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# Progress on Incorporating Climate Change into Management of California's Water Resources

July 2006

Technical Memorandum Report

California Department of Water Resources

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# Progress on Incorporating Climate Change into Planning and Management of California's Water Resources

Technical Memorandum Report

July 2006

Department of Water Resources

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*Prepared under the direction of:*
Francis Chung, Ph.D., P.E. ........................................................................ Principal Engineer

*Prepared by:*
**California Department of Water Resources:**
Jamie Anderson, Ph.D., P.E.......................................................................Engineer
Michael Anderson, Ph.D. .............................................Acting State Climatologist
Daniel Easton, P.E.......................................................................................Engineer
Michael Floyd, P.E. ....................................................................... Senior Engineer
Roy Peterson, Ph.D..........................................................Environmental Scientist

Joel Dudas, P.E.............................................................................................Engineer
Messele Ejeta, Ph.D. P.E. ............................................................................Engineer
Brian Heiland, P.E.......................................................................................Engineer
Arthur Hinojosa,Jr., P.E.....................................................Supervising Engineer
Jim Goodridge ..........................................................Retired State Climatologist
John King, P.E..............................................................................................Engineer
Bunloeurng Lek, P.E. ...................................................................................Engineer
Aaron Miller, P.E. ........................................................................................Engineer
Stephen Nemeth, P.E....................................................................................Engineer
Al Olson, P.E.................................................................................................Engineer
Morteza Orang, Ph.D..............................................Land and Water Use Scientist
Michael Perrone, Ph.D.....................................................Environmental Scientist

*Prepared by (continued):*

**California Department of Water Resources (continued):**

Tawnly Pranger, P.E. .......... Engineer
David Rizzardo, P.E. .......... Senior Engineer
Maurice Roos, P.E. .......... State Hydrologist
David Todd .......... Land and Water Use Program Manager
Matt Winston .......... Senior Meteorologist
Hongbing Yin, P.E. .......... Senior Engineer

**U.S. Bureau of Reclamation:**

Levi Brekke, Ph.D., P.E. .......... Engineer
Russell Yaworsky .......... Engineer

**University of California, Davis:**

Richard Snyder, Ph.D. .......... Biometeorologist

**Lawrence Berkeley National Laboratory:**

Norman Miller, Ph.D. .......... Staff Scientist

**California Energy Commission:**

Guido Franco, P.E.. .......... Technical Lead, Climate Change Research

*Editorial and design services were provided by:*

Mike Durant .......... Research Writer
Gretchen Goettl .......... Research Writer

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# Executive Summary

## Background

On June 1, 2005, Governor Arnold Schwarzenegger issued Executive Order S-3-05 establishing greenhouse gas emissions targets for California and requiring biennial reports on potential climate change effects on several areas, including water resources. The Governor established a Climate Action Team (CAT) to guide the reporting efforts. The CAT selected four climate change scenarios that reflect two greenhouse gas emissions scenarios represented by two Global Climate Models (GCMs). The CAT requested that those four climate change scenarios be used whenever possible in the climate change reporting efforts.

This report is the Department of Water Resources response to the Executive Order. This report describes progress made incorporating climate change into existing water resources planning and management tools and methodologies.

## Climate Change and California's Water Resources

California water planners are concerned about climate change and its potential effects on our water resources. Projected increases in air temperature may lead to changes in the timing, amount and form of precipitation - rain or snow, changes in runoff timing and volume, effects of sea level rise on Delta water quality, and changes in the amount of irrigation water needed due to modified evapotranspiration rates.

More than 20 million Californians rely on two massive water projects: the State Water Project (SWP) and federal Central Valley Project (CVP). 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) for water supply, flood management, environmental protection and recreation.

DWR and Reclamation have formed a joint Climate Change Work Team to provide qualitative and quantitative information to managers on potential effects and risks of climate change to California's water resources. The mission of the team is to coordinate with other state and federal agencies on the incorporation of climate change science into California's water resources planning and management. The team will provide and regularly update information for decision-makers on potential impacts and risks of climate change, flexibility of existing facilities to cope with climate change, and available mitigation measures. This report is the first product of the Work Team.

## Report Overview

This report contains eight chapters that present progress and future directions on incorporating climate change science into management of California's water resources. It focuses on assessment methodologies and preliminary study results. The technical chapters of this report, Chapters 4-7, were peer-reviewed by experts from water resources-related agencies and research institutions. Policy implications and recommendations are beyond the scope of this report.

## Uses and Limitations

The purpose of this report is to demonstrate how various analysis tools currently used by DWR could be used to address issues related to climate change. The methods and results presented in this report could be used to guide future climate change analysis and to identify areas where more information is needed.

All results presented in this report are preliminary, incorporate several assumptions, reflect a limited number of climate change scenarios, and do not address the likelihood of each scenario. Therefore, these results are not sufficient by themselves to make policy decisions.

## Chapter 1: Introduction

Chapter 1 describes the purpose of this report, details the DWR-Reclamation Climate Change Work Team's mission and goals, and provides a summary of each chapter of the report. The complete text of Executive Order S-3-05 is in an appendix.

## Chapter 2: Potential Impacts of Climate Change on California's Water Resources

Chapter 2 provides a statewide overview of California's water resources. Causes of climate change are summarized with an emphasis on aspects of climate change that pose a potential threat to California's water resources. It identifies measures that could be taken to adapt to or mitigate the effects of climate change. Topics covered in Chapter 2 include:

- Overview of California's water resources
- The role of water management and use in greenhouse gas emissions
- Observed and projected changes in air temperature
- Observed and projected changes in precipitation and runoff
- Observed and projected sea level rise and potential effects on groundwater and the Delta
- Potential effects of climate change on
    - Future water demands
    - Colorado River basin
    - Fish
- Sudden climate change
- Climate change and water supply planning challenges

## Chapter 3: DWR Climate Change Studies

Chapter 3 presents the background and approach used for the climate change studies completed for this report. Climate change researchers have used global climate models to simulate projected changes in air temperature and precipitation. The global results were converted to represent regional changes in air temperature and precipitation in a process known as downscaling. DWR staff used the downscaled data to conduct preliminary impacts assessments for water resources. The studies use 2050 climate change projections for precipitation and runoff and 2020 land use estimates. The four climate change scenarios and the impacts assessment methodology are described in this chapter.

## Chapter 4: Impacts of Climate Change on the State Water Project and Central Valley Project

Chapter 4 presents potential impacts of the selected climate change scenarios on SWP and CVP operations. Analysis includes changes in reservoir inflows, delivery reliability and annual average carryover storage due to 2050 level climate change induced shifts in precipitation and runoff patterns and 2020-level land use. The chapter discusses interaction of various operating rules and regulations such as water allocations, flood control, in-stream flow requirements, and Delta water quality requirements under climate change scenarios. Current management practices and existing system facilities were used in the analysis for this report. No changes to management practices or system facilities were made to try to mitigate the effects of climate change or sea level rise. Implications for possible changes to operations to mitigate climate change impacts are discussed, however exploring these operations changes is left for future work. The studies presented in this chapter did not incorporate potential effects of sea level rise. Future work will investigate possible changes in system operations and Delta outflow requirements that may be needed to lessen effects of sea level rise on Delta water quality.

Current management practices and existing system facilities were used in the analysis for this report. No changes were made to lessen the effects of climate change or sea level rise.

No changes were made to:

- ❑ System structures, such as added water storage, pumping, or canal capacity
- ❑ Reservoir operating rules, such as changing the space required for flood control
- ❑ Streamflow requirements
- ❑ Water quality standards
- ❑ Delta outflow requirements
- ❑ Operations to account for sea level rise

Some of the main results related to climate change impacts on the SWP and CVP include:

- ❑ In three of the four climate scenarios simulated, there were significant shortages in CVP north-of-Delta reservoirs during droughts. In future studies, operational changes are necessary to avoid these shortages. At this time, it is not clear whether the necessary changes in operations will be insignificant or substantial.

- ❑ Changes in annual average SWP south-of-Delta Table A deliveries ranged from a slight increase of about 1 percent for a wetter scenario to about a 10 percent reduction for one of the drier climate change scenarios.

- Increased winter runoff and lower Table A allocations resulted in slightly higher annual average Article 21 deliveries in the three drier climate change scenarios. The boosts in Article 21 did not offset losses to Table A though. The wetter scenario with higher Table A allocations resulted in fewer Article 21 delivery opportunities and slightly lower annual average Article 21 deliveries.

- Changes in annual average CVP south-of-Delta deliveries ranged from increases of about 2.5 percent for a wetter scenario and decreases of as much as 10 percent for drier climate change scenarios. The CVP results of the drier climate change scenarios are in question due to the north-of-Delta shortages mentioned above. These shortages will have to be addressed in future climate change studies.

- For both the SWP and CVP, carryover storage was negatively impacted in the drier climate change scenarios and somewhat increased in the wetter climate change scenario.

Sea level rise effects on water project operations to repulse a greater salt water intrusion under these conditions were not examined due to lack of existing tools for that type of analysis. Surrogates to provide an indication of the increased operation challenges from sea level rise to repulse sea water are discussed in chapter 5. Future work in this area will include the development of the necessary tools to quantify the impacts of sea level rise on saltwater intrusion and the incremental water supply impacts to repulse greater saltwater intrusion forces into the Delta. As discussed in chapter 5 these water supply impacts are expected to be significant.

## Chapter 5: Impacts of Climate Change on the Sacramento-San Joaquin Delta

Chapter 5 focuses on potential impacts of climate change on Delta water quality and water levels. The reservoir operations and Delta exports for the four climate change scenarios determined in the studies for Chapter 4 were used to examine potential effects of climate change on Delta water quality. The Delta impacts reflect adjustments in reservoir operations and Delta exports due to shifting precipitation and runoff patterns. The studies in Chapter 4 include the assumption that meeting Delta water quality standards is a top priority for the SWP and CVP operations. Climate change will make meeting Delta water quality standards a larger challenge in the future. (see Table 4.12 in Chapter 4). In the interest of time, no additional changes were made to system operations in Chapter 5 to try to lessen the effects of climate change on Delta water quality as a result of sea level rise.

Sea level rise is an aspect of climate change of great interest in the Delta. Although current analysis tools are not available to determine changes in system operations required to lessen the effects of increased salt intrusion, there are tools that can estimate how much salt could enter the Delta due to sea level rise. For this report preliminary analyses were conducted to examine potential salt intrusion for a one foot rise in sea level. These results will provide information vital to the development of tools to determine changes in system operations that would be needed to maintain compliance with Delta water quality standards.

For the sea level rise scenarios, simulated water quality constituent concentrations without additional changes in system operations were compared to threshold values as a surrogate for evaluating the effects of sea level rise on water project operations to meet existing standards. Assuming these standards are not changed, this analysis shows that more water will be needed to repulse seawater to meet these standards as sea level rises. Tools are being developed to quantify the incremental impacts of sea level rise on water supplies to counteract increased salt water intrusion. Until these tools become available, the analysis below provides an indication of the water project operational challenges due to sea level rise. Chloride loadings at the urban intakes are also estimated.

Some of the main results related to climate change impacts on the Delta include:

- For the four climate change scenarios, Delta inflows typically increase during the late winter and early spring and decrease during the summer and fall. On average, Delta exports are reduced with the largest reductions occurring during the summer and fall. Inflows and exports are most sensitive to climate change during extremely wet or extremely dry periods.

- Flexibility in the system to modify reservoir operations and Delta exports for the climate change scenarios at present sea level results in minor impacts to compliance with chloride standards at Municipal and Industrial intakes.

- A one foot rise in sea level without any changes to the system operations would result in chloride concentrations below the 250 mg/l threshold 90 percent of the time at Old River at Rock Slough. In real time, operational adjustments will take place so these effects will translate into water supply impacts to the SWP and CVP. As stated above these impacts to water supply cannot be quantified at this time. Maintaining chloride concentrations below the 150 mg/l threshold was also more challenging during critical and dry years. These results indicate the need to develop a tool to quantify the additional water supplies that would need to be dedicated to repulse sea water in order to maintain Delta water quality under sea level rise conditions.

- There was complete compliance with the chloride standards at the SWP and CVP for the climate change at present sea level scenarios. Chloride concentrations remained below threshold values for the sea level rise and combined climate change and sea level rise scenarios.

- Chloride mass loadings at the municipal and industrial intakes are typically reduced for the climate change only scenarios due to lower export rates. Increased intrusion of salt water from the ocean for the sea level rise and combined climate change and sea level rise scenarios lead to increased chloride mass loadings at the municipal and industrial intakes.

- For a one foot rise in sea level, maximum daily water levels exceeded the minimum levee crest elevation on Sherman Island twice during the 16-year analysis period. Water levels did not exceed the minimum crest elevation for present sea level conditions.

## Chapter 6: Climate Change Impacts on Flood Management

Chapter 6 discusses implications of climate change for managing floods. It presents historical trends that reflect potential climate change effects. Representation of historical periods by climate projection models are compared to historical data. Data requirements for analysis of climate change effects on flood frequency are also discussed.

Over the past century observed data indicate:

- Increasing maximum, mean, and minimum temperatures
- Increasing precipitation in north; decreasing precipitation in south
- Shift in annual runoff to a greater percentage in October-March vs. April-July
- Annual flood peaks increasing in mean and variance

Estimates of future climate temperatures suggest:

- Higher snow levels
- Larger direct runoff from individual storm events
- Earlier spring melt

Uncertainties in future precipitation prevents further analysis at this time

## Chapter 7: Climate Change Impacts on Evapotranspiration

Chapter 7 focuses on potential increases in crop water use under climate change scenarios. California is a semiarid region, and to grow crops, water is needed for irrigation in addition to that supplied by precipitation. On a regional basis, most of the water used in agriculture is consumed by evapotranspiration (ET). There is concern that the ET might increase with climate change, which could increase the demand for developed water. This chapter provides theoretical energy budget analyses of climate change impacts on ET. Physiological processes that influence ET may explain changes in the energy budget for climate change conditions. Application of analysis tools to assess changes in estimated net irrigation requirements for crops is presented.

Some of the main issues related to climate change effects on evapotranspiration include:

- Evapotranspiration is comprised of two parts: (1) evaporation from soil, water and plant surfaces; and (2) transpiration, which occurs when water vaporizes inside the plant leaves and diffuses through the pores (i.e., stomata) to the ambient air. Both of these contributions to ET could be influenced by climate change.

- For a 3°C increase in air temperature, increases in evapotranspiration for a reference grass crop ranged from 3 percent to 6 percent. Although this is a small percentage, the volume of water, when summed over the entire state, is substantial. It is assumed that other crops will show a similar response to climate change.

- Potential higher demands for irrigation water due to increases in evapotranspiration rates could possibly be offset by improved water use efficiencies including adjusting cropping patterns and using more efficient on-farm irrigation methods.

- There is a need for canopy level experiments to validate assumptions relating canopy resistance to elevated atmospheric carbon dioxide concentrations to ensure accurate ET projection in response to climate change.

- The importance of crop life cycles and their physiological responses to expected climate change need more analysis to better project irrigation demand resulting from ET.

- The Simulation of Evapotranspiration and Applied Water (SIMETAW) model shows promise as an analytic tool to investigate potential ET of applied water responses to climate change. SIMETAW could be used in conjunction with other DWR analytic modeling tools to help managers better understand implications of climate change on agricultural water demands in California.

## Chapter 8: Future Directions

Chapter 8 presents directions for further work in incorporating climate change into the management of California's water resources. Emphasis is placed on associating probability estimates with potential climate change scenarios in order to provide policymakers with both ranges of impacts and the likelihoods associated with those impacts. A better understanding of the likelihoods associated with potential climate change impacts will aid decision-makers in planning appropriate response strategies.

Future efforts will also involve addressing data and analysis gaps that were identified during these preliminary studies. For these preliminary studies, four scenarios that were readily available were selected by the Climate Action Team mainly for expediency. In collaboration with climate change scientists, criteria will be developed to assist water resource planners in determining which climate change scenarios to examine. For sea level rise studies, a tool will be developed to determine how system operations may need to be modified to maintain Delta water quality under sea level rise conditions. That tool would provide an essential component for a suite of modeling tools for climate change impacts and risk assessment.

With the accomplishments to date and planned future directions, DWR is working with other agencies and researchers to provide leadership in incorporating climate change impacts and risks into the planning and management of California's precious water resources.

## Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
**July 2006**

# Chapter 1: Introduction

**Authors:**

Jamie Anderson, Ph.D., P.E. and Francis Chung, Ph.D., P.E.
California Department of Water Resources, Bay-Delta Office, Modeling Support Branch,
Sacramento

# 1 Introduction

## 1.1 Background

Before the United Nations World Environment Day in San Francisco in June 2005, Governor Arnold Schwarzenegger said:

> "As of today California is going to be the leader in the fight against global warming. … I say the debate is over. We know the science. We see the threat. And we know the time for action is now."

Executive Order S-3-05 (see Section 1.7) established the following goals for reducing green house gas emissions:

- By 2010, reduce emissions to the 2000 level
- By 2020, reduce emissions to the 1990 level
- By 2050 reduce emissions to 80 percent below 1990 emissions

The Executive Order requires the secretary of the California Environmental Protection Agency to report to the Governor and legislature biannually on progress toward reaching the goals. Biennial reports are also required on potential climate change impacts and possible mitigation and adaptation plans focusing on these topics:

- Water supply
- Public health
- Agriculture
- California coastline
- Forestry

The first reports were due to the Governor and legislature in January 2006. To meet this deadline, and guide the preparation of the reports, a Climate Action Team (CAT) was formed with members from various State agencies and commissions. In addition to the overview reports being produced under the guidance of the CAT, the California Department of Water Resources (DWR) has established a complimentary report titled "Incorporating Climate Change into Management of California's Water Resources." This report describes progress on incorporating climate change science into water resources planning and management.

## 1.2 Climate Change and California's Water Resources

California water planners are concerned about climate change and its potential effects on our water resources. More than 20 million Californians rely on two massive water projects: the State Water Project (SWP) and federal Central Valley Project (CVP). These complex water storage and conveyance systems are operated by DWR and the Bureau of Reclamation (Reclamation) for water supply, flood management, environmental protection and recreational uses.

The ability of the SWP and the CVP to meet the water demands of its customers and the environment depends heavily on the accumulation of winter mountain snow melting into spring and summer runoff. A warming planet may reduce this natural water storage mechanism. Projected increases in air temperature may lead to changes in the timing, amount and form of precipitation – rain or snow, changes in runoff timing and volume, sea level rise effects on Delta water quality, and changes in the amount of irrigation water needed due to modified evapotranspiration rates.

