USING FUTURE CLIMATE PROJECTIONS TO SUPPORT WATER RESOURCES DECISION MAKING IN CALIFORNIA

DRAFT

A Report From:
California Climate Change Center

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California's electricity and natural gas ratepayers. The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts focus on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

In 2003, the California Energy Commission's PIER Program established the **California Climate Change Center** to document climate change research relevant to the states. This center is a virtual organization with core research activities at Scripps Institution of Oceanography and the University of California, Berkeley, complemented by efforts at other research institutions. Priority research areas defined in PIER's five-year Climate Change Research Plan are: monitoring, analysis, and modeling of climate; analysis of options to reduce greenhouse gas emissions; assessment of physical impacts and of adaptation strategies; and analysis of the economic consequences of both climate change impacts and the efforts designed to reduce emissions.

The California Climate Change Center Report Series details ongoing center-sponsored research. As interim project results, the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the center seeks to inform the public and expand dissemination of climate change information, thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website www.energy.ca.gov/pier/ or contract the Energy Commission at (916) 654-5164.

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Abstract

One of the challenges facing California's water planners is how to assess the possible effects of climate change, such as changes in rainfall and snowfall patterns, snowpack, runoff volume and timing, sea levels, and urban and agricultural water demands. This paper presents several advances in using future climate projection information in water resources planning, such as an improved understanding of how well selected climate models represent historical climate conditions and refined methodologies for representing streamflows, outdoor urban and agricultural water demands, and sea level rise in planning tools. Twelve climate projections were used to assess the future reliability of California's main water supply projects. Mid-century and end-of-the-century impacts were estimated for Sacramento-San Joaquin Delta exports, reservoir carryover storage, groundwater pumping, power supply, and the Delta salinity standard known as X2. The vulnerability of the system to operational interruption was also examined. A sensitivity analysis was also conducted to examine the effects of air temperature on runoff in the Upper Feather River basin, the main inflow source to Lake Oroville. The range of impacts presented in this paper indicates a need to explore adaptation measures to improve the reliability of future water supplies in California.

Keywords: Artificial Neural Network (ANN), CalSim-II, climate change, climate projection downscaling, power supply, precipitation, Sacramento-San Joaquin Bay-Delta, sea level rise, State Water Project (SWP) and Central Valley Project (CVP), and water supply reliability

1.0 Introduction

One of the challenges facing California's water planners is how to include possible effects of climate change in the decision making process. Planners already have to account for large natural variability in precipitation and runoff in California. Projected increases in air temperature and changes in precipitation patterns could modify rainfall and snowfall patterns, reduce snowpack, change runoff volume and timing, increase sea levels, and change urban and agricultural water demands. More than 23 million Californians rely on two large water projects: the State Water Project (SWP) and the federal Central Valley Project (CVP) (Figure 1). These complex water storage and conveyance systems are operated by the California Department of Water Resources (DWR) and the U.S. Bureau of Reclamation (Reclamation) to provide water supply, flood management, environmental protection, and recreation.

In June 2005, Governor Arnold Schwarzenegger issued Executive Order S-3-05, which requires biennial reports on climate change impacts in several areas, including water resources. In response to that executive order, DWR prepared a report titled *Progress on Incorporating Climate Change into Management of California's Water Resources* (DWR 2006). This paper presents an overview of advances that DWR has made since the 2006 report toward using future climate projection information to support decision making by quantifying possible impacts to water resources for a range of future climate scenarios.

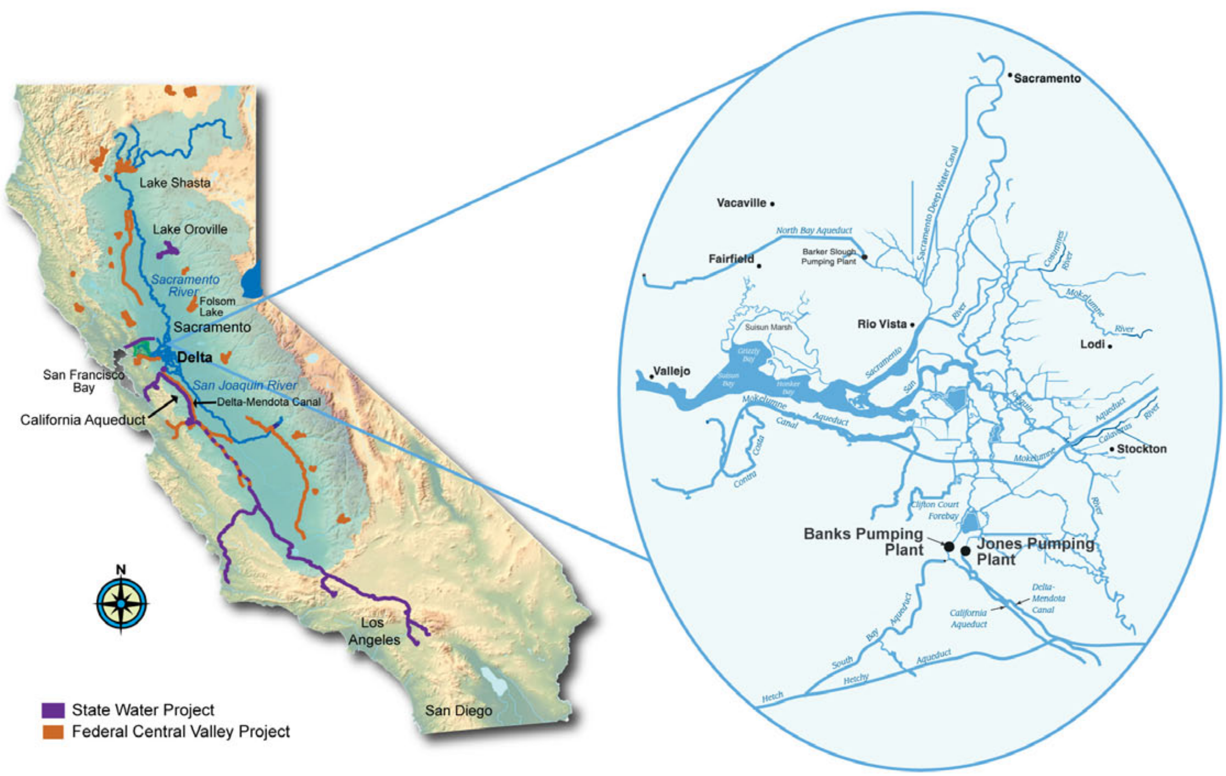


Figure 1. State Water Project and Central Valley Project in California (left). Sacramento-San Joaquin Delta (right).

1.1. Objectives

The main objective of the work presented in this paper is to develop ways to use future climate projection information to manage California's water for future urban, agricultural, environmental, and recreational uses. Some specific questions to be addressed are:

- How well do selected climate models represent historical conditions—such as air temperature, precipitation, and streamflow—that affect water resources in California?
- How do the methods used to convert global information to regional information affect the subsequent water resource impacts analyses and decision making?
- How can future projections for rainfall, runoff, streamflow, and sea level rise be incorporated into water resources planning?
- How can management tools be used to quantify the possible impacts of climate change on water systems in the Central Valley?

1.2. Organization

This paper is organized around the four main objectives listed above. A general approach for investigating how to use future climate projection information in water resources planning is described in Section 2.0. The ability of global climate models to represent key climatic and hydrologic processes in California is examined in Section 3.0. New methods and applications for using climate change information in water resources planning are presented in Section 4.0. Potential impacts of climate change on the SWP and CVP are assessed in Section 5.0.

1.3. Key Findings

Since the 2006 climate change assessment (DWR 2006), several advances have been made in using future climate projection information in water resources planning in California, including improved understanding of how well selected climate models represent historical climate conditions and refined methodologies for representing streamflows, outdoor urban and agricultural water demands, and sea level rise in planning tools. The range of impacts presented in this paper indicates the need for adaptation measures to improve the reliability of future water supplies in California (DWR 2008).

Possible climate change impacts to SWP and CVP operations were assessed using 12 future climate projections (Section 2.2). Median results for the 12 projections are presented in Table 1. The range of results for the12 projections are detailed throughout the paper. Uncertainties in the results increase as the projections move further into the future. These studies assumed that no changes were made to the existing SWP and CVP infrastructure in the future. Future system operations used State Water Resources Control Board Decision 1641 (SWRCB D1641) regulations (SWRCB 1995). Operations guidelines that are subject to change, such as restrictions on Delta exports contained in Endangered Species Act biological opinions, were not included in these studies due to the high uncertainty of how such restrictions may be applied 50 or 100 years from now. The reliability of the SWP and CVP water supply systems is expected to be reduced for the range of future climate projections studied (Section 5.2.3). Decreases in annual Delta exports would reduce water deliveries south of the Delta. Reductions in reservoir carryover storage would reduce the systems' flexibility during water shortages. In the Sacramento Valley, reduced surface water supplies are likely to be augmented by increased groundwater pumping. Both power generation and power use by the SWP and CVP are anticipated to decrease under climate change due to the expected reduction in water deliveries. The SWP and CVP are expected to continue meeting X2 Delta salinity standards. Under climate change, in some years water levels in the main supply reservoirs (Shasta, Oroville, Folsom, and Trinity) could fall below the lowest release outlets making the system vulnerable to operational interruption. In those years, additional water would be needed to meet current regulatory requirements and to maintain minimum system operations. This water could be obtained through additional water supplies, reductions in water demands, or a combination of the two. For current conditions, the system is not considered vulnerable to operational interruption.

Table 1. Summary of water resources impacts considering 12 future climate scenarios

		Mid-Century: Some Uncertainty		End of Century: More Uncertainty	
		A2: Higher GHG Emissions	B1: Lower GHG Emissions	A2: Higher GHG Emissions	B1: Lower GHG Emissions
Delta Exports		-10%	-7%	-25%	-21%
Reservoir Carryover Storage		-19%	-15%	-38%	-33%
Sacramento Valley Groundwater Pumping		+9%	+5%	+17%	+13%
Power Supply					
	CVP Generation	-11%	-4%	-13%	-12%
	CVP Use	-14%	-9%	-28%	-24%
	SWP Generation	-12%	-5%	-16%	-15%
	SWP Use	-10%	-5%	-16%	-16%
X2 Delta Salinity Standard		Expected to be Met	Expected to be Met	Expected to be Met	Expected to be Met
System Vulnerability to Interruption*		1 in 6 years	1 in 8 years	1 in 3 years	1 in 4 years
Additional Water Needed to Meet Regulations and Maintain Operations**		750 TAF/yr	575 TAF/yr	750 TAF/yr	850 TAF/yr

* The SWP-CVP system is considered vulnerable to operational interruption during a year if the water level in one or more of the major supply reservoirs (Shasta, Oroville, Folsom, and Trinity) is too low to release water from the reservoir. For current conditions, the SWP-CVP system is not considered vulnerable to operational interruption.

** Additional water is needed only in years when reservoir levels fall below the reservoir outlets.

In addition to the climate projection analyses, a sensitivity analysis was conducted to examine the effects of air temperature on runoff in the Upper Feather River basin, the main inflow source to Lake Oroville (Section 5.1).

- When air temperatures in the study increased by 4°C (7.2°F), the average day that 50% of the annual inflow arrives at Lake Oroville shifts from mid-March to mid-February, which is 36 days earlier than in the base scenario.

- Warmer air temperatures lead to more winter precipitation falling as rain instead of snow, which reduces the amount of snowpack that traditionally has produced runoff in the late spring.
- The 30-year trend indicates that the fraction of annual runoff occurring from April through July decreases from about 35% for the historical base scenario (historical conditions with no increase in air temperature) to about 15% for the +4°C scenario.
- In addition to the water supply and flood management impacts of earlier snowmelt, current water year classifications and their associated regulatory standards may need to be revisited because they are partly based on runoff from April to July, which is anticipated to decrease under climate change.

Because uncertainties associated with impacts analyses increase as the projection moves further into the future, and because a practical engineering planning horizon for most facilities is less than 50 years, DWR believes that the mid-century analyses are more relevant to water resources planning and management. However, the end of the century analyses will serve as a useful reference guide because many water facilities are expected to have useful lives into the next century.

2.0 Approach

This section details the general approach for developing ways to use climate change information for water resources planning. It also describes the future climate projections used in the analysis.

2.1. Using Climate Change Information for Planning

Information on climate and climate change used for decision making is typically provided by historical observations or model results of projected future conditions. At DWR, a three-pronged approach is being used to develop ways to use climate change information in the water resources planning process (Figure 2): (1) examining historical data, (2) comparing global climate model (GCM) simulations of historical climate, and (3) exploring possible impacts of projected future climate conditions on California's water resources.

The first approach examines historical data for evidence of changing climate conditions and the related effects on water resources, such as runoff patterns. Knowing how the climate has already changed and how those changes have affected water resources provides insight into what may happen in the future. Because this paper focuses on ways to use future climate projection information, the historical analysis is not presented in this paper, but it can be found in other DWR reports (for example, DWR 2006).

To build confidence in using selected GCMs to project future climate conditions, the second approach compares simulations of the late twentieth century to observed data to see how well the downscaled climate information from the GCMs represent the climate and water cycle in California (Section 3.0). Planners may give more consideration to future climate projections from GCMs that do a better job at reflecting climate conditions in California.

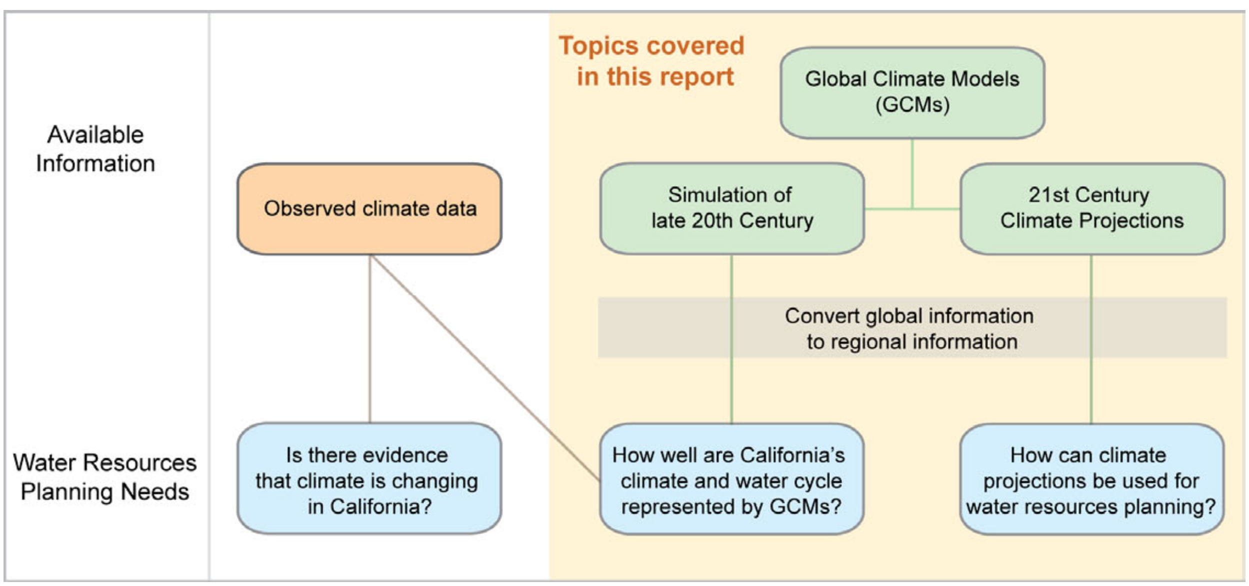


Figure 2. Using climate change information to plan for California's future water needs

The third approach develops ways to use twenty-first century climate projections from the GCMs in decision-making tools (Section 4.0) and to use those tools to assess possible impacts of climate change on California's water resources (Section 5.0). Different downscaling methods were used to convert global-scale output from the GCMs to regional-scale information; then the output was examined to see how these methods affect the subsequent estimates of streamflows. Refinements were also made to methods for estimating the effects of the future climate on water resources parameters—such as streamflows and agricultural crops, and urban outdoor water demands—used in decision support tools. Techniques were developed to include the possible effects of sea level rise in planning tools. Computer models were then used to estimate the potential effects of climate change on the SWP and CVP, California's major water projects.

2.2. Future Climate Projections

The Climate Action Team (CAT) was formed in response to California's executive order S-3-05 to guide the preparation of biennial reports on climate change impacts. To help unify analysis across topic areas, the CAT worked with scientists from the California Applications Program's (CAP) California Climate Change Center (CCCC) to select a set of future climate projections to be used for analysis. They defined a climate projection as a GCM simulation of twenty-first century climate conditions for a future greenhouse gas (GHG) emissions scenario. The following criteria were used to select future climate projections for the 2009 impacts analyses (Cayan et al. 2009):

- Ability to adequately represent:
    - El Niño-Southern Oscillation (ENSO) climate patterns
    - Periods of drought over California
    - Annual patterns of monthly mean temperature and precipitation for California
- Daily outputs for air temperature and precipitation
- Available model and application documentation
- Global grid spacing finer than 5° latitude/longitude
- Simulations of both the second half of the twentieth century and projections for the twenty-first century

2.2.1. Global Climate Projections

For the 2008-2009 assessment of climate change impacts, the CAT selected 12 climate projections from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (IPCC 2007). These projections come from six GCMs used to simulate the two GHG emission scenarios known as A2 and B1 (Figure 3) (CAP/CCCC 2008). The A2 scenario assumes high growth in population, regionally based economic growth, and slow technological changes. The B1 scenario represents low growth in population, globally based economic growth, and sustainable development. The B1 scenario has lower future projected GHG emissions than the A2 scenario (IPCC 2000). Each GCM was used to simulate a historical period from 1950-1999 and a future projection period from 2000 to 2100. The use of 12 climate projections (6 GCMs x 2 GHG emissions scenarios) adds 8 projections to the 4 projections (2 GCMs x 2 GHG emissions scenarios) that were used for the 2006 assessment (DWR 2006).

