower magnitude of runoff events in the San Joaquin and Tulare Lake basins especially in the early 21st century period. The lower average annual runoff in the San Joaquin and Tulare Lake basins in most of the 12 CAT scenarios as compared to the NoCC scenario would result in lower flows into the Delta and lower storage levels in CVP and SWP reservoirs in these scenarios, resulting in lower overall water supply available for agricultural, urban, and environmental uses within the study area.

Chapter 7 – Water Demand Assessment

The impacts of potential climate changes on water demands were also assessed for each of the three major hydrologic basins in the study area. These assessments included evaluating changes in both urban and agricultural water demands. The full suite of 18 transient climate projections was simulated using the WEAP-CV model to characterize the wide range of uncertainty associated with water demands during the 21st century.

Figure 16 presents the annual time series of projected total agricultural water demand in the three major hydrologic basins comprising the Central Valley of California for the 18 different socioeconomic-climate scenarios. With the exception of the early 21st century as noted previously, the short-term variability and longer-term trends in the simulated water demands in the CAT and EI simulations are similar.

For the agricultural demands, the simulations were performed by assuming there were no changes in the management or types of crops being grown, but changes in climate and atmospheric carbon dioxide did impact the rate of crop growth and the amount of evapotranspiration. Furthermore, it was assumed population growth in urban areas would encroach into agricultural lands and would result in a corresponding decrease of agricultural lands. However, as irrigated lands decreased, it was also assumed higher value crops would be less affected than lower value ones.

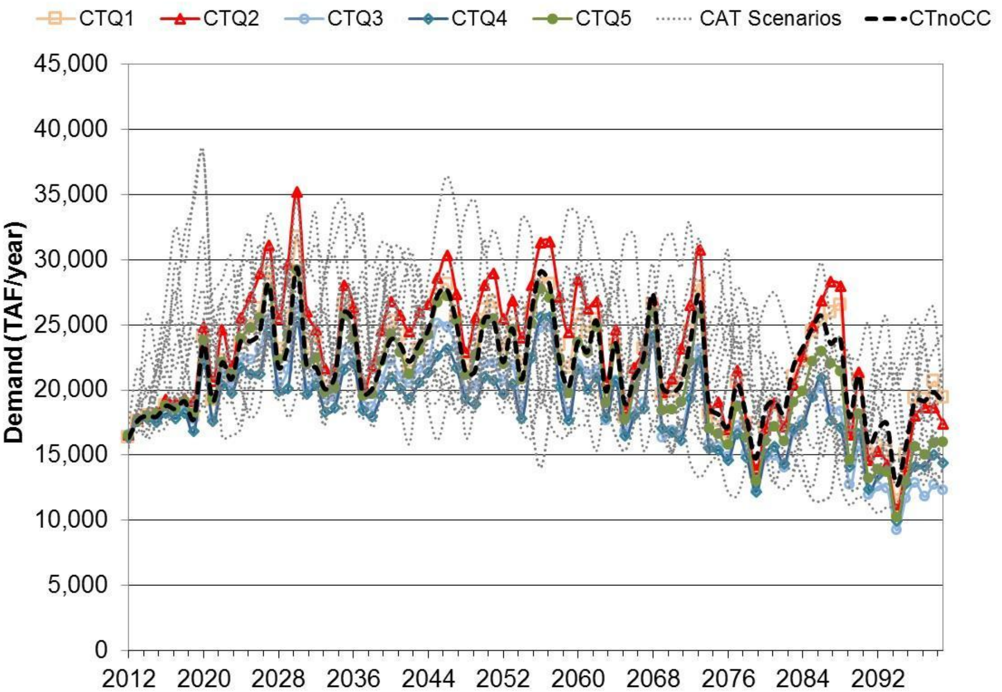


Figure 16. Annual Time Series of Agricultural Applied Water Demand in the Central Valley in Each Scenario

The short-term demand variability seen on Figure 16 is highly correlated with the variability in annual precipitation. In years of low precipitation, demand is higher; in years of high precipitation, agricultural water demands decrease. The longer-term trends include the effects of decreased irrigated lands and increasing carbon dioxide especially in the latter half of the 21st century. This latter impact can be observed by comparing the relationship between the CT_NoCC, CT_Q2, and CT_Q5 scenarios in the late 21st century. In this case, both the CT_Q2 and CT_Q5 projections are drier and hotter than the CT_NoCC but because of elevated carbon dioxide, agricultural water demands are lower.

Figure 17 presents annual time series of projected total urban water demands in the study area for the 18 socioeconomic-climate scenarios. In contrast to agricultural demands, the urban demands do not show as large a degree of year-to-year variability because much of the urban demand is for indoor uses, which are assumed to be insensitive to precipitation and temperature variability. Because the urban demands are driven largely by population, they tend to increase steadily over time with the growth in population and concurrent expansion of residential, commercial and industrial development. However, there is some variability between the different climate scenarios because the outdoor urban demand is affected by shifts in temperature and precipitation patterns that differ between the scenarios.

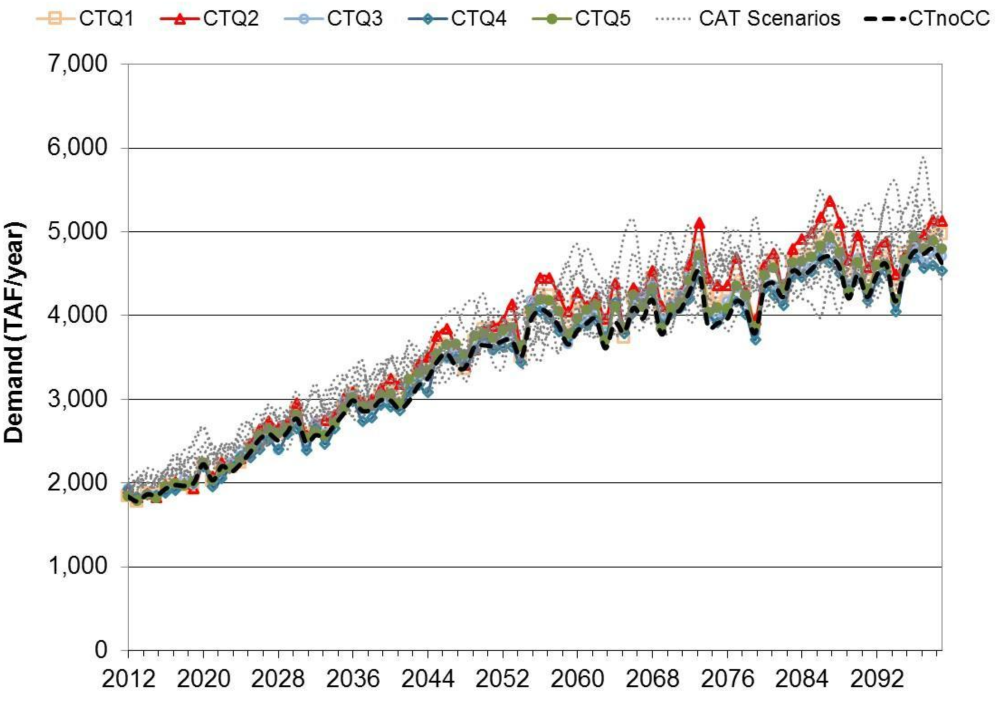


Figure 17. Annual Time Series of Urban Applied Water Demand in the Study Area in Each Scenario

Chapter 8 – System Risk and Reliability Assessment

The assessment of system risk and reliability in California's Central Valley during the 21st century was based on simulating the full suite of 18 transient socioeconomic-climate scenarios with the CalLite and other performance assessment models. While many measures of risk might be employed, the analysis presented in this section includes six major resource categories. The following resource categories were selected to generally correspond with resource categories identified in Section 9503 of the SECURE Water Act.Delivery Reliability

- Delivery Reliability
- Water Quality
- Hydropower and GHG emissions
- Flood Control
- Recreational Use
- Ecological Resources

To assess the risk and reliability for each of these resource categories, specific attributes of interest associated with each resource category were selected. Performance metrics indicating the ability of the water system to meet resource needs under changed socioeconomic-climate conditions were developed, and locations where metrics would offer relevant information about the system performance were identified.