## 1.3 DWR-Reclamation Climate Change Work Team

In the past, climate change was typically considered qualitatively in the planning process. Legislative mandates in California including Executive Order S-3-05 and the latest update to the California Water Plan (Bulletin 160) call for more quantitative assessments of climate change effects. To address these concerns, DWR and Reclamation formed a joint Climate Change Work Team to provide qualitative and quantitative information to managers on potential effects and risks of climate change to California's water resources.

The mission of the Climate Change Work Team is to coordinate with other State and federal agencies on the incorporation of climate change science into California's water resources planning and management. The team will provide and regularly update information for decision-makers on potential impacts and risks of climate change, flexibility of existing facilities to cope with climate change, and available mitigation measures.

In water resources planning, climate change studies often focus on what might happen without providing information about how likely it is to happen. A major long-term objective of the Work Team is to extend impacts analysis to include likelihoods associated with each climate change effect. In order to meet this objective, the Work Team set these goals:

- ❑ Build coalitions with experts in climate change and seek their guidance in estimating risk of climate change effects
- ❑ Support mandates on climate change
  - Governor's Executive Order S-3-05, June 1, 2005
  - California Water Plan Bulletin 160
- ❑ Assess impacts to operations of the SWP and CVP for several climate change scenarios
- ❑ Assess risk for the SWP and CVP systems based on impact studies and estimates of impact likelihood
- ❑ Evaluate risk-mitigation options

This report presents progress to date by the Work Team on incorporating climate change science into planning and management of California's water resources. This report also provides direction for continued efforts at developing probabilistic risk assessments of climate change impacts for water resources management. Figure 1.1 depicts the progress of the Work Team towards its goals. The target shape of the figure represents the focus of our efforts towards the ultimate goal, or bulls-eye, of probabilistic risk assessments. The components of Figure 1.1 that are shaded blue or white represent progress reflected in this report. The yellow and red components of Figure 1.1 represent future directions.

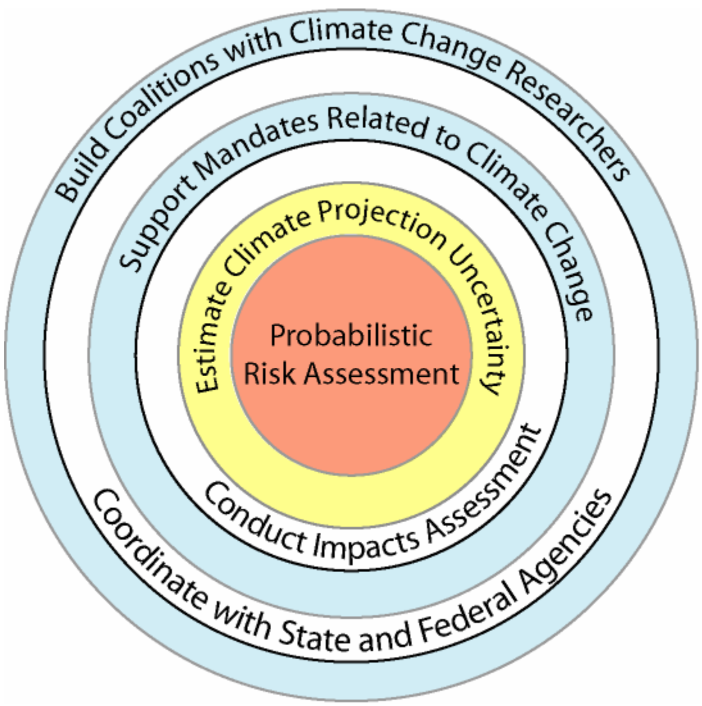


**Figure 1.1: DWR-Reclamation Climate Change Work Team Goals**

## 1.4 Report Overview

This report contains eight chapters that present progress and future directions on incorporating climate change science into management of California's water resources. It focuses on assessment methodologies and preliminary study results. The technical chapters of this report, Chapters 4-7, were peer reviewed by experts from water resources related agencies and research institutions. Policy implications and recommendations are beyond the scope of this report.

Chapter 2 provides a statewide overview of California's water resources. Causes of climate change are summarized with an emphasis on aspects of climate change that pose a potential threat to California's water resources. It then identifies measures that could be taken to adapt to or mitigate the effects of climate change.

Chapter 3 presents the background and approach used for the climate change studies completed for this report. It also describes climate change scenarios used in this report.

Chapter 4 presents potential impacts of the selected climate change scenarios on SWP and CVP operations. Analysis includes changes in reservoir inflows, delivery reliability and annual average carryover storage due to climate change induced shifts in precipitation and runoff patterns. It discusses interaction of various operating rules and regulations such as water allocations, flood control, in-stream flow requirements, and Delta water quality requirements under climate change scenarios. It also presents implications for possible changes to operations to mitigate climate change impacts. Exploring these changes is left for future work.

Chapter 5 focuses on potential impacts of climate change on Delta water quality and water levels. It presents effects of modified Delta inflows and exports on compliance with water quality standards. It also discusses implications of sea level rise including a study of levee overtopping potential.

Chapter 6 discusses implications of climate change for managing floods. It presents historical trends that reflect potential climate change effects. Representation of historical periods by climate projection models are compared to historical data. It discusses data requirements for analysis of climate change effects on flood frequency.

Chapter 7 focuses on potential increases in crop water use under climate change scenarios. It discusses potential responses of evapotranspiration to global warming. It characterizes physiological processes that influence ET and might be influenced by climate change. Also, it presents application of analysis tools to assess changes in estimated net irrigation requirements for crops.

Chapter 8 presents directions for further work in incorporating climate change into the management of California's water resources. Emphasis is placed on associating probability estimates with potential climate change scenarios in order to provide policymakers with both ranges of impacts and the likelihoods associated with those impacts.

## 1.5 Uses and Limitations

The purpose of this report is to demonstrate how various analysis tools currently used by DWR could be used to address issues related to climate change. The methods and results presented in this report could be used to guide future climate change analysis and to identify areas where more information is needed.

Current management practices and existing system facilities were used in the analysis for this report. No changes to management practices or system facilities were made to try to mitigate the effects of climate change or sea level rise. All results presented in this report are preliminary, incorporate several assumptions, reflect a limited number of climate change scenarios, and do not address the likelihood of each scenario. These results are not sufficient by themselves to make policy decisions.

## 1.6 Acknowledgements

The report authors would like to acknowledge the peer reviewers for their time and valuable technical input on this report:

Chapter 4: Nancy Parker-U.S. Bureau of Reclamation and Richard Palmer-University of Washington

Chapter 5: Paul Hutton-Metropolitan Water District, Leah Orloff-Contra Costa Water District, and K.T. Shum-East Bay Municipal Utility District;

Chapter 6: David Goldman-U.S. Army Corps of Engineer's Cold Regions Lab, and Philip Mote-University of Washington

Chapter 7: Richard Allen-University of Idaho at Kimberley, Hugo Hidalgo-Scripps Institute of Oceanography, and Ted Hsiao-University of California at Davis

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## 1.7 Appendix: Executive Order S-3-05

# Executive Order

**EXECUTIVE DEPARTMENT**

**STATE OF CALIFORNIA**

**EXECUTIVE ORDER S-3-05**
**by the**
**Governor of the State of California**

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# Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
**July 2006**

# Chapter 2:
# Potential Impacts of Climate Change on California's Water Resources


**Authors:**

[illegible]
[illegible]

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**Contributors:**

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# 2 Potential Impacts of Climate Change on California's Water Resources

## 2.1 Introduction

The purpose of this chapter is to:

- provide a brief description of California's water resources
- summarize the anthropogenic causes of climate change
- describe the aspects of climate change that pose a potential threat to the State's water management systems

This chapter is general and statewide in scope. It describes impacts that could occur through the end of this century. Subsequent chapters are primarily focused on the effects of climate change on Central Valley water management systems based on selected downscaled climate model projections for mid-century.

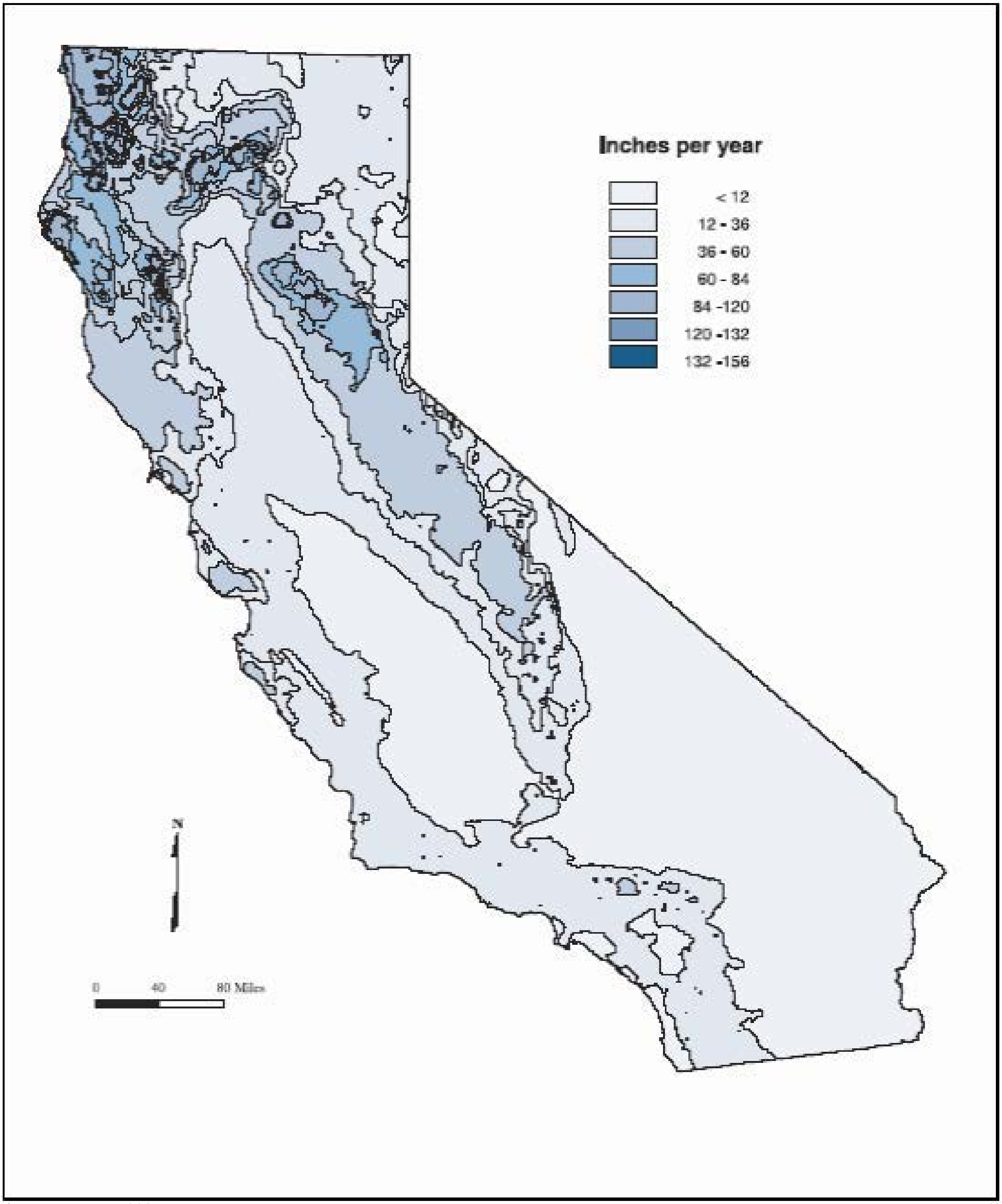
## 2.2 Background - California's Water Resources

### 2.2.1 Distribution of Precipitation

California's water resources vary significantly throughout the State as the result of varying climates and the distribution of precipitation. On average, more than 140 inches of precipitation falls annually in the mountains of northwestern California while fewer than four inches falls in parts of the desert in the southeast portion of the State. Figure 2-1 depicts the distribution of average annual precipitation in the State. Statewide average annual precipitation is about 23 inches (DWR, 2003).

Variability in the distribution of precipitation in California is due in part to hemispheric-scale atmospheric circulation patterns. Most winter storms typically move from the Pacific Ocean east across the northern part of the State. A progressively smaller percentage of storms move across the State to the south.

Most of the State's precipitation falls in the northern Coast Range, Klamath and Cascade ranges and the western slope of the Sierra Nevada due to orographic effects. The Mojave Desert, San Joaquin Valley floor and areas east of the Sierra Nevada receive much less precipitation, partly because they are in a rain shadow.




Source: DWR, 2003

**Figure 2-1 Distribution of Average Annual Precipitation in California, 1961 to 1990**

### 2.2.2 California's Water Management Systems

The majority of California's population of about 37 million people is concentrated in and near major urban centers. About half of the State's population resides in Southern California where annual precipitation and runoff is much less than in Northern California.

Much of the State's agriculture also is in areas with limited precipitation, including the San Joaquin Valley and the Imperial Valley. Agriculture is critical to the State's economy and usually consumes about 40 percent of the State's total annual developed water supply (DWR, 2005a). California uses this water to produce more than 350 crops, which in 2003 were valued at $29.4 billion. California produces more than half of the vegetables, nuts, and fruits produced in the U.S. (USDA, 2003).

An extensive network of reservoirs and aqueducts has been developed throughout much of California to provide water to major urban and agricultural areas. This network serves to store and transport runoff from where it is plentiful to where it is scarce. It also serves to store winter and early spring runoff so that it will be available when water demand is the highest in the late spring and summer. Figure 2-2 shows the location of major federal, State and local surface reservoirs and aqueducts in California.

The largest system of surface reservoirs and aqueducts in California is in the Central Valley. The historical natural average annual runoff in the Central Valley is about 33.6 million acre-feet, or about 48 percent of California's total natural runoff (DWR, 1951). About two-thirds of the runoff in the Central Valley typically originates in the Sacramento Valley.

Surface reservoirs collecting runoff in the Central Valley have a combined total capacity of about 29 million acre-feet. The two largest water projects in the Central Valley, the State Water Project (SWP) and the federal Central Valley Project (CVP), provide a combined average total of about 10 million acre-feet of water annually for urban and agricultural uses. More than 20 million Californians rely on the SWP and the CVP for at least part of their water supply. These projects irrigate an average of nearly 3.6 million acres of farmland each year (DWR, 2005a).

Other major water storage and conveyance systems in California include the All-American Canal and the Colorado River Aqueduct, both of which divert water from the Colorado River in Southern California. The All-American Canal supplies water to cities and agriculture in the Imperial and Coachella valleys. The Colorado River Aqueduct supplies water to the south coast region. In the recent past, California has diverted as much as 5.3 million acre-feet of water annually from the Colorado River. This is in excess of the State's allotment of 4.4 million acre-feet (DWR, 2005a). Additional discussion of the Colorado River and California's diversions from the river is in Section 2.8.


**Figure 2-2 Major Federal, State and Local Water Storage and Conveyance Systems in California**

Groundwater also plays a critical role in providing for the State's water needs. In an average year, groundwater meets about 30 percent of California's applied urban and agricultural water demands. This increases to more than 40 percent during drought years. In 1995, an estimated 13 million Californians, nearly 43 percent of the State's population, were served by groundwater (DWR, 2003).

### 2.2.3 Climate Change and California's Water Resources

Theories concerning climate change and global warming existed as early as the late 1800s. It wasn't until the late 1900s that understanding of the earth's atmosphere had advanced to the point where many climate scientists began to accept that the earth's climate is changing. Today, many climate scientists agree that some warming has occurred over the past century and will continue through this century.

The United Nations Intergovernmental Panel on Climate Change predicts that changes in the earth's climate will continue through the 21st century and that the rate of change may increase significantly in the future because of human activity (IPCC, 2001b). Many researchers studying California's climate believe that changes in the earth's climate have already affected California and will continue to do so in the future.

Climate change may seriously affect the State's water resources. Temperature increases could affect water demand and aquatic ecosystems. Changes in the timing and amount of precipitation and runoff could occur. Sea level rise could adversely affect the Sacramento-San Joaquin River Delta and coastal areas of the State. Some of the projected effects of climate change on California's water resources and the consequences of those effects are summarized in Table 2-1.

Climate change is identified in the 2005 update of the California Water Plan (Bulletin 160-05) as a key consideration in planning for the State's future water management (DWR, 2005a). The 2005 Water Plan update qualitatively describes the effects that climate change may have on the State's water supply. It also describes efforts that should be taken to quantitatively evaluate climate change effects for the next Water Plan update.

**Table 2-1 Potential Effects of Climate Change on California's Water Resources and Expected Consequences**

| Potential Water Resource Impact | Expected Consequence |
|---|---|
| **Reduction of the State's average annual snowpack** | • Potential loss of 5 million acre-feet or more of average annual water storage in the State's snowpack<br>• Increased challenges for reservoir management and balancing the competing concerns of flood protection and water supply |
| **Changes in the timing, intensity, location, amount, and variability of precipitation** | • Potential increased storm intensity and increased potential for flooding<br>• Possible increased potential for droughts |
| **Long-term changes in watershed vegetation and increased incidence of wildfires** | • Changes in the intensity and timing of runoff<br>• Possible increased incidence of flooding and increased sedimentation |
| **Sea level rise** | • Inundation of coastal marshes and estuaries<br>• Increased salinity intrusion into the Sacramento-San Joaquin River Delta<br>• Increased potential for Delta levee failure<br>• Increased potential for salinity intrusion into coastal aquifers (groundwater)<br>• Increased potential for flooding near the mouths of rivers due to backwater effects |
| **Increased water temperatures** | • Possible critical effects on listed and endangered aquatic species<br>• Increased environmental water demand for temperature control<br>• Possible increased problems with foreign invasive species in aquatic ecosystems<br>• Potential adverse changes in water quality, including the reduction of dissolved oxygen levels |
| **Changes in urban and agricultural water demand** | Changes in demand patterns and evapotranspiration rates |

## 2.3 The Role of Water Management and Use in Greenhouse Gas Emissions

### 2.3.1 Executive Order S-03-05

Executive Order S-3-05, signed by Governor Arnold Schwarzenegger June 1, 2005, establishes aggressive greenhouse gas emission reduction goals for California. These goals are:

- by 2010, reduce emissions to 2000 levels
- by 2020, reduce emissions to 1990 levels
- by 2050, reduce emissions to 80 percent below 1990 levels

Since water management and use are a significant part of California's energy matrix, both in terms of energy generation and consumption, they are an important consideration in meeting the emission reduction goals established by the Governor.

### 2.3.2 Water Supply and Treatment

In the draft "Statewide Assessment of Energy Used to Manage Water," the California Energy Commission estimated that an average of about 44 million tons of carbon dioxide is emitted into the atmosphere each year to provide water in California. Any reductions in energy consumption related to water will help the State meet its greenhouse gas reduction goals.

