

Draft

Climate Change Modeling Appendix

Shasta Lake Water Resources Investigation, California

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Bureau of Reclamation
Mid-Pacific Region**



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Abbreviations and Acronyms

°C	degrees Celsius
°F	degrees Fahrenheit
ANN	artificial neural network
B	site-specific parameter
Bay-Delta	San Francisco Bay/Sacramento-San Joaquin Delta
BDCP	Bay Delta Conservation Plan
BO	Biological Opinion
CDF	cumulative distribution function
cfs	cubic feet per second
CIMIS	California Irrigation Management Information System
cm	centimeter
CMIP3	Coupled Model Intercomparison Project Phase 3
CO ₂	carbon dioxide
CP	comprehensive plan
CT	Current Trends
CT-noCC	Current Trends-no climate change
CVP IRP CalLite	Central Valley Project Integrated Resources Plan version of the California Lite Simulation Model
CVP	Central Valley Project
CVPIA	Central Valley Project Improvement Act
CWP	California Water Plan
DCP	downscaled climate projection
DEIS	Draft Environmental Impact Statement
Delta	Sacramento-San Joaquin Delta
DSM2	Delta Simulation Model Version 2
DWR	California Department of Water Resources
EG	Expansive Growth
ENSO	El Nino Southern Oscillation
ET	evapotranspiration
FACE	Free Air Carbon Exchange
GCM	Global Circulation Model
GHG	greenhouse gas
GIS	geographical information system
GWh	gigawatt hours

in/yr	inches per year
IPCC	Intergovernmental Panel on Climate Change
IRP	Integrated Resource Plan
kg	kilogram
km	kilometer
Ko	dew point depression
LAWS	Land Atmosphere Water Simulator
LCPSIM	Least Cost Planning Simulation Model
LOD	level of development
LTGen	LongTermGen
M&I	municipal and industrial
MAF	million acre-feet
mm/yr	millimeters per year
msl	mean sea levels
mT CO _{2e}	metric tons of carbon dioxide equivalents
OMWEM	Other Municipal Water Economics Model
ppm	parts per minute
RBPP	Red Bluff Pumping Plant
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
RH	relative humidity
Ro	clear radiation
Rs	solar radiation
SBWQM	South Bay Water Quality Model
SG	Slow Growth
SJRWQM	San Joaquin River Water Quality Model
SLWRI	Shasta Lake Water Resources Investigation
SOD	south-of-Delta
SRWQM	Sacramento River Water Quality Model
SWAP	Statewide Agricultural Production Model
SWE	Snow Water Equivalent
SWP Power	State Water Project Power
SWP	State Water Project
TAF	thousand acre feet
Tdew	dew point temperature
Tmax	daily maximum temperature
Tmin	daily minimum temperature
VIC	Variable Infiltration Capacity
VPD	vapor pressure deficit

Shasta Lake Water Resources Investigation
Climate Change Modeling Appendix

WCRP	World Climate Research Program
WEAP	Water Evaluation and Planning

Chapter 1

Introduction

Historical warming of the climate system, including Earth's near-surface air and ocean temperatures, is now considered to be unequivocal (IPCC, 2007) with global surface temperature increasing approximately 1.33 degrees Fahrenheit (°F) over the last 100 years. Continued warming is projected to increase global average temperature between 2°F and 11°F over the next 100 years.

The causes of this warming have been identified as both natural processes and human actions. The Intergovernmental Panel on Climate Change (IPCC) concludes that variations in natural phenomena, such as solar radiation and volcanoes, produced most of the warming from preindustrial times to 1950, and had a small cooling effect afterward. However, after 1950, greenhouse gas (GHG) concentrations resulting from human activity, such as fossil fuel burning and deforestation, have been responsible for most of the observed temperature increase (CEC, 2006). These conclusions have been endorsed by more than 45 scientific societies and academies of science, including all of the national academies of science of the major industrialized countries. Since 2007, no scientific body of national or international standing has maintained a dissenting opinion.

The average mean annual temperature is projected to increase by 5 to 6°F during this century, though with substantial variability in warming in the Central Valley (ICF, 2012). Northern California is expected to experience changes to the physical environment as a result of climate change. Climatic modeling results indicate that climate change will result in a change from snow to rain in winter, leading to reduced snowpack, earlier snowmelt, and reduced river flows and reservoir storage in summer (Knowles and Cayan 2002; Miller et al. 2003; Mote et al. 2005), causing changes to the seasonal timing of flows in rivers (ICF, 2012).

A projected increased in surface temperatures and changes in timing and magnitude of stream runoff will have important implications for California's water supply and are also expected to affect aquatic species due to changes in river flows and water temperatures. Projected changes in climate are likely to influence the potential benefits of the Shasta Lake Water Resources Investigation (SLWRI) project.

The focus of this document is to present an assessment of the potential to achieve the objectives of the SLWRI under projected future climate change.. The primary objectives of the alternatives identified in the SLWRI are (1) increase survival of anadromous fish populations in the Sacramento River

primarily upstream from the Red Bluff Pumping Plant; and, (2) increase water supply and water supply reliability for agricultural, municipal and industrial, and environmental purposes, to help meet current and future water demands, with a focus on enlarging Shasta Dam and Reservoir.

To assess the potential to achieve these objectives these under projected future climate change, two SLWRI comprehensive plans (i.e., alternatives) were selected. Comprehensive Plan 4 (CP4) maximizes anadromous fish survival, and was therefore selected to assess the potential to benefit anadromous fish survival under climate change. Comprehensive Plan 5 (CP5) maximizes the potential benefits to water supply reliability, and was therefore selected to assess the potential to benefit water supply reliability under climate change.

The potential to benefit water supply reliability under climate change was evaluated using climate modeling tools developed by U.S. Department of the Interior, Bureau of Reclamation (Reclamation) for the Central Valley Project (CVP) Integrated Resource Plan (IRP). Under the CVP IRP, transient changes in projected climatic conditions in the future are applied. The transient method assumes gradual warming as the simulation moves forward based on an interpolation between current and projected future conditions. For evaluating the potential to benefit anadromous fish survival under climate change, a different method based on the mean state of projected climate changes (“delta” method) was applied. Unlike the transient method, the delta method assumes a constant change in climate for simulation of future scenarios. In this method, temperature and/or precipitation are adjusted by the mean shift from one historical 30-year period to a future 30-year period. These two methods apply different hydrologic and CVP/State Water Project (SWP) system operations modeling tools, but use the same future climatic projections.

This appendix is organized as follows:

- Chapter 2 of this appendix presents information on a summary of global climate projections and relevant research on climate change implications for California water resources, particularly those for Shasta Lake.
- Chapter 3 of this appendix presents the results of the transient method analysis of the potential to benefit water supply reliability under climate change, using CP5.
- Chapter 4 presents the results of the delta method analysis of the potential to benefit anadromous fish survival under climate change, using CP4.
- Chapter 5 contains the technical references list.

This appendix provides context for the consideration of climate change within resource areas and cumulative condition chapters of the SLWRI Draft Environmental Impact Statement (DEIS). Assessments of specific impacts of climate change on environmental resource areas are discussed in the DEIS.

While it is unlikely that any single project could have a significant impact on the projected production of GHG, the cumulative effect of human activities has been clearly linked to quantifiable changes in the composition of the atmosphere, which in turn have been shown to be the main cause of global climate change (IPCC, 2007). Possible effects of the SLWRI on GHG production are discussed in the “Air Quality and Climate” chapter of the DEIS. The regulatory framework pertaining to air quality, climate change, and the emission of GHGs is also described in the “Air Quality and Climate” chapter of the DEIS.

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Chapter 2

Summary of Previous Studies of Climate Change in the Study Area

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

Study Area Setting

Shasta Dam and Shasta Lake are located on the upper Sacramento River in Northern California, approximately 9 miles northwest of Redding in Shasta County. The SLWRI includes both a primary and extended study area because of the potential influence of the proposed modification of Shasta Dam and Reservoir and subsequent system operations and water deliveries on resources over a large geographic area. This area is represented by the Sacramento and San Joaquin rivers and the Delta system, plus the CVP and SWP facilities and water service areas.

The Sacramento River drains the northern portion and the San Joaquin drains the central and southern portions of the Central Valley, a large north to south trending alluvial basin extending over 450 miles from the southern Cascade Mountains near the City of Redding to the Tehachapi Mountains south of the City of Bakersfield. The basin is about 40 to 60 miles wide and is bounded by the Coast Range to the west and the Sierra Nevada Mountains on the east. Hydrologically, the Central Valley is divided into three hydrographic regions including the Sacramento, San Joaquin and Tulare Lake Basins. Both the Sacramento and San Joaquin rivers flow into the Sacramento-San Joaquin Delta (Delta). This region is the largest estuary on the west coast of the United States. Typically, the Tulare Lake Basin is internally drained. However, in some wetter than normal years, flow from the Tulare Lake region reaches the San Joaquin River. Together, the Sacramento and San Joaquin rivers drain an area of approximately 59,000 square miles.

The Sacramento River is the largest river in California with an historic mean annual flow of 22 million acre-feet. It drains an area of about 27,000 square miles. The Sacramento River arises in the volcanic plateaus of northern California where it is joined by the Pit River above Shasta Dam, a Reclamation facility. Below Shasta Dam, transmountain diversions from the Trinity River (tributary to the Klamath River) along with many small-

and moderate-sized tributaries join the river as it flows south through the Sacramento Valley. Major tributaries also join the river from the east including the Feather, Yuba, and American Rivers. Major facilities on these rivers include Oroville Dam operated by the California State Water Project on the Feather River and Folsom Dam operated by Reclamation on the American River. After a journey of over 400 miles, the river reaches Suisun Bay in the Sacramento-San Joaquin Delta before discharging into San Francisco Bay and the Pacific Ocean.