The metrics were evaluated in either a quantitative or qualitative fashion. A metric was evaluated quantitatively if: (a) direct evaluation was possible using output from the model package or results from post-processing of modeling output data was feasible, or (b) an indirect measure of the attribute of interest at the specified location could be developed, based on modeling output or from post-processing of modeling results.

Delivery Reliability

Three attributes of interest were used to characterize the delivery reliability resource category. These attributes included unmet demands, end-of-September reservoir storage and CVP and SWP exports from the Delta. The results for each of these performance metrics are discussed in the sections below.

Unmet Demands

Unmet demands provide an indication of the reliability of the system in meeting water supply needs in the study area. This performance metric is applicable to all three of the California's Central Valley hydrologic basins.

Table 4 provides a summary of the overall Central Valley of California unmet demand results for the central tendency CT_Q5 of the EI scenarios as well as the mean of the 12 CAT simulations for the early, middle, and late 21st century. The overall 21st century projected average unmet demands ranged from a low of about 3.7 MAF/year to a maximum of 10.5 MAF/year in the EI scenarios. The projected unmet demands increase through mid-century as both urban and agricultural demands increase but tend to decline toward the end of the century as agricultural demands are reduced. The decline in agricultural demands at the end of the century is greater in the climate change scenarios than in the NoCC scenario because of the effects of atmospheric carbon dioxide on the rate of crop growth and the amount of evapotranspiration. This results in a decline in unmet demands in CT_Q5 relative to CT_ NoCC in the later part of the century.

Because of their greater range of variability and more frequent low runoff events, resulting in less average annual water supply, the 12 CAT projections have significantly greater unmet demands throughout the 21st century. Their overall 21st century average annual unmet demands ranged from a low of about 4.7 MAF/year to a maximum of 13.1 MAF/year.

Table 4. Summary Central Valley Unmet Demands Results for Delivery Reliability Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Central Valley Unmet Demands (average in TAF/year)	2012-2040	5,198	5,486	8,432	6%	62%
	2041-2070	7,673	8,155	9,730	6%	27%
	2071-2099	5,556	5,316	7,956	-4%	43%

For comparison purposes, Figure 18 presents an annual time series representing NoCC (CT_NoCC) in the 21st century and shows sources of water supplies (groundwater pumping and surface water deliveries) and remaining unmet demands for the entire Central Valley of California.

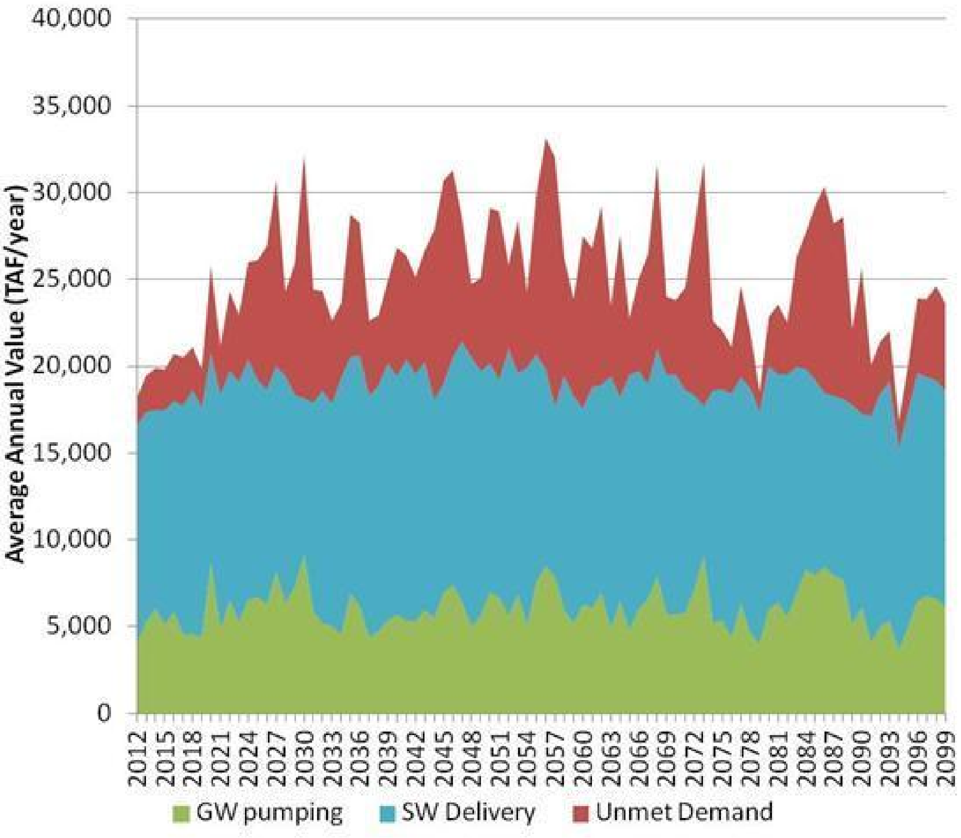


Figure 18. Annual Time Series of Supplies and Unmet Demand in the Central Valley in the CT_NoCC Scenario

Figures 19-21 present the same information for the central tendency (Q5), warmer and drier (Q2), and less warming and wetter (Q4) scenarios. All four scenarios showed similar year-to-year variability, with demands increasing and surface water supplies decreasing during dry periods, and the opposite occurring in wetter years. In the NoCC scenario, unmet demands (represented in the top portion of the figure) ranged from a low of about 495 TAF per year (TAF/year) to a high of about 11,365 TAF/year over the course of the simulation period.

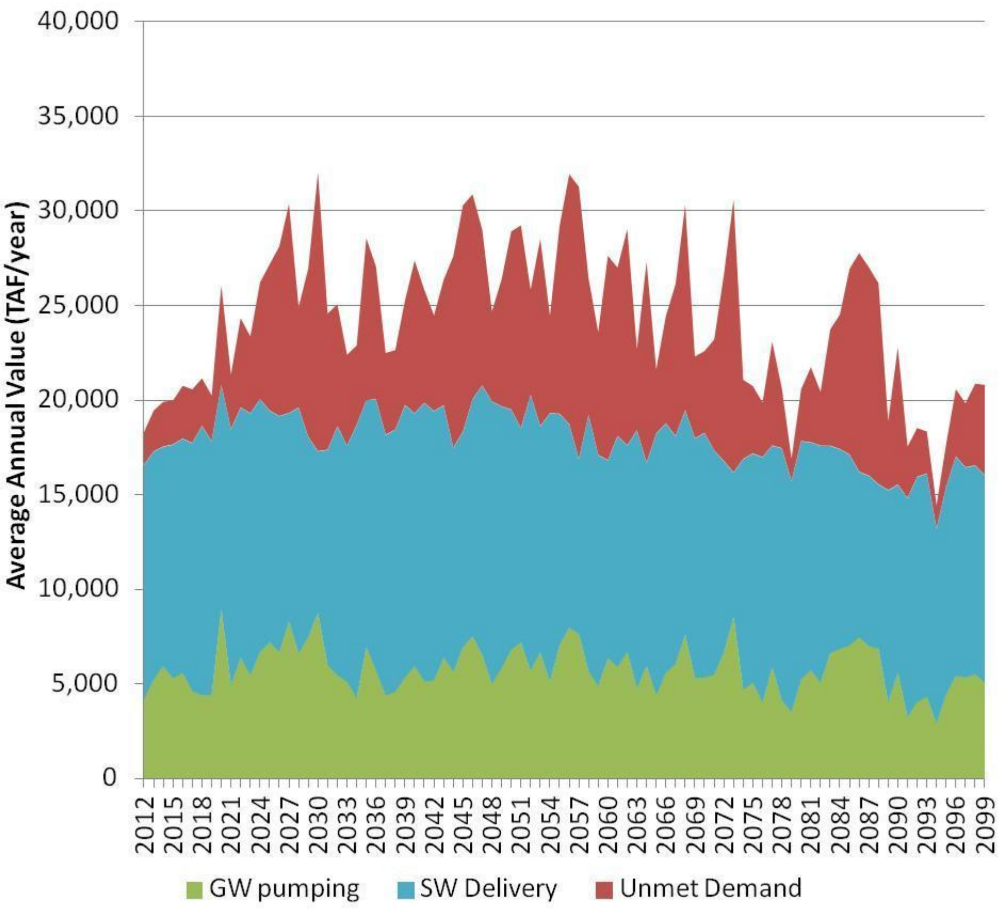


Figure 19. Annual Time Series of Supplies and Unmet Demand in the Central Valley in the CT-Q5 Scenario

The central tendency (Q5) scenario showed only modest increases in demand and reductions in supply relative to the NoCC, with unmet demands ranging from 653 to 11,342 TAF/year. The warmer and drier (Q2) scenario had much greater increases in demand and reductions in supply as compared to the CT_NoCC scenario, with unmet demands ranging from 863 to 16,573 TAF/year. Conversely, the less warming and wetter (Q4) scenario had lower demands, higher supplies, and, consequently, lower unmet demands than the CT_NoCC scenario, with unmet demands ranging from 280 to 8,031 TAF/year.