California's aqueduct systems are one of the larger users of electricity in the State. Other significant uses of electrical power related to water in California include:

- pumping groundwater from wells
- treating drinking water
- delivering of water to consumers through local distribution systems
- treating wastewater and wastewater reclamation.

Diesel, gasoline, and natural gas-powered pumps are used for some water supply and treatment operations. Diesel-powered pumps are most prevalent in agriculture.

End uses of water also result in the consumption of electrical energy and natural gas, such as heating of water for domestic, commercial, and industrial operations. Various industrial processes that use water also result in energy consumption.

### 2.3.3 Hydroelectric Power

Hydroelectric power is generated at most publicly-owned water supply reservoirs in California and at many privately-owned reservoirs. Hydroelectric power is also generated by run-of-river hydroelectric plants and by power recovery plants along aqueducts and water distribution systems. Most of California's hydroelectric power is produced in the Sierra Nevada and Cascade

Range. This is due to the relatively large amount of precipitation that falls there and the amount of elevation change available for power generation.

Hydroelectric power production varies from year to year in California with changing hydrologic conditions. Hydroelectric power produced outside of California is also imported into the State to help meet energy needs. Hydroelectric power production is a critical consideration for meeting greenhouse gas emission reduction goals set by Executive Order S-3-05. Other than the construction of hydroelectric power facilities, hydroelectric power production essentially does not result in the emission of greenhouse gasses. As discussed in Section 2.5, climate change could reduce hydroelectric power production by existing facilities, especially at reservoirs in the foothills of the Sierra Nevada. This is due to expected losses in annual snow pack and changes in the timing of annual runoff as the result of climate change.

### 2.3.4 Future Plans

The 2005 California Water Plan Update (DWR, 2005) estimates that water use efficiency can reduce annual urban water use by 1.1 million to 2.3 million acre-feet by 2030. It is also estimated that water use efficiency can reduce annual agricultural water use by 0.5 million to 2.0 million acre-feet by 2030. Accelerating efforts to attain those water use reductions by 2015 could result in a cumulative reduction of greenhouse gas emissions of approximately 30 million tons by 2030.

The Department of Water Resources is developing water use efficiency measures that can help California meet the greenhouse gas emission reduction goals established by the Governor. These measures are described in a Department staff report titled "Reduction of Greenhouse Gas Emissions through Water Use Efficiency Measures, October, 2005."

In the next sections of this chapter, past and potential future changes in temperature, precipitation, and sea level are described. An overview of the potential impacts of possible future changes is also presented.

## 2.4 Changes in Air Temperature

### 2.4.1 Past Changes

The Earth's climate has had numerous periods of cooling and warming in the past. Significant periods of cooling have been marked by massive accumulations of sea and land-based ice extending from the Earth's poles to as far as the mid-latitudes. Periods of cooling have also been marked by lower sea levels due to the accumulation of water as ice, and cooling and contraction of the Earth's oceans. Periods of warming caused recession of the ice toward the poles, warming and thermal expansion of the Earth's oceans, and sea level to rise. More discussion on past changes in sea level is in Section 2.6.

Figure 2-3 depicts significant periods of cooling and warming over about the past 400,000 years based on analysis of ice cores. The causes of the temperature changes are unknown, although they may be due to changes in solar radiation, the Earth's orbit, the composition of the atmosphere, ocean circulation patterns and other factors. Average temperatures in the Northern Hemisphere appear to have been relatively stable from about 1000 to the mid-1800s based on temperature proxy records from tree rings, corals, ice cores and historical observations (IPCC, 2001a). However, there is a significant amount of uncertainty related to proxy temperature records, especially those extending far back into the past.

The United Nations Intergovernmental Panel on Climate Change stated that the Earth's climate has warmed since the pre-industrial era and that some of this change is attributable to the activities of humans (IPCCb, 2001). Global average near-surface air temperatures and ocean surface temperatures have increased 0.6 ± 0.2°C over the 20th century (IPCCa, 2001). Much of the rise occurred during 1910 to 1945 and 1976 to 2000, as depicted in Figure 2-4.

There is evidence that temperatures in the western United States and California have increased during the past century based on temperature measurements, apparent trends in reduced snowpack and earlier runoff, and other evidence such as changes in the timing of blooming plants (NWS, 2005) (Mote, 2005) (Cayan, 2001). More discussion of observed changes in temperature and related changes in snowpack and runoff in the western United States and California is contained in Section 2.5 and Chapter 6.

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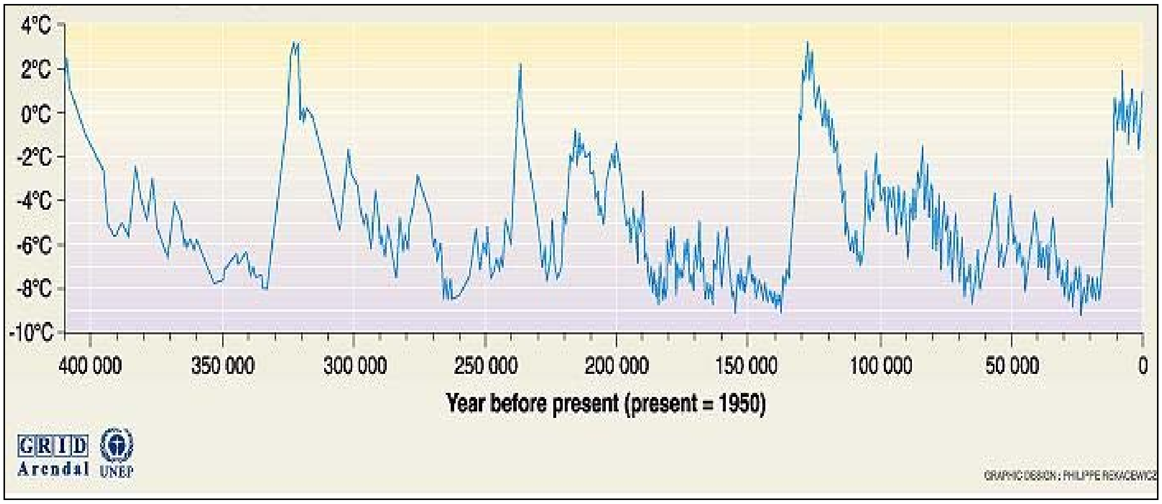


**Figure 2-3 Changes in Air Temperature Over About the Past 400,000 Years**

Explanation: Graph depicts changes in air temperature as evidenced by isotopic analysis of ice cores obtained at the Russian Vostok station in central east Antarctica. For additional explanation visit: http://cdiac.esd.ornl.gov/trends/temp/vostok/jouz_tem.htm.
Source: United Nation's Environment Programme Global Resource Information Database - Arendal website at http://www.grida.no/climate/vital/02.htm.

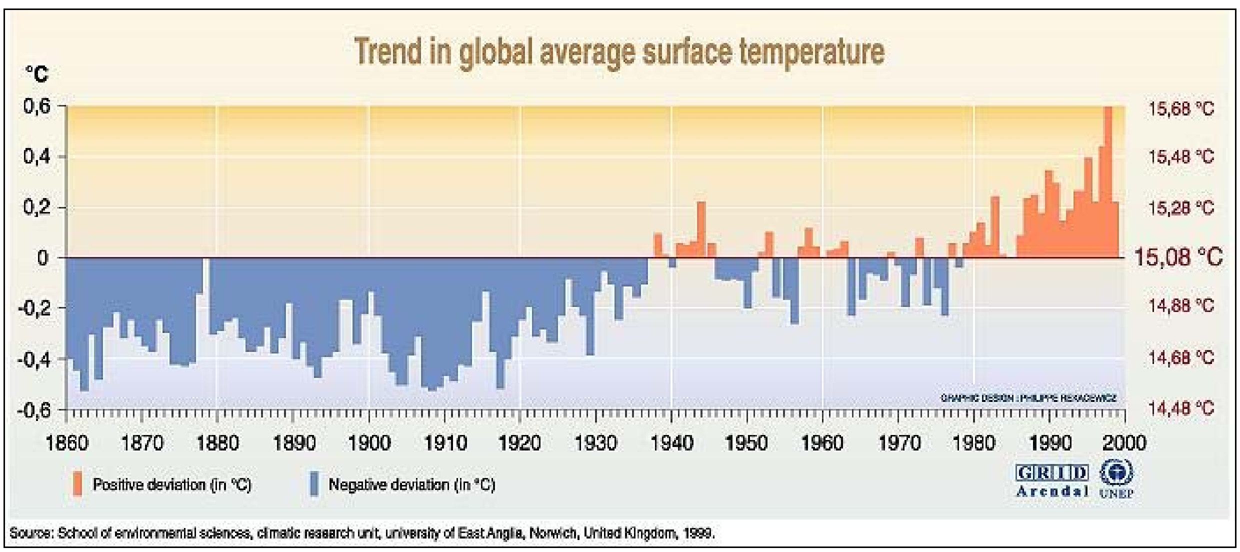


**Figure 2-4 Trend in Global Average Temperature from 1860 to 2000**

Explanation: The figure depicts global average combined land-surface air and sea surface temperatures from 1861 to 1998 relative to the average temperature between 1961 and 1990. The left vertical scale is in degrees Celsius.
Source: United Nation's Environment Programme Global Resource Information Database - Arendal website at: http://www.grida.no/climate/vital/17.htm.

### 2.4.2 Causality

Human-induced changes in the Earth's temperature have been tied to increased concentrations of greenhouse gases in the atmosphere caused by the production and burning of fossil fuels and land uses. The primary gases of concern are carbon dioxide, methane, and nitrous oxide. Table 2-2 lists changes in atmospheric concentrations of these gases from 1750 to 1998, as well as their efficacy in causing warming. Figure 2-5 depicts changes in atmospheric carbon dioxide concentration measured at Mauna Loa Hawaii from 1958 to 2005.

**Table 2-2 Abundance of Well-Mixed Greenhouse Gases in 1750 (pre-industrial age) and in 1998 and Radiative Forcing Due to the Change in Abundance**

| Gas | Abundance (Year 1750) | Abundance (Year 1998) | Radiative Forcing ($Wm^{-2}$) |
|---|---|---|---|
| Carbon Dioxide | 278 | 365 | 1.46 |
| Methane | 700 | 1745 | 0.48 |
| Nitrous Oxide | 270 | 314 | 0.15 |

Source: IPCC, 2001a
Explanation: Volume mixing ratios for carbon dioxide are in parts per million and are in parts per billion for methane and nitrous oxide. $Wm^{-2}$ = watts per square meter.

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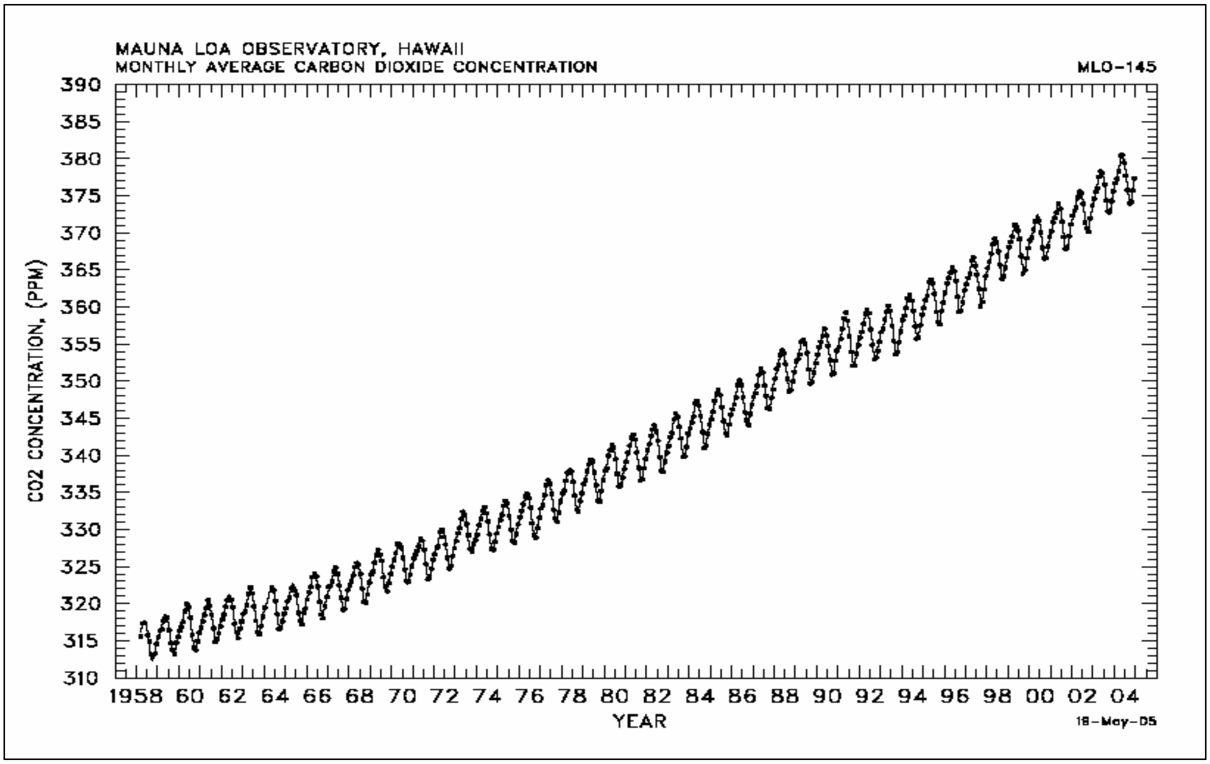



**Figure 2-5 Changes in Atmospheric Carbon Dioxide Concentration Measured at Mauna Loa, Hawaii from 1958 to 2005.**

Source: United States Department of Energy, Carbon Dioxide Information Analysis Center website at: http://cdiac.esd.ornl.gov/trends/co2/sio-mlo.htm .
Explanation: PPM = parts per million. Annual decreases in atmospheric carbon dioxide concentration at Mauna Loa, Hawaii occur each summer and are due to seasonal increases in plant respiration in the Northern Hemisphere.

### 2.4.3 Temperature Projections

The United Nations Intergovernmental Panel on Climate Change reports that global average surface temperatures are projected to rise between 1.4 to 5.8°C from 1990 to 2100, based on various climate models and greenhouse gas emission scenarios (IPCC, 2001a). Figure 2-6 is a generalized representation of the range of temperature projections reported by the IPCC in its Third Assessment Report (TAR). Information on the various projections making up the range, as well as their basis can be found in the TAR[1].

[1] Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001a). http://www.grida.no/climate/ipcc_tar/wg1/index.htm

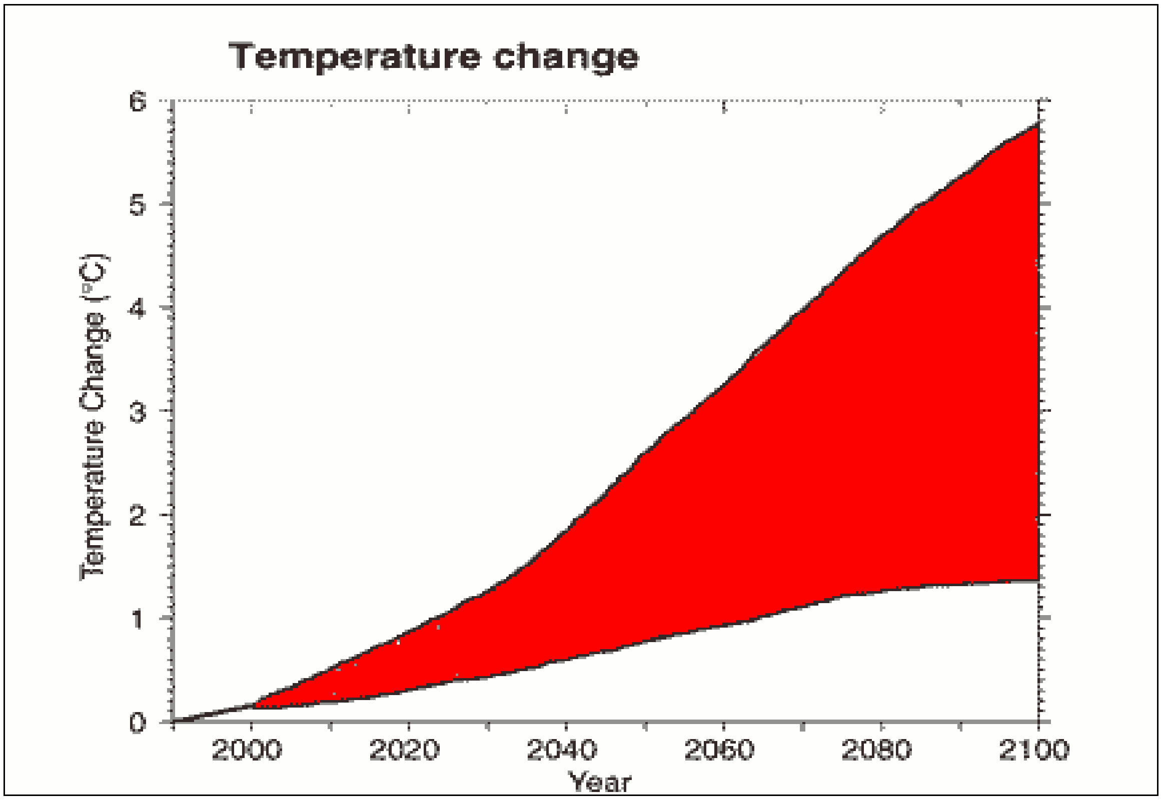



**Figure 2-6 Range of Projections Reported by the Intergovernmental Panel on Climate Change for Increasing Global Average Surface Temperature Through 2100.**

Source: United States Environmental Protection Agency website at: http://yosemite.epa.gov/oar/globalwarming.nsf/content/ClimateFutureClimateGlobalTemperature.html

Climate change and temperature projections can be developed on a regional basis using techniques to "downscale" from the results of global models. The level of uncertainty related to regional climate change and temperature projections is generally higher than global projections since downscaling adds more uncertainty. One relatively large group of model projections that was recently examined for California provides a range of about 2.5 to 9 degrees Celsius temperature rise for Northern California by 2100. An analysis of the distribution of the projections generally showed a central tendency at about 3 degrees Celsius of rise for 2050, and about 5 degrees Celsius for 2100 (Dettinger, 2005).

## 2.5 Changes in Precipitation and Runoff

Climate change appears to have already affected precipitation and runoff in California. More changes are expected in the future as additional changes in the Earth's climate occur. Some of the possible effects of climate change on precipitation as well as potential consequences of those effects are listed in Table 2-3.