The San Joaquin River is the second largest river in California with an historic mean annual flow of 7.5 million acre-feet. It drains an area of 32,000 square miles. The San Joaquin originates in the high Sierra Nevada Mountains in east-central California. The river initially flows westward reaching Friant Dam, a Reclamation facility, before entering the San Joaquin Valley. At Friant Dam, diversions are made to the Friant Division of the Central Valley Project, which is primarily located in the Tulare Lake Basin. Before implementation of the San Joaquin Restoration Program, flows below the dam were minimal except during flood conditions. Releases from the dam flow initially westward until reaching the Chowchilla Bypass (a constructed flood control facility) or the Mendota Pool (a managed irrigation water control facility). From there, the river turns northward and begins receiving returns flows from agricultural and wildlife refuge areas upstream from its confluence with the Merced River, a major tributary. As the river continues northward, it receives inflows from several eastside tributaries including the Toulumne, Stanislaus, Calaveras, and Mokelumne Rivers, each of which have major dams that store water and regulate flows. After a distance of 330 miles, the San Joaquin joins the Sacramento River near Suisun Bay in the Sacramento-San Joaquin Delta.

Reclamation's major role in the Central Valley began in 1933 with the construction of the CVP. Today the CVP consists of 20 dams, 11 powerplants and more than 500 miles of canals that serve many purposes including providing, on average, 5 million acre-feet of water per year to irrigate approximately 3 million acres of land in the Sacramento, San Joaquin, and Tulare Lake basins, 600,000 acre-feet per year of water for urban users, and 800,000 acre-feet of annual supplies for environmental purposes.

Historical Climate

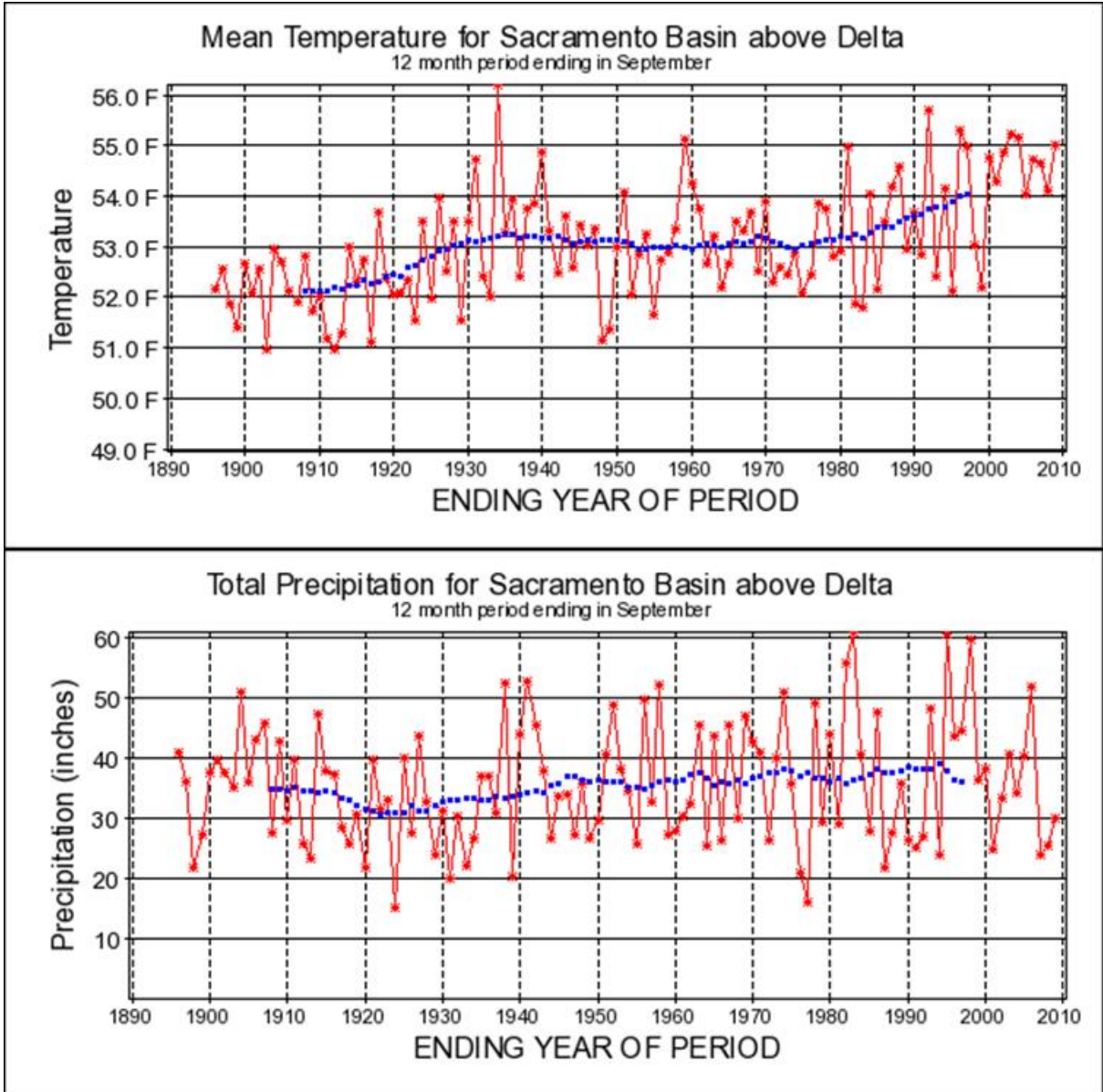
The historical climate of the Central Valley is characterized by hot and dry summers and cool and damp winters. Summer daytime temperatures can reach 90°F with occasional heat waves bringing temperatures exceeding 115°F. The majority of precipitation occurs from mid-autumn to mid-spring. The Sacramento Valley receives greater precipitation than the San Joaquin and Tulare Lake basins. In winter, temperatures below freezing may occur, but snow in the valley lowlands is rare. The Central Valley typically has a frost-free growing season ranging from 225 to 300 days.

During the growing season, relative humidity is characteristically low; in the winter, values are usually moderate to high, and ground fog may form. The Central Valley is located within the zone of prevailing westerly winds, but local terrain exerts a significant influence on wind directions. Warmer-than-normal temperatures often are associated with more northerly winds flowing out of the Great Basin to the east. During summer, strong westerly winds driven by the large temperature difference between the San Francisco Bay and interior Great Valley often occur in the Sacramento-San Joaquin Delta.

The inter-annual variability of the Central Valley climate is strongly influenced by conditions occurring in the Pacific Ocean including the El Niño Southern Oscillation (ENSO) and the existence of a semipermanent high-pressure area in the northern Pacific Ocean. During the summer season, the northerly position of the Pacific high blocks storm tracks well to the north and results in little summertime precipitation. During the winter months, the Pacific high typically moves southward allowing storms into the Central Valley. Such storms often bring widespread, moderate rainfall to the Central Valley lowlands and the accumulation of snow in the surrounding mountainous regions. When strong ENSO global circulation patterns occur, storm centers can approach the California coast from a southwesterly direction, transporting large amounts of tropical moisture with resulting heavy rains that can produce high runoff and the potential for widespread flooding in the Central Valley.

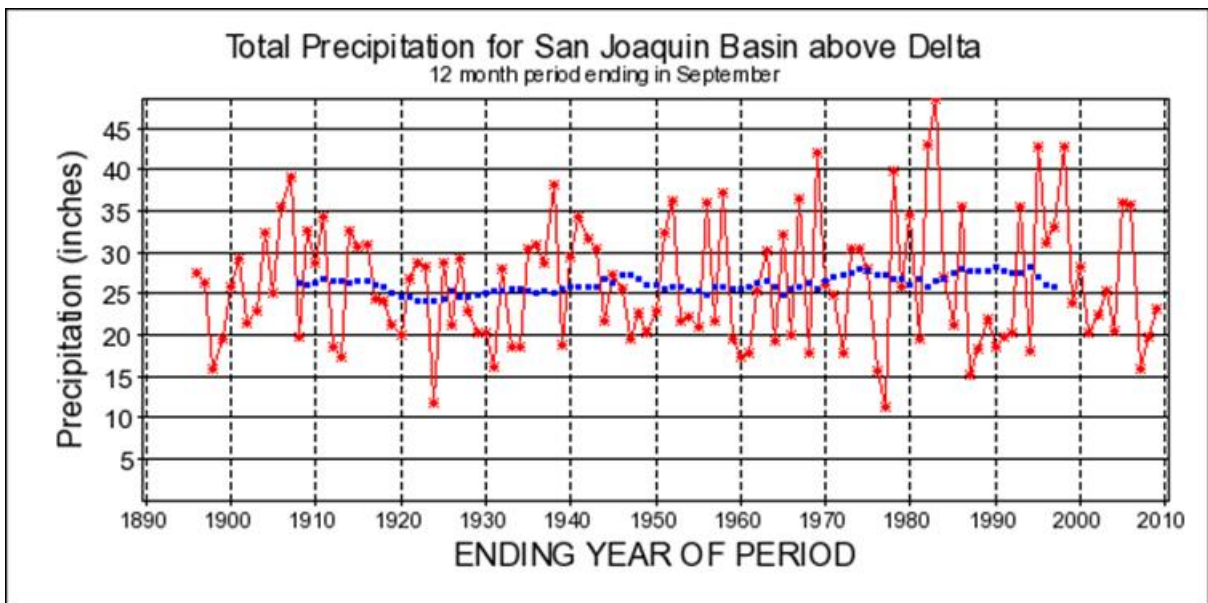
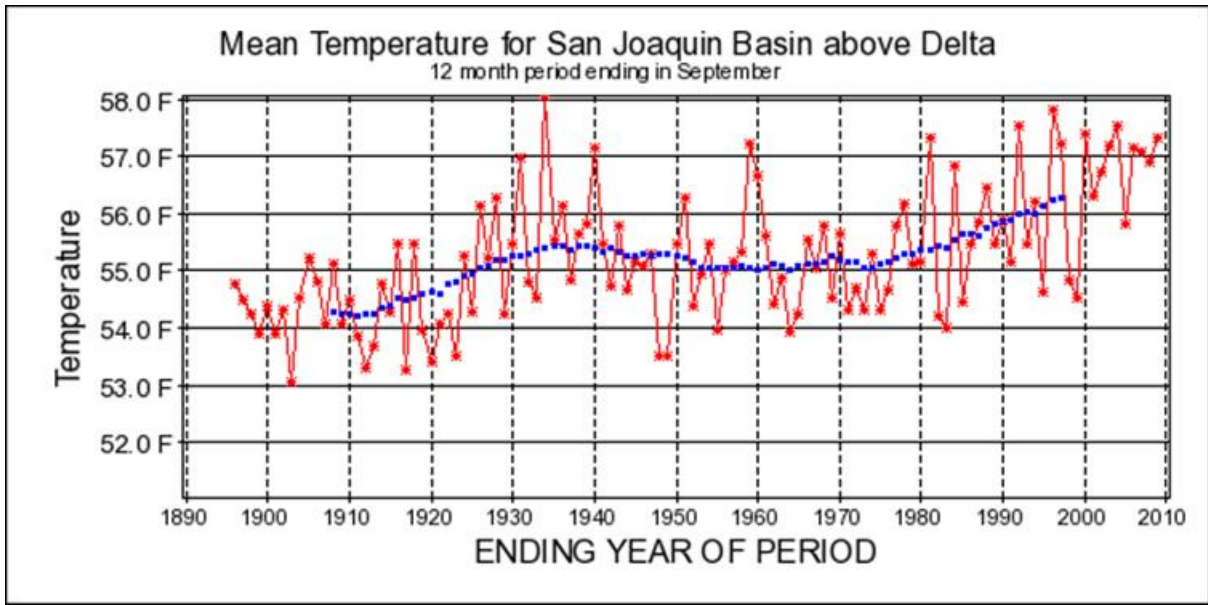
Over the course of the 20th century, warming has been prevalent over the Sacramento and San Joaquin River basins. Basin average mean-annual temperature has increased by approximately 2°F during the course of the 20th century for just the Sacramento River basin above the Delta (Figure 2-1) or the San Joaquin River basin above the Delta (Figure 2-2).