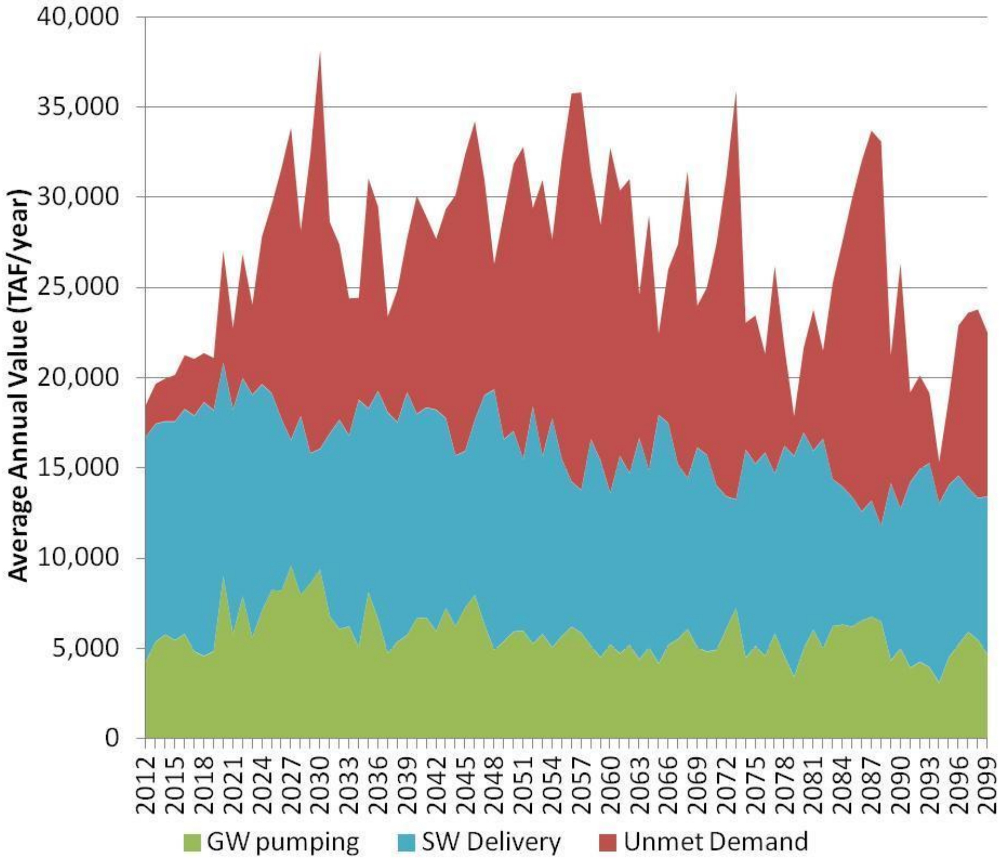


Figure 20. Annual Time Series of Supplies and Unmet Demand in the Central Valley in the CT_Q2 Scenario

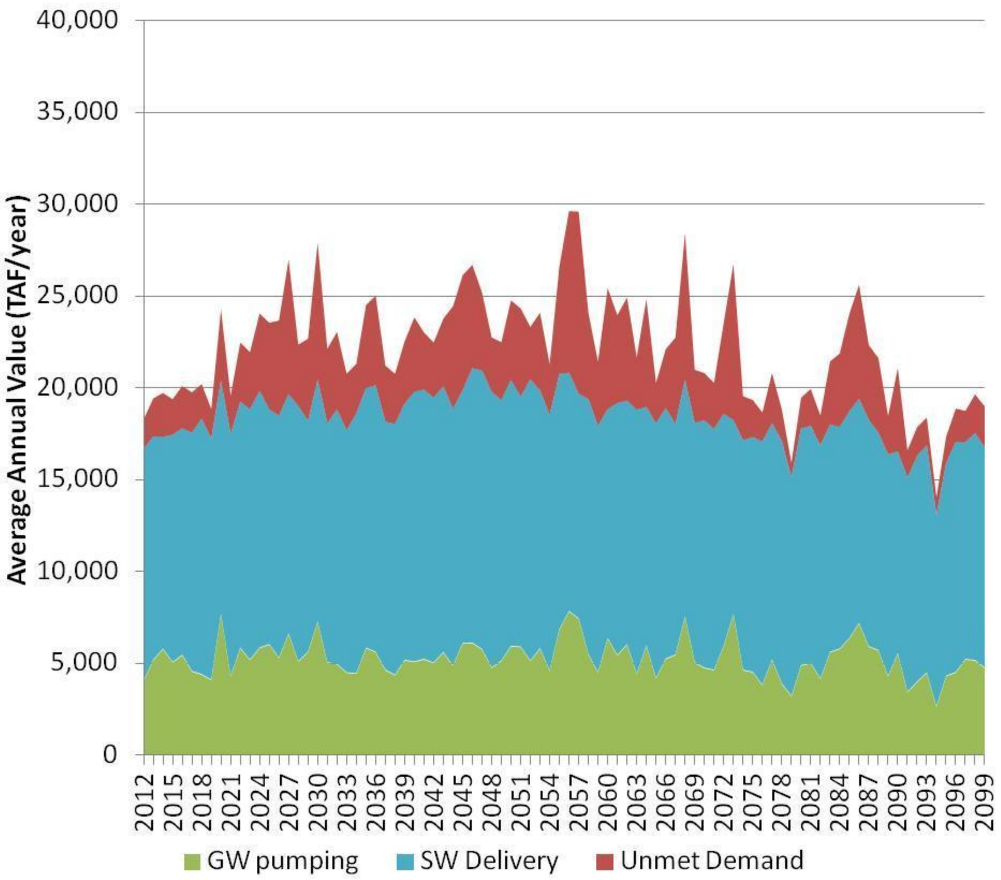


Figure 21. Annual Time Series of Supplies and Unmet Demand in the Central Valley in the CT_Q4 Scenario

End-of-September Storage

End-of-September storage provides a measure of relative risk to making future deliveries, particularly during periods of extended drought. This “carryover” storage metric is applicable to major CVP, SWP and other reservoirs in all three of the Central Valley of California’s hydrologic basins.

Table 5 summarizes the results for this metric using end-of-September storage in the major Sacramento Valley reservoirs. The metric used in the analysis is the percent of months with storage below the 10th percentile of Sacramento Valley storage in the CT_NoCC scenario which is included in the table for reference.

The central tendency of the EI scenarios (CT_Q5) has results generally similar to the NoCC scenario (CT_NoCC). The increase in carryover storage at mid-century is an artifact of using the historical climate as the basis for the EI projected climates. In the drier climate projections (Q1 and Q2) which are not included in the table, less carryover storage was retained in the reservoirs whereas in the wetter climate projections (Q3 and Q4), more end-of-September water was retained in the reservoirs.