While all possible changes in precipitation due to climate change are of potential concern for management of the State's water resources, this section deals mainly with potential changes in the amount, form and variability of precipitation. Existing climatologic and hydrologic data are generally suitable for evaluating historical trends for these three factors. Most research and climate change modeling efforts have focused on potential changes in the amount and form of precipitation in California. Historical information and research efforts are not as abundant or as conclusive for other past and possible future changes in precipitation in California.

### 2.5.1 Worldwide Precipitation Observations and Projections

Worldwide trends in precipitation over land are hard to determine. The difficulties arise from limited measurements worldwide and measurement problems, such as "undercatch" for precipitation gauges (Hulme, 1995). Where available, streamflow measurements and other information can be used as a proxy record for precipitation.

Worldwide precipitation is reported to have increased about 2 percent since 1900. While global average precipitation has been observed to increase, changes in precipitation over the past century vary in different parts of the world. Some areas have experienced increased precipitation while other areas have experienced a decline (NOAA, 2005). Figure 2-7 illustrates worldwide variation in changes in precipitation over the past century.

Precipitation and streamflow records indicate an increase in precipitation over land at a rate of about 0.5 to 1 percent per decade for the middle and high latitudes of the northern hemisphere, except for East Asia. No comparable wide-scale changes in precipitation have been observed for the Southern Hemisphere. Land surface rainfall in the subtropics has decreased an average of about 0.3 percent per decade (IPCC, 2001a).

Total atmospheric water vapor content has been noted to increase at a rate of several percent each decade in the Northern Hemisphere since about 1980 (IPCC, 2001a). Some studies suggest that regional cloudiness has increased over the past century. Satellite data show a general trend for increasing cloud cover over land and the oceans since the early 1980s. This trend appears to have reversed in the early 1990s (NOAA, 2005).

**Table 2-3 Possible Effects of Climate Change on Precipitation in California and Potential Consequences**

| Possible Changes in Precipitation | Potential Consequences |
|---|---|
| Amount | Increased precipitation could benefit water supplies and improve environmental conditions in some areas, especially where water supply diversions have significantly affected streamflow. Increased precipitation could also increase the incidence of flooding, depending on the timing and intensity of precipitation.<br><br>Decreased precipitation could have serious consequences for water supplies and the environment. |
| Form | Climate warming is expected to increase minimum snow elevations in California's mountains and cause more precipitation to fall in the form of rain rather than snow. This will result in reductions of annual snowpack and reduce effective water storage for maintaining spring and summer streamflow/water supply diversions. Reductions in snowpack could also negatively affect hydroelectric power generation and flood control operations. |
| Intensity, Duration, and Timing of Precipitation Events | Increased intensity or duration of precipitation events could increase the frequency and severity of flooding. Decreases could reduce flooding.<br><br>Climate change could affect the incidence of precipitation events where rain falls on accumulations of snowpack. If the incidence or severity of such events increase, it could have serious flood control and water supply implications. |
| Variability | Increased variability in annual precipitation could present significant challenges for water managers in meeting water demands and providing flood control. Increased surface storage capacity, operational changes for reservoirs and additional use of groundwater storage could be required.<br><br>Decreased variability could benefit water management. |
| Location | Shifts in the annual average distribution of precipitation in the State, due to possible changes in regional circulation patterns or other possible causes, could benefit some regions and negatively affect others. California's major water storage and conveyance systems are located and designed in accordance with the historic distribution of precipitation. Significant shifts in the distribution of precipitation could pose serious water management challenges, jeopardize the effectiveness of the State's existing water supply infrastructure and alter ecosystems. |

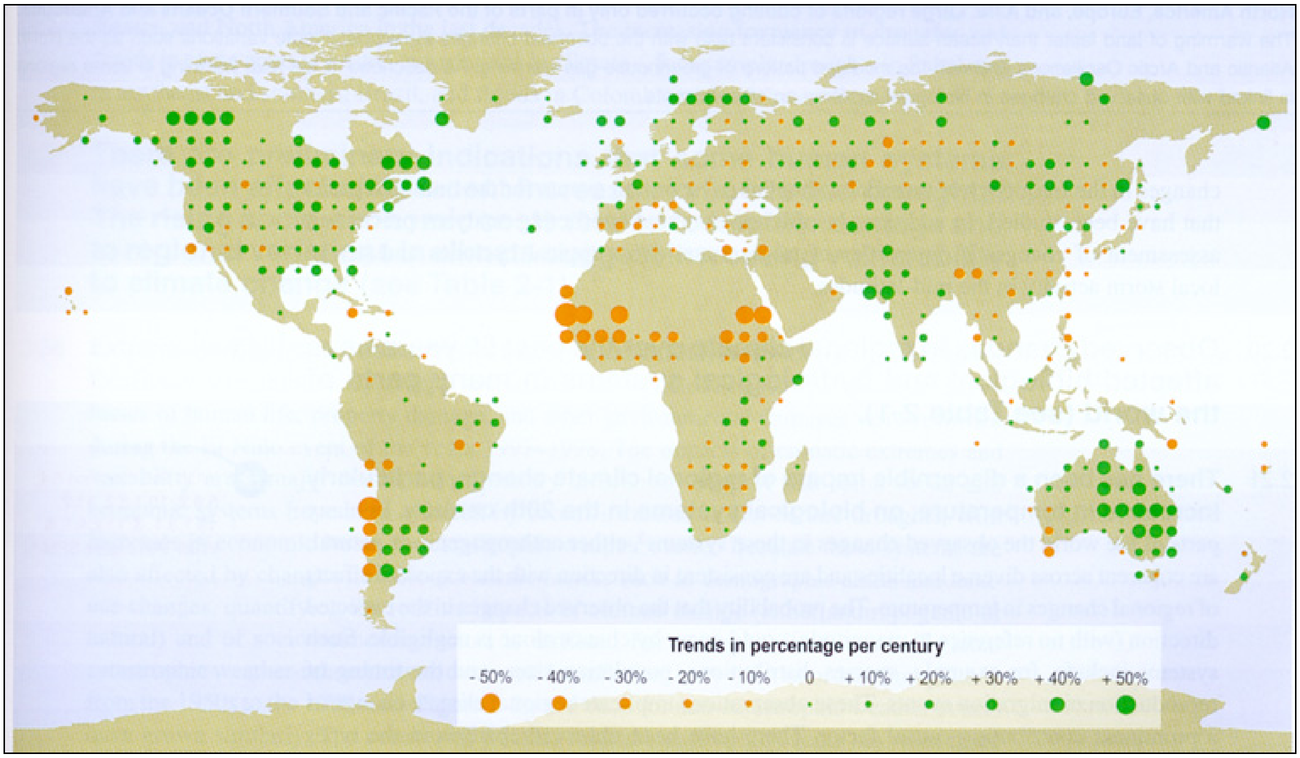



**Figure 2-7 Worldwide Precipitation Trend for 1900 to 2000**
Source: (IPCC, 2001b) http://www.grida.no/climate/ipcc_tar/vol4/english/fig2-6a.htm

The Intergovernmental Panel on Climate Change predicts that increasing global surface temperatures are very likely to result in changes in precipitation (IPCCb, 2001). Rising temperatures are expected to increase the activity of the world's hydrologic cycle and increase the moisture content of the atmosphere. Water vapor in the atmosphere is a greenhouse gas and will likely provide a positive feedback mechanism for climate warming.

Global average precipitation is expected to increase during the 21st century as the result of climate change based on global climate models for a wide range of greenhouse gas emission scenarios. Regional changes in precipitation will vary (IPCCa 2001). Global climate models are generally not well suited for predicting regional changes in precipitation due to their coarse discretization compared to the scale of regionally-important factors that affect precipitation.

Climate warming may have resulted in an increased occurrence of high-intensity rainfall in various areas with significant regional variation, including the United States (Groisman, 2005; Easterling, 2000). Continued warming through the 21st century may result in further increases in the occurrence of high-intensity rainfall (IPCC, 2001a; Groisman, 2005).

### 2.5.2 Precipitation Trends in the Western United States and California

An analysis of trends in total annual precipitation in the western United States by the National Weather Service, Climate Prediction Center provides evidence that annual precipitation has increased in much of California, the Colorado River Basin, and the West since the mid-1960s. Figure 2-8 depicts linear trends in annual precipitation in the western United States for areas referred to as "climate divisions."

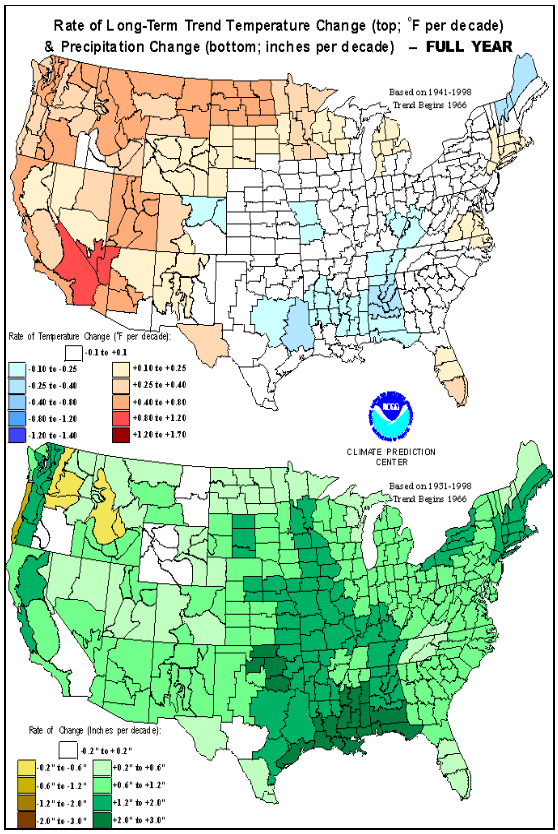



**Figure 2-8 Long-Term Linear Trend Rates for Annual Precipitation in Western United States**

Explanation: Rate of change is depicted for areas referred to as climate divisions. Trends are based on precipitation data from 1931-1998; however, the linear trends shown are from 1966 to 1998. For additional information concerning this figure and the determination of depicted precipitation trends visit: http://www.cpc.ncep.noaa.gov/trend_text.shtml#limits.

Adapted From: National Weather Service, Climate Prediction Website at http://www.cpc.ncep.noaa.gov/anltrend.gif

Most of the precipitation in the western U.S. falls in November through March, although monsoonal rainfall can be a locally-important factor in the Southwest from July to September. California's precipitation season is generally considered to start about mid-October and end in

April. However, most of the State's precipitation typically falls in the months just before and just after the beginning of each calendar year.

Mote and others (Mote, 2005) evaluated trends in annual November through March precipitation for the western United States and southwest Canada. Figure 2-9 depicts linear trends in November through March precipitation for two periods, 1930 to 1997 and 1950 to 1997. Precipitation trends for most of California and the Southwest are positive (increasing precipitation) during both periods.

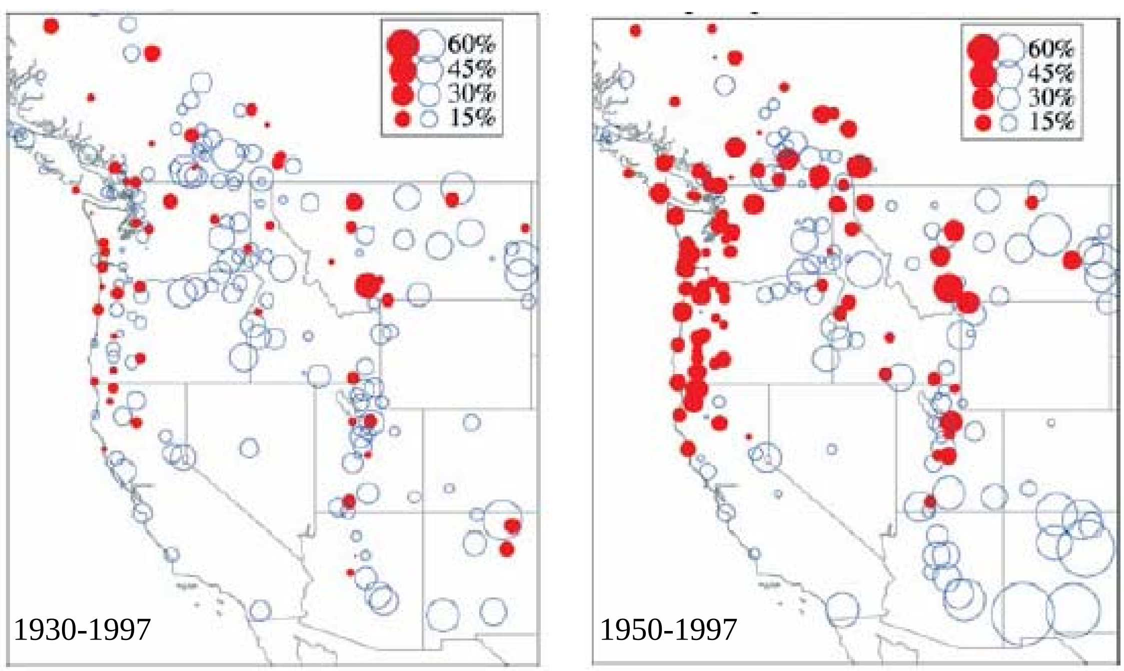



**Figure 2-9 Precipitation Trends for the Western United States and Southwest Canada from 1930 to 1997 (left figure) and 1950 to 1997 (right figure)**

Explanation: Depicted linear trends are for annual precipitation occurring from November through March. Decreasing precipitation trends are depicted in solid red circles. Increasing precipitation trends are depicted in open blue circles.

Source: Adapted from Mote (2005).

Former State Climatologist James Goodridge compiled an extensive collection of long-term precipitation records from throughout California. These data sets were used to evaluate whether there is a trend in precipitation in the State over the past century. Long-term runoff records in selected watersheds in the State were also examined. Figure 2-10 illustrates the variability in statewide annual average precipitation from 1890-2002. Statewide average precipitation was determined from 102 stations throughout the State. Based on a linear regression of the data, the long-term historical trend for statewide average annual precipitation appears to be relatively flat (no increase or decrease) over the entire record. However, it appears that there may be an upward trend in precipitation toward the latter portion of the record.

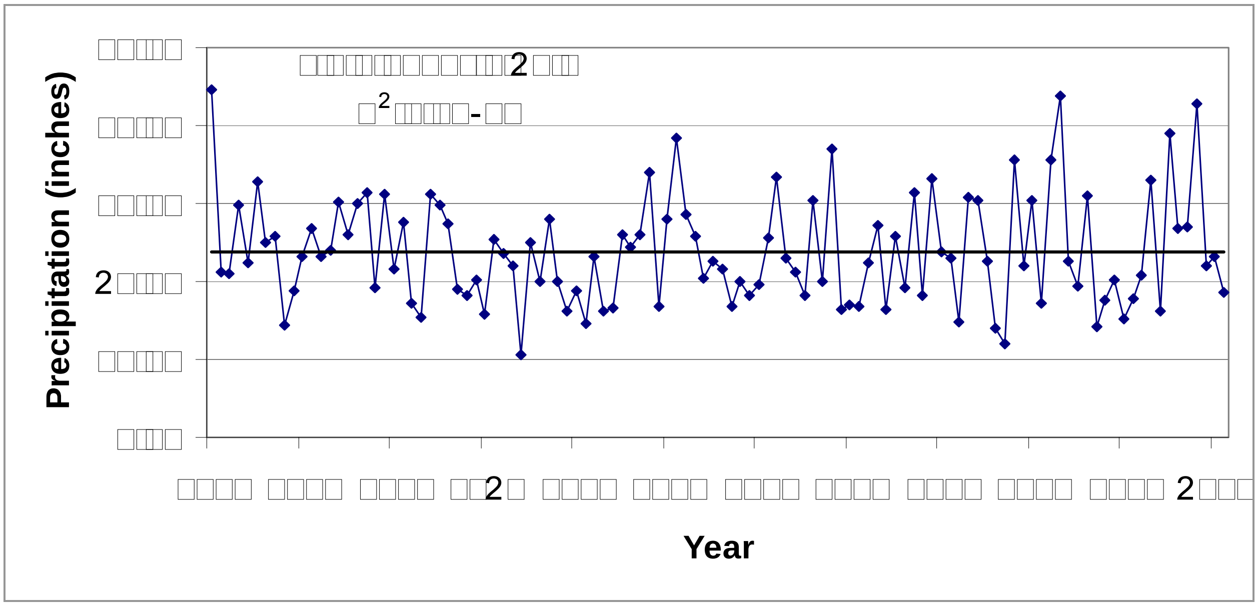



**Figure 2-10 Annual Average Precipitation for California from 1890 to 2002 with Linear Trend**

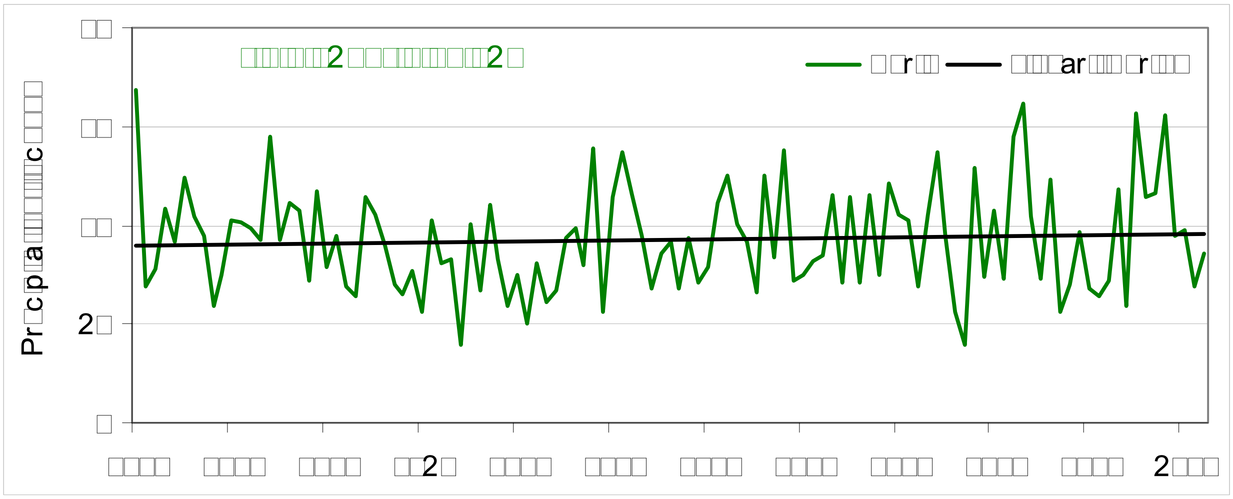
Most of the State's precipitation occurs as the result of storms from the Pacific Ocean. Hemispheric-scale circulation patterns typically cause most of these storms to move eastward across the northern part of the State. The largest amounts of precipitation fall in the mountains due to orographic effects. While a significant number of Pacific storms also cross the central and southern portions of the State, annual precipitation tends to decrease with decreasing latitude.