Warming has not occurred steadily throughout the 20th century. Increases in air temperatures occurred primarily during the early part of the 20th century between 1910 and 1935. Subsequently, renewed warming began again in the mid-1970s and appears to be continuing at present, as shown for the Sacramento River basin in Figure 2-1. Similar results are apparent for the San Joaquin River basin (Figure 2-2) and have been reported in other studies. Cayan et al. (2001) reported that Western United States spring temperatures have increased 1 to 3 degrees Celsius (°C) (1.8 to 5.4°F) since the 1970s; whereas, increased winter temperature trends in central California were observed to average about 0.5°C (0.9°F) per decade (Dettinger and Cayan 1995). In both the Sacramento and San Joaquin basins, the overall 20th century warming has been about 3°F.



Source: Western Climate Mapping Initiative (WestMap) available at: <http://www.cefa.dri.edu/Westmap/>. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 1994; Gibson et al. 2002).

Figure 2-1. Observed Annual (red) and Moving-Mean Annual (blue) Temperature and Precipitation, Averaged over the Sacramento River Basin



Source: Western Climate Mapping Initiative (WestMap) available at: <http://www.cefa.dri.edu/Westmap/>. Red line indicates annual time series for the given geographic region. Blue line indicates 25-year moving annual mean values, where each value is plotted on the center year of its respective 25-year period. WestMap data are derived from the PRISM climate mapping system (Daly et al. 1994; Gibson et al. 2002).

Figure 2-2. Observed Annual (red) and Moving-Mean Annual (blue) Temperature and Precipitation, Averaged over the San Joaquin River Basin

In the Sacramento basin, the warming trend also has been accompanied by a gradual trend starting in the 1930s toward increasing precipitation (Figure 2-1, bottom panel). However, a similar precipitation trend is not evident in the San Joaquin basin (Figure 2-2). Other studies have shown similar results.

Regonda et al. (2005) reported increased winter precipitation trends from 1950 to 1999 at many Western United States locations, including several in California's Sierra Nevada; but a consistent region-wide trend was not apparent. The variability of annual precipitation appears to have increased in the latter part of the 20th century, as can be seen by comparing the range of differences in high and low values of the solid red line in Figure 2-1 and Figure 2-2. These extremes in wet and dry years have been especially frequent since the mid-1970s in both the Sacramento and San Joaquin basins.

Historical Hydrology

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

The historical changes in climate described in preceding sections have resulted in several important effects on Sacramento and San Joaquin basin hydrology. Although annual precipitation may have slightly increased or remained relatively unchanged, corresponding increases in mean annual runoff in the Sacramento and San Joaquin rivers did not occur (Dettinger and Cayan 1995). One change that has been observed is a change in the seasonal timing of runoff. In the Sacramento River basin, a decrease of about 10 percent in the fraction of total runoff occurring between April through July has been observed over the course of the 20th century (Roos 1991). Similar results were obtained from analyses of the combined basin runoffs for both the Sacramento and San Joaquin basins by Dettinger and Cayan (1995).

Along with the declining spring runoff, corresponding increases in winter runoff have been observed. Analysis of data for 18 Sierra Nevada river basins found earlier runoff trends (Peterson et al. 2008). Of the potential climatic factors that could produce such changes, analyses indicated that increasing spring temperatures rather than increased winter precipitation was the primary cause of the observed trends (Cayan 2001). Studies by these researchers and others showed that the magnitude of the decreases in April through July runoff was correlated with the altitude of the basin watershed. High altitude basins like the San Joaquin exhibited less decrease in spring runoff than lower elevation watersheds such as the Sacramento. However, it is noted that the appearance of runoff trends in the basins

depends on location and period of record being assessed. For example, runoff trends were evaluated for this report during the last half of the 20th century; and although similar trend directions were found, they were found to be statistically weak.¹

Other studies of the magnitude of spring snowpack changes during the 20th century found that snowpack as measured by April 1st Snow Water Equivalent (SWE) showed a decreasing trend in the latter half of the 20th century (Mote 2005). Coincident with these trends, reduced snowpack and snowfall ratios were indicated by analyses SWE measurements made from 1948 through 2001 at 173 Western United States stations (Knowles et al. 2007). Regonda et al. (2005) reported decreasing spring SWE trends in 50 percent of Western United States locations evaluated.

The changes discussed in the previous paragraphs over regional drainages such as the Sacramento and San Joaquin River basins are sensitive to the uncertainties of station measurements as well as the periods of analyses and analyzed locations. For the entire Western United States, observed trends of temperature, precipitation, snowpack, and streamflow might be partially explained by anthropogenic influences on climate (e.g., Barnett et al. 2008; Pierce et al. 2008; Bonfils et al. 2008; Hidalgo et al. 2009; and Das et al. 2009). However, it remains difficult to attribute observed changes in hydroclimate to historical human influences or anthropogenic forcings. This is particularly the case for trends in precipitation (Hoerling et al. 2010) and for trends in basin-scale conditions rather than at the larger Western United States scale (Hidalgo et al. 2009).

Sea level change is also an important factor in assessing the effect of climate on California's water resources because of its effect on water quality in the Sacramento-San Joaquin Delta. Higher mean sea levels (msl) are associated with increasing salinity in the Delta, which influences the suitability of its water for agricultural, urban, and environmental uses. The global rate of msl change was estimated by IPCC (2007) to be 1.8 +/- 0.5 millimeters per year (mm/yr) (0.07 +/- 0.02 inches per year (in/yr)) from 1961–2003 and 3.1 +/- 0.7 mm/yr (0.12 +/- 0.03 in/yr) during 1993–2003. During the 20th century, msl at Golden Gate Bridge in San Francisco Bay has risen by an average of 2 mm/yr (0.08 in/yr) (Anderson et al. 2008). These rates of sea level rise appear to be accelerating based on tidal gauges and remote sensing measurements (Church and White 2006; Beckley et al. 2007).

¹ Trend significance was assessed using statistical testing during the period from 1951 through 1999 applied to historical simulated runoff results under observed historical weather conditions (Reclamation 2011a). Trends were computed and assessed for four Missouri basin locations, focusing on annual and April–July runoff. In all cases, computed trends were judged to not be statistically significant with 95 percent confidence.

Future Changes in Climate and Hydrology

This section summarizes results from studies focused on future climate and hydrologic conditions within the Sacramento and San Joaquin River basins. The first subsection summarizes literature relevant to the study area. The subsequent section focuses on results from Reclamation (2011c), which were produced within the context of a western United States-wide hydrologic analysis to identify risks to water supplies in a consistent manner throughout the Colorado, Columbia, Klamath, Missouri, Rio Grande, Sacramento, San Joaquin, and Truckee river basins consistent with Public Law 111-11, Subtitle F (the SECURE Water Act).

Summary of Future Climate and Hydrology Studies in Study Area

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

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

Sea level changes also have been projected to occur during the 21st century due to increasing air temperatures causing thermal expansion of the oceans and additional melting of the land-based Greenland and Antarctic ice sheets (IPCC 2007). The CALFED Independent Science Board estimated a range of sea level rise at Golden Gate of 1.6 feet to 4.6 feet by the end of the century (CALFED ISB 2007). The California Department of Water Resources (DWR) used the 12 future climate projections to estimate future sea levels. Their estimates indicate sea level rise by mid-century ranges

from 0.8 feet to 1.0 feet with an uncertainty range spanning 0.5 feet to 1.3 feet. By the end of the century, sea level was projected to rise between 1.8 feet and 3.1 feet, with an uncertainty range spanning from 1.0 feet to 3.9 feet. There is also the potential for increased extremely high sea level events to occur when high tides coincide with winter storms (Moser et al. 2009).

Projections of Future Climate

This section summarizes climate projections developed by Reclamation (2011c) consistent with the SECURE Water Act. The methods and assumptions used to develop the projections discussed below are described in detail in a report titled *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections* (2011a).