2.2.2. Regional climate information

Air temperature and precipitation information from the GCM simulations were converted to regional-scale data using two statistical downscaling methods (Figure 3): (1) Bias Correction and Spatial Disaggregation (BCSD, which is sometimes referred to as Bias Correction and Spatial Downscaling) (Wood et. al. 2002); and (2) Constructed Analogue (CA) (Hidalgo 2008, Van den Dool 1994). The BCSD approach first adjusts output from the GCMs to account for tendencies in the model to be too wet, dry, warm, or cool during the historical period (bias correction), and then the adjusted data are converted to regional data (spatial downscaling). The CA approach uses previously observed coarse-scale data and the corresponding fine-scale data to generate a relationship between the observed weather patterns and the daily GCM patterns (analogue) at a coarse scale; this relationship is then translated to a finer scale to produce regional information. The BCSD approach was applied to the output from of all six GCM simulations under both emission scenarios, resulting in twelve regional-scale climate change data sets. The CA approach was applied to the output from three GCMs—CNRM-CM3, GFDL-CM21, and NCAR-PCM1[1]—under both emission scenarios, resulting in an additional six sets of regional-scale climate change data. The range of projected changes in air temperature and precipitation for the Sacramento region using the BCSD data are shown in Table 2. The A2 greenhouse gas emissions scenarios tend to be warmer than the B1 scenarios.

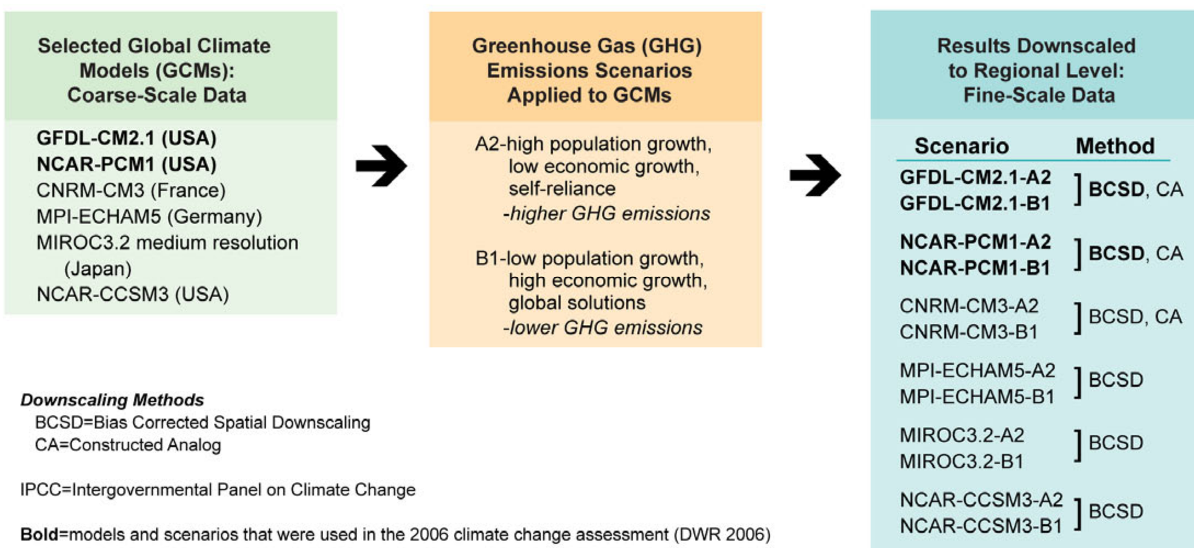


Figure 3. Process for developing the climate projections selected by Climate Action Team for the 2009 analyses

1. CNRM-CM3 (Centre National de Recherches Météorologiques), GFDL (Geophysical Fluid Dynamics Laboratory), and NCAR (National Center for Atmospheric Research)

Table 2. 21st century climate projections from 6 GCMS for the Sacramento region using BCSD

	Air Temperature Increase			Precipitation Change			
	A2 Avg.	B1 Avg.	Range		A2 Avg.	B1 Avg.	Range
Mid-Century	1.7°C (3.0°F)	1.5°C (2.7°F)	0.7°C - 2.2°C (1.3°F - 4.0°F)	Sacramento Valley	-13%	-9%	-2% to -19%
				N. Sierra Nevada	-7%	-2%	-12% to +7%
End of Century	3.7°C (6.7°F)	2.3°C (4.1°F)	1.5°C -4.5°C (2.7°F - 8.1°F)	Sacramento Valley	-16%	-14%	-6% to -23%
				N. Sierra Nevada	-9%	-7%	-19% to +3%

2.2.3. Streamflows

Increases in air temperature and changes in precipitation patterns due to climate change would affect snowpack and runoff, which in turn would affect the timing and amount of flow in the streams that provide California's water supply. Streamflows for projected future climate conditions were estimated for 18 river locations in California, mainly in the Sierra Nevada and Southern Cascade ranges that form the eastern border to the Central Valley (CAP/CCCC 2008). Downscaled climate data from GCMs were used as the input data for the Variable Infiltration Capacity (VIC) model (Liang et al. 1994, CAP/CCCC 2008) to generate regional runoff estimates for runoff, snowpack, snowmelt timing, and soil moisture content (Maurer 2007, Maurer and Duffy 2005). The VIC model runoff results were then routed through river system models to obtain daily and monthly streamflows at specific locations (Maurer et al. 2007, Cayan et al. 2008).

2.2.4. Water Resources Impacts

The goal of the work presented in this report is to evaluate the potential impacts of climate change to the State Water Project (SWP) and Central Valley Project (CVP) (Figure 4) using the information that the CAT team selected. To ensure consistency in all of the analyses conducted in response to the climate change executive order, the GCM and downscaled data and streamflow estimates were provided by the CAP/CCCC group through their website or personal communication (CAP/CCCC 2008).

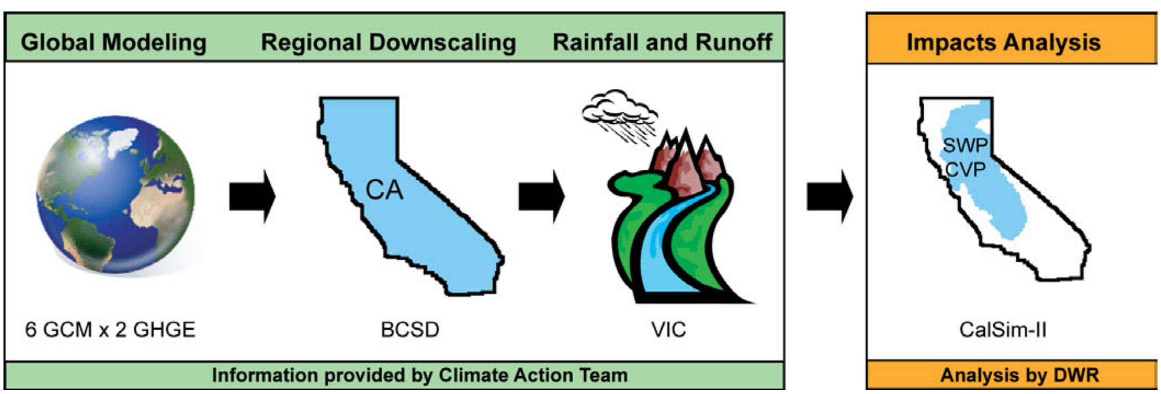
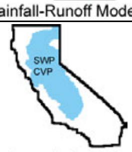
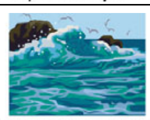
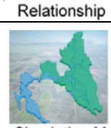
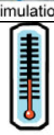


Figure 4. The stages used to analyze the impacts of climate change on California's water resources

2.3. Data Sources

Each section in this paper has a sidebar to clarify the source of the data used in each of the analyses presented—data directly from a GCM, downscaled data, etc. The symbols used in the data source sidebars are defined in Table 3.

Table 3. Symbols for data source sidebars

Symbol	Definition
 Global Climate Models	Data provided by six Global Climate Models (GCMs) for two future greenhouse gas emissions scenarios (A2 has higher emissions and B1 has lower emissions)
 Regional Downscaling	Coarse-scale climate data from GCMs is converted to the regional scale using statistical downscaling. For this study, the two downscaling methods used are Bias Correction and Spatial Disaggregation (BCSD) and Constructed Analogue (CA).
 Rainfall-Runoff Modeling	Downscaled climate data are input into the Variable Infiltration Capacity (VIC) model, which is a rainfall-runoff model used to estimate streamflows.
 Impacts Analysis	State Water Project (SWP) and Central Valley Project (CVP) impacts of climate change—such as changes in reservoir operations, amount of water delivered to customers, and amount of water in storage—were studied using CalSim-II, a water allocation model for the SWP and CVP.
 Temperature / Sea Level Relationship	Sea level rise projections are calculated using a known relationship between air temperature and amount of sea level rise originally developed by Stefan Rahmstorf (Rahmstorf 2007).
 Delta Simulation Models	Data were provided by simulation models of Delta flows and salinity: the Delta Simulation Model 2 (DSM2) and the UnTRIM model.
 Temperature Ranges	Climate change is represented by increases in historical air temperature of 1°C (1.8°F) increments. The scenarios used for this study are hypothetical increases in air temperature of 1°C, 2°C, 3°C, and 4°C (1.8°F, 3.6°F, 5.4°F, and 7.2°F).

2.4. Uncertainty

Making decisions about water resources requires an understanding of the sources and effects of uncertainty in future planning (Ajami et al. 2008). Researchers are addressing a wide range of topics related to uncertainties in climate change and water resources planning (for example, Maurer et al. 2008, Groves et al. 2008, Milly et al. 2008, Koutsoyiannis et al. 2007, and Hartmann 2005). This report includes advancements in addressing uncertainty that DWR has made since the 2006 assessment (DWR 2006). One way to address uncertainties associated with future climate projections is to look at a wide range of available projections. For this report, the number of future climate projections examined was expanded from four scenarios in the 2006 assessment to twelve scenarios. Because uncertainties increase the further we look into the future, water resources impacts are presented at both the mid-century and at the end of the century (Section 5.2). Another way to address future uncertainties is to use flexible tools that allow managers to select their own risk tolerance. This report presents one such methodology for determining relative risks related to sea level rise projections at different times in the future (Section 4.1.2). Continuing to address issues of uncertainty in assessing potential climate change impacts on California's water resources will remain a priority for researchers and decision makers.

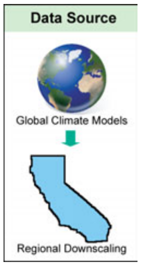
3.0 GCM Representations of the Late Twentieth Century

Objectives	How well do selected climate models represent historical conditions in California that affect water resources, such as air temperature, precipitation and streamflow? How do the methods used to convert global information to regional information affect the subsequent water resource impacts analyses and decision making?

The six GCMs used in this study have all been used to simulate climate for the second half of the twentieth century (1950–1999). One of the objectives of this work was to compare the regional climate and streamflow information based on the historical period GCM results to observed data (Figure 2). An improved understanding of how well downscaled information from GCMs represents California's historical climate can build confidence in using future climate projections from those models for water resources planning.

Because water resources planning depends on regional-scale data, this study examined climate data from the GCMs that had been converted to regional data by a process called *downscaling*. In general, downscaling methods represent regional air temperature well, but they have variable results in representing regional precipitation (Fowler et al. 2007). For this study, regional-scale air temperature, precipitation, and streamflow estimates from two downscaling methods (BCSD and CA) were compared to observed data for selected locations throughout California. A study by Maurer and Hidalgo (2008) showed that air temperature and precipitation estimates using these two methods are similar when looking at monthly data. The analysis in this paper confirms that finding for the 12 future climate projections; however, the two downscaling methods resulted in different streamflow estimates.

3.1. Air Temperature



Observed air temperatures estimates for the second half of the twentieth century were compared to estimates based on output from six GCM and downscaled by two methods, BCSD and CA, for selected locations across California, including Redding, Sacramento, Fresno, and Bakersfield. The air temperatures closely matched both the average temperatures and the range of temperatures (Figure 5). There were no significant differences in average air temperature estimates using BCSD or CA downscaling methods. The BCSD air temperature estimates were expected to match observed data well because the bias correction step of BCSD adjusts the model values to have the same average values as the observed data. The CA air temperatures also matches observed data averages well even though CA does not include a bias correction step. These results indicate that the six GCMs and the two downscaling methods used in this study capably represent historical air temperatures in California (Figure 5).

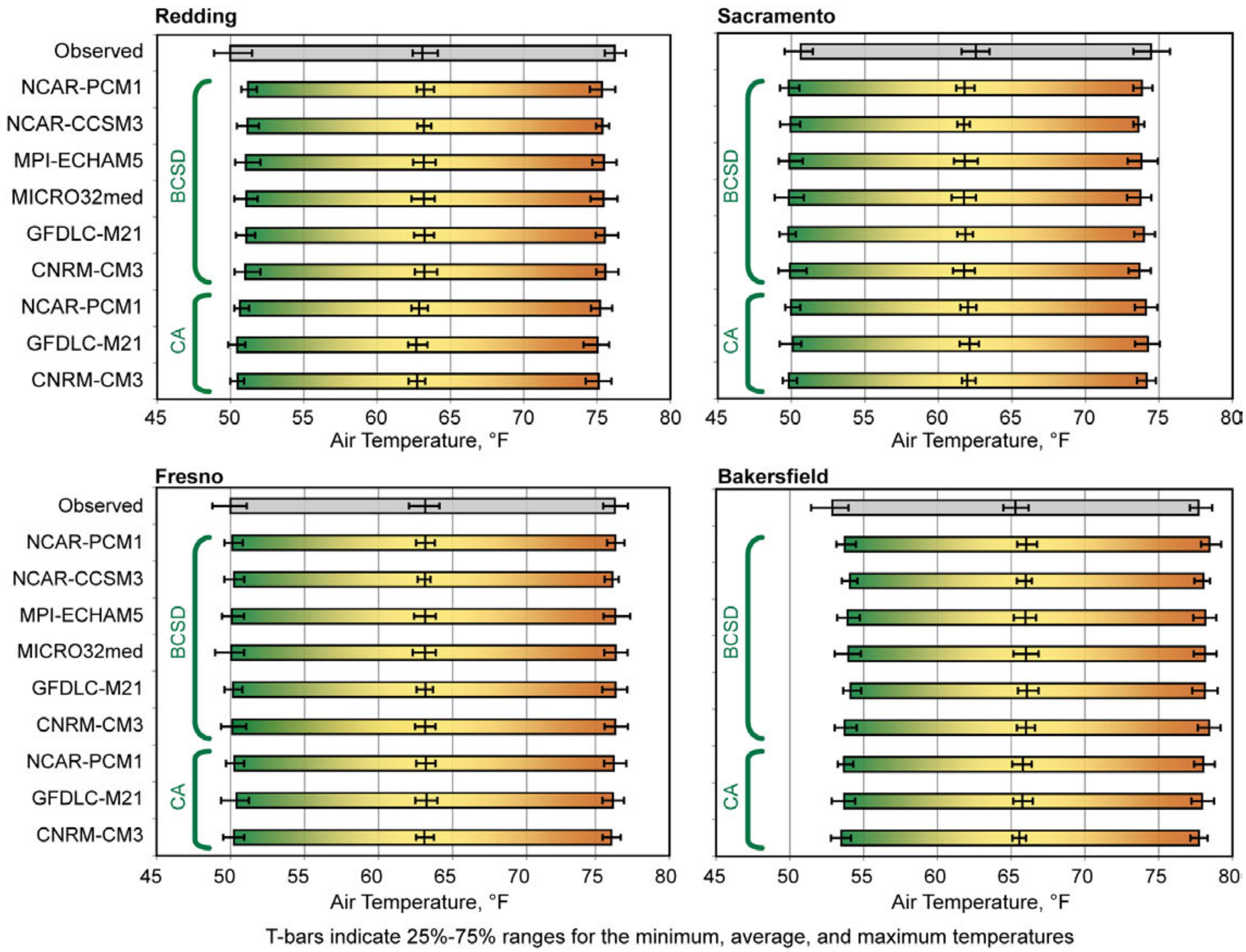
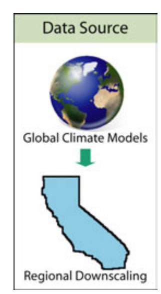


Figure 5. Comparison of observed and GCM-based air temperatures for two downscaling methods at four locations in California for 1950–1999

3.2. Precipitation



DWR estimates of Sacramento Valley floor precipitation based on historical gauge data (Figure 6) were compared to simulated precipitation data for the second half of the twentieth century from six GCMs and two downscaling methods. Sacramento Valley floor precipitation was chosen for this comparison because it is used to adjust outdoor urban and agricultural consumptive water use in SWP and CVP impacts analyses (Section 4.3). Mountain precipitation is also important for California's water supply; it is incorporated in the impacts analyses in the reservoir inflow estimates (Section 5.2), which accounts for infiltration/percolation and evapotranspiration in the mountainous regions that provide runoff to the modeled SWP and CVP regions.

For the BCSD downscaling method, the mean monthly rainfall plots from the six GCMs are practically identical and are similar to the historical precipitation estimated by DWR (Figure 6). This result is expected because the bias correction step of the BCSD method adjusts the output from the GCM to statistically match the observed data for the selected historical period, 1950-1999 in this case. Although the monthly average BCSD downscaled precipitation pattern was similar to DWR estimates of historical data (Figure 6), the long-term trends of the BCSD downscaled annual precipitation differ from the corresponding long-term trends for the observed data (Figure 7). The historical long-term precipitation trend is increasing, but only two of the six GCMs showed an increasing trend in BCSD downscaled precipitation. This means that the majority of the models simulated conditions in California that were drier than it really was at the end of the 20th century.

The CA downscaled precipitation data from three GCMs for the historical period does not closely match the historical precipitation estimates by DWR (Figure 6). In the fall, precipitation is underestimated by 20%-55%. Winter precipitation is overestimated by 15%-30%. The historical long term precipitation trend is increasing, but CA downscaled precipitation from only one of the three GCMs showed an increasing trend.