Table 5. Summary Central Valley End-of-September Storage Results for Delivery Reliability Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
End-of-September Storage in Sacramento Valley reservoirs (percent of months less than 10th percentile storage in the NoCC)	2012-2040	24%	31%	11%	7%	-14%
	2041-2070	0%	0%	11%	0%	11%
	2071-2099	7%	7%	11%	0%	4%

For the 21st century as a whole, there was substantial variability in end-of-September storage between the different climate scenarios, with a range from a high of 40 percent to a low of 2 percent in the percentage of years that Shasta end-of-September storage is less than the 10th percentile of the NoCC results. Unlike the NoCC and EI scenarios, the average of the 12 CAT scenarios shows similar carryover storage results across the 21st century. This result occurs because the 12 CAT scenarios do not use the historical hydrology sequence, which cause the average runoff in the 12 CAT scenarios to be similar through the early, mid, and late portions of the 21st century. Because of this, the frequency of low storage levels in the 12 CAT scenarios in the 2012-2040 period is less than in the CT_NoCC scenario. However, all of the 12 CAT scenarios have increased frequency in low end-of-September storage levels as compared to the NoCC scenario over the course of the entire 21st century, with a range of a high of 27 percent to a low of 2 percent more years with low storage levels as compared to the NoCC scenario.

CVP and SWP Delta Exports

The CVP and SWP Delta exports are a significant portion of the water supply available to San Joaquin Valley, Tulare Lake Basin, and out-of-the-study area water users. The CVP exports water at the C. W. “Bill” Jones Pumping Plant and SWP exports occur at the Harvey O. Banks Pumping Plant. Both pumping plants are located in the southern part of the Delta.

Table 6 presents a summary of the performance metrics for CVP and SWP exports at the Jones and Banks Pumping Plants. In the CT_NoCC scenario, the pumping at both locations shows only small differences between the averages for the early, middle, and late portions of the 21st century. The CT_Q5 pumping results show decreases ranging from 0 percent to -3 percent in the early 21st century to -3 percent to -7 percent by the end of the century relative to the CT_NoCC results. The average of 12 CAT projections ranges from pumping increases of +1 percent to +5 percent in the early 21st century from -8 percent to -13 percent by the end of the century.

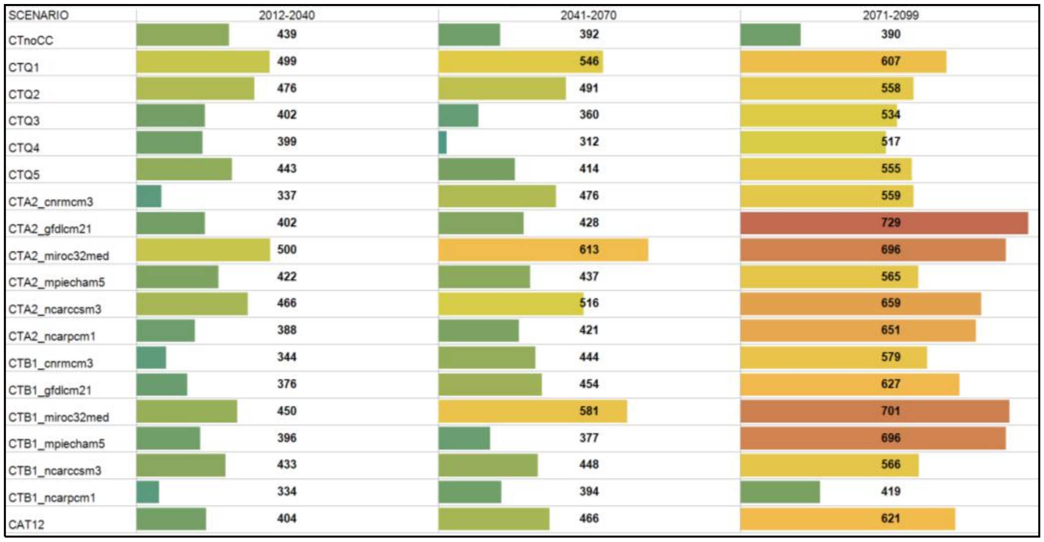
Table 6. Summary CVP and SWP Exports Results for Delivery Reliability Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
CVP Exports – Jones Pumping Plant (TAF/year)	2012-2040	2,237	2,161	2,350	-3%	5%
	2041-2070	2,460	2,427	2,277	-1%	-7%
	2071-2099	2,490	2,424	2,302	-3%	-8%
SWP Exports – Banks Pumping Plant (TAF/year)	2012-2040	2,663	2,653	2,680	0%	1%
	2041-2070	2,859	2,677	2,563	-6%	-10%
	2071-2099	2,982	2,780	2,594	-7%	-13%

Over the 21st century, the CT_Q5 scenario has an average of -2 percent lower exports than occurs without climate change. During this period, the EI scenarios show decreases at the Jones and Banks Pumping Plants ranging from -18 percent to -23 percent to increases ranging from +8 percent to +14 percent respectively.

The 12 CAT average change over the 21st century is -4 percent at Jones, and -8 percent at Banks less than without climate change. During this period, the 12 CAT scenarios show decreases at Jones and Banks ranging from -16 percent to -26 percent to increases ranging from +6 percent to +7 percent respectively.

Figure 22 shows the projected average annual total CVP and SWP exports at the Jones and Banks Pumping Plants for three future time periods. As compared to the CT_NoCC scenario, total CVP and SWP exports are reduced in the central tendency EI scenario (CT_Q5) in all the future periods. Overall, 21st century average exports ranged from a low of 4.1 MAF/year to maximum of 5.8 MAF/year. As compared to the CT_NoCC scenario, the average of 12 CAT scenarios shows slightly increased exports in the early 21st century but declines in mid and late century total exports. Overall 21st century average exports ranged from a low of 4.1 MAF/year to maximum of 5.5 MAF/year.



SCENARIO	2012-2040	2041-2070	2071-2099
CTnoCC	439	392	390
CTQ1	499	546	607
CTQ2	476	491	558
CTQ3	402	360	534
CTQ4	399	312	517
CTQ5	443	414	555
CTA2_cnrmcm3	337	476	559
CTA2_gfdlcm21	402	428	729
CTA2_miroc32med	500	613	696
CTA2_mpiecham5	422	437	565
CTA2_ncarccsm3	466	516	659
CTA2_ncarpcm1	388	421	651
CTB1_cnrmcm3	344	444	579
CTB1_gfdlcm21	376	454	627
CTB1_miroc32med	450	581	701
CTB1_mpiecham5	396	377	696
CTB1_ncarccsm3	433	448	566
CTB1_ncarpcm1	334	394	419
CAT12	404	466	621

Figure 22. Projected Average Annual Total Delta Exports Expressed in MAF/year in Each Scenario for Three Future Periods

Water Quality

Two attributes of interest were used to characterize the water quality resource category. These attributes include Delta salinity conditions and the volume of the cold water pool in Shasta Reservoir. The results for each of these performance metrics are discussed in the sections below.

Delta Salinity

Delta salinity conditions provide a measure of the risk to in-Delta and export water users that their water supplies will have higher salinity than what is required to be in compliance with standards for urban and agricultural beneficial uses set by the SWRCB in Decision 1641. The salinity standards are specified in units of electrical conductivity (EC) expressed as micro-Siemens per centimeter (µS/cm) at several Delta compliance locations including Emmaton and Jersey Point from April through August (ranging from 450 to 2,750 µS/cm depending on the month and water year type) and at Rock Slough throughout the year (ranging from 631 to 965 µS/cm depending on the month and water year type).