First, basin-wide averages of projected climate conditions are presented and, secondly, those projected climate conditions as they may be distributed throughout the basin is presented. A summary of snow-related effects under future climate conditions as they may be distributed throughout the basin is then presented; and, finally, climate and snowpack changes translated into effects on annual and seasonal runoff as well as acute runoff events relevant to flood control and ecosystems management are discussed. Runoff-Reporting locations described in this section are shown in Figure 2-3.

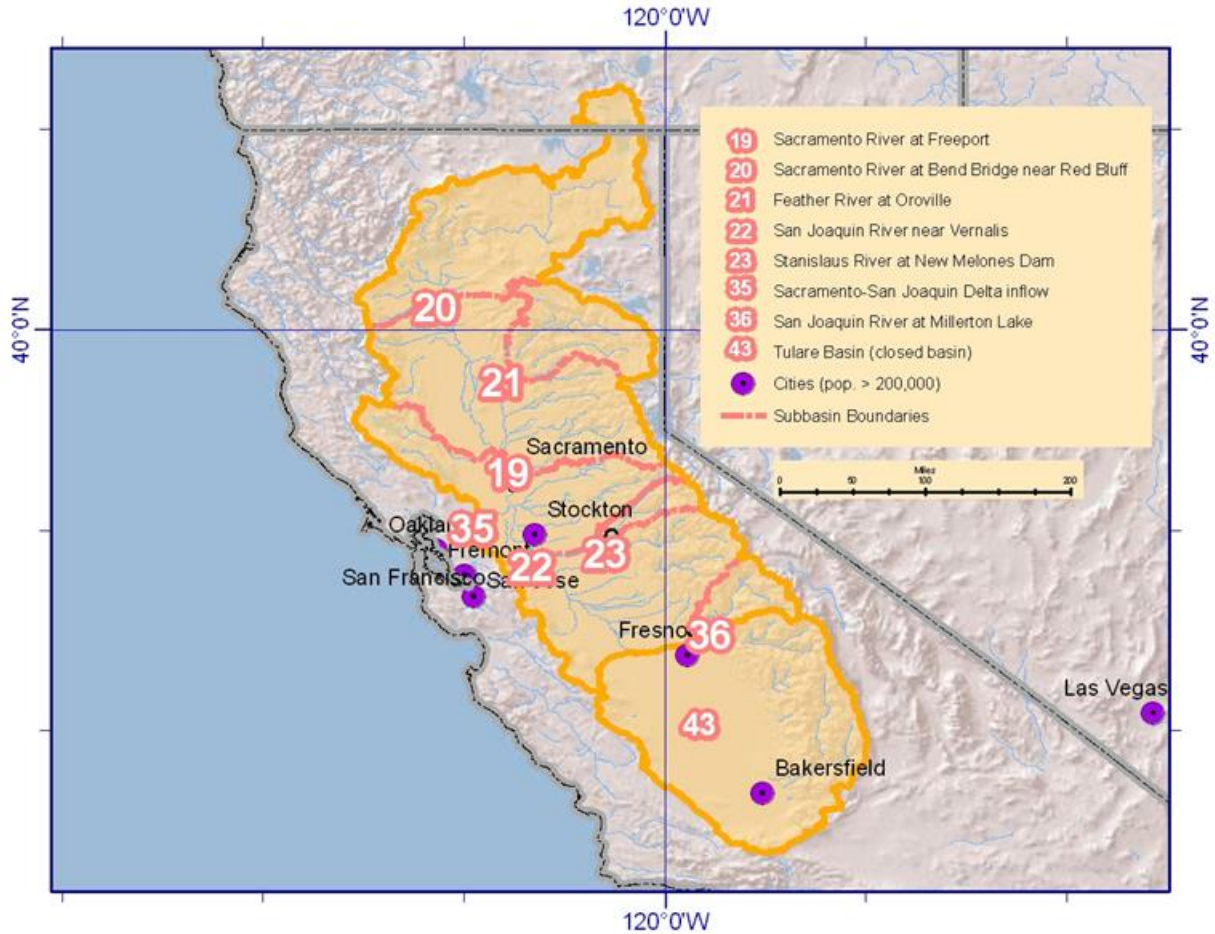


Figure 2-3. Runoff-Reporting Locations in the Sacramento River, San Joaquin River, and Tulare River Basins Described in this Section

Before summarizing climate projection and climate change information, it is noted that the projected changes have geographic variation, they vary through time, and the progression of change through time varies among climate projection ensemble members. Starting with a regional view of the time series climate projections and drawing attention to the projections’ median condition through time, results suggest that temperatures throughout the Sacramento and San Joaquin basins may increase steadily during the 21st century. Focusing on the Sacramento River subbasin at Freeport, San Joaquin River subbasin at Vernalis, and on the combined basins’ inflow to the Delta (Figure 2-4), the basin-average mean-annual temperature is projected to increase by roughly 5°F to 6°F during the 21st century. For each subbasin view, the range of annual possibility appears to widen through time.

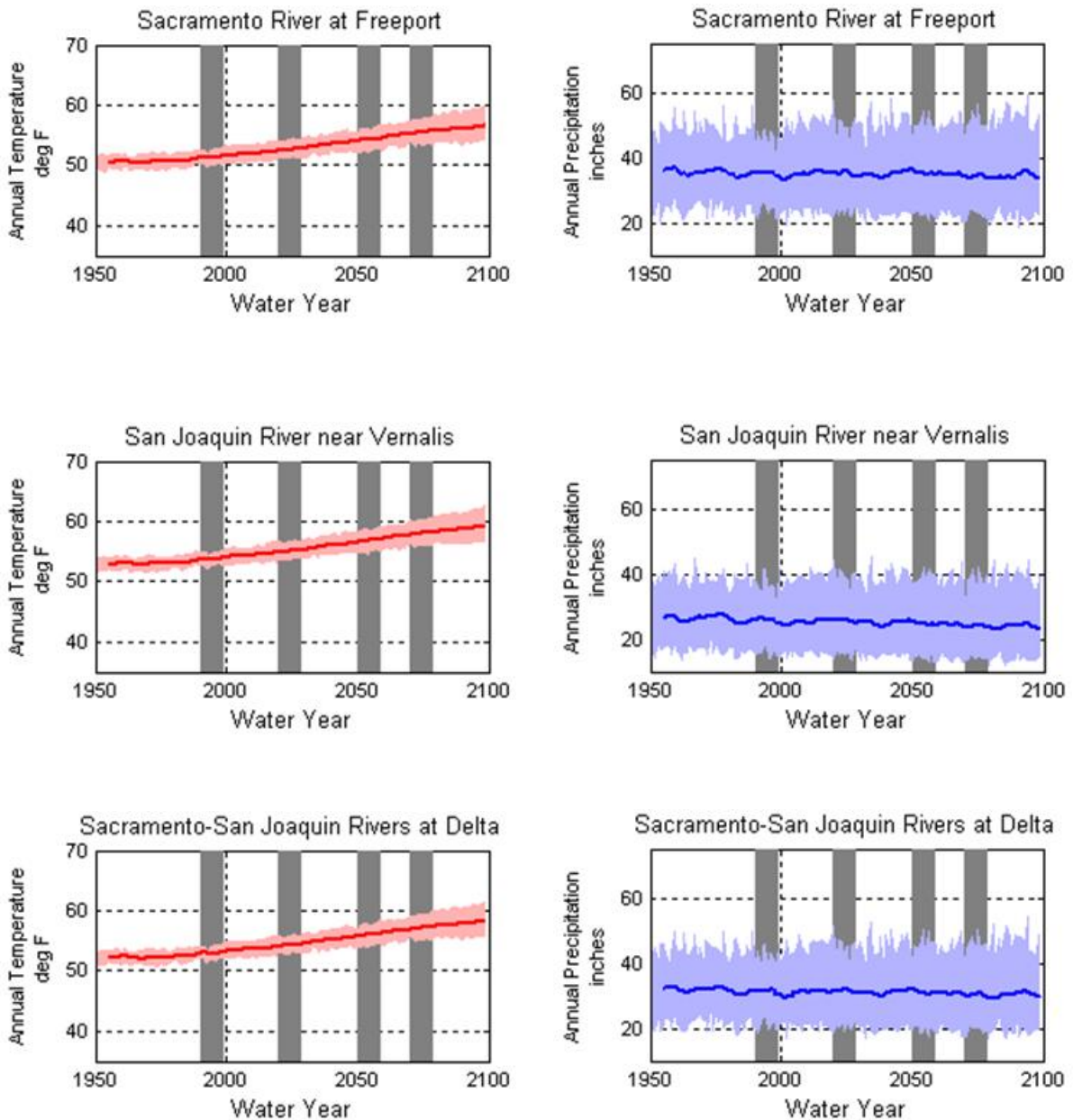


Figure 2-4. Simulated Annual Climate Averaged over Sacramento and San Joaquin River Subbasins

The ensemble mean of projections indicates that mean-annual precipitation, averaged over either subbasin (Figure 2-4), appears to stay generally steady during the 21st century, with perhaps a slight increase in the northern portion of the Central Valley (Sacramento River subbasin at Freeport) and a slight decrease within the southern portion (San Joaquin River near Vernalis). This is evident by following the ensemble median of the annual

precipitation through time for both basins. The projections also suggest that annual precipitation in the Sacramento and San Joaquin basins should remain quite variable over the next century. Despite the statements about the mean of the ensemble, there is significant disagreement among the climate projections regarding change in annual precipitation over the region.