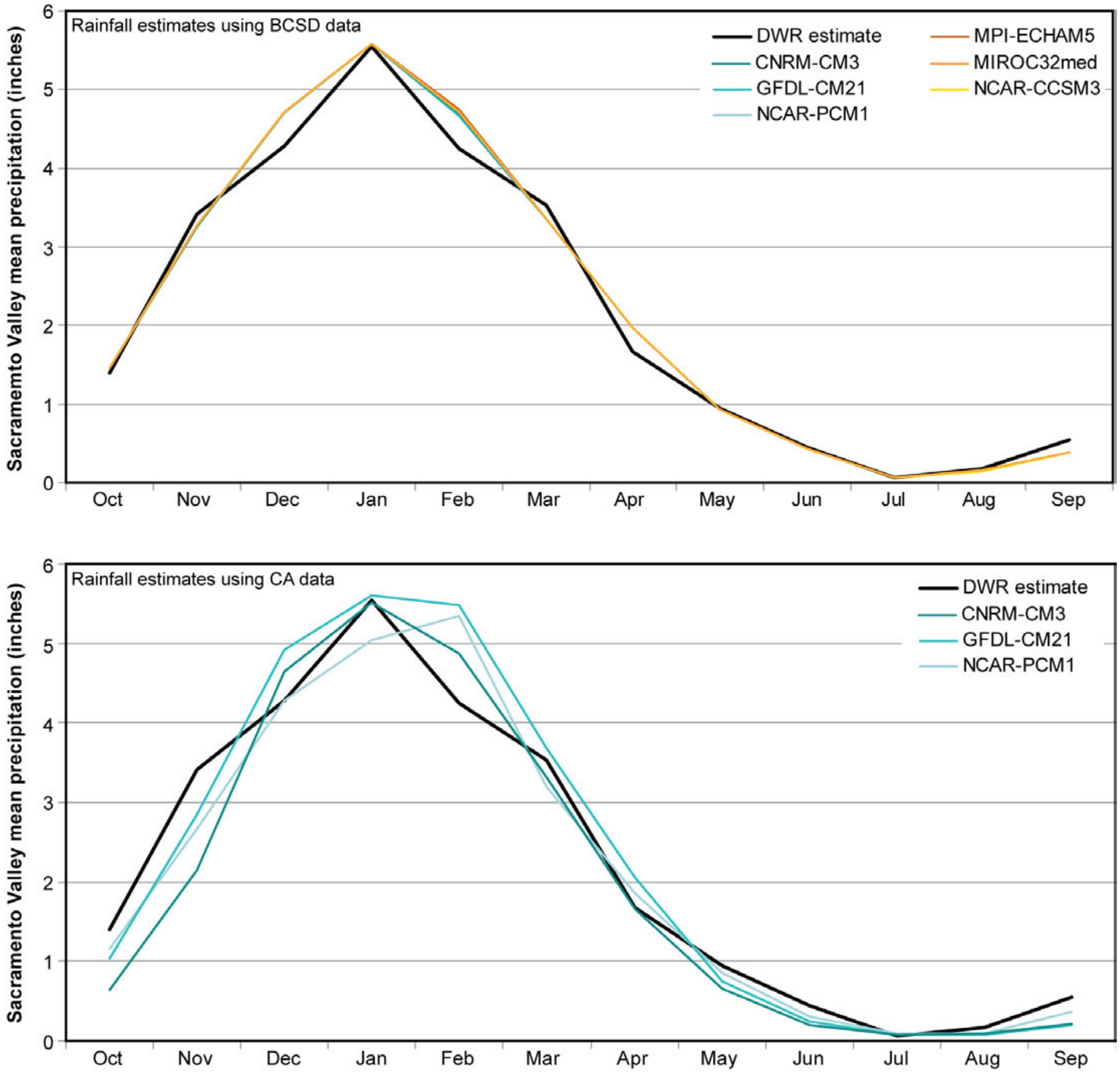
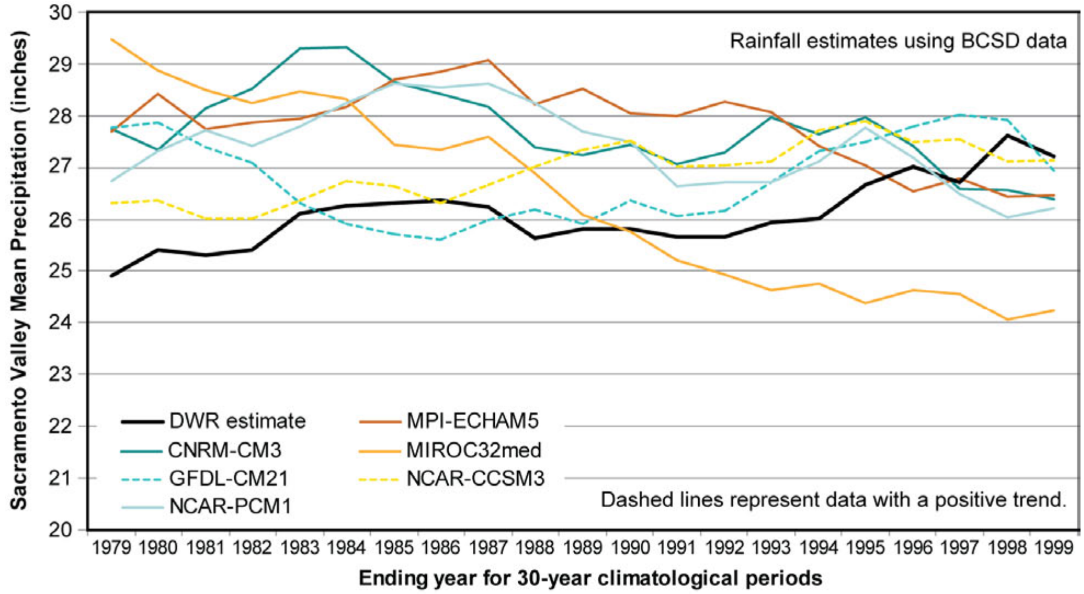


Figure 6. Comparison of historical and GCM-based monthly precipitation for the Sacramento Valley for 1950–1999



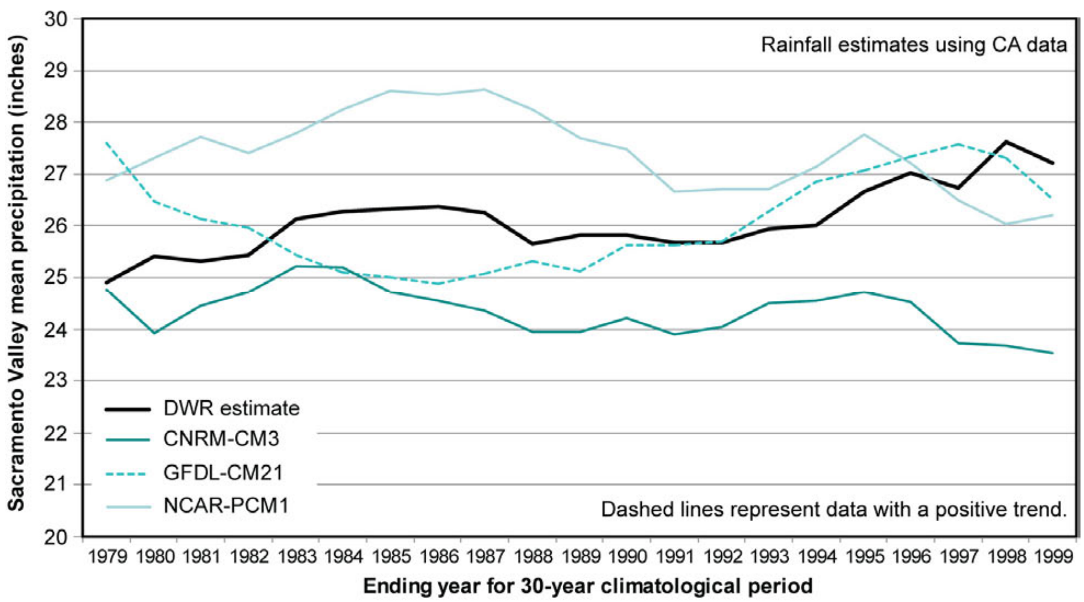
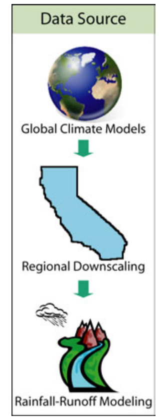


Figure 7. Comparison of historical and GCM-based monthly precipitation for the Sacramento Valley for 1950–1999

The increasing trend in the observed precipitation data in the Sacramento Valley for the second half of the 20th century is consistent with studies that suggest that anthropogenic forcing may have caused a small increase in global mean precipitation (Zhang et al. 2007). The ability of GCMs to capture this observed precipitation trend is an area of continuing research which could help reduce uncertainties associated with using precipitation information from GCMs for impacts assessments.

3.3. Streamflow



Streamflows for the second half of the twentieth century were estimated by the CAT at 18 river locations in California, mainly in the foothills of the Sierra Nevada and Southern Cascade ranges that form the eastern border to the Central Valley (CAP/CCCC 2008). Downscaled climate data from historical GCM simulations were used by the CAT as input climate data for the Variable Infiltration Capacity (VIC) model (Liang et al. 1994, CAP/CCCC 2008). For this study, daily and monthly streamflows estimates provided by the CAT were evaluated for flood and water supply planning respectively.

3.3.1. Daily Streamflows

For flood management, it is important to understand how well historical high flow conditions are represented by daily streamflow estimates based on runoff computed by the VIC model, which uses downscaled GCM output to represent twentieth century climate conditions. Two measures that may be used for flood planning purposes are three-day and five-day peak flows, which are the highest average flow over a three-day or a five-day period during a year. For this analysis, two locations were chosen that have not been significantly affected by upstream water storage or conveyance development: the Sacramento River near the town of Delta upstream of Shasta Lake and the Merced River at Pohono Bridge near Yosemite. Historical three-day and five-day peak flows were computed from the United States Geological Survey's daily gauge records from 1950–1999. These historical streamflows were compared to peak flow estimates based on runoff data from VIC simulations that used climate data from six GCMs downscaled by two different methods: BCSD and CA.

Estimates of peak flows were closer at the Merced River location than at the Sacramento River location (Table 4). For the Merced River location, three-day peak flows from both downscaling methods were within 10% of the historical estimates, and the five-day peak flows were overestimated by 10%–30%. For the Sacramento River near the town of Delta, the CA method underestimated peak flows by 5% to 55%, while the BCSD estimates ranged from underestimates of 25% to overestimates of 50%. These substantial error ranges indicate that a better understanding of model-choice, downscaling, and subsequent rainfall-runoff estimation methods is needed before using daily streamflow projections for water management. This is why analyses for this report focused on the monthly streamflow estimates (Section 3.3.2)

Table 4. Range of GCM-based estimates of 3-day and 5-day peak flows compared to the 1950–1999 historical period

Location	BCSD		CA	
	3-day	5-day	3-day	5-day
Sacramento River near the town of Delta (Shasta County)	76%–146%	72%–142%	46%–96%	43%–96%
Merced River at Pohono Bridge near Yosemite	90%–104%	113%–133%	90%–101%	116%–120%

3.3.2. *Monthly Streamflows*

Natural flow is the flow that a stream would have without regulation, control, diversion, or artificial additions. Natural streamflow estimates for eight major rivers in the Sacramento and San Joaquin valleys were compared to monthly streamflow estimates based on runoff data from VIC simulations for 1950–1999 using climate data from six GCMs downscaled by two different methods: BCSD and CA. Typically, streamflows estimated using the BCSD method reflected the observed annual flow better than the CA method (Table 5 and Figure 6). In general both methods underestimate streamflow during the winter months. In addition, the CA method generally underestimated streamflows in the Sacramento Valley and overestimated them in the San Joaquin Valley (Table 5).

Because the CA method generally underestimated daily flows and did not adequately represent annual inflows to some of the major water supply reservoirs, streamflow estimates based on CA were not used for further impacts analysis at this time. However, the CA method has been shown to produce better daily data for air temperature and precipitation than BCSD for certain locations (Maurer and Hidalgo 2008). If the ability of this method to create good estimates of daily data can be extended to streamflow estimates, the data could be useful for flood management and other water resources planning applications. Thus, DWR has provided feedback to the researchers working on the CA method, and those researchers are working to improve streamflow estimates. This highlights the importance of cooperation between water planners and climate change researchers to develop research products that are more useful for water resources planning.

Table 5. Comparison of simulated to observed streamflows in California for 1950–1999

Location		Percent Change (%): Simulated vs. Observed	
		BCSD	CA
Sacramento Valley	Sacramento River at Bend Bridge	1	-10
	Feather River at Oroville	-6	-20
	Yuba River near Smartville	37	12
	American River at Folsom Dam	10	-48
San Joaquin Valley	Stanislaus River at New Melones Dam	-15	-18
	Tuolumne River at New Don Pedro	-2	6
	Merced River at Lake McClure	1	17
	San Joaquin River at Millerton Lake	9	17

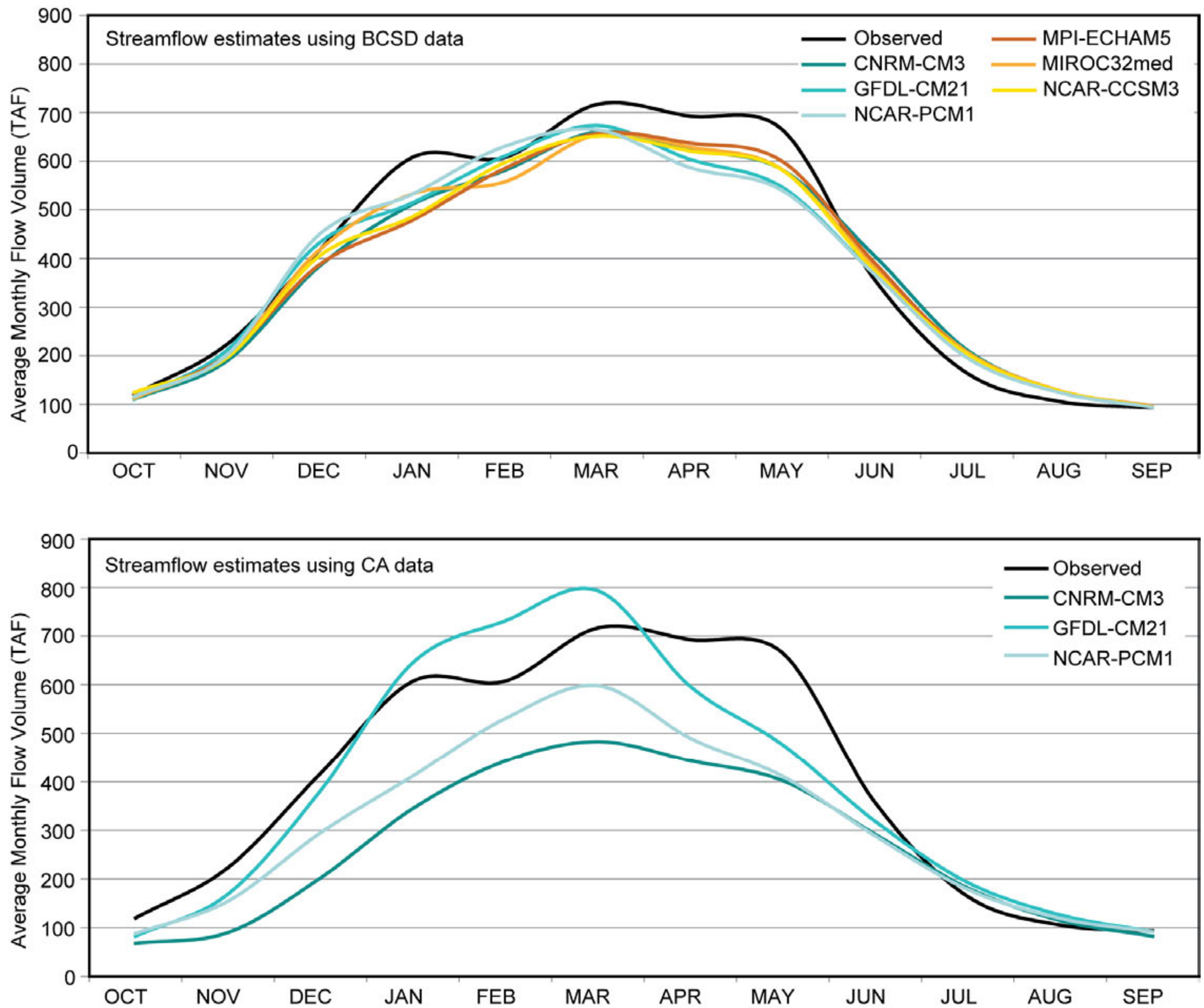


Figure 8. Natural and GCM-based flow for the Feather River at Lake Oroville for 1950–1999

4.0 Obtaining Water Resources Information from Future Climate Projections

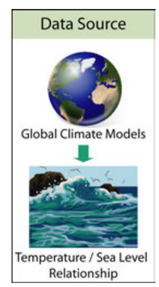
This section presents advances in methods for obtaining water resources information from future climate projections. Topics to be covered include using sea level rise projections for water resources planning, estimating streamflows for impact assessments, and evaluating the effects of changes in precipitation on agricultural crop and urban outdoor water demands.

4.1. Sea Level Rise

Objective	How can future projections for sea level rise be incorporated into water resources planning?

Over the twentieth century, sea levels near San Francisco Bay increased by more than 0.6 feet (DWR 2006). Some tidal gauge and satellite data indicate that rates of sea level rise are accelerating (Church and White 2006, Beckley et al. 2007). Sea levels are expected to continue to rise due to increasing air temperatures which will cause thermal expansion of the ocean and land-based ice to melt in areas such as Greenland and in southeastern Alaska (IPCC 2007). Two related questions on the uncertainty of future sea levels are key for water planners. First, what is the expected sea level at a specific time in the future? For example, what is the expected sea level in 2050? And second, what is the expected point of time in the future when sea levels will exceed a certain height? For example, when will sea levels rise by one foot? The following sections present progress DWR made in addressing these two questions in the context of water resources planning.

4.1.1. Sea Level Rise Projections



Water resources planners need information on future sea levels. One option is to extend the current rate of sea level rise into the future (Figure 9). This results in a sea level rise of about 0.5 ft at mid-century and of 1.0 ft by the end of the century. However, because recent data indicate rates of sea level rise are accelerating, methods that account for this acceleration are needed to estimate sea level rise. One such method is a linear relationship between projected air temperatures and estimated future global sea levels that is based on a correlation between historical surface temperatures and the rate of historical sea level rises (Rahmstorf 2007). The CALFED Independent Science Board (ISB) used this study to estimate ranges of sea level rise of 2.3–3.3 ft (70–100 centimeters, cm) at mid-century and of 1.6–4.6 ft (50–140 cm) by the end of the century (CALFED ISB 2007)

We applied Rahmstorf's approach to the 12 future climate projections selected by the CAT (Section 2.2) to estimate future sea levels. The historical 95% confidence interval was extrapolated to estimate the uncertainties in the future projections (Figure 9). At mid-century, sea level rise estimates based on these climate projections ranged from 0.8 ft to 1.0 ft with an uncertainty range spanning 0.5 ft to 1.2 ft. By the end of the century, sea level rise projections ranged from 1.8 ft to 3.1 ft, with an uncertainty range spanning from 1.0 ft to 3.9 ft. These estimates are slightly lower than those from the Rahmstorf (2007) study because the maximum projected air temperature increase in that study was 5.8°C (10.4°F) based on the full range of IPCC future climate scenarios, and the maximum projected air temperature increase for the 12 future climate projections selected by the CAT for this study was 4.5°C (8.1°F). It should be noted that projections using this air temperature-sea level rise relationship represent the average sea level rise trend and do not reflect water level fluctuations due to factors such as astronomical tides, atmospheric pressure changes, wind stress, floods, or the El Niño/Southern Oscillation.