State precipitation records were sorted into three regions by latitude as follows:

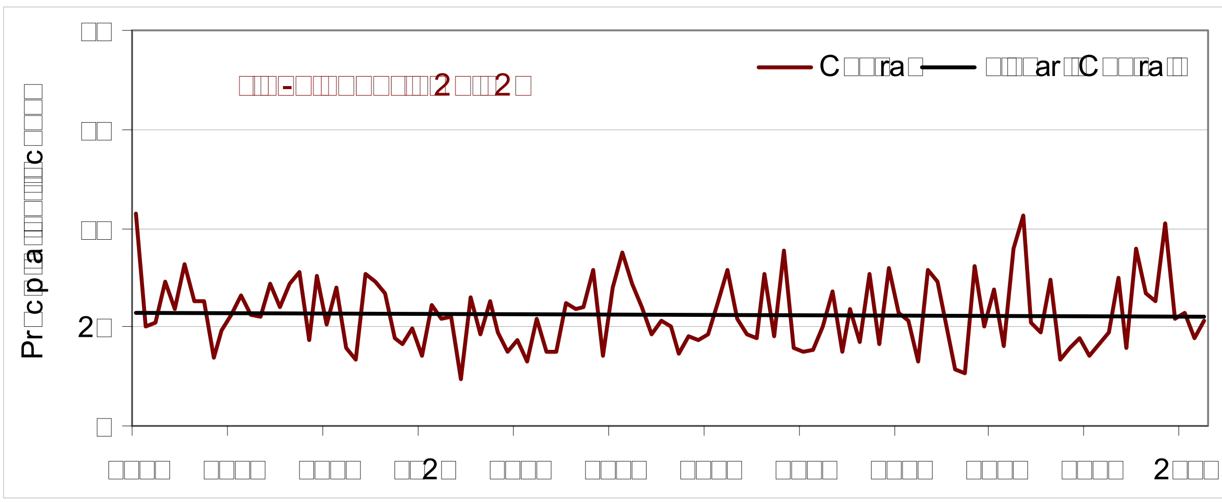
- North; from the California - Oregon border to 39 degrees latitude (latitude where California's eastern border begins to trend northwest at Lake Tahoe);
- Central; 39 to 35 degrees latitude (approximate latitude of Santa Maria); and
- South; 35 degrees latitude to the California – Mexico border.

Annual average precipitation values from 1890 to 2002 are plotted with linear trend lines for these three regions in Figure 2-11. The plots depict decreasing precipitation with decreasing latitude. Precipitation in the northern portion of the State appears to have increased slightly from 1890 to 2002. Increasing runoff trends observed for various Northern California watersheds, as discussed in Section 2.5.3 below, are consistent with the apparent increasing precipitation trend in this part of the State. Precipitation in the central and the southern portions of the State appear to have slightly decreasing trends from 1890 to 2002.

a) Northern Region: California-Oregon border to 39º latitude



b) Central Region: 39º - 35 º latitude



c) Southern Region: 35 º latitude to California-Mexico border

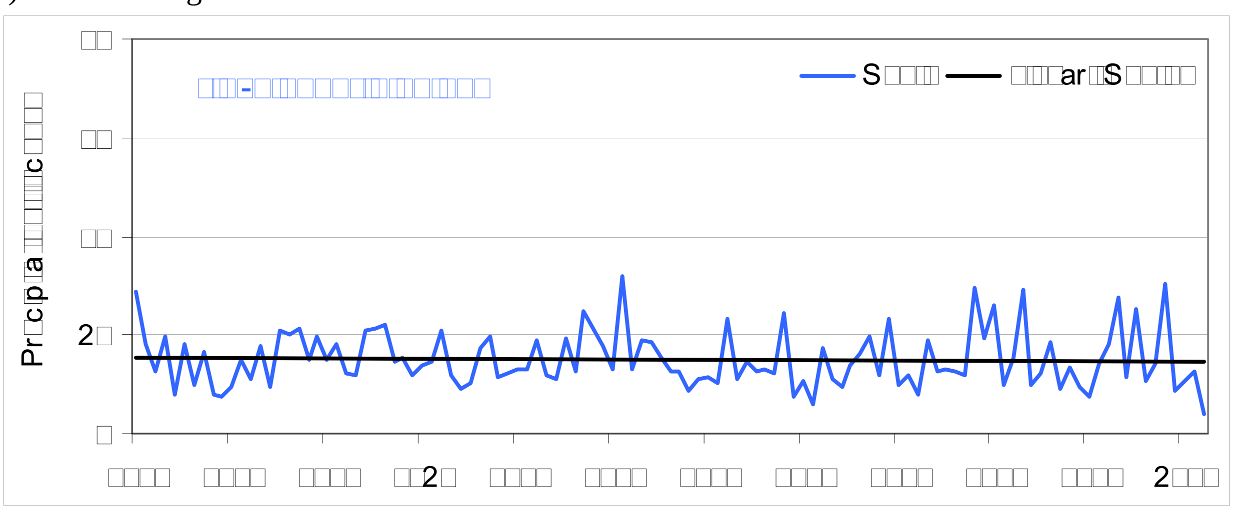


**Figure 2-11 Annual Average Precipitation from 1890 to 2002 with Linear Trends by Region**

Differences in California precipitation trends between those observed by the National Weather Service, Mote and others, and above analysis are likely due to differences in the:

- the period of analysis
- number and location of precipitation measurement stations used
- geographic regions selected for analysis

While increasing precipitation on a global scale is generally an expected result of climate change, significant regional differences in precipitation trends can be expected. More analysis of precipitation trends in California is probably needed for determining whether changes in California's regional annual precipitation totals have occurred as the result of climate change or other factors.

In addition to possible long-term trends in annual amounts of precipitation, increased variability of annual precipitation is also a possible outcome of climate change. Figure 2-12 depicts the coefficient of variation (standard deviation divided by the mean) based on a 10-year moving average of mean and standard deviation values for statewide annual average precipitation. There appears to be an upward trend in the variability of precipitation over the past century with end-of-period variability values about 75 percent larger than beginning-of-period values. This indicates that there tended to be more extreme wet and dry years at the end of the century than there were at the beginning of the century. This trend may continue with on-going climate change.

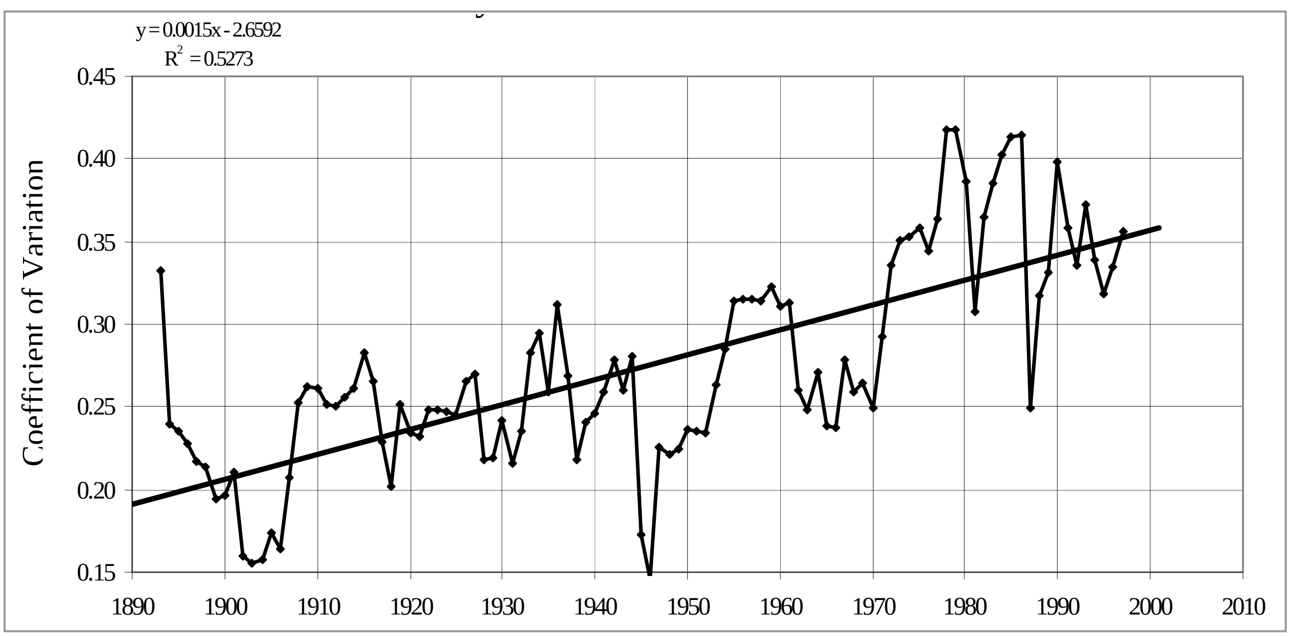



**Figure 2-12 Coefficient of Variation for Annual Average Precipitation in California from 1890 to 2001 with Trend Line**

### 2.5.3 Trends in Snowfall and Related Runoff in California

Precipitation in California's higher mountains during the late fall and winter typically falls in the form of snow. Significant accumulations of snow, referred to as snowpack, typically occur each year in the Sierra Nevada along the eastern flank of the Central Valley. A significant annual snowpack also typically occurs in the Cascade Range north and northeast of the Central Valley, and in the Klamath Mountains in the northwest corner of the State. Most of the runoff from the State's snowpack flows into the Central Valley, although snowmelt is also important for flows in rivers and streams on the east slope of the Sierra, such as the Truckee, Carson, and Owens rivers, and for the Klamath River and its tributaries.

California's annual snowpack is, on average, mostly accumulated from November though the end of March. It typically melts from April though July. Snowmelt provides significant quantities of water to streams and reservoirs for several months after the annual storm season has ended. The length and timing of each year's period of snowpack accumulation and melting can vary somewhat due to temperature and precipitation conditions.

California's snowpack is important to the State's annual water supply, because of its volume and when it typically melts. Average runoff from melting snowpack is usually about 20 percent of the State's total annual natural runoff, and probably about 35 percent of the State's total useable annual surface water supply. The State's snowpack is estimated to contribute an average of about 15 million acre-feet of runoff each year, about 14 million acre-feet of which is estimated to occur in the Central Valley. In comparison, total reservoir capacity in the Central Valley is about 24.5 million acre-feet in watersheds with significant annual accumulations of snow (DWR, 2005c).

California's reservoir managers use snowmelt to help fill reservoirs once the threat of large winter and early spring storms and related flooding risks have passed. Water stored in reservoirs is used to help meet downstream water demands when flows from snowmelt begin to recede and are typically not sufficient for satisfying downstream uses.

Some of the annual runoff collected in California's reservoirs is held from one year to the next. Water stored from one year to the next is typically referred to as "carryover storage". California's annual precipitation and snowpack can vary significantly from year to year in California. There may also be decadal-scale variation in precipitation over the Sierra (Freeman, 2002), and possibly other parts of California. Carryover storage can help meet water demand in years where precipitation and runoff is low.

Rising temperatures as the result of climate change threaten California's snowpack. An inchoative analysis of annual runoff trends in the Sacramento Valley was performed by Maurice Roos of DWR in the late 1980s (Roos, 1989). The purpose of the analysis was to determine if changes in the timing of annual runoff in the Sacramento Valley watershed had occurred as the result of possible increasing temperatures and diminished snowpack. It was concluded that, since the beginning of the 20th century, the amount of annual runoff from April though July in the upper Sacramento River watershed had a downward trend compared to each year's total runoff. This was determined to be a possible indication of a long-term reduction in the State's snowpack due to temperature rise.

An updated evaluation of runoff trends was performed for this report. Figure 2-13 presents combined unimpaired April through July runoff for four rivers in the Sacramento Valley (Sacramento, Feather, Yuba, and American rivers) as a percent of total water year runoff from 1906 to 2005. Figure 2-14a presents total April through July unimpaired runoff volume for the same period of record and for the same four rivers. Figure 2-14b presents total unimpaired water year runoff volume for the same period and rivers.

Based on the linear trends depicted in Figure 2-13 and Figure 2-14 for the four Sacramento Valley rivers:

- April through July runoff, as compared to total water year runoff, has declined about 9 percent over the past 100 years
- April through July runoff volume has decreased over the same period and total water year runoff during the same period has remained about the same

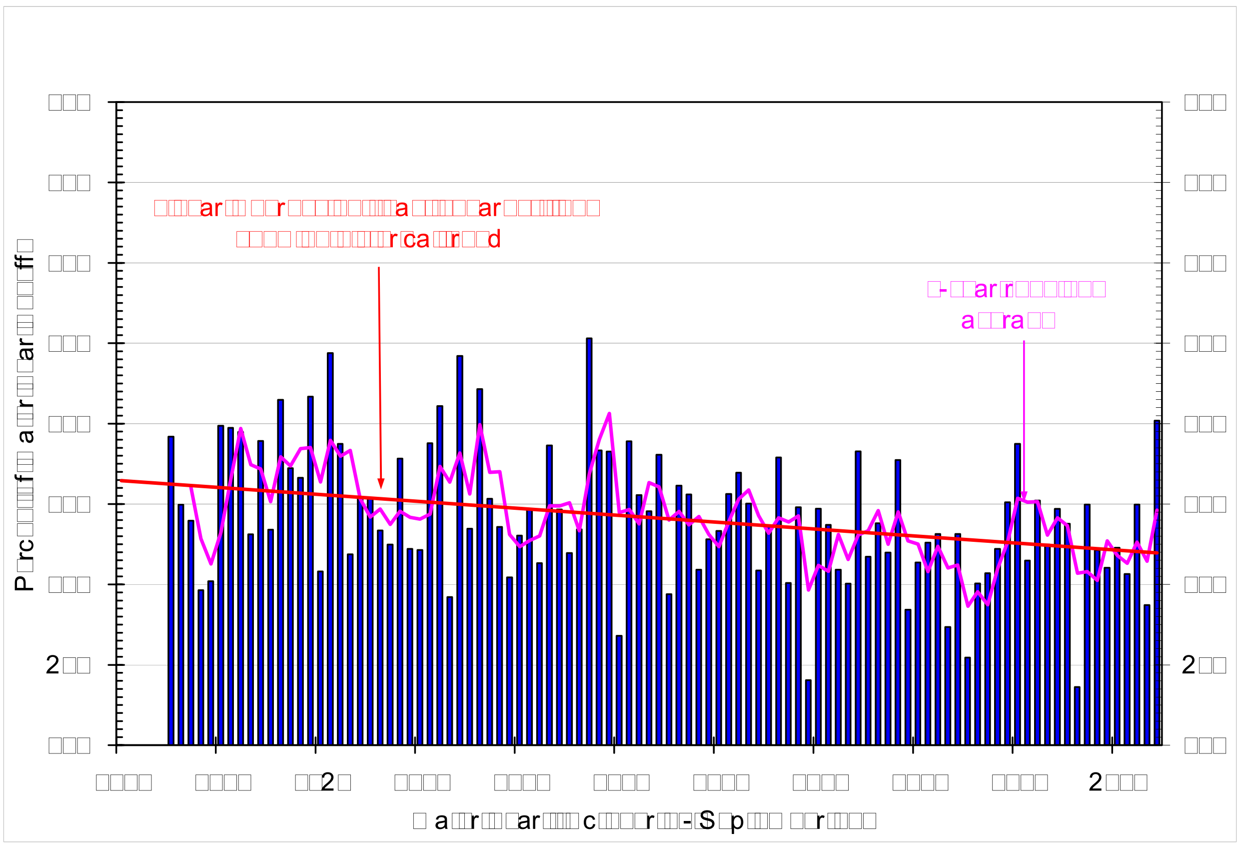
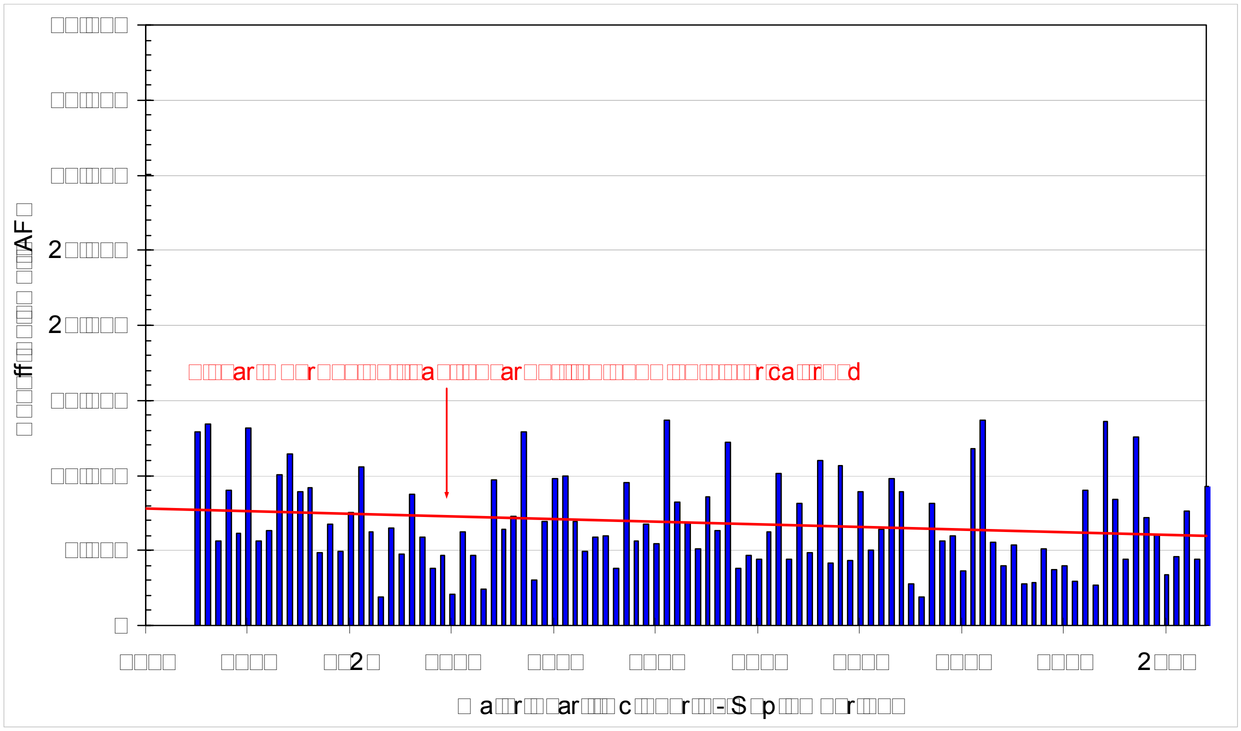