Projection of climate change is geographically complex over the Sacramento and San Joaquin River basins, particularly for precipitation. For example, consider the four decades highlighted on Figure 2-4 (vertical gray bars): the 1990s, 2020s, 2050s, and 2070s. The 1990s provide the baseline climate from which climate changes are assessed for the three future decades (2020s, 2050s, and 2070s). The baseline climate indicates that local climate varies considerably within the basin. For example, in the Sacramento River at Freeport (Figure 2-4, top left panel), annual average temperatures are generally cooler in the high-elevation upper reaches in the north and along the mountainous rim to the east. Warmer temperatures occur to the south and in the lower lying valley area. This is similarly the case for the San Joaquin River near Vernalis (Figure 2-4, top right panel). For precipitation, amounts are generally greater along the mountainous spine extending from the Cascades in the north-central part of the basin throughout the Sierra Nevada to the southeast (Figure 2-4, top left panel) and lesser in the interior plateau northeast of these mountain ranges and in the lower lying valley areas to the south and west. In the San Joaquin River Basin, precipitation amounts are also greater in the Sierra Nevada (Figure 2-4, top left panel).

Regarding climate change, temperature changes are generally uniform over both the Sacramento River (Figure 2-4) and San Joaquin River basins (Figure 2-4) and steadily increase through time. Changes are projected to be perhaps slightly greater in the eastern portions of the basins. For precipitation, similar geographic consistency is found, although there is a little less uniformity in the direction of change between the two basins and through the progression of 21st century decades. For example, the Sacramento River basin is projected to generally experience slight increase in precipitation during the early to mid 21st century (2020s and 2050s) followed by a reversal to slight precipitation decline (2070s). In the San Joaquin River Basin, a similar progression is projected but with the reversal occurring earlier in the 21st century (i.e., slight increase to no change in precipitation projected for the 2020s followed by slight decrease by the 2050s and continuing through the 2070s). It is important to note that, while the mean-annual amount of precipitation may only change slightly under increasing temperature projections, the character of precipitation within the Sacramento and San Joaquin River basins also is expected to change under warming conditions, resulting in more frequent rainfall events, less frequent snowfall events.

Figure 2-4 displays the ensemble of temperature and precipitation projections from Bias Corrected and Spatially Downscaled WCRP CMIP3 Climate Projections. Annual conditions represent spatially averaged results over the basin. Darker colored lines indicate the median-annual condition through time, sampled from the ensemble of 112 climate simulations, and then smoothed using a 5-year running average. Lighter-colored areas represent the time-series range of 10th to 90th percentile annual values within the ensemble from simulated 1950 through simulated 2099.

Figure 2-5 presents basin-distributed views of change in mean annual temperature over the Sacramento River Basin upstream from Freeport. Figure data are simulated conditions as described in Reclamation (2011a). The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. Temperature units °F for baseline and change. Precipitation and SWE units are inches for baseline and percentage for change. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

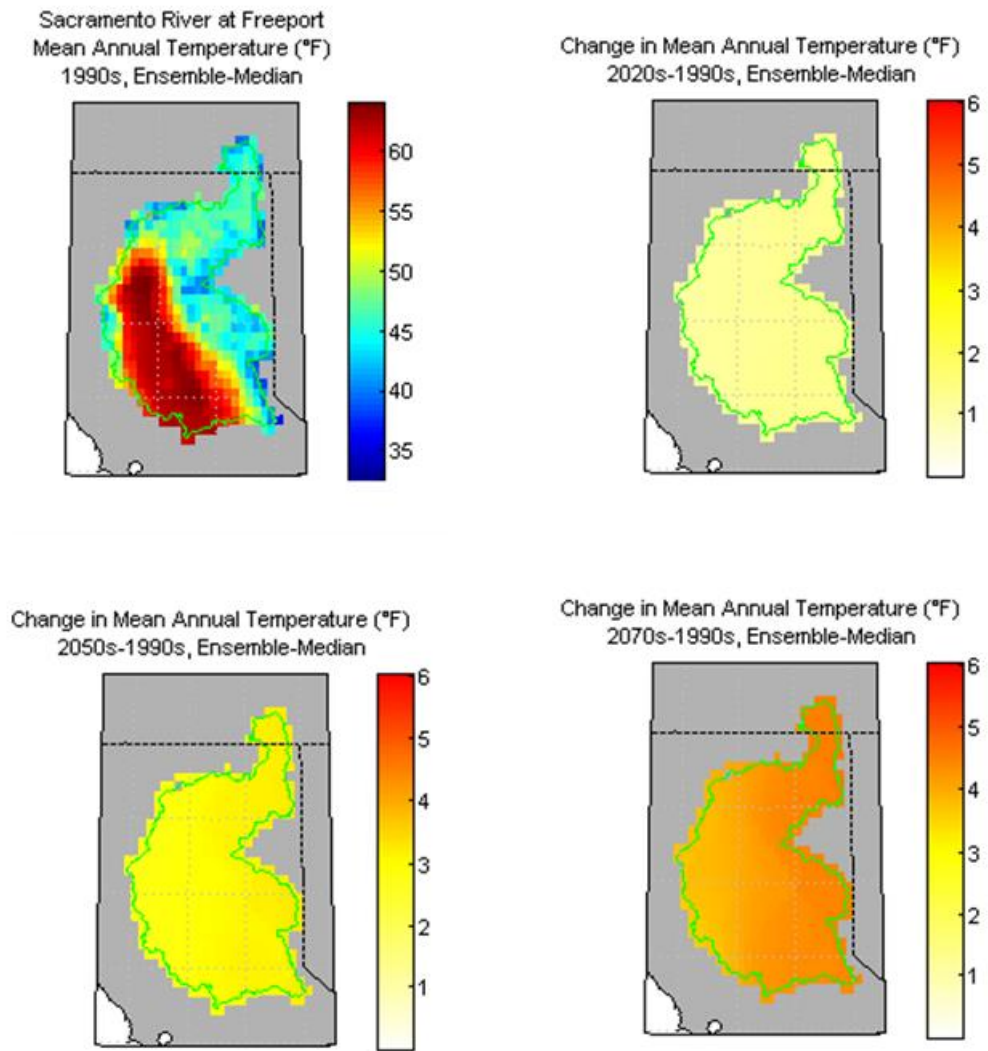


Figure 2-5. Simulated Decade-Mean Temperature over the Sacramento River Basin Above Freeport, California

Figure 2-6 presents basin-distributed views of change in mean annual temperature over the San Joaquin River Basin upstream from Vernalis. Figure data are simulated conditions as described in Reclamation (2011a). The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations.

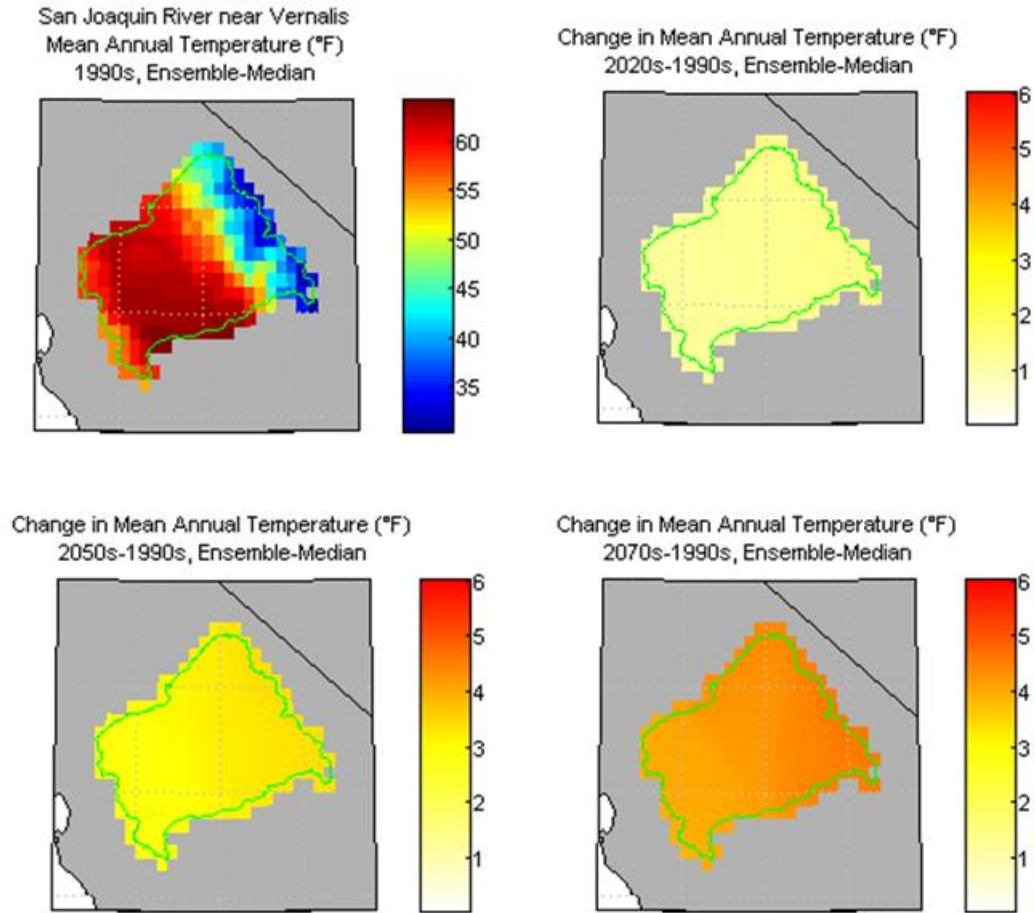


Figure 2-6. Simulated Decade-Mean Temperature over the San Joaquin River Basin Above Vernalis, California

Figure 2-7 presents basin-distributed views of change in mean annual precipitation over the Sacramento River Basin upstream from Freeport. Figure data are simulated conditions as described in Reclamation 2011a. The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