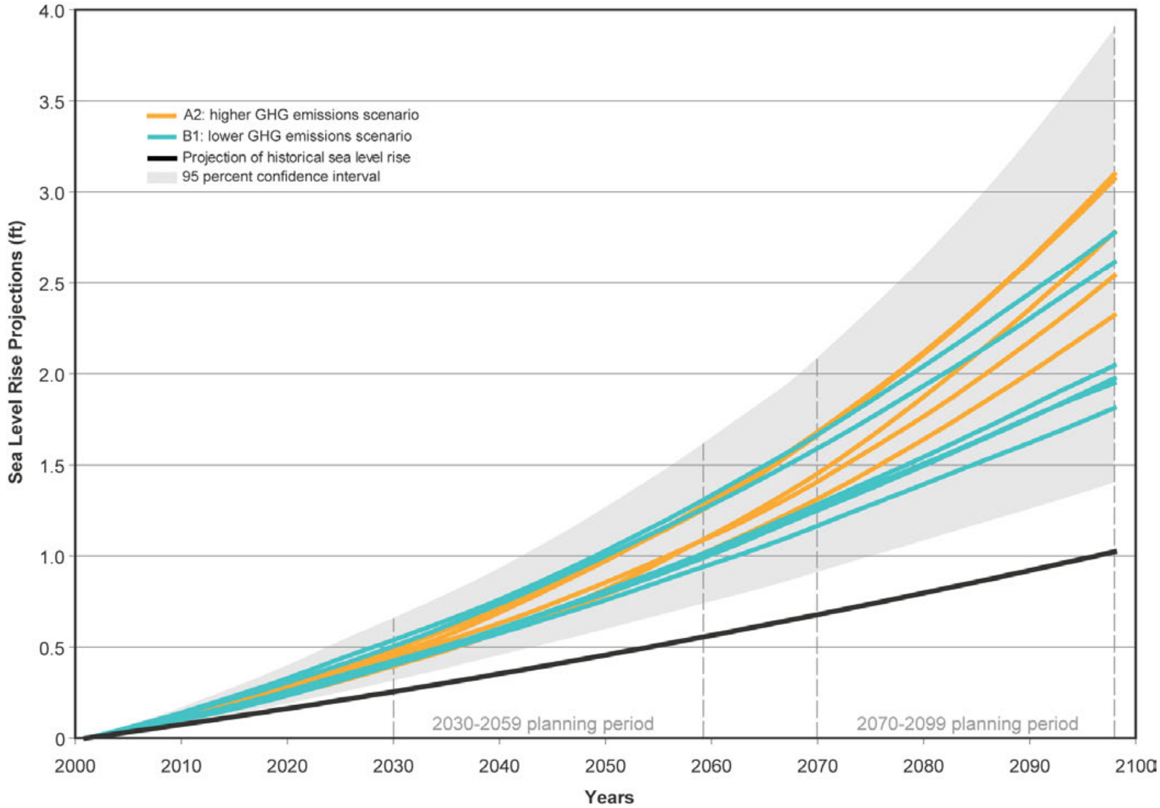
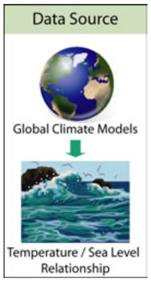


Figure 9. Sea level rise projections based on air temperatures from 12 future climate scenarios

4.1.2. Developing Sea Level Rise Criteria for Decision Making



In 2008, the Governor's Delta Vision Blue Ribbon Task Force issued a report and recommendations for managing the Sacramento-San Joaquin Delta in the future. One of the recommendations states that "State government should promptly incorporate expected sea level increases into decision-making …and should publicly announce the expected sea level rise incorporated into their decisions" (DVBRTF 2008). This raises the question of what level of sea level rise should be incorporated into decision making. A single best estimate of sea level rise for a given time in the future could be used, but this "one size fits all" approach does not take into account factors such as economics, the time period affected by the decision, or the amount of risk that can be tolerated. Progress on developing ways to jointly consider the amount and the likelihood of future sea level rise is presented here.

When incorporating sea level rise in the Delta into the decision-making process, two key factors need to be considered: the long-term sea level rise trend and extreme water level fluctuations. We are exploring a two-step approach that uses both of these factors to create sea level rise projections to use in decision making. The first step is to develop likelihoods for projections of long-term sea level rise trend. Initial progress on this step is presented in this paper. The second step is to develop ways to account for short-term sea level rise fluctuations associated with extreme water levels. This step will be completed in the future.

Relative likelihood distributions of sea level rise trends can be useful in making decisions that are based on the level of risk tolerance. These distributions are analogous to the design curves used in engineering. The likelihoods are based on the range of sea level rise projections using air temperatures from 12 future climate projections (Figure 9). Two methods were used for initial attempts at creating sea level rise likelihood distributions: a lognormal probability distribution and a generalized extreme value probability distribution (Figure 10). The two methods produce similar likelihood distributions for near-term projections, but there are more differences between the two distributions as the sea level projections move further into the future. These preliminary estimates indicate that there is a 5% likelihood that average sea level rise would be greater than about 1.1 ft by the year 2050 and 3.0 ft by the year 2090. The choice of method to create the distribution and the estimation of parameters for each method are subjective and involve uncertainties. These distributions provide an example of how likelihood distributions can be made for sea level rise projections, but further research is needed to better understand how choice of method and parameter estimations affect likelihood distributions and the possible effects on subsequent decision making based on those distributions.

These likelihood distributions are just the first step in creating a method for determining which sea level rise amounts to use in decision making. Average trends do not take into account the effects of factors such as astronomical tides, changes in atmospheric pressure, wind stress, floods, or the El Niño/Southern Oscillation. These factors will cause sea level fluctuations on scales ranging from minutes to decades, and the combined effects of these fluctuations can lead to extreme high water events. Figure 11 shows that the maximum sea levels at San Francisco are significantly higher than the average sea level trend. Therefore, making decisions based on long-term trends of average sea level alone may not be sufficient. Further study will be needed to assess how to address these sea level fluctuations when selecting sea level rise criteria for decision making (Cayan et al. 2008, Bromirski and Flick 2008).

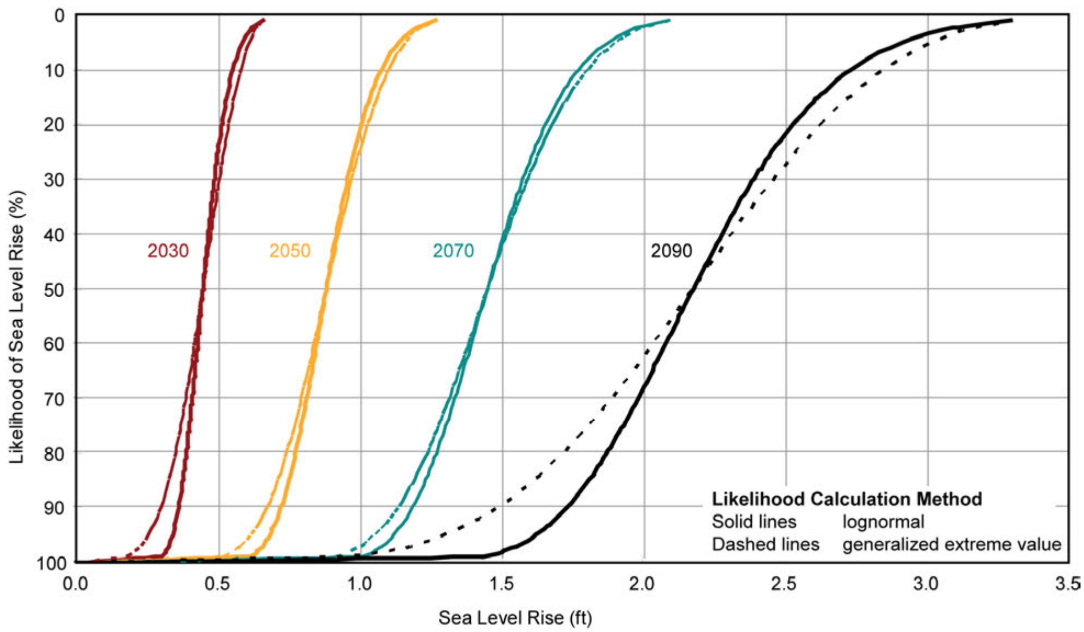


Figure 10. Sea level rise trend distributions computed using two methods

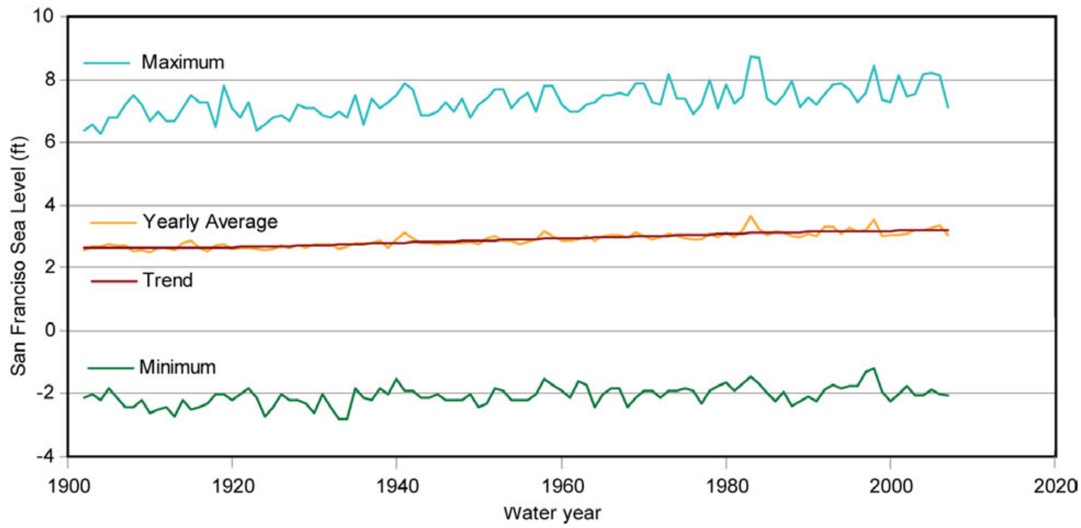
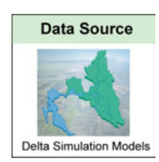


Figure 11. Historical sea levels for San Francisco for 1902–2007

4.1.3. Sea Level Rise Artificial Neural Networks



Because Delta salinity standards affect operations of the SWP and CVP, a method was needed to represent salinity in the Sacramento-San Joaquin Delta for sea level rise scenarios that could be used to analyze climate change impacts. A sea level rise Artificial Neural Network (SLR ANN) is a computer tool that quickly estimates Delta salinity for a specific scenario. This tool can be used in Central Valley water management models such as CalSim-II (Draper et al. 2004) and CalLite (DWR and USBR 2008).

Because sea level rise would increase salinity intrusion into the Delta, new ANNs are needed to represent the Delta salinities for each future sea level rise scenarios of interest.

New sea level rise (SLR) ANNs can be developed using data derived from computer models of Delta flows and salinity. In this case, the Delta Simulation Model 2 (DSM2) (DWR 2009) was used to generate detailed descriptions of potential Delta flow and salinity conditions for sea level rise scenarios. However, DSM2 does not fully represent the complex mixing that is important for representing salt movement into the Delta under sea level rise. Thus, results from other modeling studies that do represent those processes are used to improve DSM2's representation. Salinity concentrations at the mouth of the Delta near Martinez were based on results from complex modeling studies by the UnTRIM model (Gross 2007). In addition, to increase the amount of salinity intrusion into the Delta, adjustments were made in the DSM2 studies (Chung and Seneviratne 2009) to match salinity changes from recent Public Policy Institute of California (PPIC) studies using the Water Analysis Module (PPIC 2008, URS 2007). After incorporating these modifications for sea level rise conditions, the resulting DSM2 data for Delta flows and salinity were then used to develop SLR ANNs for a 1 ft and a 2 ft sea level rise scenario. The resulting SLR ANNs can be used in other management tools to quickly represent how sea level rise affects salinity conditions in the Delta. A summary of the input and output data for each SLR ANN is presented in Figure 12.

For the SWP and CVP impacts analysis presented in Section 5.2, SLR ANNs were used in the CalSim-II model to represent sea level rise impacts on Delta salinity. The combination of CalSim-II and a SLR ANN represents the effects of changes in inflows and exports due to changing air temperature and precipitation patterns and to sea level rise. The 1 ft SLR ANN was used for the mid-century assessments and the 2 ft SLR ANN was used for the end-of-the-century assessments. These values fall within the range of projections based on projected increases in air temperature (Figure 9).

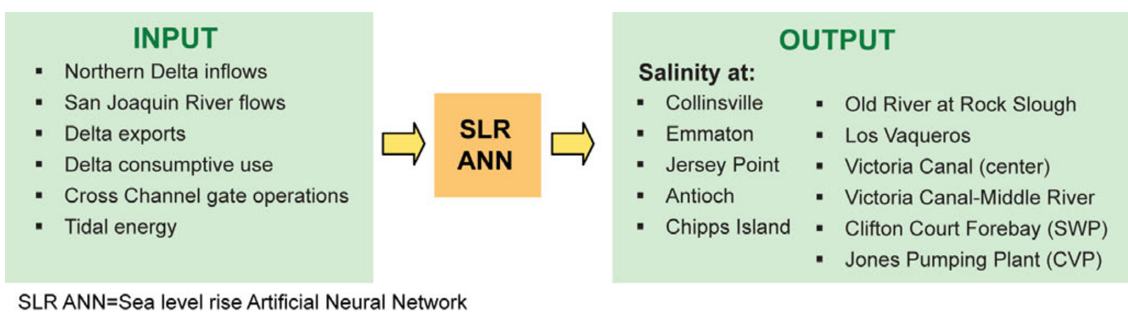


Figure 12. Sea level rise Artificial Neural Network (SLR ANN) input and output

4.2. Estimating Streamflows to Use in Impacts Assessments

Objective	How can future climate projection information be used to estimate streamflows for water resources impacts assessments?

Streamflows estimated from downscaled future climate projection information (Section 3.3) were not considered sufficient to use directly in climate change impacts analyses for SWP and CVP operations. However, these projections offer reasonable estimates of how streamflows might change in the future relative to the past. For the 2006 impacts assessment (DWR 2006), a perturbation ratio method (Miller et al. 2001) was used to modify historically based sequences of SWP and CVP reservoir inflows to reflect future climate projections. Using estimated streamflows from the VIC model, monthly average changes in reservoir inflow were determined by comparing predicted streamflows in tributary basins during a 30-year future period relative to a 30-year historical period. This ratio between future and historical streamflows is called a perturbation ratio because it represents how much future conditions changed (were perturbed) relative to historical conditions. The 12 monthly perturbation ratios were then used to modify an 82-year historical sequence of reservoir inflows traditionally used to evaluate SWP and CVP operations. The modification is intended to represent the monthly average changes in upper basin streamflow due to future climate changes.

However, using the monthly perturbation ratio method to estimate future streamflows does not preserve the projected trends in annual streamflows. Thus, for the 2008-2009 assessment, a new three-step flow adjustment method was used to create future streamflow estimates that reflect both seasonal and annual trends from future climate projections.

The first step in the method is identical to the perturbation ratio method used in the 2006 assessment (DWR 2006), as described above. The second and third steps adjust the streamflows to represent the mean annual runoff trends produced from the VIC analysis[2]. The second step adjusts the streamflows to reflect projected seasonal shifts in runoff while preserving historical annual runoff volumes. The third step also adjusts the streamflows to reflect projected changes in the annual runoff volume.

For the impacts assessment presented in Section 5.2, this three-step method was applied to streamflow estimates from VIC for all 12 future climate projections to produce estimates of reservoir inflows and streamflows into the Sacramento and San Joaquin valleys. Future reservoir inflows were estimated using the three-step perturbation method for data from six GCMs that were downscaled to the regional scale using BCSD. Peak inflows to large reservoirs like Shasta and Oroville are estimated to occur one month earlier at mid-century and two months earlier by the end of the century. For smaller reservoirs such as Folsom Lake, peak

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2. This three-step streamflow adjustment method provides equivalent results to the two-step streamflow adjustment method used for the Operations Criteria and Planning (OCAP) biological assessment (USBR 2008). The extra step in this method provides additional insight into seasonal patterns of inflow changes.

inflows occur two months earlier by mid-century and three months earlier at the end of the century. Most of the future climate projections show reduced reservoir inflows in the future.

4.3. Estimating Agricultural Crop and Urban Outdoor Water Demands for Future Climate Projections

Objective	How would precipitation shifts due to climate change affect water demands in the Sacramento and San Joaquin valleys?

The changes in precipitation and evapotranspiration rates resulting from climate change are expected to affect agricultural crop and urban outdoor water demands. The 2006 climate change impacts analyses did not adjust these demand estimates to reflect possible changes in demand under future climate conditions (DWR 2006). For the 2009 impacts assessment (Section 5.2), agricultural crop and urban outdoor water demands in the Sacramento Valley were adjusted to reflect changes in precipitation for the 12 future climate projections. A three-step method, similar to the process used to develop streamflow estimates, was used to adjust the precipitation estimates (Section 4.2). The effects of climate change on evapotranspiration rates and the associated impacts on crop water demands are still being studied by researchers (for example, Long et al. 2004). Because the research community has not reached a consensus on this issue, no changes were made to the evapotranspiration rates used in the impacts analyses. Changes in precipitation due to climate change increased agricultural crop and urban outdoor water demands in the Sacramento Valley by up to 6%.