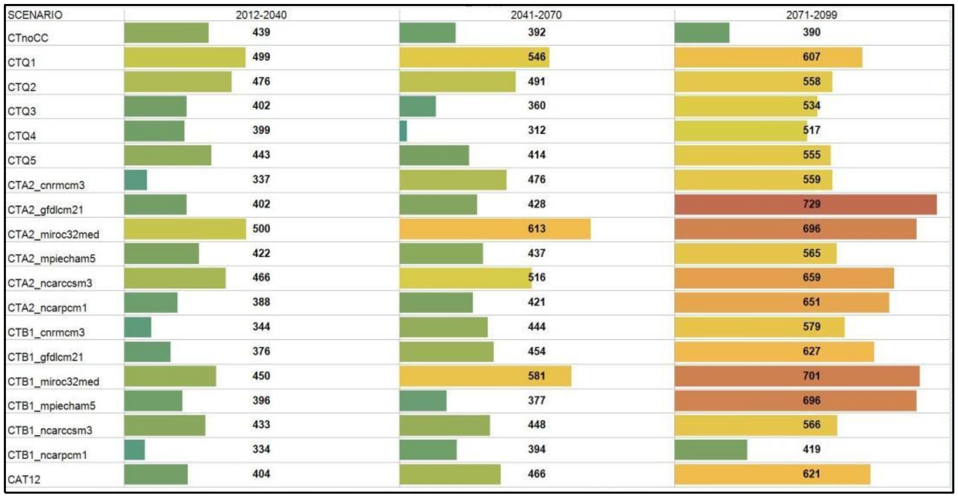
Table 7 presents a summary of the performance metrics for water quality performance at Emmaton and Jersey Point. In the CT_NoCC scenario, the EC at both locations shows only small differences between the averages for the early, middle, and late portions of the 21st century. The CT_Q5 EC results show a steady increase from about 10 percent higher in the early 21st century to more than 50-80 percent higher by the end of the century relative to the CT_NoCC results. This primarily reflects the effects of increasing sea level rise over the course of the 21st century, and does not include the possible effects of potential Delta levee failures. The average of 12 CAT projections ranges from EC increases of 18 to 23 percent in the early 21st century to 65 to 88 percent by the end of the century.

Table 7. Summary the Emmaton and Jersey Point EC Performance Metric Results for the Water Quality Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Delta Salinity – Emmaton (average annual EC in µS/cm)	2012-2040	1,782	1,985	2,198	11%	23%
	2041-2070	1,768	2,268	2,751	28%	56%
	2071-2099	2,151	3,940	4,036	83%	88%
Delta Salinity – Jersey Point (average annual EC in µS/cm)	2012-2040	1,536	1,654	1,807	8%	18%
	2041-2070	1,600	1,885	2,211	18%	38%
	2071-2099	1,718	2,629	2,837	53%	65%

Figure 23 shows the average annual EC at Rock Slough from October through September. Almost all the climate scenarios have higher EC values than the CT_NoCC scenario, reflecting the effects of sea level rise on Delta salinity. Among the climate change scenarios, the EC levels are highest among the driest scenarios (e.g., Q2) and lowest among the wetter scenarios (e.g., Q4). In addition, a substantial increase in EC is observed after mid-century due to the increasing influence of sea level rise.

Over the 21st century, the central tendency CT_Q5 scenario shows an EC increase of approximately 16 percent at Rock Slough. During this period, the EI scenario ECs range from a low increase of 0.5 percent in the wetter CT_Q4 to a high of 36 percent in the drier CT_Q2 relative to the CT_NoCC scenario. For the CAT12 scenarios, the average EC increases range from a low increase of 12 percent to a high increase of 48 percent relative to the CT_NoCC scenario.



SCENARIO	2012-2040	2041-2070	2071-2099
CTnoCC	439	392	390
CTQ1	499	546	607
CTQ2	476	491	558
CTQ3	402	360	534
CTQ4	399	312	517
CTQ5	443	414	555
CTA2_cnrmcm3	337	476	559
CTA2_gfdlcm21	402	428	729
CTA2_miroc32med	500	613	696
CTA2_mpiecham5	422	437	565
CTA2_ncarccsm3	466	516	659
CTA2_ncarpcm1	388	421	651
CTB1_cnrmcm3	344	444	579
CTB1_gfdlcm21	376	454	627
CTB1_miroc32med	450	581	701
CTB1_mpiecham5	396	377	696
CTB1_ncarccsm3	433	448	566
CTB1_ncarpcm1	334	394	419
CAT12	404	466	621

Figure 23. Projected Average Annual Electrical Conductivity (µS/cm) at Rock Slough in Each Scenario for Three Future Periods

End-of-May Storage Results

The end-of-May storage is the attribute of interest chosen to represent the water supply available for meeting agricultural, urban, and environmental water demands during the summer and fall months. This low storage volume performance metric is applicable to major reservoirs in the CVP and SWP water management systems. Shasta Reservoir was the location chosen for discussion in this report because it is the largest reservoir in the CVP/SWP water system and manages the largest average annual runoff.

Table 8 shows the percentage of time that the end-of-May storage is less than the 10th percentile value in the CT_NoCC scenario.

Table 8. Summary the End-of-May Storage Performance Metric Results for the Water Quality Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Shasta Reservoir Storage (percent of months Shasta Reservoir end-of-May storage less than 10th percentile storage in CT_NoCC)	2012-2040	24%	28%	7%	4%	-17%
	2041-2070	0%	0%	9%	0%	9%
	2071-2099	7%	10%	11%	3%	4%

Over the 21st century, the CT_Q5 scenario has an average of 13 percent more frequent low end-of-May storages. During this period, the frequency of EI scenarios having increased low storages range from a low of 2 percent for the CT_Q4 wetter scenario to a high of 40 percent in the drier CT_Q2 scenario.

The 12 CAT average changes range from a -17 percent decrease in the early 21st century to a 9 percent increase in the frequency of low end-of-May storage. The early century decrease is an artifact of several exceptionally high runoff events projected to occur during this period. Over the 21st century, the 12 CAT scenario results have more frequent low end-of-May storages in the range from +1 percent to +25 percent. These lower storage levels would result in reduced capability to deliver water supplies to water users during the summer months.

Hydropower and GHG Emissions

Net hydropower generation is the attribute chosen as an indicator of the energy balance for the operations of CVP and SWP systems. Net hydropower generation is defined as the difference between its generation and use. It is positive when generation is greater than use. Both the CVP and SWP generate hydropower at reservoirs and use it to pump and convey water to users in the Central Valley of California as well as outside the study area. Net hydropower generation is measured in units of gigawatt hours per year (GWh/year).

The GHG emissions considered in this report are an indicator of environmental footprint or carbon intensity of the operations of the CVP and SWP systems. Hydropower generation is assumed to occur without GHG emissions. When the CVP and SWP have positive net hydropower generation, the surplus energy can be made available to reduce reliance on fossil fuel-based sources of electricity used either by the projects or elsewhere and thereby reduce overall GHG emissions. These “offsets” are shown in the ensuing table as negative changes in GHG emissions, and primarily when net hydropower generation is positive. The unit of measurement for GHG emissions is metric tons of carbon dioxide equivalents per gigawatt hour of power generation.

In the simulations, the CVP system was assumed to provide excess power to an electrical grid system which produces 300 mTCO2e GHG emissions per GWh generated. For the SWP system, the sources of power used by the project are assumed to gradually transition from sources with higher GHG emissions to those with lower GHG emissions over the course of the 21st century. Therefore, SWP emissions drop sharply over the first half of the century due to this assumption.

Table 9 presents the summary net hydropower generation for the CVP and SWP systems. The CVP has a net positive hydropower generation in all scenarios. The central tendency CT_Q5 scenario shows a slight decrease in hydropower generation in the middle and latter parts of the century relative to the NoCC (CT_NoCC) scenario. For the 5 EI scenarios, the overall 21st century average annual change in net generation is -2 percent for the CVP with a range of -19 percent to +18 percent. The SWP is a net consumer of power because of its high electrical consumption needed for conveyance. Therefore, in the drier scenarios, the SWP’s net generation becomes more positive as less power is used for conveyance. For the 5 EI scenarios, its overall 21st century average annual change in net generation is +9 percent with respect to the CT_NoCC reflecting the reduced amount of water available for export with a range -6 percent to +21 percent.

The 12 CAT scenarios show results similar to the EI scenarios. The projected early 21st century increase for the CVP becomes projected decreases in the mid and latter parts of the century. The overall 21st century CVP average annual net hydropower generation increases by 4 percent with a range from -13 percent to +23 percent. The overall 21st century SWP average net generation increases by +13 percent with a range from +2 percent to +27 percent for the CAT12 scenarios.