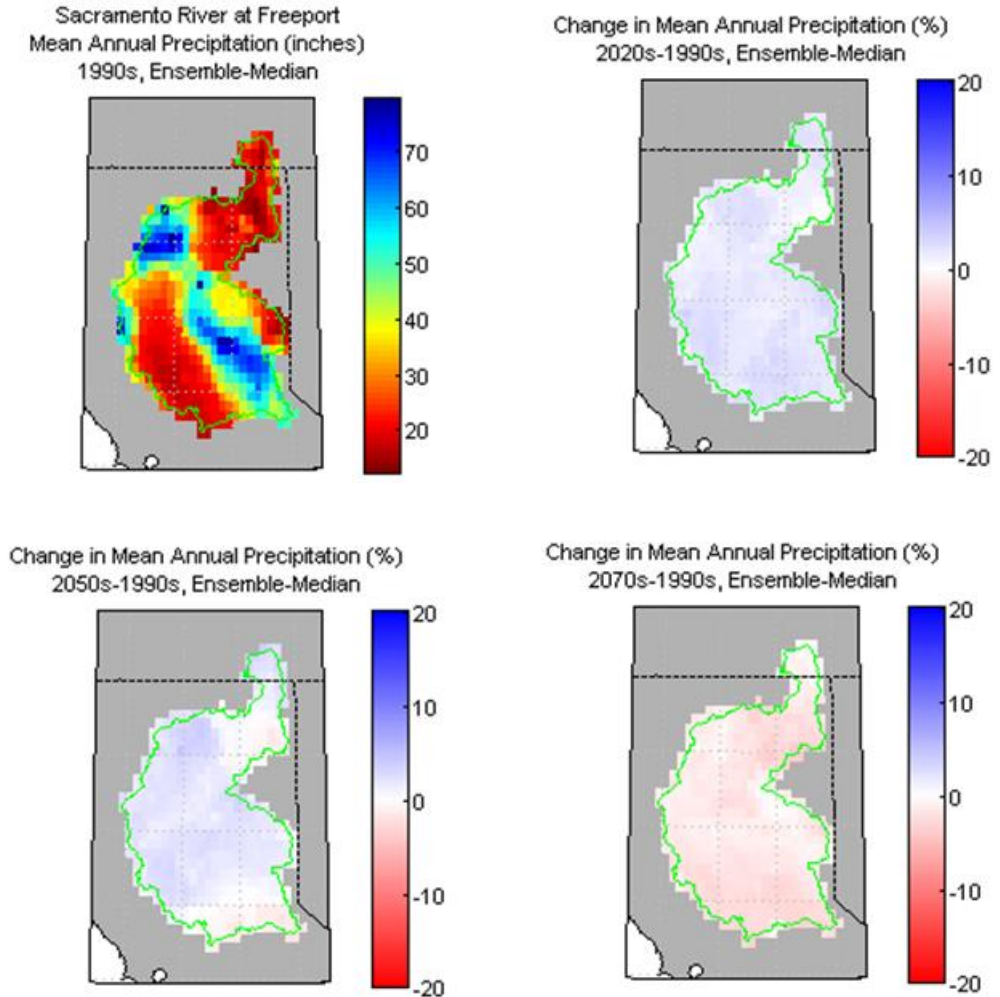


Figure 2-7. Simulated Decade-Mean Precipitation over the Sacramento River Basin Above Freeport, California

Figure 2-8 presents basin-distributed views of change mean annual precipitation over the San Joaquin River Basin upstream from Vernalis. Figure data are simulated conditions as described in Reclamation 2011a. The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

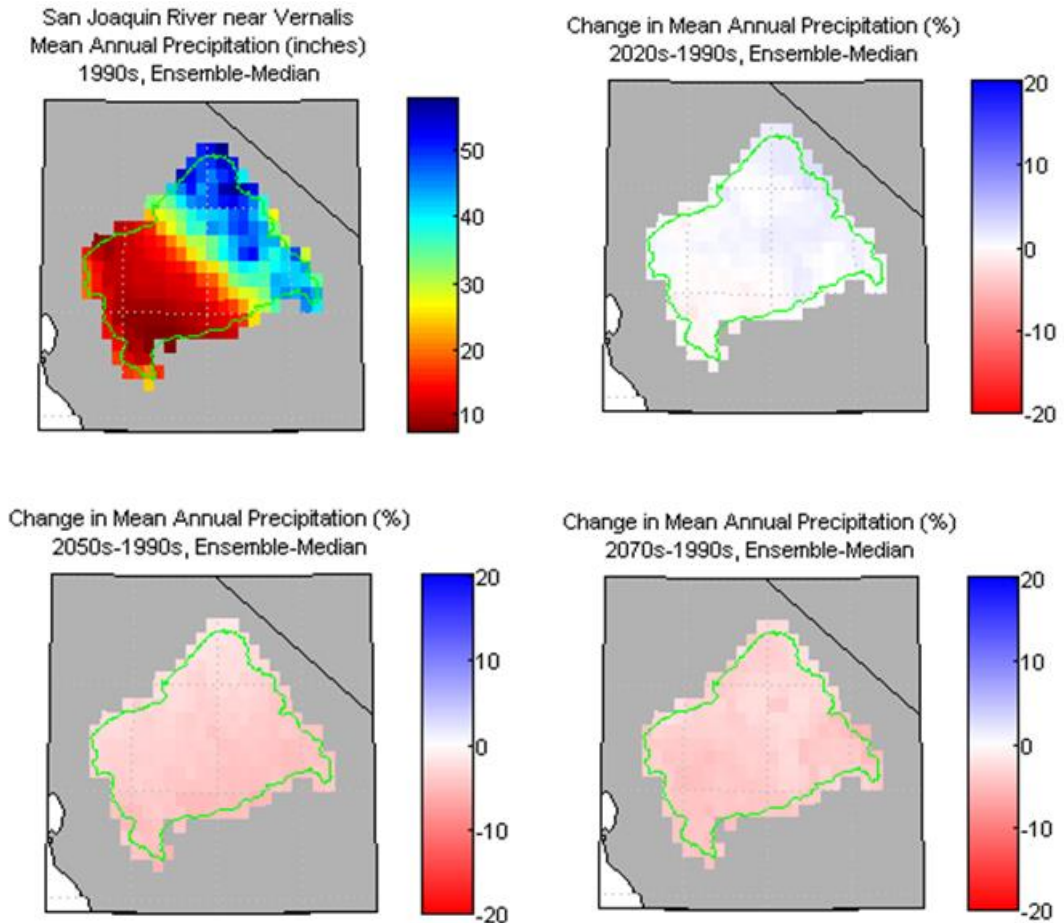


Figure 2-8. Simulated Decade-Mean Precipitation over the San Joaquin River Basin Above Vernalis, California

Temperature and precipitation changes are expected to affect hydrology in various ways including snowpack development. As noted previously, increased warming is expected to diminish the accumulation of snow during the cool season (i.e., late autumn through early spring) and the availability of snowmelt to sustain runoff during the warm season (i.e., late spring through early autumn). Although increases or decreases in cool season precipitation could somewhat offset or amplify changes in snowpack, it is apparent that the projected warming in the Sacramento River and San Joaquin River basins tends to dominate projected effects (e.g., changes in April 1st snowpack distributed over the basin, shown on Figure 2-9 and Figure 2-10 for the two basins, respectively). Snowpack decrease is projected to be more substantial over the portions of the basin where baseline cool season temperatures are generally closer to freezing thresholds and more sensitive to projected warming. Such areas include much of the northern Sierra Nevada and Cascade Mountains of the Sacramento River

basin as well as lower to middle elevations in the southern Sierra Nevada of the San Joaquin River basin. However, even in the highest elevations of the southern Sierra Nevada, losses are projected to be significant by the late 21st century.

Figure 2-9 presents basin-distributed views of change SWE over the Sacramento River Basin upstream from Freeport. Figure data are simulated conditions as described in Reclamation 2011a. The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations.

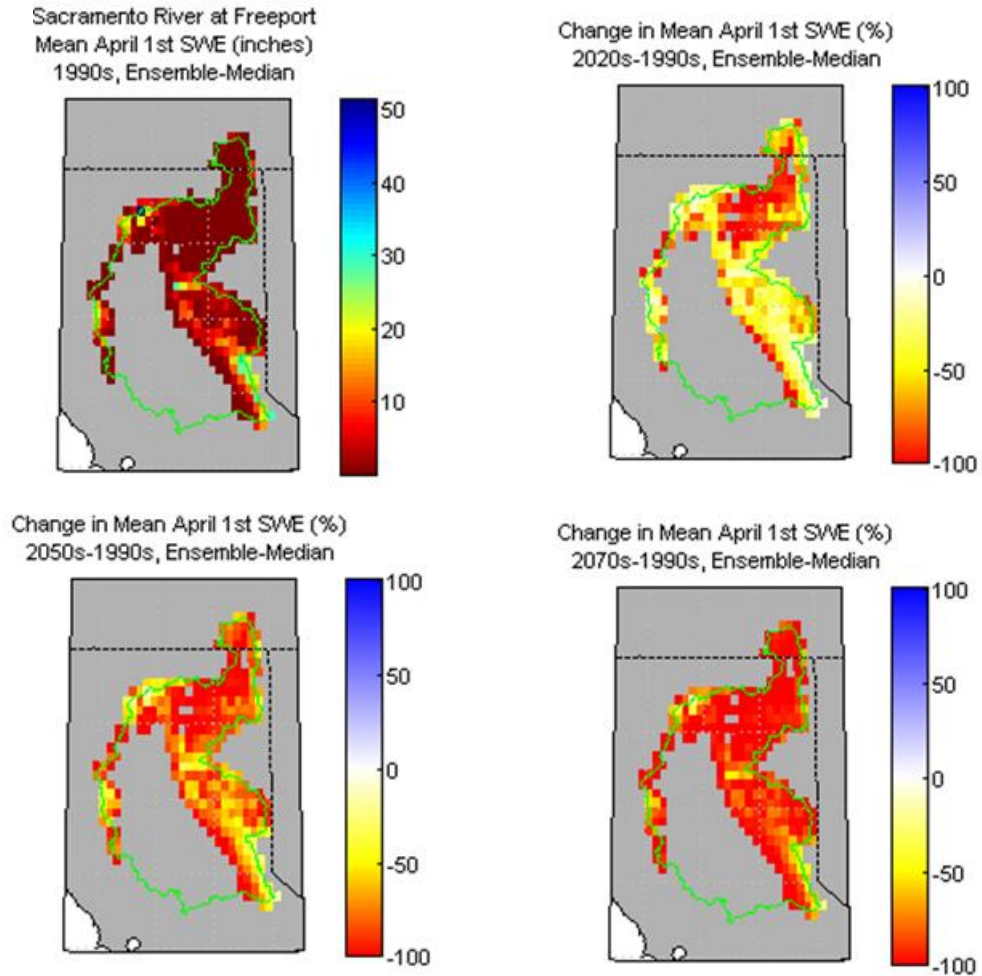


Figure 2-9. Simulated Decade-Mean April 1st Snow Water Equivalent over the Sacramento River Basin Above Freeport, California

Figure 2-10 presents basin-distributed views of change in SWE over the San Joaquin River Basin upstream from Vernalis. Figure data are simulated conditions as described in Reclamation 2011a. The upper left panel shows the baseline mean-annual condition (1990s), and next three panels show changes from baseline conditions for three future decades (2020s, 2050s, and 2070s). Both historical and future conditions are from climate simulations. Mapped values for baseline conditions (1990s) are median-values from the collection of climate simulations. Mapped changes (next three panels) are median changes from the collection of climate simulations. For SWE, areas that are white on the plots have less 1990s decade-mean conditions of less than 0.0004 inch and are not considered in the change assessment.