4.4. Future Climate Variability

In water resources planning, it is often assumed that future hydrologic variability will be similar to historical variability, which is an assumption of a statistically stationary hydrology. This assumption no longer holds true under climate change where the hydrological variability is non-stationary. Recent scientific research indicates that future hydrologic patterns are likely to be significantly different from historical patterns, which is also described as an assumption of a statistically non-stationary hydrology. In an article in *Science*, Milly et al. (2008) stated that "Stationarity is dead" and that "finding a suitable successor is crucial for human adaptation to changing climate." Therefore, approaches that analyze the impacts from climate change on water resources planning are evolving to take into account that future hydrologic patterns may be significantly outside the range of historical patterns.

Some of the climate change impacts analyses currently conducted at DWR implicitly assume statistically stationary hydrology, such as the streamflow estimation method presented in Section 4.2. Other analyses conducted at DWR allow for statistically non-stationary hydrology. One example is the physically based models, such as the PRMS rainfall-runoff model (Section 5.1), that can represent future changes in climate and hydrologic variability. For future analyses, we will continue to explore ways to account for changes in future climatic and hydrologic variability.

5.0 Climate Change Impacts Analysis for Water Resources

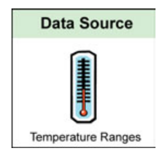
Objective	How can management tools be used to quantify the possible impacts of climate change to Central Valley water systems?

This section focuses on how Central Valley water systems may be affected by climate change. Two impacts analyses were conducted. First, the effects of changes in air temperature on runoff processes were examined for the Feather River basin, the basin that supplies water to Lake Oroville, which is the SWP's main water supply reservoir (Section 5.1). Second, the impacts of 12 future climate projections on SWP and CVP water supply reliability were assessed (Section 5.2). The indicators of water supply reliability analyzed were annual Delta exports, reservoir carryover storage, groundwater pumping, power supply, the position of a Delta salinity indicator known as X2, and the frequency and extent of system vulnerability to operational interruption.

5.1. Upper Feather River Basin Runoff

Objectives	Quantify the effects of increasing air temperature on watershed runoff processes.

This section presents an application of a physically based model that was used to examine potential changes in runoff processes due to changes in ambient air temperature.



5.1.1. Motivation

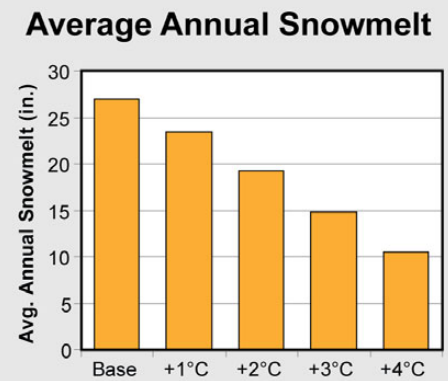
The design, maintenance, operation, and management of large water resources systems are heavily influenced by hydrologic data. Statistical properties of hydrologic data (for example, mean, standard deviation, and skew) may no longer be reliable for planning purposes if future climatic conditions can heavily influence these properties. While traditional hydrologic analysis uses the amount and distribution of precipitation as a starting point, changing climatic conditions may justify using air temperature as the starting point. This may be especially important in higher elevation watersheds that receive both rain and snow. Even minor changes in air temperatures can have significant effects on runoff characteristics in those watersheds if those temperature increases change whether the precipitation falls as rain or snow (DWR 2006).

Looking at a wide range of future climate projections, air temperatures consistently increase everywhere, while changes in the amount and timing of precipitation are less certain (Bader et al. 2008). Thus, it may be more appropriate to use air temperature as a starting point for hydrologic analysis for future climate conditions. Physically based models provide one approach that allows many parameters to be quantified and to provide insight into the impact of climatic changes on the different physical processes affecting runoff.

Lake Oroville, the backbone of the SWP, receives much of its inflow from the upper Feather River basin in the Sierra Nevada mountain range. Sierra Nevada means “snowy mountains” in Spanish, and, true to this name, snowpack that accumulates from October through March in the upper Feather Basin provides the majority of the spring and summer runoff that eventually flows into Lake Oroville. Because snow melting and sublimation is heavily dependant on temperatures, it is important to the operation of Lake Oroville to know how projected future climate conditions can affect both the timing and quantity of flows arriving there. This study uses a physical model of the upper Feather Basin to better understand the effects of increasing air temperature on precipitation, snowpack, and runoff.

5.1.2. Approach

A sensitivity analysis was conducted to determine how increases in air temperature of 1°C, 2°C, 3°C, and 4°C (1.8°F, 3.6°F, 5.4°F, and 7.2°F) in the upper Feather River basin would affect natural flows into Lake Oroville. PRMS, a physically based precipitation-runoff model, was developed by the U.S. Geological Survey for DWR (Koczot et al. 2004). It was used to study the impacts of increasing daily minimum and maximum temperatures over a 30-year period (water years 1972–2001) on different hydrological components, including streamflow and base flow. The model simulates all the major snowmelt and precipitation-related physical processes, including snowpack accumulation or melting, sublimation, evapotranspiration, surface runoff, subsurface flow, and groundwater flow. Air temperature was the only parameter that changed for each simulation. Spatial and temporal distributions of precipitation and all other model parameters were the same for each simulation. This paper focuses on comparing alternative air temperature scenarios with the historical base scenario (Chung et al. 2009).



Warming air temperatures may cause some of our precipitation to shift from snow to rain. This would lead to a reduction in the amount of snowpack, an important natural reservoir for storing water in the winter and later augmenting the water supply as spring snowmelt. Climate-change-induced shifts in the timing and the amount of snowmelt runoff may require traditional water planning practices to be revised.

5.1.3. Key Findings

Increases in air temperature are expected to have significant impacts on watersheds that traditionally receive at least some of their precipitation in the form of snow. One of the key results from the sensitivity analysis for the upper Feather River basin is that the day in the water year when 50% of the annual inflow arrives in Lake Oroville moves earlier in the year as air temperatures increase (Figure 13). The average day that 50% of the annual inflow arrives at Lake Oroville decreased from March 18 for the base scenario to February 10 for an air temperature increase of 4°C, a change of 36 days. The range of days when 50% of the annual inflow arrives at Lake Oroville also shifts earlier in the year. For the base case the range was January 7 to April 29, and in the +4°C scenario the range was December 24 to March 14. Thus, in the +4°C scenario case, the latest day that 50% of the annual inflow arrived at Lake Oroville was earlier than the average day that 50% of the inflow arrived for the base scenario. These results indicate that increases in air temperature will have a significant impact on the timing of runoff for the upper Feather River basin. These results are consistent with findings from other research studies that show earlier runoff in California due to projected warming in the future (for example, Stewart et al. 2004, Peterson et al. 2005)

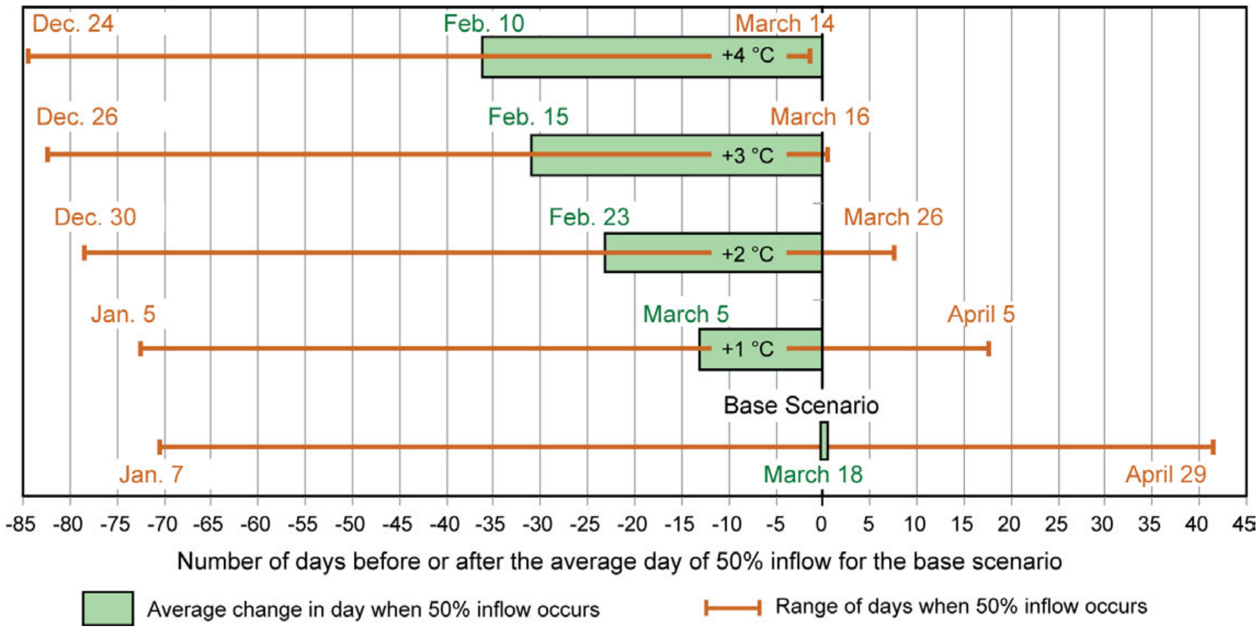


Figure 13. Average number of days earlier that 50% of annual inflow occurs in Lake Oroville

In California, water resources are managed for multiple purposes, including flood protection, water supply, environmental uses and recreation. Traditionally April 1 marks a transition point in water resources management. Prior to April 1 snowpack is considered to be building and reservoir operations are focused on flood control. After April 1, reservoir operations change focus to water supply generated from snowmelt runoff, which traditionally occurs from April through July. Water supply forecasts are based on runoff forecasts for these four months.

Increased air temperatures are expected to change the amount and timing of annual runoff. The fraction of runoff that occurs during the traditional period of April through July was examined for the base and the increased air temperature scenarios (Figure 14). The fraction of runoff that occurs from April through July decreases through time for all scenarios (including the base scenario), and it also decreases as air temperatures increase. This indicates that snowmelt is occurring before April 1 and that the fraction of snowmelt that occurs before April 1 will increase as air temperatures increase. The 30-year trend indicates that the fraction of annual runoff occurring from April through July decreases from about 35% for the base scenario to about 15% for the +4°C scenario. In addition to the water supply and flood management impacts of earlier snowmelt, these changes could also require changes to the current water year classifications and their associated regulatory standards because those classifications are partly based on April–July runoff. For example, the Sacramento Water Year Index is determined as (SWRCB 1995):

> Sacramento 40-30-30 Water Year Type Index =
> 0.4*Current April–July Runoff + 0.3 Current Oct.–Mar. Runoff + 0.3 Previous Year's Index

Because 40% of the water year type index value is based on runoff that occurs from April through July, this index may no longer be an appropriate indicator of water year types if the fraction of annual runoff that occurs during those months changes significantly. How water year types are classified and the relationship between these classifications and regulatory standards may need to be explored and modified.

5.1.4. Future Directions

Additional work is under way to evaluate hydrologic impacts on the upper Feather River basin using both the air temperature and precipitation projections for the 12 GCM-based future climate projections.

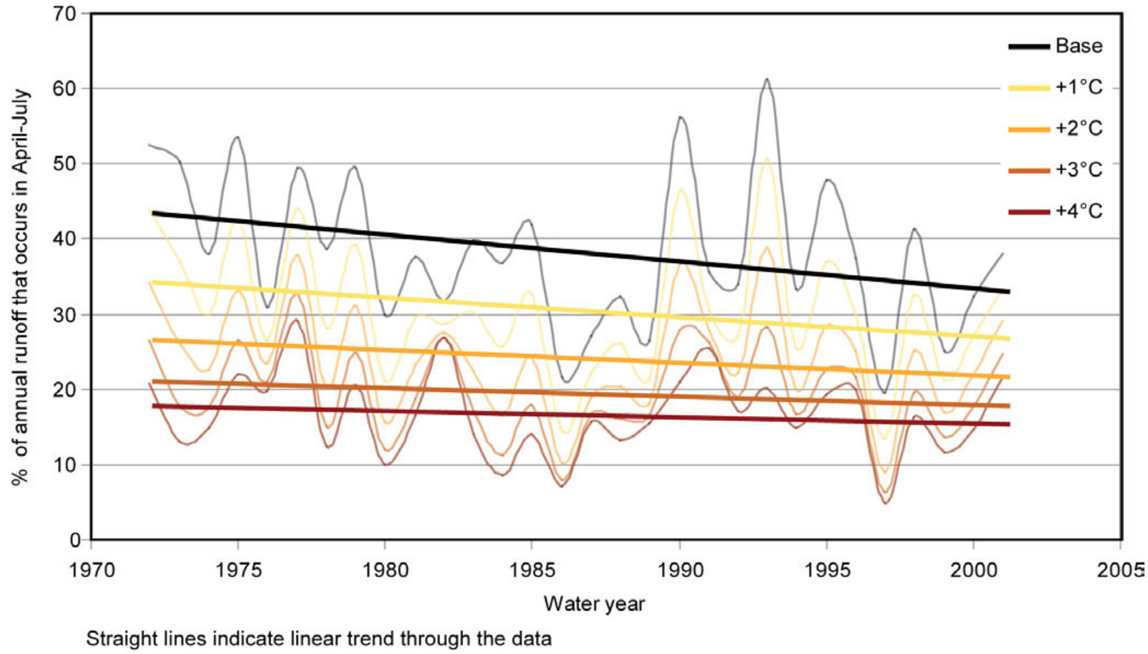
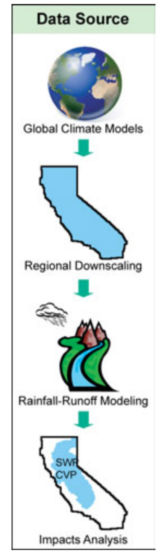


Figure 14. Fraction of annual runoff that occurs from April through July for inflow into Lake Oroville for water years 1972–2001

5.2. Impacts to the Central Valley Water System

Objectives	How could climate change affect the reliability of the SWP and CVP water supply system considering its current infrastructure and regulatory and operating rules? Use 12 future climate projections to reflect future uncertainty.

5.2.1. Approach



In 2006, climate change impacts to SWP and CVP operations were assessed for four future climate projections. Those projections were based on climate simulations from two GCMs that were each used to represent two GHG emissions scenarios (DWR 2006). For the 2008-2009 climate change assessment, a total of 12 projections were used that were based on climate simulations from six GCMs for two GHG scenarios (Section 2.2).

Several steps are required to convert the climate data from the GCMs into streamflow data that can be used for SWP-CVP impact studies (Figure 15). For each of the 12 future climate projections, the coarse-scale climate data were converted to regional-scale data using the BCSD spatial downscaling method. Although regional data were available for both the BCSD and CA downscaling methods, this analysis used the BCSD data because it more closely matched historical streamflow estimates (Section 3.3). Streamflow estimates for 18 streams in California were made by the VIC model based on the regional climate data. All of these data were taken from the CAP/CCCC website (CAP/CCCC 2008).

Consistent with the practice of the National Center for Atmospheric Research (NCAR), DWR selected two future periods for mid-term and long-term climate change impact investigations: 2030–2059 and 2070–2099, which cover the middle and the end of this century. The climate and streamflow data for the 12 future climate projections were evaluated for these two future periods to create input data for CalSim-II, a Central Valley water resource planning model developed jointly by DWR and Reclamation to simulate much of the water resources infrastructure in the Central Valley of California and the Sacramento-San Joaquin Delta region.

For the 2006 assessment, only the reservoir inflows were adjusted to reflect climate change. Many advances have been made in reflecting climate change in the impact analysis process (Section 4.0). A three-step streamflow adjustment method was used to estimate inflows to major SWP and CVP reservoirs for the 2008-2009 assessment (Section 4.2). An 82-year sequence of reservoir inflows that reflects a wide range of hydrologic variability was determined for each of the 12 future climate projections for both the mid-century and end-of-century analysis periods. Because some water allocation and water quality regulations are based on water year type designations (for example, wet or dry years), these designations were modified if necessary to reflect the future climate projections. Agricultural crop and urban outdoor water demands were adjusted to reflect changes in precipitation (Section 4.3). Although there is a wide range of uncertainty in sea level rise projections (Figure 9), for simplicity's sake, sea level rise estimates of 1 ft for the mid-century and 2 ft for the end of century were chosen for these impact studies

(Section 4.1.3). Because this analysis focuses on potential impacts on the existing SWP-CVP system, no changes were made to the representation of the existing system infrastructure and SWRCB D1641 regulations were used for all studies. Operations guidelines that are subject to change, such as restrictions on Delta exports contained in Endangered Species Act biological opinions, were not included in these studies due to the high uncertainty of how such restrictions may be applied 50 or 100 years from now.