**Figure 2-13 Annual April through July Unimpaired Runoff for Four Sacramento Valley Rivers Compared to Total Unimpaired Annual Runoff***

* Based on the flows of four rivers in the Sacramento Valley; Sacramento River at Bend Bridge (near Red Bluff), Feather River into Lake Oroville, Yuba River at Smartville, and American River below Lake Folsom.

a) Annual April through July Runoff Volume



b) Total Water Year Runoff Volume (October-September)

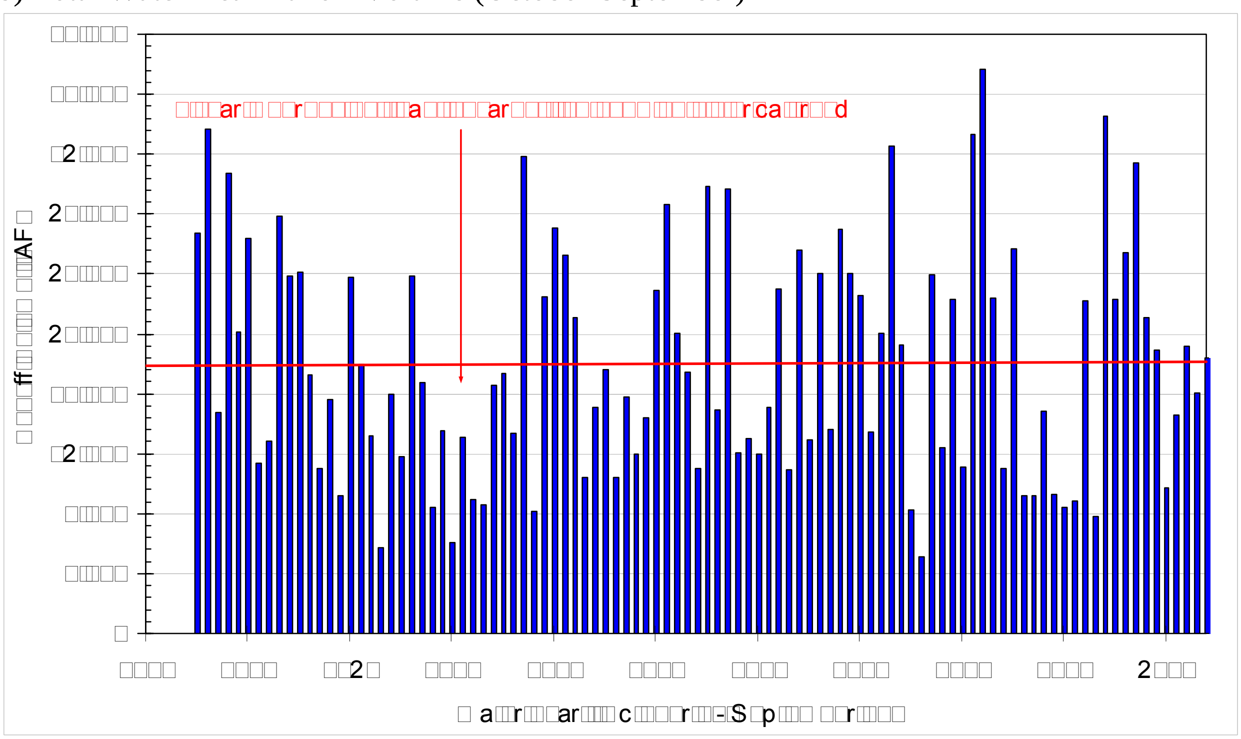


**Figure 2-14 Unimpaired Runoff Volume for Four Sacramento Valley Rivers***

* Based on the flows of four rivers in the Sacramento Valley; Sacramento River at Bend Bridge (near Red Bluff), Feather River into Lake Oroville, Yuba River at Smartville, and American River below Folsom Lake. (taf) = thousand acre feet.

Figure 2-15 presents combined unimpaired runoff from April through July for four rivers in the San Joaquin River watershed (Stanislaus, Tuolumne, Merced, and San Joaquin rivers) as a percentage of total water year runoff from 1901 to 2005. Figure 2-16a presents total unimpaired April through July runoff volume for the same four rivers and for the same period of record. Figure 2-16b presents total unimpaired water year runoff volume.

The trends depicted in Figure 2-15 and Figure 2-16 for the four San Joaquin Valley rivers indicate that:

- April through July runoff, as compared to total water year runoff, has declined about 7 percent over about the past 100 years
- while total water year runoff volume decreased somewhat during the past 100 years, April through July runoff volume decreased at even a greater rate.

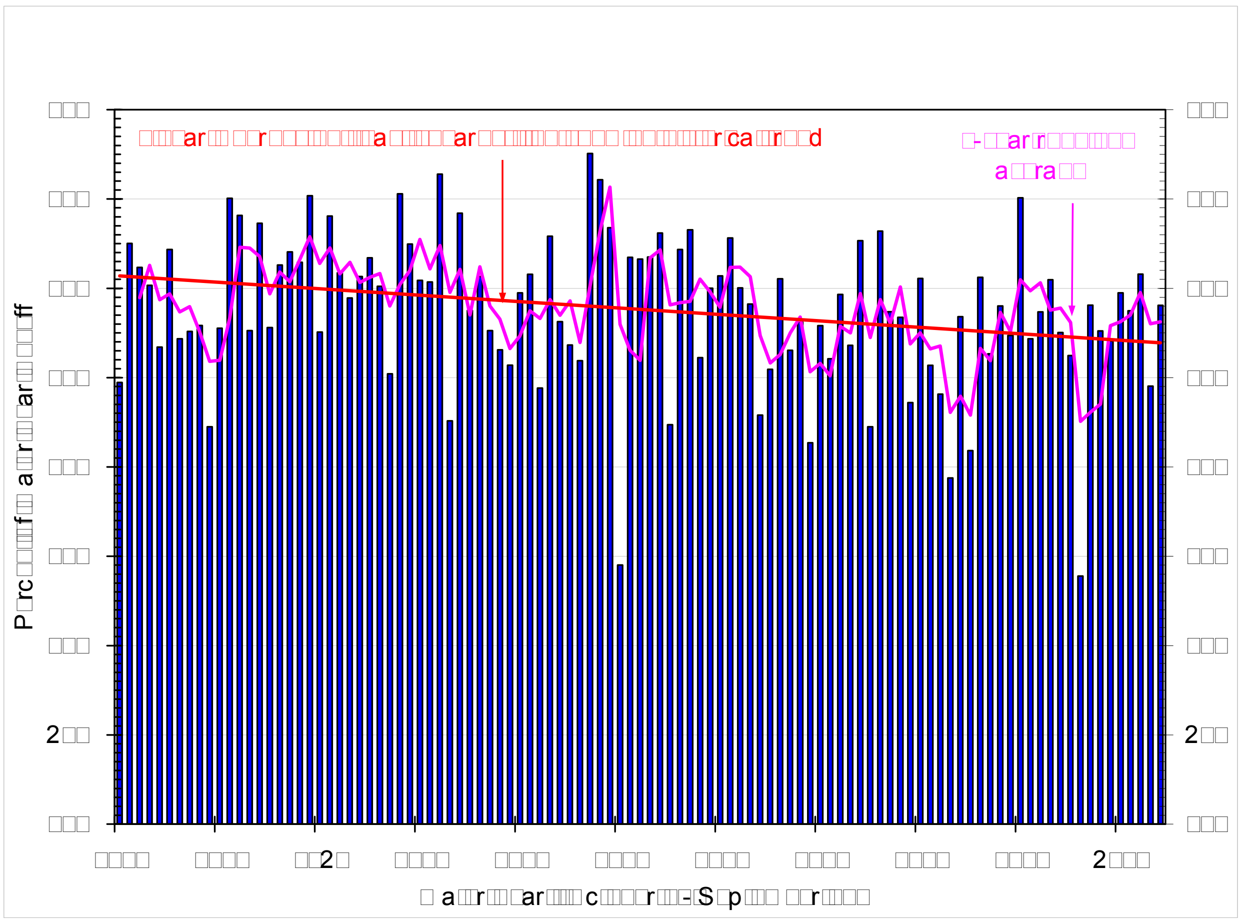
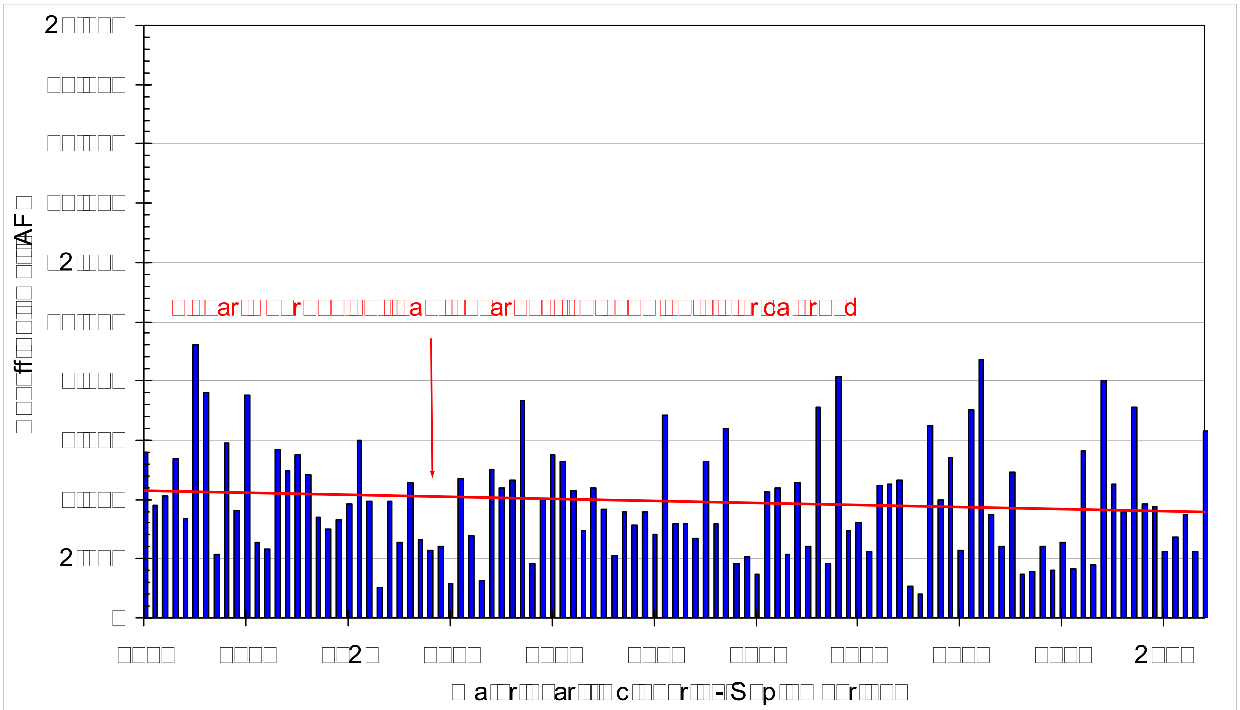


**Figure 2-15 Annual April through July Unimpaired Runoff for Four San Joaquin Valley Rivers Compared to Total Unimpaired Annual Runoff***

*Based on the flows of four rivers in the San Joaquin Valley; Stanislaus River into New Melones Reservoir, Tuolumne River into Don Pedro Reservoir, Merced River into Lake McClure, and San Joaquin River into Lake Millerton.

a) Annual April through July Runoff Volume



b) Water Year Runoff Volume

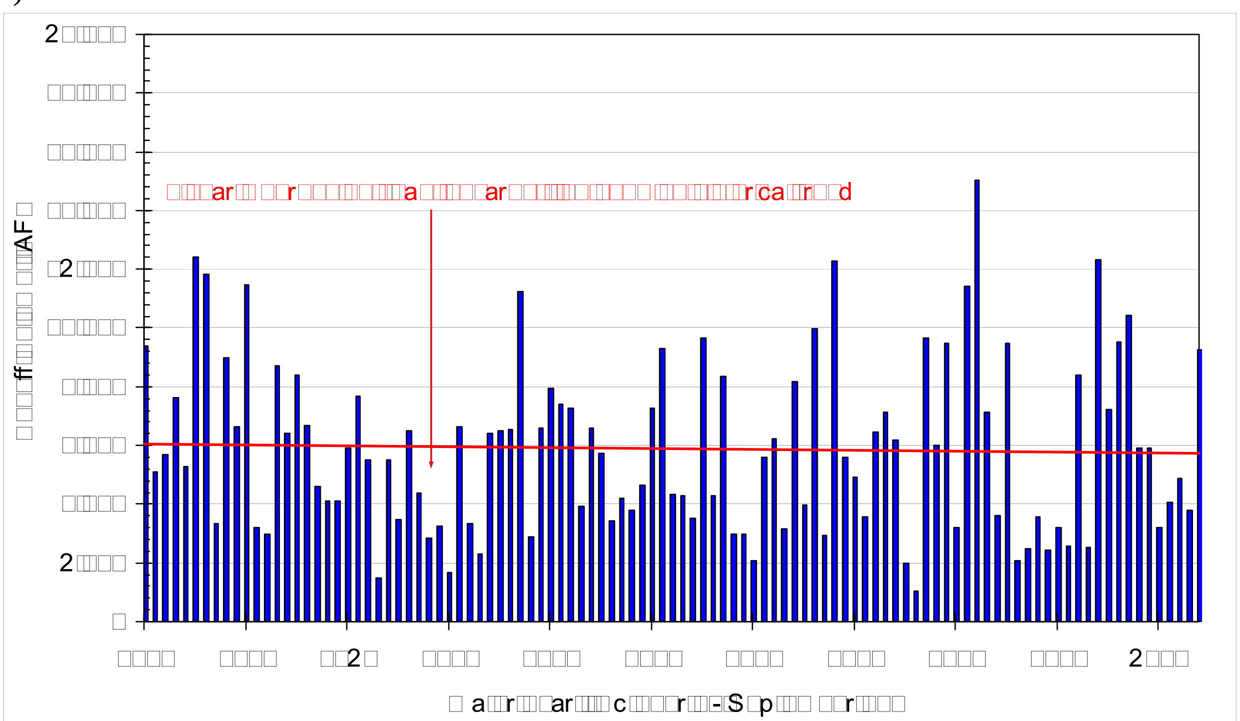


**Figure 2-16 Total Unimpaired Runoff Volume for Four San Joaquin Valley Rivers***

*Based on the flows of four rivers in the San Joaquin Valley; Stanislaus River into New Melones Reservoir, Tuolumne River into Don Pedro Reservoir, Merced River into Lake McClure, and San Joaquin River into Lake Millerton. (taf) = thousand acre feet.

Some investigators have evaluated trends in Sierra runoff for different time periods over the past century. Figure 2-17 depicts two trends in April through July runoff as a percentage of total annual runoff for eight western Sierra rivers. No statistically significant downward or upward trend was determined for the period before 1945. However, the trend following 1945 is toward diminished runoff from April through July as compared to total annual runoff (Dettinger, 2005a).

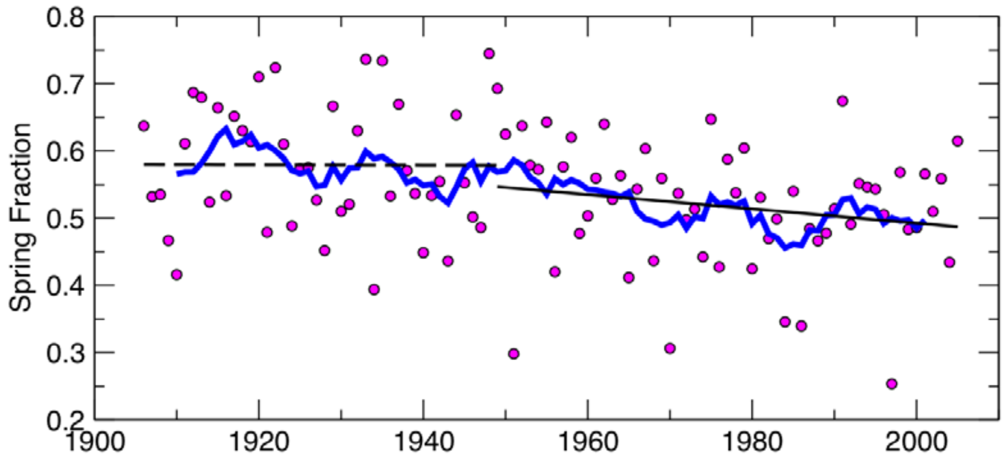



**Figure 2-17 Annual April through July Unimpaired Runoff in the Central Valley Compared to Total Unimpaired Annual Runoff**

[illegible]

Updated runoff data for the Sacramento Valley and San Joaquin Valley, as discussed above, continue to support the conclusion from earlier analyses that there appears to be a long-term trend toward reduced April though July runoff compared to total annual runoff from the Sierra. It is reasonable to conclude that this trend is the likely result of climate change and warming and an attendant decline in Sierra snowpack. A portion of the trend may also be attributable to progressively earlier melting of Sierra snowpack due to warming.

The trend toward diminished April through July runoff, as compared to total annual runoff, appears to be stronger for the Sacramento Valley than for the San Joaquin Valley, as evidenced by Figure 2-13 and Figure 2-15. This may be due to elevation differences between the northern and southern Sierra. Rising temperatures could be expected to impact the northern Sierra snowpack to a greater degree than the southern Sierra snowpack because the northern Sierra is generally lower in elevation than the southern Sierra.

Table 2-4 summarizes runoff statistics and linear trends for the Sacramento and San Joaquin Valleys, selected river basins in the two valleys, and selected rivers elsewhere in the State where data could be readily obtained and where unimpaired flows could be determined or inferred. The long-term trend in April through July runoff volumes for the Sacramento and San Joaquin valleys is downward, as are the trends for individual Sacramento Valley basins listed in the table. April through July runoff volume trends for most of the San Joaquin Valley basins listed in the table are also downward. These trends are consistent with the previously discussed conclusion that the Sierra snowpack is undergoing decline, possibly because of warming. Total water year runoff in the Sacramento Valley has an increasing trend while total water year runoff in the San Joaquin Valley appears to be decreasing on a long-term basis.

Outside of the Central Valley, the most noteworthy temporal change evident in Table 2-4 is an increasing trend in total water year runoff in the major river basins in the north coast portion of the State.