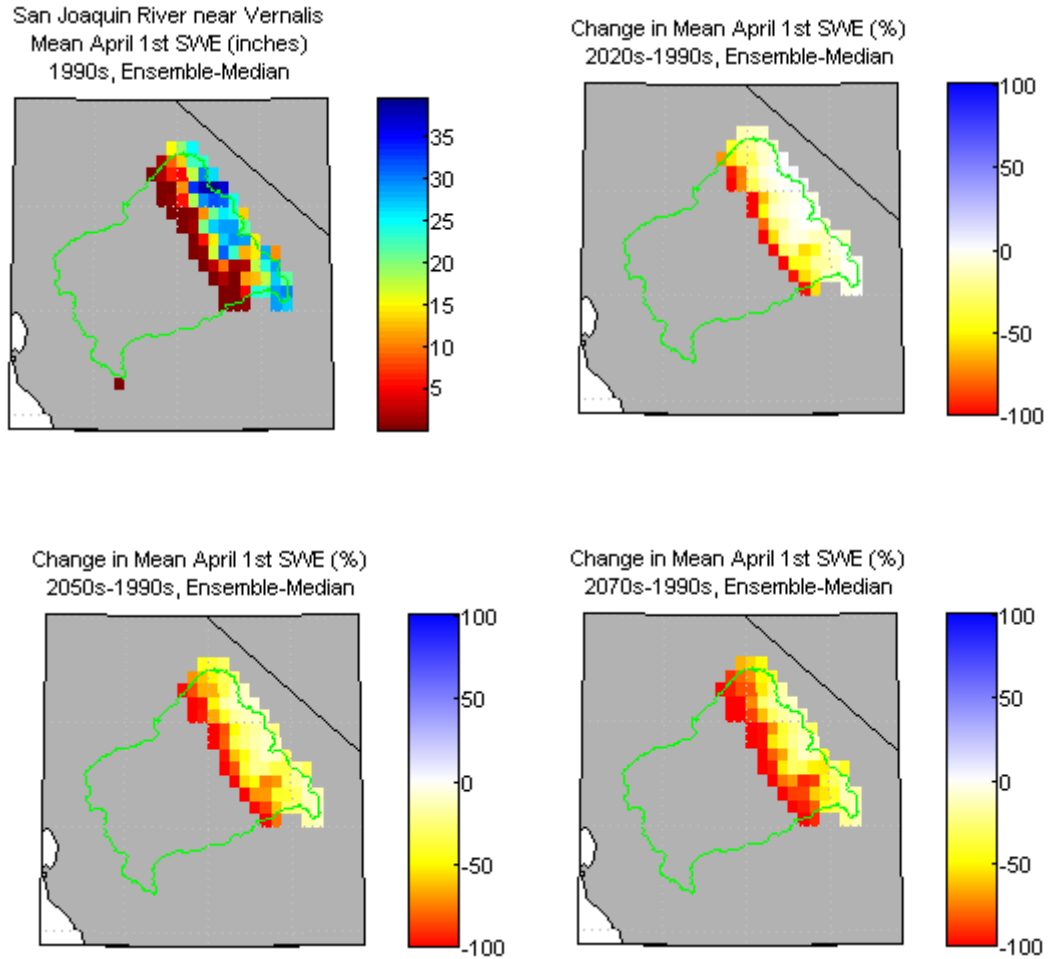


Figure 2-10. Simulated Decade-Mean April 1st Snow Water Equivalent over the San Joaquin River Basin Above Vernalis, California

Changes in climate and snowpack within the Sacramento and San Joaquin River basins will change the availability of natural water supplies. These effects may be experienced in terms of changes to annual runoff and changes in runoff seasonality. For example, warming without precipitation change may lead to increased evapotranspiration from the watershed and decreased annual runoff. Precipitation increases or decreases (either as rainfall or snowfall) offset or amplify the effect.

Figure 2-11 presents annual, December through March, and April through July runoff impacts for subbasins shown. Each panel shows percentage changes in mean runoff (annual or either season) for three future decades (2020s, 2050s, and 2070s) relative to baseline conditions (1990s). Development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed. Results from

Reclamation (2011a) suggest that annual runoff effects are generally consistent but do slightly vary by location within the basins, as shown in Figure 2-11, depending on baseline climate and the projected temperature and precipitation changes. For example, in the Sacramento River and its major tributaries, the Feather River and the American River, annual runoff increases very slightly during the early and middle part of the 21st century. However, in all of these watersheds, a slight decline is projected to occur in the latter half of the century. In the San Joaquin River basin and its major tributaries, similar results are found but with mean-annual runoff declines projected to occur by the mid-21st century.

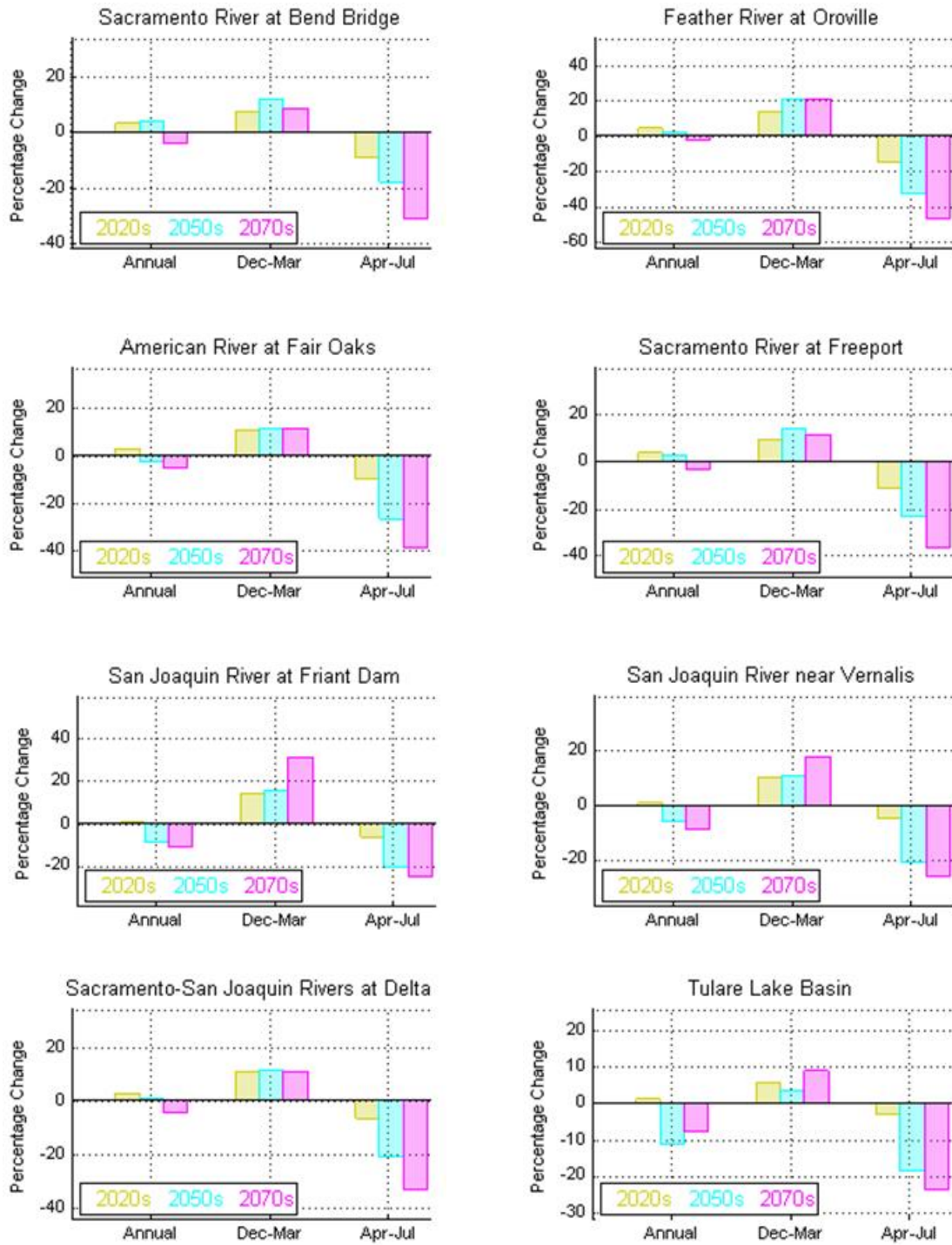


Figure 2-11. Simulated Changes in Decade-Mean Runoff for Several Subbasins in the Sacramento and San Joaquin River Basins

The seasonality of runoff is also projected to change. Warming may lead to more rainfall-runoff during the cool season rather than snowpack

accumulation. This conceptually leads to increases in December through March runoff and decreases in April through July runoff. Results over the two basins suggest that this concept generally holds throughout the two basins, but the degree of seasonal change does vary by basin location (Figure 2-11).