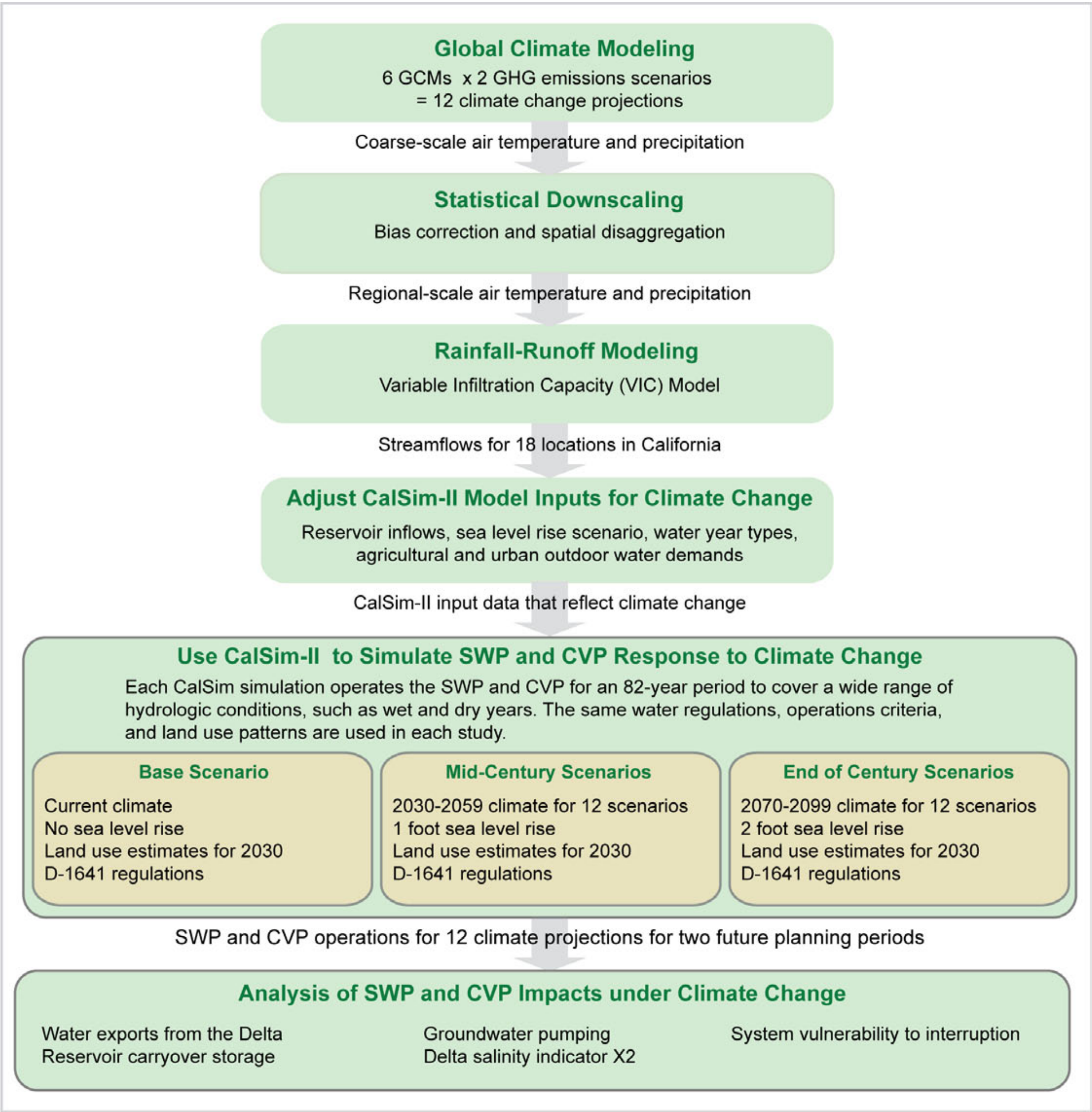


Figure 15. Approach for analyzing potential impacts of climate change to the SWP and CVP systems

5.2.2. Assumptions

The assumptions made in the SWP-CVP impact analyses are summarized in Table 6. Because the goal of this analysis is to evaluate the potential impacts of projected future climate conditions on the current SWP and CVP system, selected processes physically linked to climate changes (such as reservoir inflows) were adjusted for the future climate projections. Existing physical, regulatory, and operational constraints were used for all analyses. Delta exports, outflow, and water quality are regulated according to the State Water Resources Control Board Decision 1641, the Water Quality Control Plan (SWRCB 1995), and all other current regulatory and statutory requirements. However, certain operations plans that have uncertain futures—such as the Central Valley Project Improvements Act (CVPIA) 3406 (b)(2), the Environmental Water Account, and Endangered Species Biological Opinion actions—were not considered in this analysis. It was assumed that no physical changes were made to the system, such as building new storage or conveyance facilities. Land use estimates based on projections for the year 2030 were used for all analyses because mid-century and end-of-century land use estimates were not available. Water demands south of the Delta were the same for all scenarios. Reservoir inflows, water year types, and agricultural crop and urban outdoor water demands were adjusted for the climate change impacts analyses as described in Section 4.0. For simplicity, sea levels were assumed to rise by 1 ft at mid-century and 2 ft by the end of the century.

Table 6. Assumptions for SWP-CVP impacts analyses

Assumption	Base scenario	Mid-century (12 scenarios)	End of century (12 scenarios)
Regulations and operating rules	D1641 regulations, no Environmental Water Account or CVPIA b2	D1641 regulations, no Environmental Water Account or CVPIA b2	D1641 regulations, no Environmental Water Account or CVPIA b2
SWP-CVP infrastructure	No changes	No changes	No changes
Land use	Estimates for 2030	Estimates for 2030	Estimates for 2030
Reservoir inflows	Historical	Adjusted for future air temperature and precipitation	Adjusted for future air temperature and precipitation
Water year types	Historical	Adjusted for streamflow changes	Adjusted for streamflow changes
Agricultural crop and urban outdoor water demands	Based on 2030 land use estimates	In the Sacramento Valley, demands were adjusted for changes in precipitation	In the Sacramento Valley, demands were adjusted for changes in precipitation
Sea levels	No sea level rise	1 ft sea level rise	2 ft sea level rise

5.2.3. Study Limitations

These studies are investigations into *possible* future changes in water supply reliability and the results should not be interpreted as *predictions* of future conditions. In addition to the assumptions listed above and the uncertainties discussed in Section 2.4 other key uncertainties involved in the analyses include those associated with the formulation and use of all of the models used: GCMs, rainfall-runoff models, and SWP and CVP system operations models. The uncertainties associated with future climate projections include representation of the GHG emissions scenarios, use of bias corrections to adjust GCM results for known biases in the model that overestimate or underestimate temperature and precipitation, choice of downscaling method, and assumptions in adjusting streamflows to reflect future conditions. There are also uncertainties associated with future estimates of population growth, changes in land use, and the associated changes in water demands. Effects of changing air temperature on evapotranspiration and urban and agricultural water demands were not considered in this study. The physical configuration of the SWP and CVP system, including the Sacramento-San Joaquin Delta, was assumed to be unchanged in the future. Exploring possible future changes in SWP and CVP facilities and operational regulations was beyond the scope of this study.

5.2.4. Results

Potential impacts of climate change on the operation of the SWP and CVP were assessed for 12 future climate projections at both the middle and the end of the century. The water supply reliability indicators analyzed were annual Delta exports, reservoir carryover storage, groundwater pumping, power supply, position of a Delta salinity indicator known as X2, and the frequency and extent of system vulnerability to operational interruption. In analyzing the study results, it was assumed that each future climate projection was equally likely to occur (Bader et al. 2008). In the results figures, the shaded confidence intervals represent the range of 95% of the results for the 12 future climate scenarios analyzed.

Annual Delta Exports

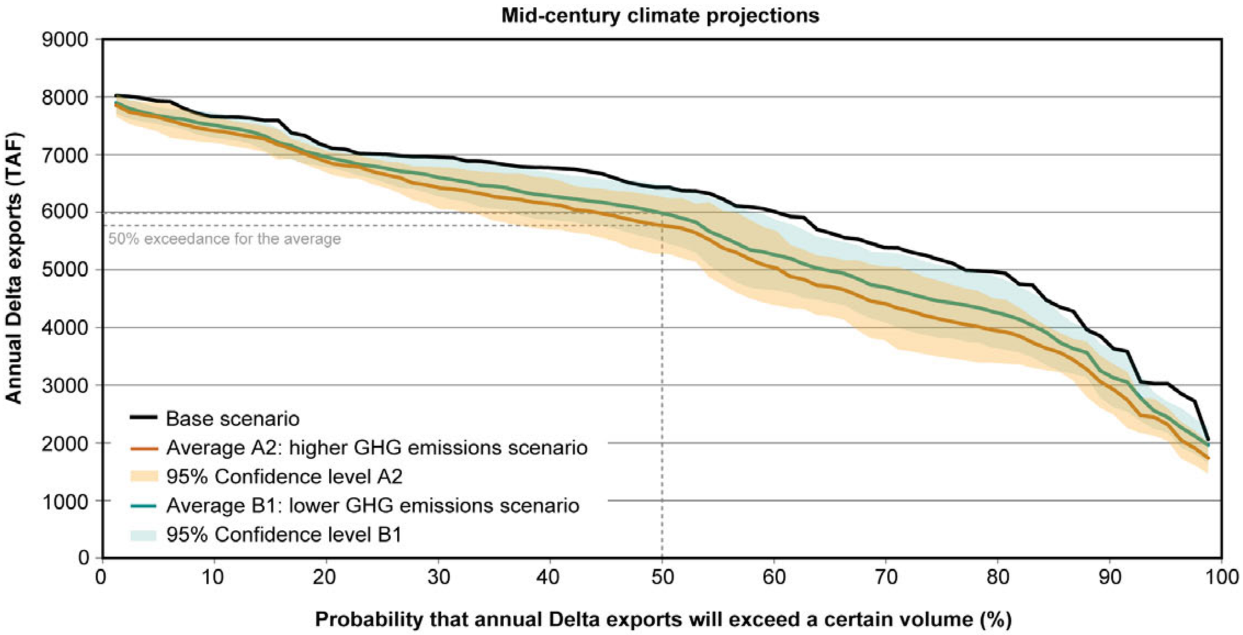
The annual Delta exports are the total amount of water transferred (exported) south of the Sacramento-San Joaquin Delta through the SWP's Banks Pumping Plant and the CVP's Jones Pumping Plant (Figure 1) during one year. Annual Delta exports are measured in units of thousand acre-feet; an acre-foot is the amount of water it would take to cover one acre of land to a depth of one foot. A suburban family of four people uses about one acre-foot of water per year.

The probability that annual Delta exports would exceed a certain volume was estimated for both the mid-century and end-of -century analysis periods (Figure 16 and Table 7). An exceedance probability is the likelihood that a variable—annual Delta exports in this case—will be greater than a certain amount. For example, based on Figure 16, annual Delta exports for the base scenario will be greater than 6,450 TAF half of the time (50% likelihood). The 50% exceedance value is equivalent to the median value.

For all exceedance levels, annual Delta exports are less than the base case for both the mid-century and end-of-century analysis periods. This indicates that SWP and CVP deliveries south of the Delta will be less reliable under projected future climate conditions using the current system infrastructure and operating rules. At mid-century, Delta exports are reduced by 7% for the lower GHG emissions scenario and by 10% for the higher GHG emissions scenario. By the end of the century, the Delta exports are reduced by 21% and 25% respectively.

Table 7. Annual Delta water exports, TAF

	Base	Mid-Century		End of Century	
		A2: Higher GHG Emissions	B1: Lower GHG Emissions	A2: Higher GHG Emissions	B1: Lower GHG Emissions
Median	6,450	5,750 (-10%)	5,950 (-7%)	4,850 (-25%)	5,100 (-21%)
95% Confidence Range	N/A	5,300-6,250	5,450-6,450	4,350-5,350	4,700-5,500



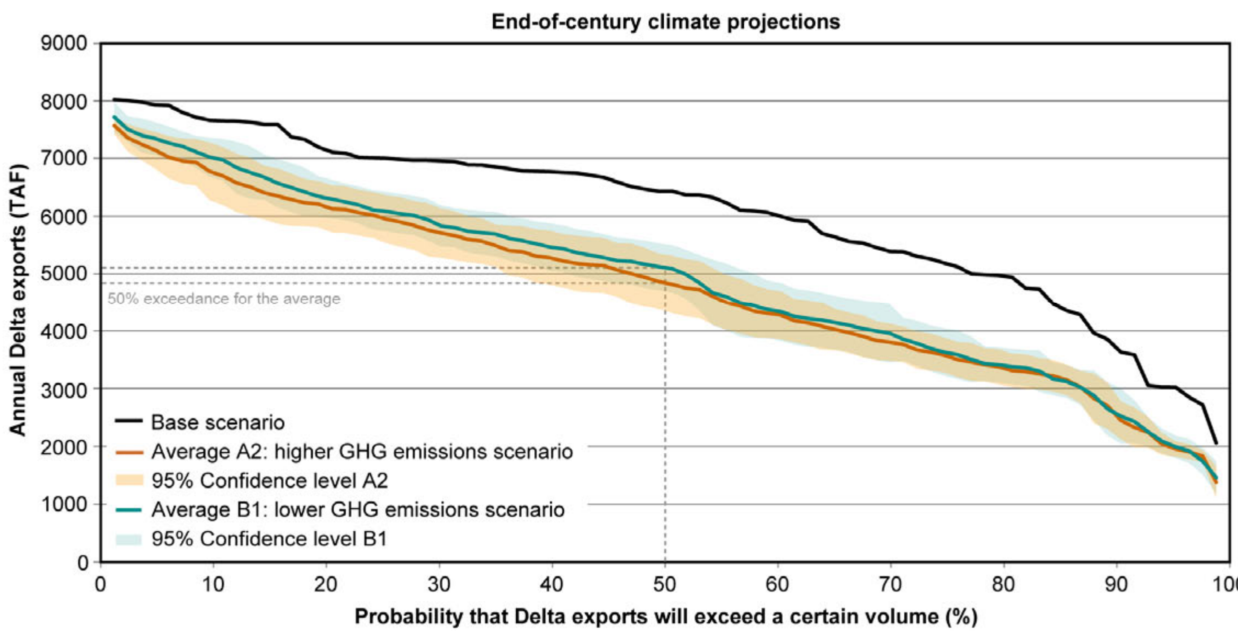


Figure 16. Probability that annual Delta exports will exceed a certain volume, based on 12 future climate projections

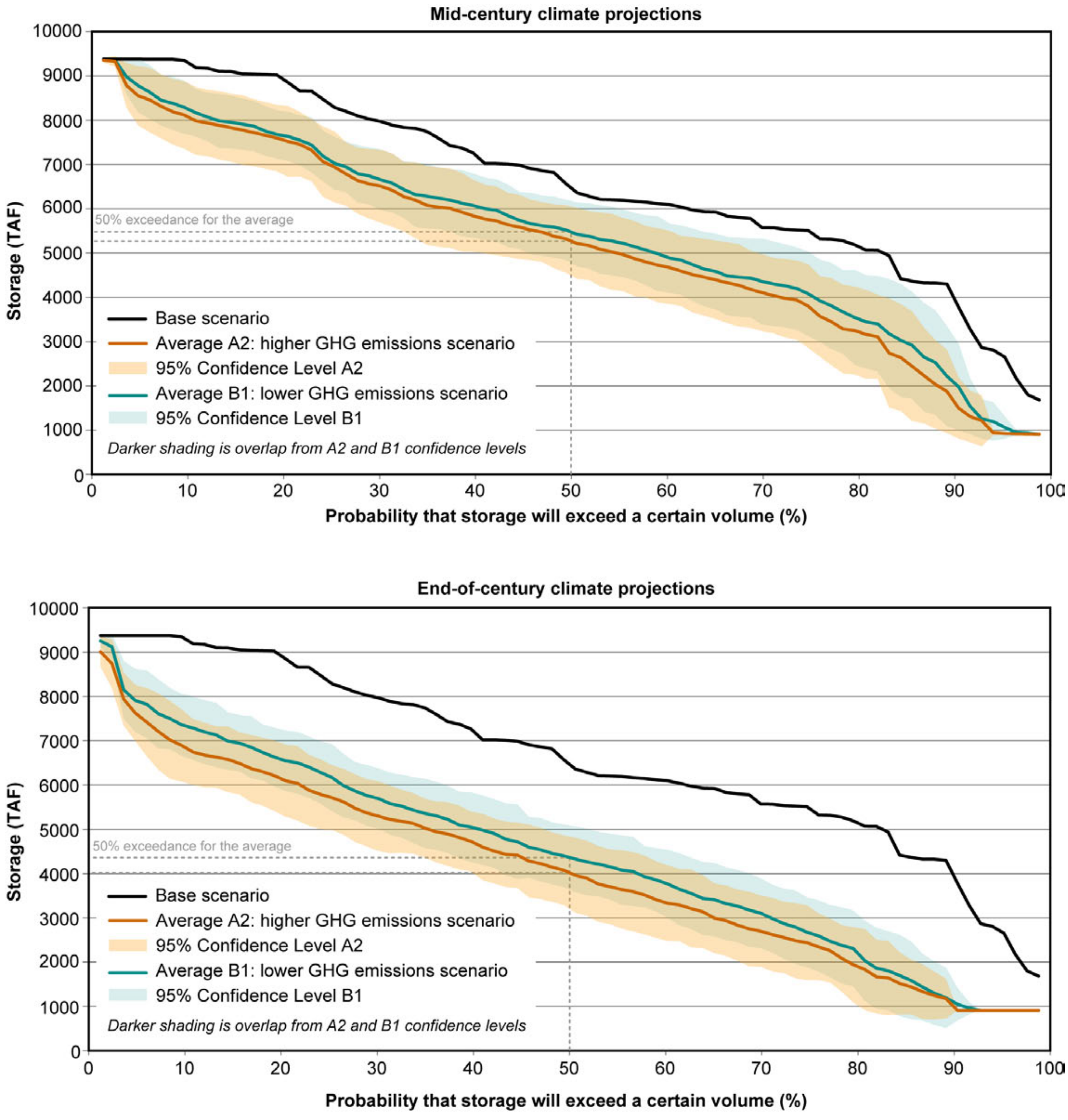
Reservoir Carryover Storage

Reservoir carryover storage is the amount of water remaining in a reservoir at the end of September that is available (carries over) for use the next water year and is an important factor in providing water supply reliability. Because California receives most of its precipitation in the winter, water managers typically plan using a water year calendar that begins in October of one year and continues through September of the next year. For example, water year 2008 stretches from October 2007 to September 2008. Carryover storage at the end of the water year is like a bank savings account that provides extra resources in the event of a shortage in the future. For this analysis, carryover storage was examined for four major SWP and CVP water supply reservoirs: Lake Shasta, Trinity Lake, Lake Oroville, and Folsom Lake. The combined capacity of those four reservoirs is about 11.5 million acre-feet of water.

Carryover storage for the 12 future climate projections was used to estimate exceedance probabilities for both the mid-century and end-of-century analysis periods (Figure 17 and Table 8). For all exceedance levels, carryover storage is less than the base case for both the mid-century and end-of-century periods. This indicates that SWP and CVP water supplies will be less reliable under projected future climate conditions using the current system infrastructure and operating rules. At mid-century, reservoir carryover storage is reduced by 15% for the lower GHG emissions scenario and by 19% for the higher GHG emissions scenario. By the end of the century, carryover storage is reduced by 33% and 38% respectively.

Table 8. Annual reservoir carryover storage, TAF

	Base	Mid-Century		End of Century	
		A2: Higher GHG Emissions	B1: Lower GHG Emissions	A2: Higher GHG Emissions	B1: Lower GHG Emissions
Median	6,350	5,200 (-19%)	5,400 (-15%)	3,950 (-33%)	4,300 (-38%)
95% Confidence Range	N/A	4,400-6,000	4,700-6,150	3,100-4,800	3,500-5,000



Note: the base scenario is identical in both plots.