**Table 2-4 Runoff Statistics and Trends for Selected River Basins in California**

| Basin/River System | Period of Record | Period A-J[1] Average (TAF)[3] | Period WY[2] Average (TAF) | Period A-J Linear Trend (TAF/yr)[4] | Period WY Linear Trend (TAF/yr)[4] |
|---|---|---|---|---|---|
| **Central Valley River Systems** | | | | | |
| Sacramento River System[5] | 1906-2005 | 6,847 | 18,024 | -17 | 3 |
| San Joaquin System[6] | 1901-2005 | 3,922 | 5,900 | -7 | -3 |
| **Sacramento Valley Basins** | | | | | |
| Sacramento at Bend Bridge | 1906-2005 | 2,522 | 8,476 | -3 | 6 |
| Feather | 1906-2005 | 1,901 | 4,490 | -6 | 2 |
| Yuba | 1901-2005 | 1,096 | 2,372 | -3 | -2 |
| American | 1901-2005 | 1,359 | 2,739 | -5 | -3 |
| **North San Joaquin Valley Basins** | | | | | |
| Cosumnes | 1908-2005 | 127 | 369 | 0 | 0 |
| Mokelumne | 1901-2005 | 487 | 758 | -1 | -1 |
| Stanislaus | 1901-2005 | 745 | 1,175 | -2 | -1 |
| Tuolumne | 1901-2005 | 1,248 | 1,911 | -1 | 0 |
| Merced | 1901-2005 | 646 | 997 | -1 | 0 |
| San Joaquin | 1901-2005 | 1,283 | 1,816 | -2 | -1 |
| **South San Joaquin Valley Basins** | | | | | |
| Kings | 1901-2005 | 1,238 | 1,683 | -2 | -1 |
| Kaweah | 1901-2005 | 285 | 432 | 0 | 0 |
| Tule | 1930-2005 | 63 | 145 | 0 | 0 |
| Kern at Isabella | 1930-2005 | 453 | 697 | 0 | 1 |
| Kern at Bakersfield | 1901-2005 | 473 | 739 | 0 | 2 |

**Table 2-4 Runoff Statistics and Trends for Selected River Basins in California (continued)**

| Basin/River System | Period of Record | Period A-J[1] Average (TAF)[3] | Period WY[2] Average (TAF) | Period A-J Linear Trend (TAF/yr)[4] | Period WY Linear Trend (TAF/yr)[4] |
|---|---|---|---|---|---|
| **Eastern Sierra Basins** | | | | | |
| East Carson and West Walker | 1922-2005 | 326 | 433 | 1 | 2 |
| Truckee | 1906-2005 | 274 | 452 | -1 | 0 |
| **North Coast Basins** | | | | | |
| Klamath | 1928-2005* | 1,665 | 4,646 | 1 | 7 |
| Salmon | 1912-2005* | 521 | 1,288 | 0 | 2 |
| Eel | 1911-2005 | 914 | 5,493 | 0 | 12 |
| Napa | 1930-2005* | 8 | 72 | 0 | 0 |
| Russian | 1941-2005 | 101 | 897 | 0 | 1 |
| **Central and South Coast Basins** | | | | | |
| Arroyo Seco near Soledad | 1906-2005 | 23 | 122 | 0 | 0 |
| Arroyo Seco near Pasadena | 1911-2005 | 2 | 7 | 0 | 0 |
| Nacimiento | 1916-2005 | 23 | 200 | 0 | 0 |
| Santa Ana | 1901-2005 | 21 | 60 | 0 | 0 |

Footnotes:
[1] A-J = April through July.
[2] WY = Water Year.
[3] TAF = Thousand acre-feet.
[4] Trend rounded to the nearest thousand acre-foot/year.
[5] Composite of runoff data for the Sacramento River at Bend Bridge, Feather River into Lake Oroville, Yuba River at Smartville, and American River below Lake Folsom.
[6] Composite of runoff data for the Stanislaus River into New Melones Reservoir, Tuolumne River into Don Pedro Reservoir, Merced River into Lake McClure, and the Kings River into Pine Flat Reservoir.

### 2.5.4 Projected Changes in Precipitation for California

#### 2.5.4.1 Changes in the Amount of Precipitation

As discussed above, there are indications that total annual precipitation in some Northern California watersheds has been increasing. While the cause of this apparent change is unknown, it may be due in part to climate change since warming is expected to result in a more active hydrologic cycle.

Climate model projections for changes in total annual precipitation in California through the end of this century are mixed. Models predicting the greatest amount of warming generally predicted moderate decreases in precipitation. Models projecting smaller increases in temperature tend to predict moderate increases in precipitation. When some of the most extreme projections are underweighted, the central tendency in the projections is toward moderately decreased precipitation (Dettinger, 2005b).

#### 2.5.4.2 Changes in Snowpack

As discussed in Section 2.4, temperatures in California are projected to increase from about 2.5 to about 9 degrees Celsius by the end of this century as the result of climate change. One expected consequence of this is further reduction in the State's annual snowpack and earlier melting of snow.

Historically, average snowline elevations in California have ranged from about 4,500 feet in the north to above 6,000 feet in the southern Sierra. DWR staff estimates that the average snow-covered area totals about 13,200 square miles in the water supply producing basins of the Central Valley and the Trinity River above Lewiston. This is about 8 percent of the State's total land surface. The northern Sierra and Trinity mountains account for about 7,000 square miles of the 13,200 square mile total. The west slope of the southern Sierra accounts for the remainder.

Rising temperatures will cause reductions in the State's snowpack by raising snowline elevations and reducing the area where annual snowpack accumulates. A rudimentary analysis of the impact of rising temperatures on snowpack, shows that a 3 degree Celsius rise will likely cause snowlines to rise about 1,500 feet based on a moist lapse rate of 500 feet per 1 degree Celsius. This would cause a significant reduction in the amount of snow-covered area in the State and an estimated average annual loss of about 5 million acre-feet of effective water storage in snowpack.

Climate model studies support projections for continued reductions in the State's snowpack as the result of warming. Simulations under various amounts of temperature rise indicate that California's snowpack is very vulnerable to warming. One set of simulations by N. Knowles and D. R. Cayan (Knowles, 2002) provide the following projections for loss in April Sierra snowpack snow-water equivalent (in comparison to existing conditions) as a result of rising temperatures:

- 0.6 degree Celsius rise, ~5 percent loss
- 1.6 degrees Celsius rise, ~33 percent loss
- 2.1 degrees Celsius rise, ~50 percent loss

These three levels of average temperature rise were projected by Knowles and Cayan to occur by 2030, 2060 and 2090, respectively.

Losses in snow were projected to occur mainly at low to mid-altitudes. Loss of snowpack was projected to be greater in the northern Sierra and Cascades than in the southern Sierra due to the relative proportions of land at low and mid-elevations. At the highest temperature projection (increase of 2.1 degrees Celsius), the northern Sierra and Cascades were projected to lose 66 percent of their April snowpack, while the southern Sierra was projected to lose 43 percent of its snowpack.

Newer climate model studies, including those for the Intergovernmental Panel on Climate Change's 4th Assessment, due to be published in 2007, will provide a new set of temperature projections in addition to those already available. Most existing temperature projections, as well as those expected from the $4^{th}$ Assessment, indicate that losses in the State's snowpack are likely to continue increasing through the end of this century.

Warming and loss of the State's snowpack will affect the operation of most major multipurpose reservoirs at low and mid-elevations in the Sierra. Operation of these reservoirs now includes maintaining empty flood-control space during winter months and then gradually allowing them to fill with snowmelt during the spring after the threat of storms and flooding has passed. Higher snow lines and more precipitation falling in the form of rain rather than snow will increase winter inflows to these reservoirs. Higher winter inflows will also likely mean that a greater portion of the total annual runoff volume will occur in the winter. Thus, more annual runoff will likely be passed through reservoirs and will not be available for hydropower production and water supply uses later in the year. Higher winter inflows may also diminish the ability of reservoir managers to store a portion of a year's runoff volume as annual carryover storage.

#### 2.5.4.3 Other Effects

As discussed at the beginning of this section, climate change could affect the intensity, duration, and timing of precipitation events in California. It could also affect the spatial distribution and temporal variability of precipitation. Significant changes in one or more of these factors could have serious consequences for water resources management. While there may be some evidence that year-to-year variation in California's precipitation has increased over the past century, additional work is needed to determine the possible nature and extent of any changes that may already be occurring or could occur as a result of climate change.

## 2.6 Sea Level Rise

One of the major areas of concern related to global climate change is rising sea level. Worldwide average sea level appears to have risen about 0.3 to 0.6 of a foot over the past century based on tide gauge data (IPCC, 2001a). Rising worldwide average sea level over the past century has primarily been attributed to:

- warming of the world's oceans and the related thermal expansion of ocean waters (steric changes)
- the addition of water to the world's oceans from the melting of land-based ice, such as from Greenland and southeast Alaska (eustatic changes)

Some researchers have attributed most of the worldwide rise to steric changes, although there is some uncertainty about the relative contributions of steric and eustatic changes (Munk, 2002). Worldwide average sea level is projected to rise from between 0.3 of a foot and 2.9 feet by 2100, as discussed below (IPCC, 2001a).

California's coastline is about 1,075 miles in length, not including inland bays, estuaries and offshore islands. The State's coastal features include broad coastal plains and wide beaches in much of Southern California. Extensive stretches of mountainous and rugged coastline occur in the central and northern parts of the State, along with more limited coastal plains than those in Southern California. California's coastal topography is shown in Figure 2-18. The State's coastline also includes major inland bays and estuaries, including the San Francisco Bay and the Sacramento-San Joaquin River Delta (Delta), as shown in Figure 2-19.

Future sea level rise, while projected to be a relatively slow and gradual process, presents a somewhat alarming prospect for California, especially in the case of the more extreme projections. The effects of sea level rise will include:

- increased erosion of beaches, bluffs and other coastal features
- inundation of coastal land and marshes
- local flooding near the mouths of rivers and streams due to backwater effects (especially on coastal plains)
- increased potential for sea water intrusion into coastal aquifers
- increased sea water intrusion into estuaries, including the Sacramento-San Joaquin River Delta
- increased potential for levee failure in the Delta
- potential adverse impacts on flow control and diversion facilities in the Delta
- inundation and critical alteration of aquatic ecosystem habitat development projects in the Delta

.

Of the effects listed above, perhaps the most significant from the standpoint of the State's water resources are increased sea water intrusion and increased potential for levee failure in the Delta. Increased sea water intrusion into the Delta threatens the operations of the State Water Project and the Central Valley Project, as well as other Delta water supply diversions due to water quality degradation. Water quality degradation in the Delta also potentially threatens the Delta's fragile ecosystem, which supports threatened and endangered species. Finally, increased sea water intrusion into the Delta could threaten some groundwater supplies through the interaction of Delta waters with underlying and adjoining portions of the Central Valley groundwater basin.


**Figure 2-18 California's Topography and Coastline**

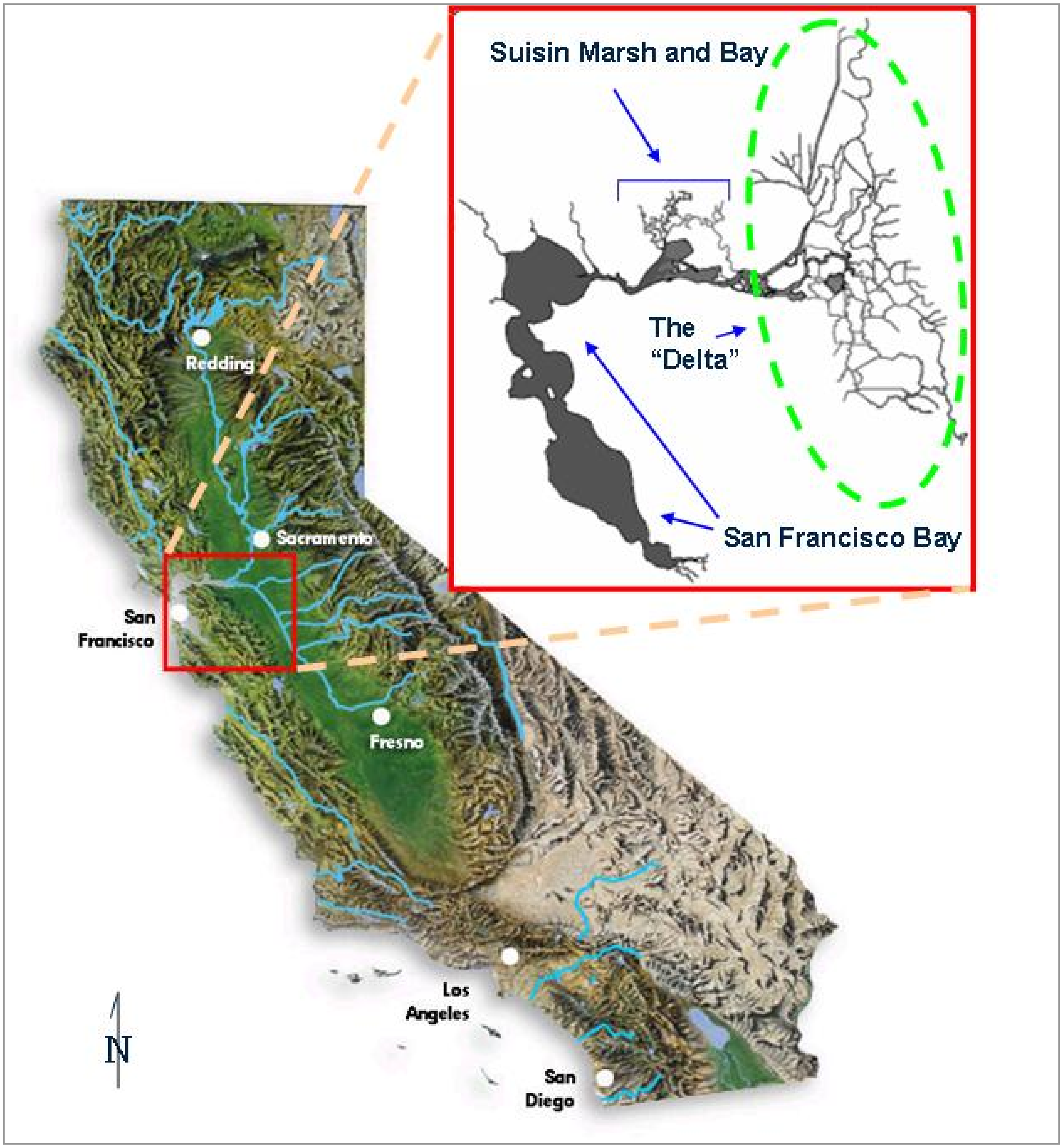



**Figure 2-19 Location of the San Francisco Bay, Suisun Marsh and Sacramento-San Joaquin River Delta**

### 2.6.1 Historical Sea Levels

#### 2.6.1.1 Sea Level Prior to Recorded History

The Earth has been subject to many periods of cooling (glacial periods) and warming (interglacial periods). Periods of glaciation are marked by massive accumulations of land- and sea-based ice extending from the Earth's poles sometimes as far as the Earth's mid-latitudes. Interglacial periods are marked by warming and the recession of ice toward the poles. Sea level during glacial periods is lowered as a significant amount of the world's water accumulates as snow and ice through precipitation. Sea level during interglacial periods rises through the melting of massive ice sheets accumulated during glacial periods.

Geologic evidence shows that for the past million years ocean levels have repeatedly risen and fallen on a somewhat cyclical basis. Figure 2-20 depicts several glacial and interglacial periods and fluctuating ocean levels over the past 800,000 years.

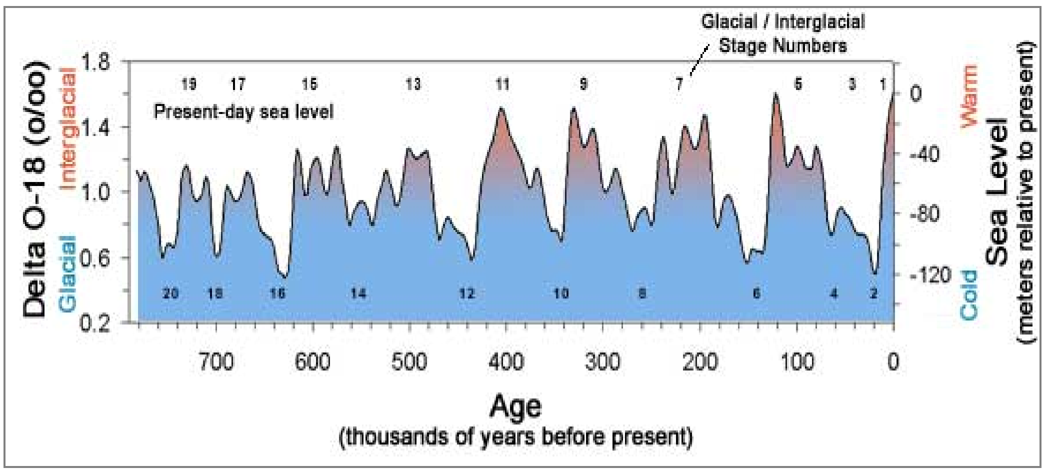



**Figure 2-20 Changes in Global Sea Level over the Past 800,000 Years**

Adapted from: http://coastalchange.ucsd.edu/st4_climatechange/sealevel.html

Coastal Morphology Group, Integrative Oceanography Division, Scripps Institution of Oceanography

The exact causes for the glacial periods and intervening periods of warming are unknown. Geologic evidence shows that global ocean levels have risen significantly since the most recent period of glaciation. The surface of the world's oceans during the coldest portion of the last glacial period, about 18,000 to 20,000 years ago, is estimated to have been about 400 feet lower than today's level, as shown in Figure 2-21. Most of the rise in sea level since this time was due to the large-scale melting of continental ice sheets, most of which occurred from 6,000 to 15,000 years ago. The average rate of sea level rise from about 6,000 years ago to present may have been about 0.5 mm/yr, or about 0.16 of a foot per century (IPCC, 2001a).