Table 9. Summary of CVP and SWP Net Hydropower Generation Results for the Hydropower Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
CVP Net Hydropower Generation (average annual in GWh/year)	2012-2040	3,062	3,100	4,013	1%	31%
	2041-2070	4,145	4,060	3,755	-2%	-9%
	2071-2099	3,654	3,459	3,576	-5%	-2%
SWP Net Hydropower Generation (average annual in GWh/year)	2012-2040	-3,841	-3,645	-3,610	5%	6%
	2041-2070	-4,002	-3,586	-3,497	10%	13%
	2071-2099	-4,382	-3,928	-3,538	10%	19%

Table 10 presents the GHG "offsets" for the CVP and GHG emissions for the SWP. The CVP has negative GHG emissions (i.e. offsets) in all scenarios. The early 21st century increase in CVP emission offsets become decreases by the middle and end of the century due to reduction in net hydropower generation relative to the CT_NoCC scenario.

Table 10. Summary of GHG CVP offsets and SWP Emissions Results for the Hydropower and GHG Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Average Annual CVP GHG Offsets in mtCO2e/year	2012-2040	-918,354	-929,793	-1,203,358	1%	31%
	2041-2070	-1,243,074	-1,217,695	-1,126,230	-2%	-9%
	2071-2099	-1,095,884	-1,037,302	-1,072,408	-5%	-2%
Average Annual SWP GHG Emissions in mtCO2e/year	2012-2040	1,011,801	951,925	950,010	-6%	-6%
	2041-2070	242,291	214,559	210,243	-11%	-13%
	2071-2099	245,651	216,487	213,208	-12%	-13%

The GHG results are highly correlated with the net generation results, as increases in net generation result in reductions in GHG emissions and vice versa. For the 5 EI scenarios, the overall 21st century average annual change in CVP offsets is -2 percent with a range of -20 percent to +18 percent relative to the CT_NoCC scenario. These changes are due primarily to changes in net generation. The SWP's average annual emissions over the 21st century are -8 percent relative to NoCC with a range from -26 percent to +11 percent. These changes are mostly associated with the assumption of using cleaner sources of power for conveyance.

The 12 CAT scenarios show results similar to the EI scenarios. The early 21st century increase in emissions offsets for the CVP become decreases in the mid and latter parts of the century. The overall 21st century average annual GHG emission offsets for the CVP increase by 7 percent relative to NoCC with a range of -13 percent to +23 percent. Over the 21st century, the SWP's average annual GHG emissions increase by 1 percent relative to NoCC with a range from -23 percent to +5 percent.

Flood Control

Two attributes of interest were used to characterize the flood control resource category. These attributes include the percentage of months when reservoir storage is within 10 TAF of the flood storage pool and the percentage of months that reservoir flow releases exceed hydropower penstock capacities. These performance metrics are applicable at major storage reservoirs during the flood control months from October to June. In this report, Shasta and Folsom reservoirs were selected for the presentation of results because they were the reservoirs having the highest percentages of storage within 10 TAF of the flood conservation pool.

Table 11 presents results for the flood storage performance metric for both Folsom and Shasta reservoirs in the early, mid, and late 21st century periods.

Table 11. Summary of Folsom and Shasta Storage Metric Results for the Flood Control Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Folsom Flood Control (percent of months that storage is near flood conservation pool)	2012-2040	39%	40%	44%	1%	5%
	2041-2070	54%	44%	42%	-10%	-12%
	2071-2099	44%	33%	34%	-11%	-10%
Shasta Flood Control (percent of months that storage is near flood conservation pool)	2012-2040	10%	8%	35%	-2%	25%
	2041-2070	35%	26%	29%	-9%	-6%
	2071-2099	36%	25%	29%	-11%	-7%

In general, the percentage of months near the flood storage pool decline during the century. For the 5 EI scenarios, the overall 21st century average Shasta storage metric declines by -7 percent with a range from -17 percent to +15 percent with respect to NoCC. At Folsom Dam, the average flood storage metric is -7 percent with a range from -21 percent to +5 percent.

For the 12 CAT scenarios, the overall 21st century average Shasta storage metric increases by +4 percent with a range from -9 percent to +19 percent with respect to NoCC. The average Folsom Dam storage metric declines by -6 percent with a range from -15 percent to +3 percent.

Table 12 presents results for the hydropower penstock exceedence capacities performance metric for both Folsom at Natomas power plant and Shasta at Keswick power plant in the early, mid, and late 21st century periods. In general, the percentage of months near the flood conservation pool decline during the century. For the 5 EI scenarios, the overall 21st century average Shasta penstock exceedence capacity performance metric increases by +1 percent with a range from -3 percent to +5 percent with respect to NoCC. The average Folsom at Natomas penstock exceedence capacity metric declines by -1 percent with a range from -6 percent to +5 percent.

Table 12. Summary of Folsom and Shasta Penstock Capacity Exceedence Results for the Flood Control Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Folsom Flood Control (percent of months that storage is near flood conservation pool)	2012-2040	21%	23%	21%	2%	0%
	2041-2070	21%	19%	19%	-2%	-2%
	2071-2099	22%	19%	18%	-3%	-5%
Shasta Flood Control (percent of months that storage is near flood conservation pool)	2012-2040	7%	7%	12%	0%	5%
	2041-2070	10%	11%	10%	1%	0%
	2071-2099	10%	10%	10%	0%	0%

For the 12 CAT scenarios, the overall 21st century average Shasta penstock capacity exceedence metric increases by +2 percent with a range from -3 percent to +8 percent with respect to NoCC. For Folsom, the average penstock exceedence capacity metric declines by -2 percent with a range from -8 percent to +4 percent.

The results of this long-term analysis suggest that climate change will likely result in lower overall storage conditions and thus more available storage to accommodate flood volumes. However, a detailed flood risk assessment was beyond the scope of this study, and this current assessment relied on monthly flow changes and monthly operations. An analysis of flood flow hydrographs on an hourly or daily time step may reveal greater peak flows and therefore a higher risk of flooding with climate change.

Recreation Results

The attribute of interest selected as an indicator of recreational use is the percentage of months from May through September that reservoir surface area is less than the reservoir's median surface area. This metric is applicable at all major CVP, SWP and non-project reservoirs in the Central Valley hydrologic basins. In this report, Shasta and Folsom reservoirs were selected for the presentation of results because they were the reservoirs having the highest percentages of exceeding the performance metric in the NoCC scenario.

Table 13 presents results for the recreation surface area performance metric for both Folsom and Shasta reservoirs in the early, mid, and late 21st century periods. In general, the percentage of months with surface area less than the median decrease slightly at Folsom but increase at Shasta during the 21st century.

For the 5 EI scenarios during the 21st century, the Folsom average percentage of months below the median reservoir surface area increases by +21 percent with a range from -2 percent to +37 percent relative to NoCC. At Shasta Reservoir, the average surface area metric increases by +15 percent with a range from -17 percent to +35 percent.

Table 13. Summary of Folsom and Shasta Recreation Surface Area Metric Results for the Recreation Resource Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Folsom Recreation (percent of months that surface area is less than the reservoir median surface)	2012-2040	64%	72%	63%	8%	-1%
	2041-2070	43%	70%	76%	27%	33%
	2071-2099	43%	70%	82%	27%	39%
Shasta Recreation (percent of months that median surface area is less the reservoir median surface)	2012-2040	76%	80%	53%	4%	-23%
	2041-2070	37%	61%	61%	24%	24%
	2071-2099	37%	54%	62%	17%	25%

For the 12 CAT scenarios during the 21st century, the percentages of months with surface are less than the median increase at both Folsom and Shasta reservoirs during the 21st century. At Folsom reservoir, the average percentage of months below the median reservoir surface area increases by +24 percent with a range from +4 percent to +38 percent relative to NoCC. At Shasta Reservoir, the average surface area metric increases by +9 percent with a range from -15 percent to +29%. Therefore, at both reservoirs the recreational benefits are likely to be reduced with climate change due to reduced storage volumes and smaller surface area in the reservoirs.