This combination of increased winter and decreased spring runoff points to the important role of temperature in determining 21st century seasonal water supplies for both basins. In the lower left-hand corner of Figure 2-11, the combined runoff change is depicted based on runoff changes in the Sacramento River, San Joaquin River, and other Delta tributaries. Overall, the changes are more similar to those found in the Sacramento River basin and are reflective of the larger contribution of the Sacramento River (see Sacramento River at Freeport) relative to the San Joaquin River (see San Joaquin near Vernalis) to Delta flows. It may be noticed that percentage reductions in April through July runoff may appear to be small compared to some percentage reductions in lower elevation April 1st snowpack from the preceding discussion. The fact that percentage April through July runoff reductions are smaller speaks to how higher elevation snowpack contributes proportionally more to April through July runoff than lower elevation snowpack, and how percentage snow losses at higher elevations are relatively smaller than those at lower elevation.

Climate change in relation to acute runoff events are also of interest as they relate to flood control and ecosystem management in both basins. There is less certainty in the analysis of these types of acute events relative to effects in annual or seasonal runoff. Generally speaking, streamflow variability over the basin is expected to continue under changing climate conditions. For this discussion, annual maximum- and minimum-week runoff are used as metrics of acute runoff events.

Figure 2-12 displays the ensemble of annual “maximum 7-day” and “minimum 7-day” runoff projections for the subbasins shown development of runoff information is described in Reclamation (2011a) based on climate simulations previously discussed. It should be noted that these results are derived from simulations that have been computed at a daily time step, but have been calibrated to monthly natural flows. As such, there is considerable uncertainty that is reflected in the lightly shaded regions around the heavier dark line. These values are presented for qualitative, rather than quantitative analysis. The maximum weekly runoff typically occurs sometime between late fall and early summer, whereas the minimum weekly runoffs are most likely to occur between late summer and early fall. Because the selected locations are upstream from major aquifers in the Central Valley, the runoff extremes are only minimally affected by groundwater and bank storage processes.

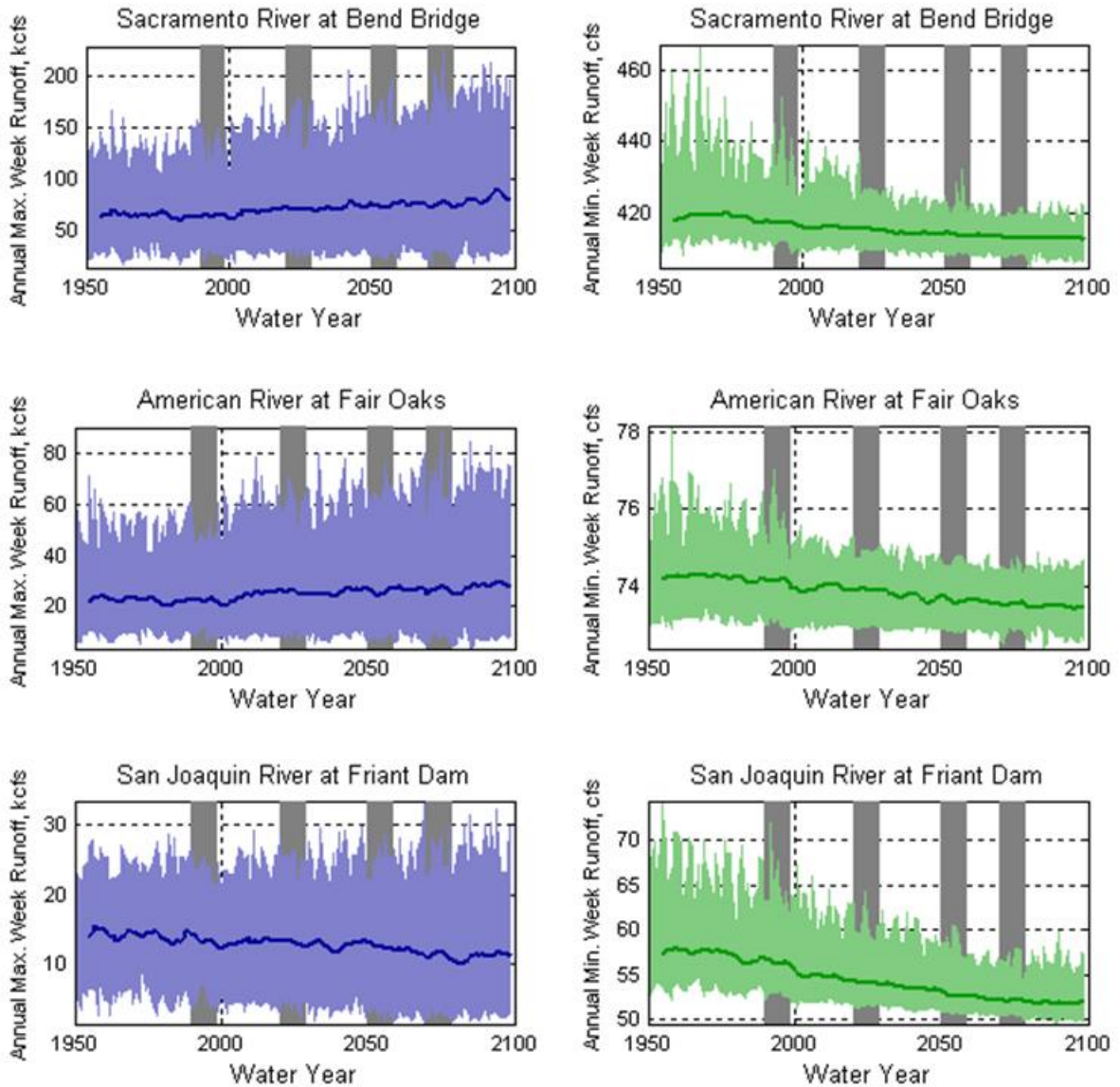


Figure 2-12. Simulated Annual Maximum and Minimum Week Runoff for Several Subbasins in the Sacramento and San Joaquin River Basins

For annual maximum-week runoff, results for the Sacramento River and San Joaquin River basins appear to differ. For the two subbasins shown in the Sacramento River basin, it appears that expected annual maximum-week runoff may gradually increase during the 21st century. The range of possibility also appears to increase during the century. These findings raise questions about whether increases in maximum weekly runoff may be indicative of potentially greater flood risks during the 21st century. However, for the San Joaquin River Basin upstream from Friant Dam, results suggest a slight decline in annual maximum-week runoff.

For annual minimum-week runoff, results suggest a gradual decrease in the expected annual value as the 21st century progresses. The range of projected possibility also reduces with time. These declines are likely the result of decreased snowpack accumulation and increased soil evaporation and plant transpiration in the upper watershed. Decreasing minimum runoff may lead to adverse effects on aquatic habitats by reducing both wetted stream perimeters and availability of aquatic habitat and through increased water temperatures detrimental to temperature-sensitive aquatic organisms.

A summary of climate and hydrologic changes is provided in Table 2-1 for four subbasins of the Sacramento River and San Joaquin River basins: Sacramento River at Bend Bridge, Sacramento River at Freeport, San Joaquin River at Friant Dam, and San Joaquin River at Vernalis. The tabulated changes reflect a subbasin-average view and are measured relative to 1990s baseline conditions, as shown on the preceding figures.

Table 2-1. Summary of Simulated Changes in Decade-Mean Hydroclimate for Several Subbasins in the Sacramento and San Joaquin River Basins

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
Sacramento River at Bend Bridge			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1st Snow Water Equivalent (%)	-53.4	-75.9	-88.6
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
Sacramento River at Freeport			
Mean Annual Temperature (°F)	1.3	3.0	4.2
Mean Annual Precipitation (%)	-0.3	0.6	-2.7
Mean April 1st Snow Water Equivalent (%)	-53.4	-75.9	-88.6
Mean Annual Runoff (%)	3.5	2.5	-3.6
Mean December–March Runoff (%)	9.0	13.6	11.0
Mean April–July Runoff (%)	-11.1	-23.0	-36.1
Mean Annual Maximum Week Runoff (%)	12.9	18.4	18.3
Mean Annual Minimum Week Runoff (%)	-0.3	-0.5	-0.6
San Joaquin River at Friant Dam			
Mean Annual Temperature (°F)	1.4	3.3	4.5
Mean Annual Precipitation (%)	-1.3	-5.3	-8.6
Mean April 1st Snow Water Equivalent (%)	-23.1	-39.6	-48.7
Mean Annual Runoff (%)	0.7	-8.7	-10.7
Mean December–March Runoff (%)	13.9	15.8	31.0
Mean April–July Runoff (%)	-6.1	-20.2	-25.0
Mean Annual Maximum Week Runoff (%)	-2.3	-6.6	-16.0
Mean Annual Minimum Week Runoff (%)	-4.0	-6.4	-7.6

Table 2-1. Summary of Simulated Changes in Decade-Mean Hydroclimate for Several Subbasins in the Sacramento and San Joaquin River Basins (contd.)

Hydroclimate Metric (change from 1990s)	2020s	2050s	2070s
San Joaquin River at Vernalis			
Mean Annual Temperature (°F)	1.3	3.1	4.3
Mean Annual Precipitation (%)	-1.0	-4.2	-7.7
Mean April 1st Snow Water Equivalent (%)	-27.2	-45.9	-56.3
Mean Annual Runoff (%)	0.8	-5.9	-8.4
Mean December–March Runoff (%)	10.1	10.7	17.2
Mean April–July Runoff (%)	-4.8	-20.6	-25.8
Mean Annual Maximum Week Runoff (%)	1.6	-1.8	-4.9
Mean Annual Minimum Week Runoff (%)	-1.2	-1.9	-2.3

Key:

°F = degree Fahrenheit