Figure 17. Probability that reservoir carryover storage is greater than a certain volume based on 12 future climate projections

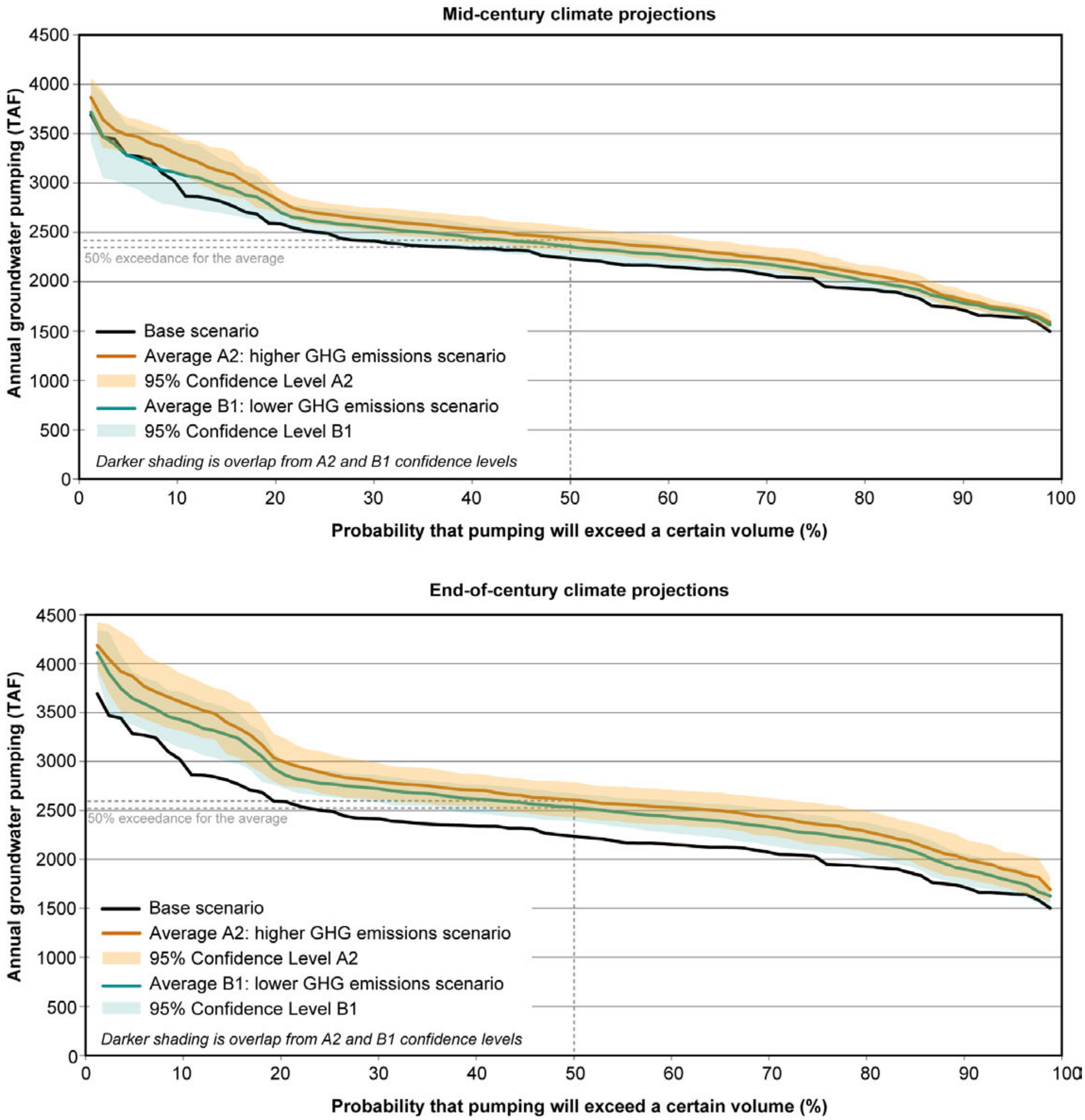
Sacramento Valley Groundwater Pumping

In the Sacramento Valley, water demands are met by a mixture of surface water and groundwater supplies. For agricultural and urban areas with access to both surface water and groundwater, this analysis assumes that minimum groundwater pumping and surface water diversions are used first up to the maximum amount allowed by current contracts. Any unmet demand is then supplied by additional groundwater pumping. For areas without surface water access, all demands are met by groundwater pumping.

Average annual groundwater pumping for the Sacramento Valley was used to estimate exceedance probabilities for both the mid-century and end-of-century analysis periods (Figure 18 and Table 9) for the 12 future climate projections. For all exceedance levels, annual groundwater pumping is greater than the base case for both the mid-century and end of the century. This indicates that groundwater pumping is likely to increase to augment surface water supplies under future climate change using the current system infrastructure and operating rules. At mid-century, Sacramento Valley groundwater pumping increases by 5% for the lower GHG emissions scenario and by 9% for the higher GHG emissions scenario. By the end of the century, Sacramento Valley groundwater pumping increases by 13% and 17% respectively.

Table 9. Annual Sacramento Valley groundwater pumping, TAF

	Base	Mid-Century		End of Century	
		A2: Higher GHG Emissions	B1: Lower GHG Emissions	A2: Higher GHG Emissions	B1: Lower GHG Emissions
Median	2,250	2,400 (+9%)	2,350 (+5%)	2,600 (+17%)	2,500 (+13%)
95% Confidence Range	N/A	2,300-2,550	2,200-2,500	2,400-2,800	2,400-2,650



Note: the base scenario is identical in both plots.

Figure 18. Probability that annual groundwater pumping in the Sacramento Valley is greater than a certain volume based on 12 future climate projections

Power Supply

The effects of climate change on CVP and SWP power supply were examined for the 12 future climate projections (Figure 19 and Table 10). Power supply calculation methods were developed by DWR's Power Operators and by Western Area Power Administration (WAPA) staff (WAPA 2004, USBR and SLDMWA 2004, FRWA 2003). Power generation is based on monthly reservoir storage and releases, and power consumption is based on pumping rates. The CVP generally generates more power than it uses and thus is a net power generator. The SWP conversely uses more power than it generates and thus is a net power consumer. As a result, the SWP must supplement the power that it generates in order to meet its total power demand for pumping.

There are several ways that climate change could affect power supply. Expected changes include shifts in the amount and timing of runoff and reservoir inflows, the amount of water stored by reservoirs, the amount and timing of water released by the reservoirs, and the amount and timing of pumping required for the CVP and SWP to supply water to their customers. Power supply is also affected by the physical constraints of the power generating facilities, such as the elevation of power plant penstock intakes in reservoirs. If water levels are below the intakes, then no power can be generated.

Average CVP annual power generation and annual power consumption are both reduced for future climate conditions due to decreased water deliveries. At mid-century, CVP annual power generation decreases by 4% for the lower GHG emissions scenario and by 11% for the higher GHG emissions scenario. By the end of the century, CVP power generation decreases by 12% and 13% respectively. At mid-century, CVP annual power consumption decreases by 9% for the lower GHG emissions scenario and by 14% for the higher GHG emissions scenario. By the end of the century, CVP power consumption decreases by 24% and 28% respectively.

Average SWP annual power generation and annual power consumption are also reduced for future climate conditions due to decreased water deliveries. At mid-century, SWP annual power generation decreases by 5% for the lower GHG emissions scenario and by 12% for the higher GHG emissions scenario. By the end of the century, SWP power generation decreases by 15% and 16% respectively. At mid-century, SWP annual power consumption decreases by 5% for the lower GHG emissions scenario and by 10% for the higher GHG emissions scenario. By the end of the century, SWP power consumption decreases by 15% and 16% respectively.

When the SWP and CVP power supply numbers (Table 10) are combined, the water projects require more energy to operate than they generate. By the end of the century, the amount of supplemental power that the combined projects will need decreases by 500-600 GWhr/year.

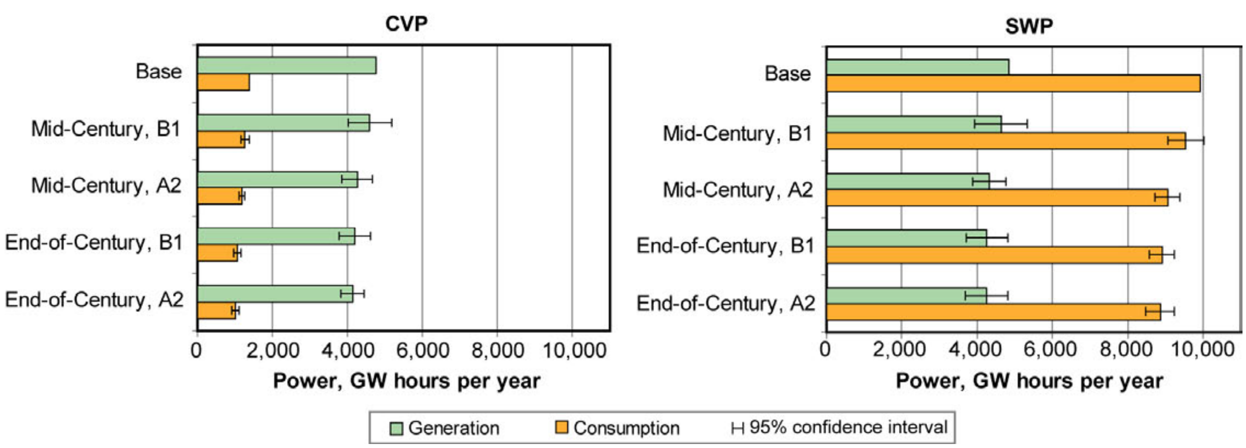


Figure 19. Future CVP and SWP power consumption and generation, based on 12 future climate projections

Table 10. Average power supply (GWhr/year) considering 12 future climate scenarios

		Base Case	Mid-Century		End of Century	
			A2: Higher GHG Emissions	B1: Lower GHG Emissions	A2: Higher GHG Emissions	B1: Lower GHG Emissions
CVP	Power Generation	4,700	4,300 (-11%) (3,800-4,700)	4,600 (-4%) (4,000-5,200)	4,100 (-13%) (3,800-4,500)	4,200 (-12%) (3,800-4,600)
CVP	Power Use	1,400	1,200 (-14%) (1,100-1,300)	1,300 (-9%) (1,100-1,400)	1,000 (-28%) (900-1,100)	1,100 (-24%) (1000-1,200)
CVP	**Net Power Generation**	**3,400**	**3,100 (-10%)** (2,700-3,400)	**3,300 (-2%)** (2,900-3,800)	**3,100 (-8%)** (2,900-3,400)	**3,100 (-8%)** (2,800-3,400)
SWP	Power Generation	4,800	4,300 (-12%) (4,000-4,600)	4,600 (-5%) (4,100-5,100)	4,000 (-16%) (3,700-4,400)	4,100 (-15%) (3,800-4,400)
SWP	Power Use	9,900	9,000 (-10%) (8,400-9,500)	9,500 (-5%) (8,800-10,200)	8,300 (-16%) (7,800-8,900)	8,400 (-15%) (7,800-8,900)
SWP	**Net Power Use**	**5,100**	**4,700 (-7%)** (4,500-4,900)	**4,900 (-3%)** (4,600-5,100)	**4,200 (-16%)** (4,100-4,400)	**4,300 (-15%)** (4,100-4,500)

Ranges indicate 95% confidence interval for the 12 projections

X2 Position

The abundance of several estuarine species has been correlated to Delta salinity. Thus, the position of X2 was developed as one fish protection measure for the operations criteria for SWP and CVP exports (SFEP 1993). X2 is the location where the salinity concentration is two parts per thousand measured one meter off of the bottom of the estuary. The position (location) of X2 is measured in kilometers from the Golden Gate Bridge along the main flow channel. X2 is tied to the amount of freshwater outflow from the Sacramento and San Joaquin rivers and other Delta tributaries. Higher freshwater outflows push the X2 position closer to the Golden Gate and lower freshwater outflows allow X2 to move inland. Historically, X2 position has been estimated to vary between 40 kilometers (km) and 90 km from the Golden Gate Bridge, which is roughly between the Carquinez Strait and Antioch (Figure 20). This X2 range was taken from historical Delta outflow estimates from the DAYFLOW model (DAYFLOW 2008). Operating criteria from SWRCB D1641 require that from February through June the X2 position cannot move inland beyond a specified position that varies depending on the water year type (for example, wet or dry) (SWRCB 1995).

The monthly average X2 position for the 12 future climate projections is shown in Figure 21 for both the mid-century and end-of-century analysis periods. A reference map of X2 positions and the range of future X2 positions is shown in Figure 20. From February to June with the X2 standards in effect, the SWP and CVP were able to comply with the standard under all future climate projections. At mid-century during the February through April compliance period, the average change in X2 position moves inland (upstream) by 1.5 km for the lower GHG emission scenario and by 2.4 km for the higher GHG emissions scenario. By the end of the century, increased salt intrusion into the Delta from sea level rise causes X2 to move inland by 4.7km for the lower GHG emissions scenario and by 4.3km for the higher GHG emissions scenario. At mid-century the maximum change in X2 position occurs in June when X2 moves inland by an average of 3.1 km for the lower GHG emission scenario and by 3.7 km for the higher GHG emissions scenario. By the end of the century, the maximum change in X2 position occurs in

May, one month earlier than at mid-century, when X2 moves inland by an average of 6.1 km for the lower GHG emission scenario and by 6.4 km for the higher GHG emissions scenario. These results show that although X2 may move inland under projected future climate conditions, the SWP and CVP can continue to meet X2 standards using the current system's infrastructure and operating rules.