Ecological Resources

The attributes of interest selected as indicators of ecological resources were selected primarily to address concerns with respect to endangered aquatic species and their habitats in the Central Valley of California watersheds. These attributes include reservoir cold water pool and floodplain processes in the Sacramento River and pelagic species habitat, adult salmon migration, and food web productivity in the Delta. The performance metrics for these attributes are described in more detail in the following sections.

Coldwater Pool

Storage levels in Shasta Reservoir at the end of April are a useful measure of the availability of cold water for management of water temperatures needed by salmonid species for survival. When storage in Shasta is less than 3,800 TAF at the end of April, management of water temperatures in the Sacramento River during the warm season months becomes increasingly difficult.

Table 14 presents results for the percentage of April months when Shasta storage is less than 3,800 TAF in the early, mid, and late 21st century periods. The central tendency CT_Q5 shows slight increases in reduced cold water pool in each period. Except in the early period, the 12 CAT scenarios have considerably increased frequencies of reduced cold water pool. The early 21st century decrease is associated with an increased frequency of high runoff events in the CAT scenarios during this period.

Table 14. Summary of the Shasta Reservoir April Storage Performance Metric Results for the Ecological Resources Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
Shasta Coldwater Pool (percent of April months with Shasta storage less than 3,800 TAF)	2012-2040	41%	48%	14%	7%	-27%
	2041-2070	0%	7%	22%	7%	22%
	2071-2099	14%	14%	29%	0%	15%

For the 5 EI scenarios, the overall 21st century average CT_Q5 change is a +5 percent increase in the frequency of reduced cold water pool with a range from -12 percent to +32 percent. For the 12 CAT scenarios, the overall 21st century average change is an increase of +4 percent in reduced cold water pool with a range from -7 percent to +20 percent. Under most climate change scenarios, the availability of cold water storage in Lake Shasta is likely to be reduced.

Floodplain Processes

Flows in excess of 15,000 cfs at Keswick Dam below Shasta Reservoir during the months of February through June are a useful indicator of floodplain processes capable of sustaining favorable riparian habitat conditions in the Sacramento River watershed. This performance metric was chosen to present in this report because it is exceeded less frequently than other ecological flow metrics in the Sacramento River watershed.

Table 15 presents results for the percentage of months from February through June when flow at Keswick Dam is less than 15,000 cfs in the early, mid, and late 21st century periods. In general, the earlier season runoff in the future scenarios results in decreased frequency of flows below this performance metric during the 21st century.

Table 15. Summary of Keswick February through June Flows Performance Metric Results for the Ecological Resources Category

Metric	Period	CT_NoCC	CT_Q5	CAT12	Percent Change from CT_NoCC	
					CT_Q5	CAT12
Sacramento River flows at Keswick Dam (percent of Feb–Jun months with <15,000 cfs)	2012-2040	96%	94%	90%	-2%	-6%
	2041-2070	97%	95%	92%	-2%	-5%
	2071-2099	94%	95%	94%	1%	0%

For the 5 EI scenarios, the overall 21st century average change is a -1 percent decrease in the percentage of flows below the metric with a range from -4 percent to 0 percent. For the 12 CAT scenarios, the overall 21st century average change is a decrease of -4 percent in flows below the metric with a range from -8 percent to -2 percent. These results indicate a small reduction in floodplain process flows under most climate change scenarios.

Pelagic Species Habitat

The attribute of interest selected for habitat suitable for endangered pelagic species such as smelt in the Delta is the spring X2 performance metric. X2 is defined as the distance measured in kilometers (km) from the Golden Gate Bridge to the location of the 2 parts per thousand salinity concentration isohaline in the Delta. The X2 position is a function of both the freshwater Delta outflow and sea level which affects tidal saltwater mixing in the western Delta. Greater X2 positions indicate that salinity has moved farther eastward into the Delta. Maintaining X2 positions of less than 74 km in spring months is one of the goals specified in the U.S. Fish and Wildlife Service's Biological Opinion and the SWRCB's Water Rights Decision D-1641.

Table 16 presents results for the percentage of months between February and June when the X2 position is greater than 74 km in the early, mid, and late 21st century periods. In general, rising sea levels during the 21st century result in a trend toward increasing frequency of eastward salinity intrusion into the Delta relative to the NoCC scenario. The variability within this trend reflects differences in Delta outflows associated with the projected hydroclimates.

Table 16. Summary of the Spring X2 Performance Metric Results for the Ecological Resources Category

Metric	Period	CT_NoCC	CT_Q5	CAT12	Percent Change from CT_NoCC	
					CT_Q5	CAT12
Delta Low Salinity Zone (percent of Feb–Jun months where X2 is greater than 74 km)	2012-2040	26%	34%	33%	8%	7%
	2041-2070	21%	33%	43%	12%	22%
	2071-2099	34%	50%	53%	16%	19%

For the 5 EI scenarios, the overall 21st century average change is a +12 percent increase in the percentage of the X2 positions exceeding the metric with a range from -2 percent to +30 percent. For the 12 CAT scenarios, the overall 21st century average change is an increase of +16 percent in X2 exceedences of the threshold with a range from +3 percent to +32 percent.

Figure 24 shows the percentage of years in which the spring X2 position exceeded 74 km for 3 future periods for each of the 18 socioeconomic-climate projections. As can be observed, there are likely to be significant increases in the X2 position in the future due to sea level rise. The sub-period variability exceeds the ranges described above for the overall 21st century average changes showing that more extreme threshold exceedences can occur.

SCENARIO	2012-2040	2041-2070	2071-2099
CTnoCC	26%	21%	34%
CTQ1	42%	47%	59%
CTQ2	48%	56%	66%
CTQ3	20%	26%	39%
CTQ4	18%	21%	34%
CTQ5	34%	33%	50%
CTA2_cnrmcm3	17%	47%	48%
CTA2_gfdlcm21	34%	37%	63%
CTA2_miroc32med	50%	58%	68%
CTA2_mpiecham5	33%	39%	44%
CTA2_ncarccsm3	41%	50%	52%
CTA2_ncarpcm1	33%	35%	43%
CTB1_cnrmcm3	30%	32%	50%
CTB1_gfdlcm21	32%	37%	60%
CTB1_miroc32med	41%	68%	68%
CTB1_mpiecham5	27%	37%	59%
CTB1_ncarccsm3	48%	38%	44%
CTB1_ncarpcm1	14%	33%	42%
CAT12	33%	43%	54%

Figure 24. Percentage of Months in Each Scenario that the February-to-June X2 Position Is Greater than 74 km for Three Future Periods

Adult San Joaquin Salmonid Migration

The attribute of interest selected for assessing the migration of endangered salmonids through the Delta is the frequency of negative (upstream) flows in the OMR channels of the San Joaquin River in the Delta. The entrainment of adult salmonids migrating to spawning habitat in the San Joaquin River watershed is highly correlated with the frequency of flows more negative than -5000 cfs in these channels during the months of October through December.

Table 17 presents results for the percentage of months from October through December when OMR flows are more negative than the performance metric threshold of -5000 cfs. In general, OMR flows exceeding the performance metric threshold are reduced in the projected future scenarios.

Table 17. Summary of the October through December OMR Negative Flow Performance Metric Results for the Ecological Resources Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
OMR Channel flows (percent of Oct-Dec months when OMR flow is less than -5,000 cfs)	2012-2040	62%	59%	45%	-3%	-17%
	2041-2070	60%	61%	44%	1%	-16%
	2071-2099	56%	59%	40%	3%	-16%

For the 5 EI scenarios, the overall 21st century average change is a 0 percent in the percentage of the OMR negative flows exceeding the metric with a range from -6 percent to +3 percent. For the 12 CAT scenarios, the overall 21st century average change is a decrease of -16 percent in OMR exceedences of the threshold with a range from -50 percent to +5 percent. The inferior performance under the climate scenarios is due to a reduction in the magnitude of flows into the Delta during the fall months as compared to the NoCC scenario.

Food Web Productivity

The attribute of interest selected for assessing the food web productivity in the Delta is the frequency of negative (upstream) flows in the OMR channels of the San Joaquin River in the Delta. Food web productivity is highly correlated with the frequency of flows more negative than -5000 cfs in these channels during the months of July through September.

Table 18 presents results for the percentage of months from July through September when OMR flows are more negative than the performance metric threshold of -5000 cfs. In general, OMR flows exceeding the performance metric threshold are reduced in the projected future scenarios.

Table 18. Summary of the July through September OMR Negative Flow Performance Metric Results for the Ecological Resources Category

					Percent Change from CT_NoCC	
Metric	**Period**	**CT_NoCC**	**CT_Q5**	**CAT12**	**CT_Q5**	**CAT12**
OMR Channel flows (percent of Jul-Sep months when OMR flow is less than -5,000 cfs)	2012-2040	76%	70%	70%	-6%	-6%
	2041-2070	92%	82%	71%	-10%	-21%
	2071-2099	92%	84%	70%	-8%	-22%

For the 5 EI scenarios, the overall 21st century average change is a -8 percent in the percentage of the OMR negative flows exceeding the metric with a range from -29 percent to +6 percent. For the 12 CAT scenarios, the overall 21st century average change is a decrease of -16 percent in OMR exceedences of the threshold with a range from -32 percent to +2 percent. The inferior performance under the climate scenarios is due to a reduction in the magnitude of flows into the Delta during the summer months as compared to the NoCC scenario.

Chapter 9. Study Limitations and Next Steps

The SSJIA provides valuable new information for long-range planning purposes as well as the SSJBS which is developing more detailed and updated assessments of the impacts of future climatic change in the Sacramento River, San Joaquin River, and Tulare Lake hydrologic basins. However, there are limitations that should be acknowledged when evaluating the results of these analyses:

- The SSJIA is a reconnaissance-level analysis that simulates the most important components of the CVP/SWP water management system by using simplified representations of the CVP, SWP, and local project operations within the Central Valley of California. Additionally, although the scope of the analysis included all supplies and demands within the Central Valley of California, the effects of climate change were not analyzed for smaller-scale local regions such as the CVP, SWP or non-project service areas. The SSJBS will address the areas served by the SWP and CVP water users as part of the analysis.

- The analyses used WEAP-CV and CalLite models developed for the CVP IRP. These models have simplified representations of much of the complexity of the CVP and SWP water management systems in comparison to more complex models such as CALSIM II. These models capture the most prominent aspects of the Central Valley of California hydrology and system operations, but simulated hydrology and water management within specific sub-basins has limited detail. Therefore, the models did not simulate some aspects of SWP/CVP operations, such as Cross Valley Canal deliveries or CVPIA (b)(2) operations.

- The CT socioeconomic scenario combined with the 18 CMIP 3 hydroclimate projections may not represent a sufficient range of uncertainty for development of adaptation strategies. The SSJBS, due to be completed in early 2015, will provide a more comprehensive analysis that includes other means of characterizing future uncertainties including paleoclimate data, more refined and updated socioeconomic information, and multiple sequences of climate variability. Additionally, this SSJIA analysis used CMIP3 climate data because CMIP5 data sets were not available at the time the analysis was performed. The SSJBS will incorporate the newer CMIP5 climate data sets.

- Although the analytical approach utilized in the SSJIA addresses a broad range of performance metrics related to the Central Valley water management system, it does not address some aspects of California water management that could be considered important metrics for assessment of impacts. In particular, additional analysis methods could be included to consider more detailed aspects of ecological resources, flood control, and recreation. Despite these limitations, the SSJIA provides a solid foundation for improved understanding of the greater range of impacts of future climate change on the Central Valley water management system. The limitations identified here provide a basis for additional improvements in the analytical approach, which will be pursued as part of the SSJBS and other future long-term Reclamation planning activities.

- The SSJIA does not analyze potential adaptation strategies that could mitigate the impacts of climate change and improve the performance of the system. The SSJIA provides comparisons among the different climate scenarios but not an analysis of tradeoffs among different portfolios of adaptation strategies. However, the analytical approach developed in the SSJIA is capable of assessing a broad range of potential adaptation strategies and portfolios. The SSJBS will include analysis of various adaptation strategies, including interactions with stakeholder groups to obtain additional information regarding the effectiveness, efficiency, and acceptability of potential adaptation strategies.

Despite these limitations, the SSJIA provides a solid foundation for improved understanding of the greater range of impacts of potential future climate change on the Central Valley of California's water management systems. The limitations identified here provide a basis for additional improvements in the analytical approach which is being pursued as part of the SSJBS and other future long-term Reclamation planning activities.

Chapter 10. References

Anderson, J., F. Chung, M. Anderson, L. Brekke, D. Easton, M. Ejeta, R. Peterson, and R. Synder. 2008. "Progress on Incorporating Climate Change into Management of California's Water Resources." *Climatic Change*, Volume 89, Supplement 1, pp. 91-108. Published online 12-22-207. ISSN: 0165-009 (Print) 1573-2480 (online)

DOI: 10.1007/s10584-007-9353-1

Beckley, B.D., F. Lemoine. S. Luthcke, R. Ray, and N. 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.

Reclamation 2011. SECURE Water Act Section 9503(c) – Reclamation Climate Change and Water 2011. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Technical Services Center, Denver, Colorado.

__________. 2013. Summary Report Central Valley Project Integrated Resource Plan. Prepared by U.S. Department of the Interior, Bureau of Reclamation, Mid-Pacific Region, Sacramento, California.

California Department of Finance (DOF). 2007. Population Projections for California and Its Counties 2000-2050, by Age, Gender and Race/Ethnicity. *http://www.dof.ca.gov/research/demographic/reports/projections/p-3/*). July.

California Department of Water Resources (DWR). 2009. California Water Plan Update 2009. Bulletin 160-09. Sacramento, California.

Cayan, D. R., A. L. Luers, G. Franco, M. Hanemann, B. Croes, and E. Vine. 2008a. "Overview of the California climate change scenarios project." *Climatic Change* 87(Suppl 1): S1–S6, doi:10.1007/s10584-007-9352-2.

Cayan, D. R., E. P. Maurer, M. D. Dettinger, M. Tyree, and K. Hayhoe. 2008b. "Climate Change Scenarios for the California Region." *Climatic Change*, published online January 26. doi:10.1007/s10584-007-9377-6.

Cayan, D. R., P. D. Bromirski, K. Hayhoe, M. Tyree, M. D. Dettinger, and R. E. Flick. 2008c. "Climate Change Projections of Sea Level Extremes Along the California Coast." *Climatic Change* 87(Suppl 1): S57–S73, doi:10.1007/s10584-007-9376-7.

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

Intergovernmental Panel on Climate Change (IPCC). 2000. Special Report on Emissions Scenarios. (Nakicenovic, N., and R. Swart, eds.). Cambridge University Press, Cambridge, United Kingdom. *http://www.grida.no/climate/ipcc/emission/*.

Johnson, H. 2008. Population Projections for California Climate Change Scenarios. Prepared for Public Policy Institute of California. February.

Livneh, B., E. A. Rosenberg, C. Lin, V. Mishra, K. Andreadis, E. P. Maurer, and D.P. Lettenmaier. 2013. A long-term hydrologically based data set of land surface fluxes and states for the conterminous U.S.: Update and extensions, *Journal of Climate*, DOI: 10.1175/JCLI-D-12-00508.1.

Maurer, E. P., L. Brekke, T. Pruitt, and P. B. Duffy. 2007. "Fine-Resolution Climate Projections Enhance Regional Climate Change Impact Studies." Eos Trans. AGU. 88(47):504.

National Research Council (NRC). 2012. *Sea-Level Rise for 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.

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

U.S. Fish and Wildlife Service (USFWS). 2008. Formal Endangered Species Act Consultation on the Proposed Coordinated Operations of the Central Valley Project (CVP) and State Water Project (SWP). December.

Western Regional Climate Center. 2013. *http://www.wrcc.dri.edu/monitor/cal-mon/frames_version.html. Accessed July 2013.*