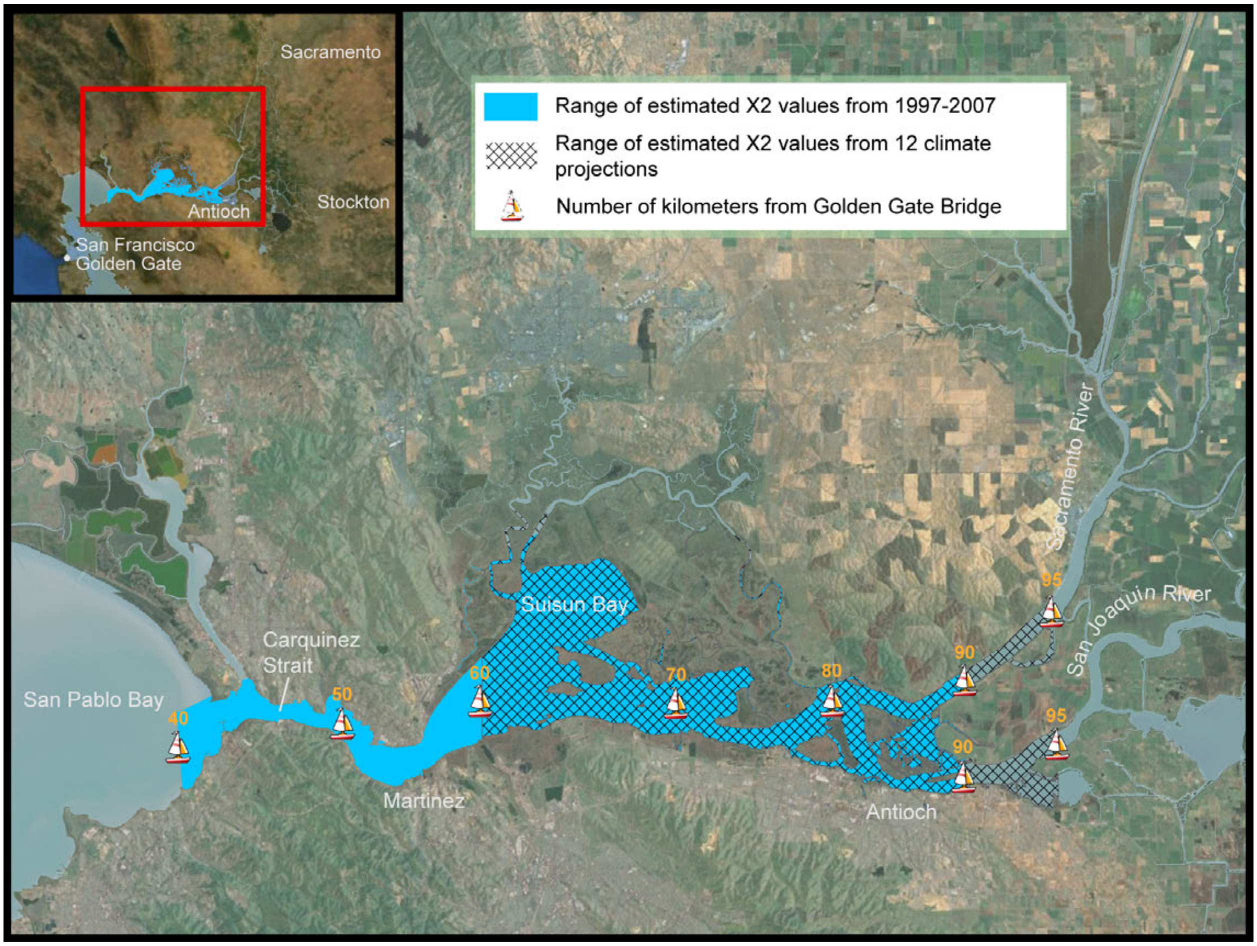


Figure 20. Ranges of historically based and future estimates of X2 locations

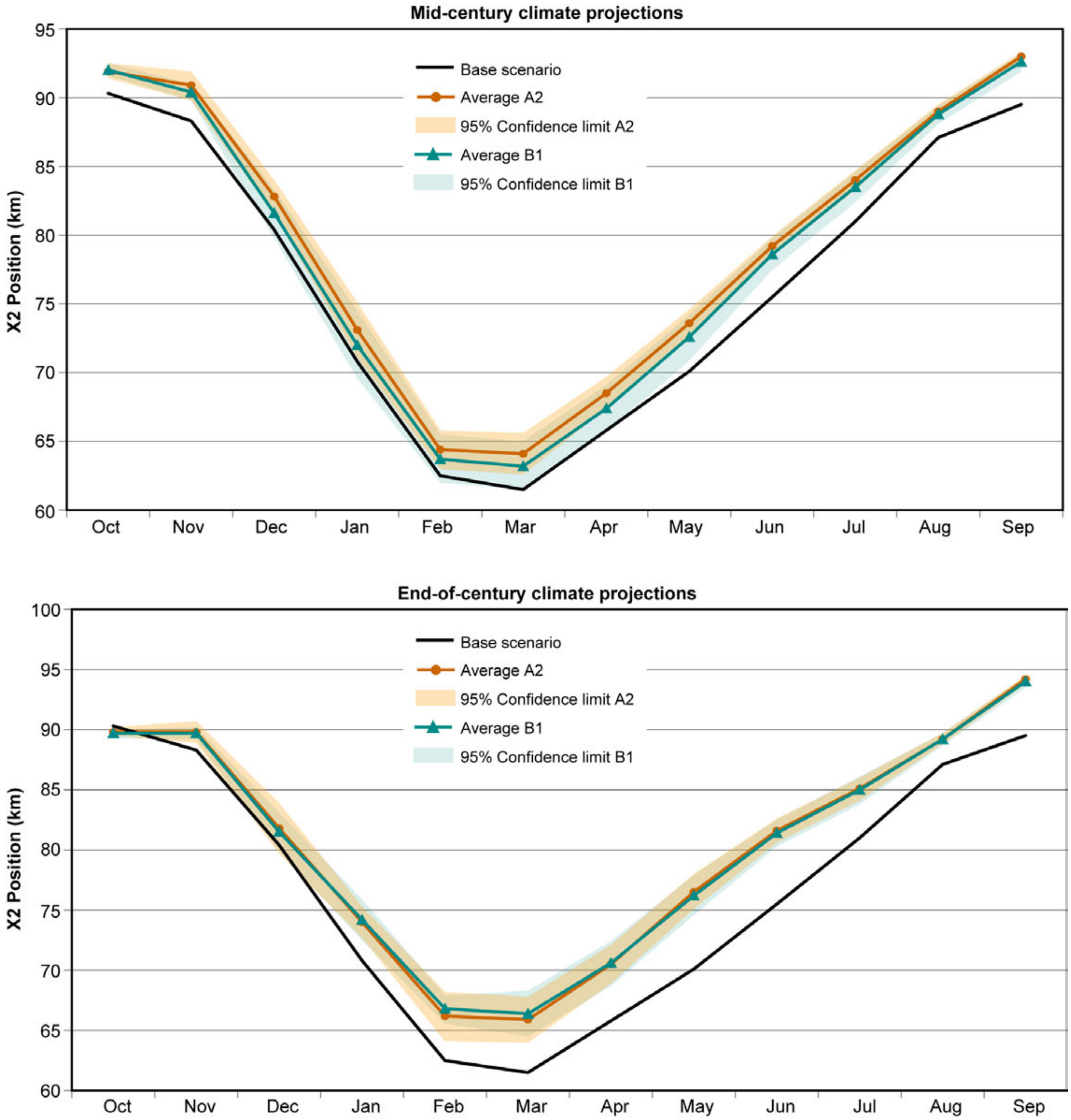


Figure 21. Average X2 position based on 12 future climate projections

System Vulnerability to Operational Interruption

As climate changes, the existing infrastructure and regulatory and operational criteria for the SWP and CVP may become inadequate at times. Two factors have been examined as indicators that the SWP-CVP system is vulnerable to operational interruption: (1) the percentage of years of system vulnerability to operational interruption, and (2) the annual amount of water needed to meet current regulatory requirements and to maintain minimum system operations during years that are vulnerable to operational interruption. The first factor reflects the frequency, and the second factor reflects the extent of system vulnerability to operational interruption.

For this analysis, the SWP-CVP system is considered vulnerable to operational interruption during a year if the storage in one or more of the major supply reservoirs (Shasta, Oroville, Folsom, and Trinity) goes below the reservoir dead storage. *Dead storage* is water in a reservoir that is below the lowest outlet and thus cannot be released from the reservoir. When dead storage is reached, the regulatory constraints below the reservoir—such as minimum instream flow and water quality requirements in the Delta—can no longer be met.

The percentage of years the system is vulnerable to operational interruption is shown in Figure 22. There are no years in which reservoir levels fall below the lowest outlets for the base scenario: however the system becomes vulnerable under the 12 future climate projections. At mid-century, reservoir levels fall below the lowest outlets in about 1 in 8 years for the lower GHG emissions scenario and in 1 in 6 years for the higher GHG emissions scenario. By the end of the century, the system becomes vulnerable to interruption in about 1 in 4 years for the lower GHG emissions scenario and in 1 in 3 years for the higher GHG emissions scenario These results indicate that the SWP and CVP will be more vulnerable under projected future climate conditions using the current system infrastructure and operating rules.

To better understand the extent of SWP and CVP system's vulnerability to operational interruption under climate change, when future climate conditions resulted in reaching dead storage in a reservoir, the amount of additional water needed to meet current regulations and to maintain minimum operations was estimated. This additional water could either come from supplemental sources or from reductions in future water demands. The extra water supply or reduction in demands was only assessed for years in which the system was determined to be vulnerable to operational interruption. In other words, this amount of extra water is not needed every year; it is only needed in years when the water projects are vulnerable to operational interruption.

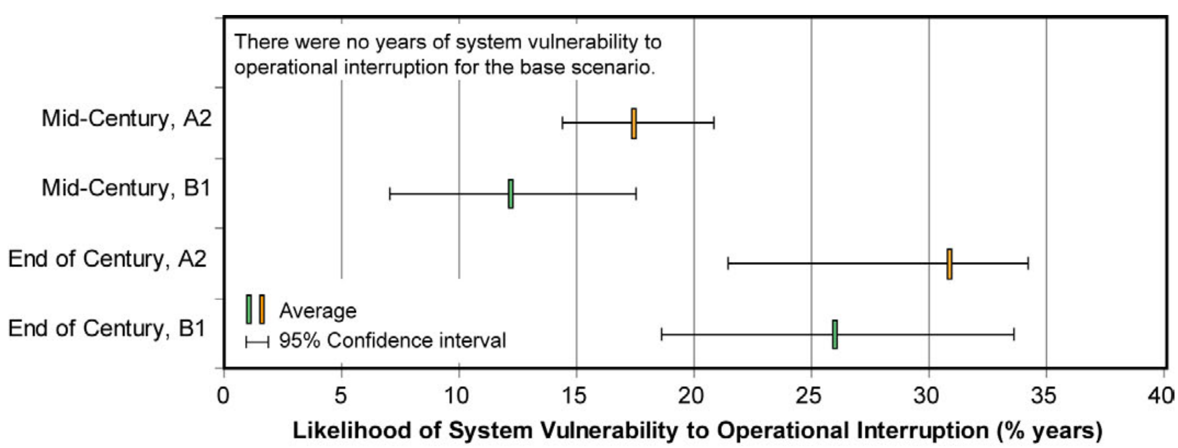


Figure 22. Percentage of years of system vulnerability to operational interruption based on 12 future climate projections

During years of system vulnerability, the additional amount of water needed to meet current regulations and to maintain minimum operations is shown in Figure 23. For the base scenario, there were no years in which the system was vulnerable to operational interruption, so no additional water supplies or demand reductions were needed. At mid-century during years of system vulnerability, the average amount of additional water needed to meet current regulations and to maintain minimum operations was 575 TAF for the lower GHG emissions scenario and 750 TAF for the higher GHG emissions scenario. By the end of the century, the amount of water needed in vulnerable years increases to 850 TAF for the lower GHG emissions scenario and remains at 750 TAF for the higher GHG emissions scenario. These results indicate that additional water supplies or reductions in demand would be needed to prevent operational interruption of the SWP and CVP under projected future climate conditions using the current system infrastructure and operating rules.

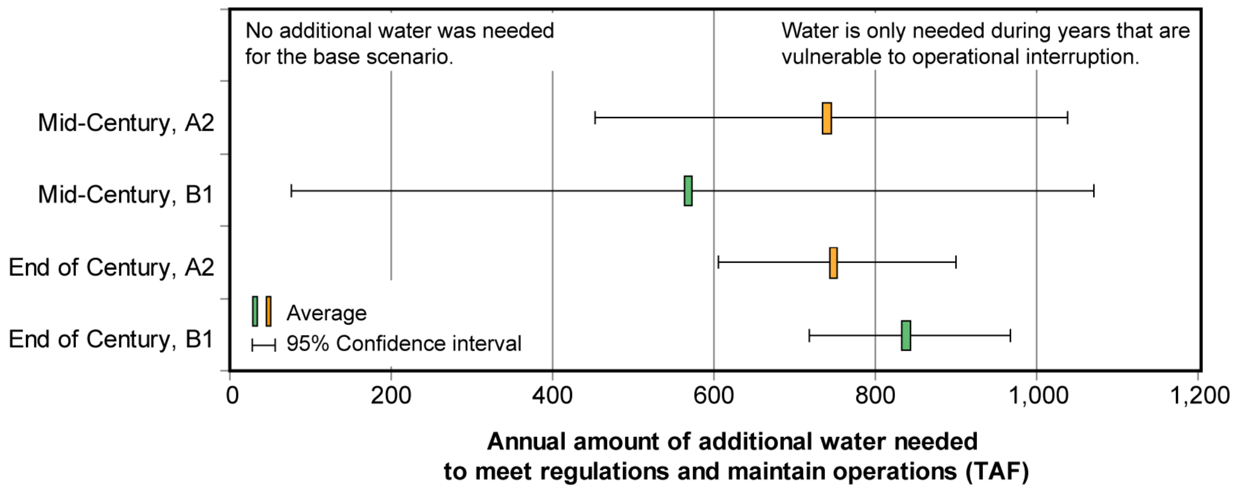


Figure 23. Annual amount of additional water needed to maintain minimum operations for years in which the system is vulnerable to interruption based on 12 future climate projections

6.0 Conclusions and Recommendations

6.1. Conclusions

This paper examined four broad objectives related to using future climate projections in water resources decision making. Main conclusions for each objective are presented below.

Objectives 1 and 2:
How well do climate models represent historical conditions in California that affect water resources such as air temperature, precipitation, and streamflow?

How do the methods used to convert global information to regional information affect the subsequent water resource impacts analyses and decision making?

> The six climate models and two downscaling methods used in this study represented average air temperatures over California well. For the BCSD method, annual precipitation estimates were reasonable, but the models tend to produce wetter winters and drier summers and falls compared to historical conditions. Streamflow estimates from the BCSD method were determined to be acceptable for impact assessments. Streamflow estimates from the CA method were not considered to be acceptable for impacts assessments at this time; however, DWR staff is working with researchers so that improvements can be made in streamflow estimates that use data produced by the CA method.

Objective 3: How can future projections for rainfall, runoff, streamflow, and sea level rise be incorporated into water resources planning?

- Methods for addressing sea level rise for planning purposes were investigated:
  - Future sea level rise was estimated using a relationship between projected air temperatures and sea levels
  - Methods were explored for developing sea level rise criteria for decision making. Sea level rise likelihood distributions were computed for different planning horizons. Investigations have begun on how to account for extreme sea level fluctuations.
  - Sea level rise Artificial Neural Networks (SLR ANNs) have been developed to represent Delta salinity for sea level rise conditions in planning models such as CalSim-II and CalLite.
- A three-step streamflow adjustment method was developed to estimate reservoir inflows and streamflow for SWP and CVP impact assessments.
- Agricultural crop and urban outdoor water demands were modified to take precipitation changes into account.

Objective 4: How can management tools be used to quantify possible impacts of climate change to Central Valley water systems?

> Two analyses were conducted to meet this objective. The first was a sensitivity analysis of how increases in air temperature would affect runoff and other hydrologic characteristics of

the upper Feather River basin, the main inflow source for Lake Oroville, the SWP's principal water supply reservoir. The second was an impact assessment of how SWP and CVP water supply reliability would be affected for 12 future climate projections.

The sensitivity analysis indicates that increasing air temperatures will have a significant effect on runoff and other hydrologic characteristics of watersheds that receive precipitation in the form of rain and snow. Key findings include:

- The average day that 50% of the annual inflow arrives at Lake Oroville decreased from mid-March for the base scenario to mid-February for an air temperature increase of 4°C (7.2°F), a change of 36 days.
- The 30-year trend indicates that the fraction of annual runoff occurring from April through July decreases from about 35% for the base scenario to about 15% for the +4°C scenario. In addition to the water supply and flood management impacts of earlier snowmelt, these changes could also affect the current water year classifications and their associated regulatory standards because those classifications are partly based on April–July runoff.

A multiple-step analysis approach was used to convert climate information from 12 GCM-based future climate projections into hydrologic and water demand information that could be used in a water allocation model of the SWP and the CVP. It was assumed that the infrastructure and regulatory and operating rules for the system did not change for the future scenarios. Climate change is expected to reduce the reliability of SWP and CVP water supplies. Median results for 12 future climate projections for both a lower GHG emissions scenario and a higher emissions scenario are summarized below. Uncertainties are greater for the end of the century results than for the mid-century results.

- Annual Delta exports are expected to be reduced by approximately 7%-10% by mid-century and by 21%-25% at the end of the century. This would reduce water deliveries south of the Delta.
- Reservoir carryover storage is expected to be reduced by 15%-19% by mid-century and by 33%-38% at the end of the century. This reduces the water supply reliability by reducing surplus storage that can be used in times of shortages.
- Annual groundwater pumping in the Sacramento Valley is expected to increase by 5%-9% by mid-century and by 13%-17% at the end of the century. Groundwater pumping is likely to increase under climate change to augment surface water supplies.
- Expected decreases in water deliveries would lead to reduced power generation and power use by the SWP and CVP. The power generation by the CVP is expected to decrease by 4%-11% at mid-century and by 12%-13% by the end of the century, and the power used by the CVP is expected to decrease by 9%-14% at mid-century and 24%-28% by the end of the century. The power generation by the SWP is expected to decrease by 5%-12% at mid-century and by 15%-16% by the end of the century, and the power used by the SWP is expected to decrease by 5%-10% at mid-century and by about 16% by the end of the century.

- The SWP and CVP are expected to be more vulnerable to operational interruption under climate change. It is expected that a water shortage worse than the one during the 1977 drought could occur in 1 out of every 6-8 years by mid-century and 1 out of every 3-4 years at the end of the century.
- In years when the system is vulnerable, the amount of additional water needed to meet regulatory requirements and to maintain minimum system operations is expected to be 575-750 TAF by mid-century and 750-850 TAF by the end of the century. This is the amount of additional water supply or reduction in water demands, or a combination of the two, that would be needed to maintain minimum system operations during years in which the SWP and CVP are vulnerable.
- The SWP and CVP are expected to continue meeting X2 Delta salinity standards under projected future climate conditions. The maximum position of X2 moved inland by 3.1 km-3.7 km by mid-century and by 6.1 km-6.4 km at the end of the century.

These results indicate a need to explore adaptation measures to improve the reliability of future water supplies in California.

6.2. Recommendations

Further work is needed to improve the use of future climate projection information in water resources planning. Advancements in the following areas are especially needed:

- Improved understanding of the uncertainties associated with future climate projections including relative likelihoods of future greenhouse gas emissions scenarios and sea level rise estimates.
- Improve understanding about how uncertainties and unknowns in each step of developing the simulations, scaling the data, and representing system operations affect the final information provided to decision makers.
- Develop and apply enhanced downscaling techniques that can account for the physical processes as well as statistical properties.
- Develop a dynamical downscaling technique for the state.
- Develop and apply a meso-scale model (such as MM5) or Weather Research and Forecasting (WRF) Model for California, and archive the data for public dissemination.
- Explore methods for incorporating possible changes in variability in future climate and hydrologic conditions (non-stationarity) into impact analyses.
- Further enhance existing management decision support tools or develop new tools for assessing risks of climate change on California’s water systems and for exploring adaptation measures such as possible re-operation of existing or projected future water resources systems to reduce the impacts of climate change.
- Develop guidelines for climate change analysis for selection of future climate projections, proper length of planning horizon, etc.
- Improve cross-sector coordination and integration of climate change related analyses.

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8.0 Glossary

A2	Greenhouse gas emissions scenario based on high population growth, regionally based economic growth, and slow technological changes
ANN	Artificial Neural Network
B1	Greenhouse gas emissions scenario based on low population growth, globally based economic growth, and sustainable development
BCSD	Bias Correction and Spatial Disaggregation downscaling method, sometimes referred to as Bias Correction and Spatial Downscaling
CA	Constructed Analogue downscaling method
CalSim-II	State Water Project and Central Valley Project water allocation model
CAP	California Applications Program
CAT	Climate Action Team
CCCC	California Climate Change Center
CNRM	Centre National de Recherches Météorologiques
CVP	Central Valley Project
CVPIA b2	Central Valley Project Improvements Act section 3406 (b)(2)
CVPIA	Central Valley Project Improvements Act
D1641	State Water Resources Control Board Decision 1641 Water quality control plan for the San Francisco Bay/Sacramento San Joaquin Delta Estuary (SWRCB, 1995)
dead storage	The water in a reservoir that is below the lowest outlet and thus can not be released from the reservoir.
DSM2	Delta Simulation Model 2
DWR	California Department of Water Resources
ENSO	El Niño/Southern Oscillation
GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	greenhouse gas
GHGE	greenhouse gas emissions
GWh/year	gigawatt hours per year

FRWA	Freeport Regional Water Authority
IPCC	Intergovernmental Panel on Climate Change
ISB	CALFED Independent Science Board
NCAR	National Center for Atmospheric Research
operational interruption	The SWP-CVP system is considered vulnerable to operational interruption during a year if the storage in one or more of the major supply reservoirs (Shasta, Oroville, Folsom, and Trinity) goes below the reservoir dead storage level.
PRMS	A physically based precipitation-runoff model the U.S. Geological Survey developed for DWR
PIER	Public Interest Energy Research Program
PPIC	Public Policy Institute of California
RD&D	research, development, and demonstration
Reservoir carryover storage	The amount of water remaining in a reservoir at the end of September that is available for use (carries over) to the next water year.
SLR ANN	Sea level rise Artificial Neural Network
SLDMWA	San Luis and Delta Mendota Water Authority
SLR	sea level rise
SRES	Intergovernmental Panel on Climate Change's **S**pecial **R**eport on **E**missions **S**cenarios (IPCC 2000)
SWP	State Water Project
SWRCB	State Water Resources Control Board
TAF	thousand acre-feet. An acre-foot is a unit of volume equivalent to one acre of land being covered with water one foot deep (325,900 gallons of water).
Reclamation	U.S. Bureau of Reclamation
UnTRIM	A multi-dimensional flow and water quality model
USGS	United States Geological Survey
VIC	Variable Infiltration Capacity model
WAM	Water Analysis Module-a tidally averaged one-dimensional simplified Delta hydrodynamics and water quality model

WAPA	Western Area Power Administration
X2	X2 is where the salinity concentration is two parts per thousand one meter off of the bottom of the estuary. The position (location) of X2 is measured in kilometers from the Golden Gate Bridge along the main flow channel. The abundance of several estuarine species has been correlated with X2.