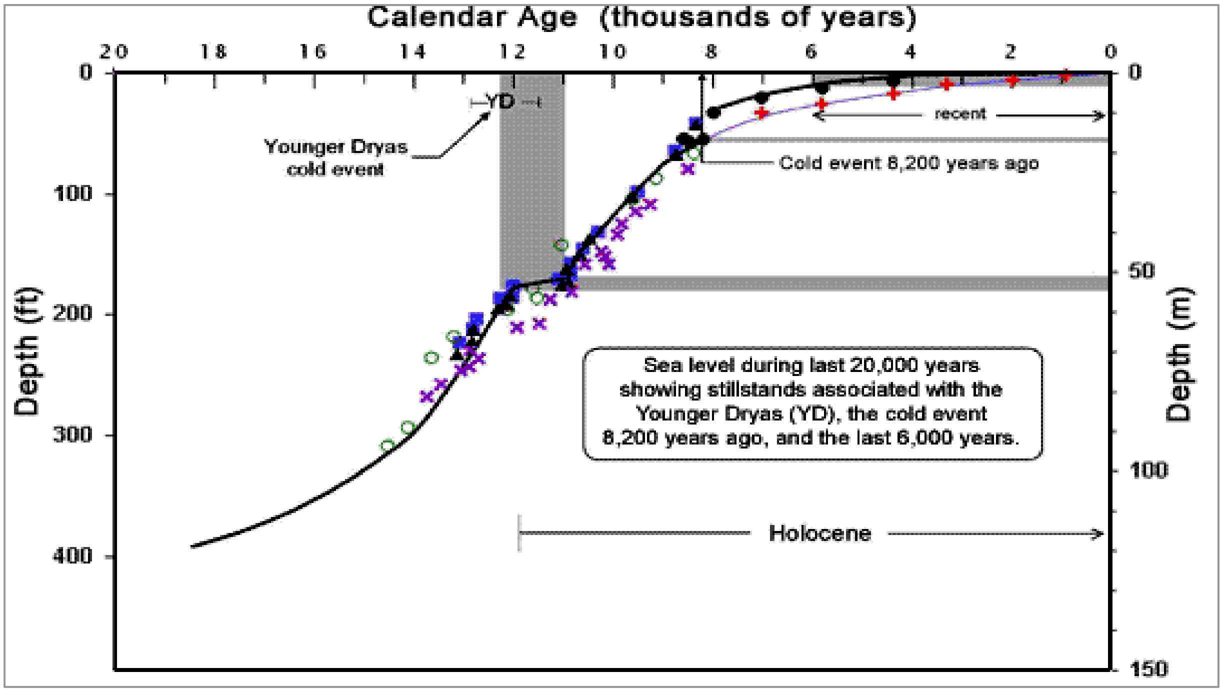



**Figure 2-21 Change in Sea Level Over the Past 18,000 Years**

Adapted from: Inman, et.al, 2002 http://coastalchange.ucsd.edu/st4_climatechange/sealevel.html
Explanation: The solid black and solid blue lines depict the estimated trend in sea level. The individual points of varying colors depict estimates of sea level at several locations by various researchers. A discussion about the "Younger Dryas" can be found at: http://en.wikipedia.org/wiki/Younger_Dryas#Abrupt_climate_change.

### 2.6.1.2 Sea Level Measurements

Direct sea level measurements began as early as the beginning of the 18th century in Europe with the use of tide gauges. Measurements for six European tide gauging stations with notably long records are depicted in Figure 2-22. All stations show a rise in relative sea level[2].

Rates of change in relative sea level measured by tide gauges along the coast of the United States over the 20th century are depicted in Figure 2-23. Since global sea level rise during the last century is believed to have been between about 0.3 and 0.6 of a foot, gauges exhibiting rates of sea level rise that significantly exceed this range could be on land masses that are subsiding. Gauges where sea level appears to rising more slowly than the worldwide average, not changing, or declining in comparison to worldwide trends may be on land masses that are rising. Table 2-5 lists areas of the U.S. coast that have been subject to recent subsidence or uplift and the causes for the changes.

Figure 2-24 depicts the locations of tide gauges along the coast of California, including eight gauges that have at least 50 years or more of record. Relative sea level trends for the eight gauges up to 2000 are shown in Figure 2-25. The trends for these gauges are summarized in Table 2-6

[2] See Section 2.6.2.3 for a discussion on "relative" sea level rise.

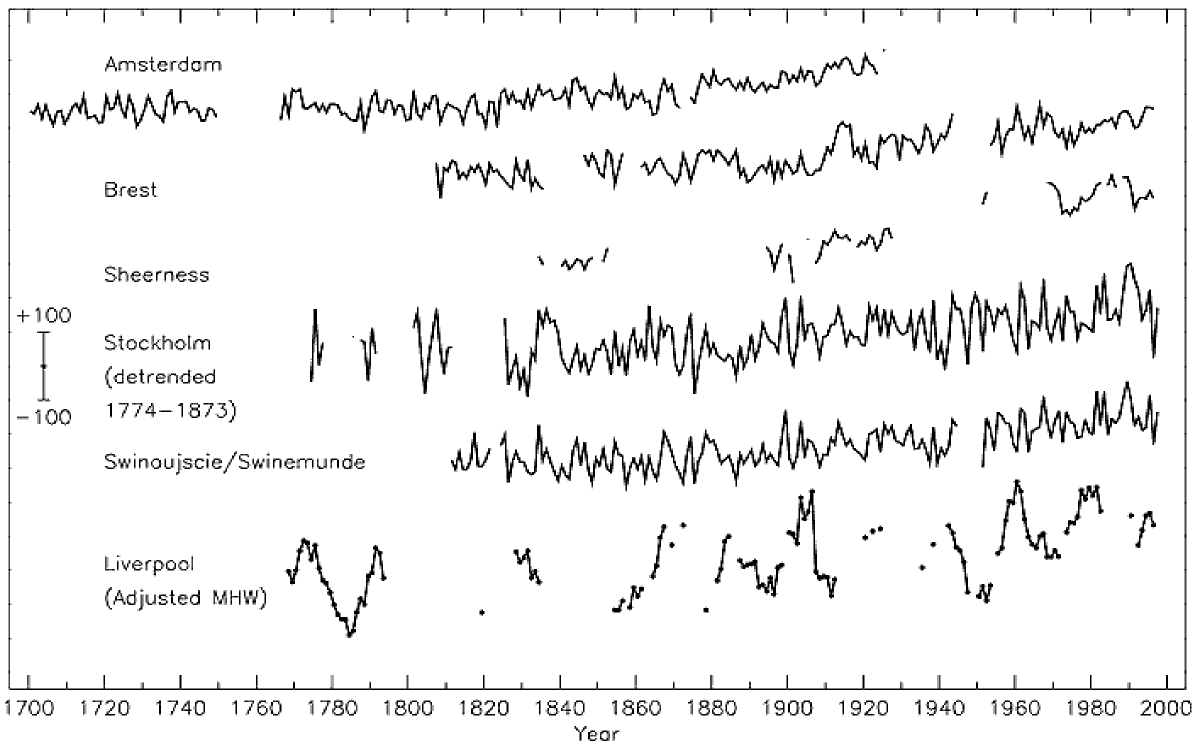



**Figure 2-22 Relative Change in Sea Level Measured at Six Locations in Northern Europe Beginning at about 1700 AD**

Locations: Amsterdam, Netherlands; Brest, France; Sheerness, UK; Stockholm, Sweden; Swinoujscie, Poland (formerly Swinemunde, Germany); and Liverpool, United Kingdom.
Scale: ± 100 mm.
Note: Data for Stockholm, Sweden is detrended over the period 1774 to 1873 to remove the first order contribution of postglacial rebound; Data for Liverpool, United Kingdom are "Adjusted Mean High Water" rather than Mean Sea Level and include a nodal (18.6 year) term.
Source: IPCCa, 2001
http://www.grida.no/climate/ipcc_tar/wg1/fig11-7.htm

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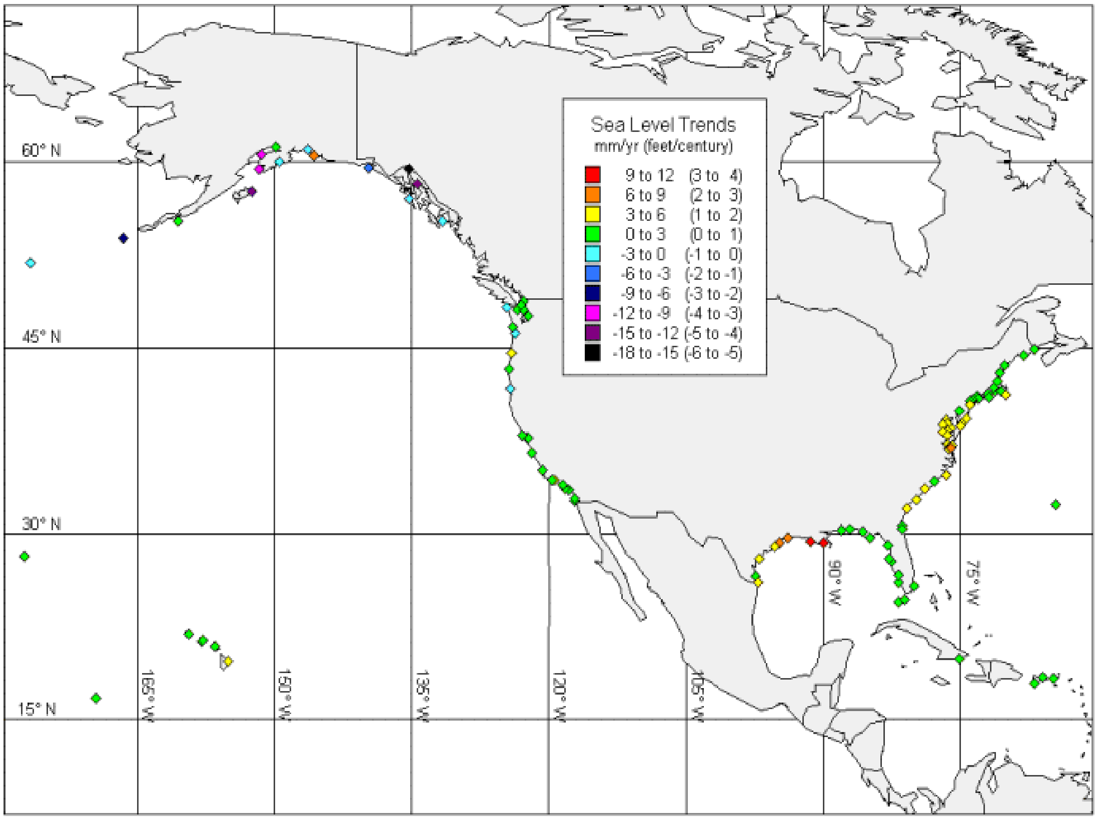


**Figure 2-23 Rates of Relative Sea Level Rise Along the Coast of the United States**
Source: National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services' website at: http://co-ops.nos.noaa.gov/sltrends/slrmap.shtml .

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**Table 2-5 Areas of the US Coast with Significant Amounts of Uplift or Subsidence**

| Coastline Area | Elevation Trend | Reason |
|---|---|---|
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] |

Source: Table developed from information obtained at: http://140.90.121.76/sltrends/slrmap.shtml and http://hvo.wr.usgs.gov/volcanowatch/1994/94_10_14.html

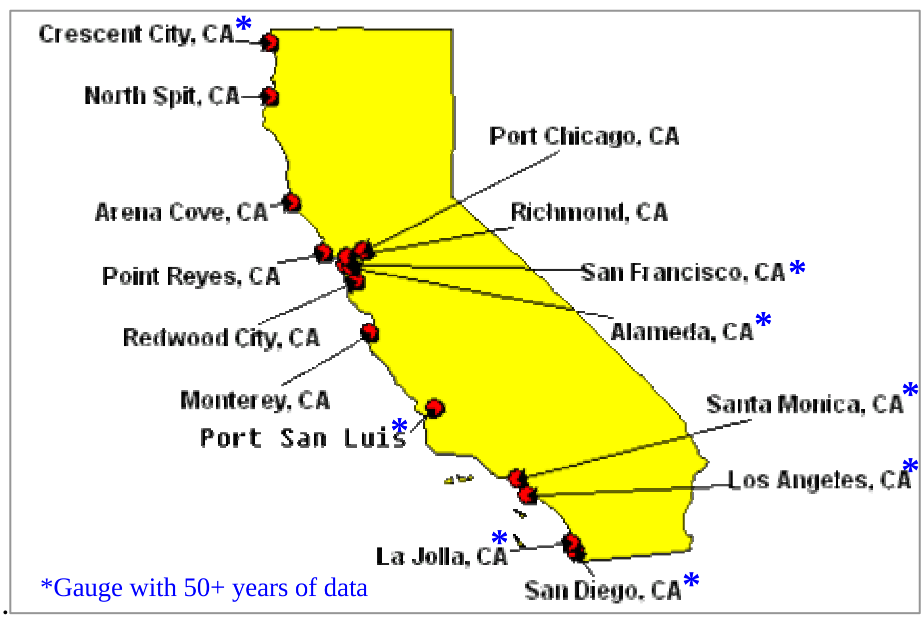
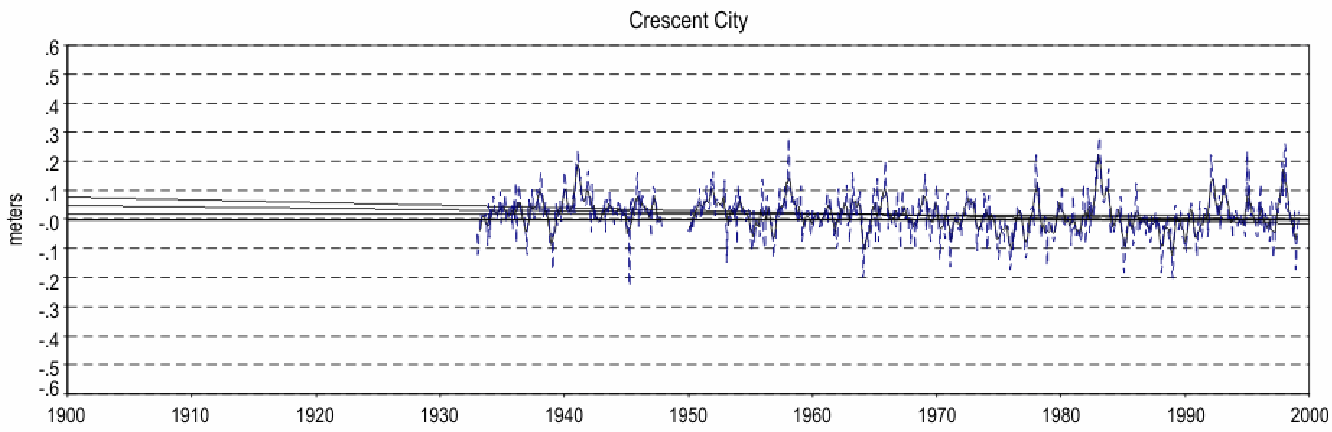
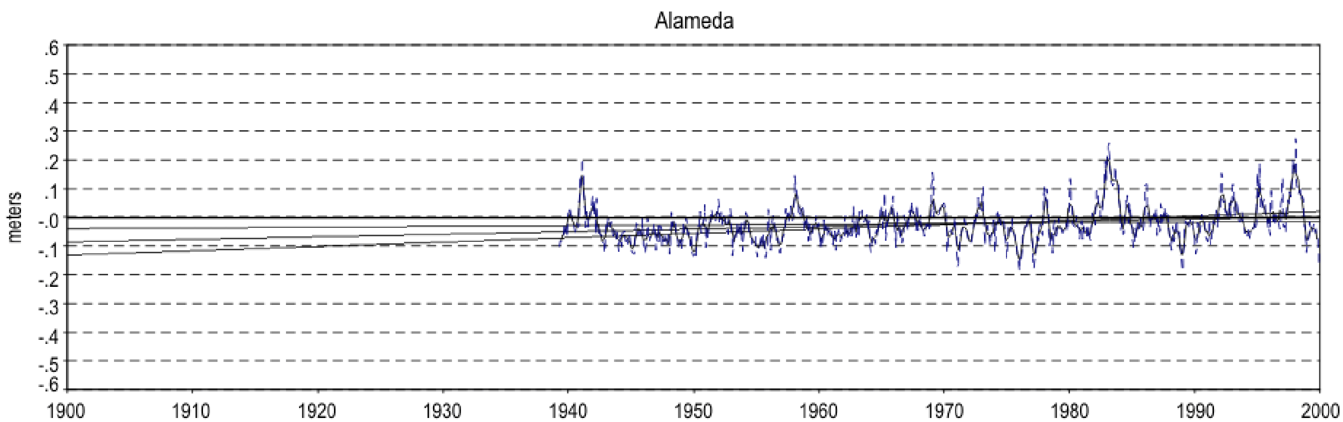



**Figure 2-24 Location of Coastal Tide Gauges in California**

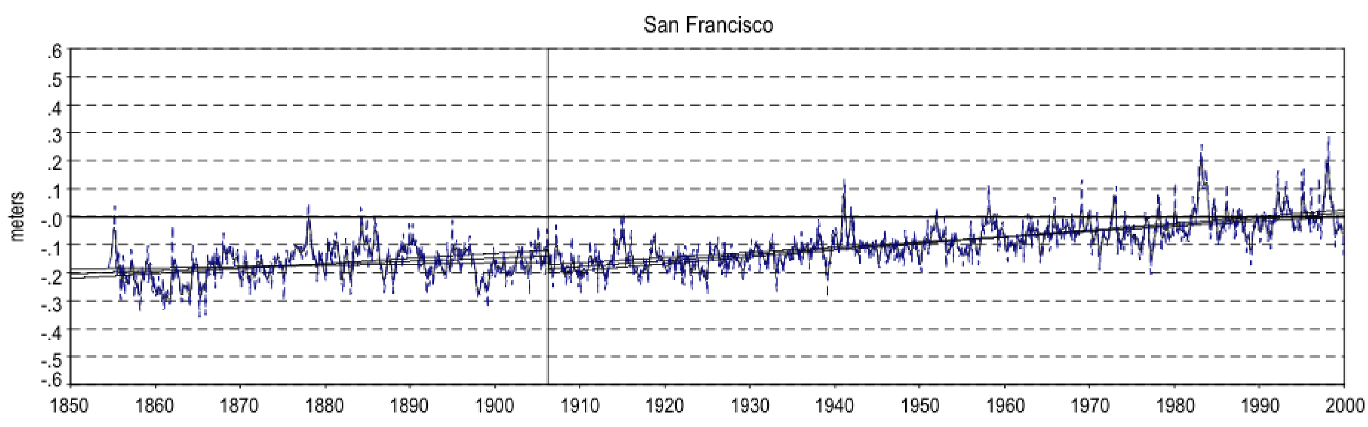
Adapted from: National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services' website at: http://co-ops.nos.noaa.gov/sltrends/slrmap.shtml
-- http://140.90.121.76/coastline.shtml?region=ca




Gauge No. 9419750--Crescent City. The mean sea level trend is -0.48 millimeters/year (-0.16 feet/century) with a standard error of 0.23 mm/yr based on monthly mean sea level data from 1933 to 1999.

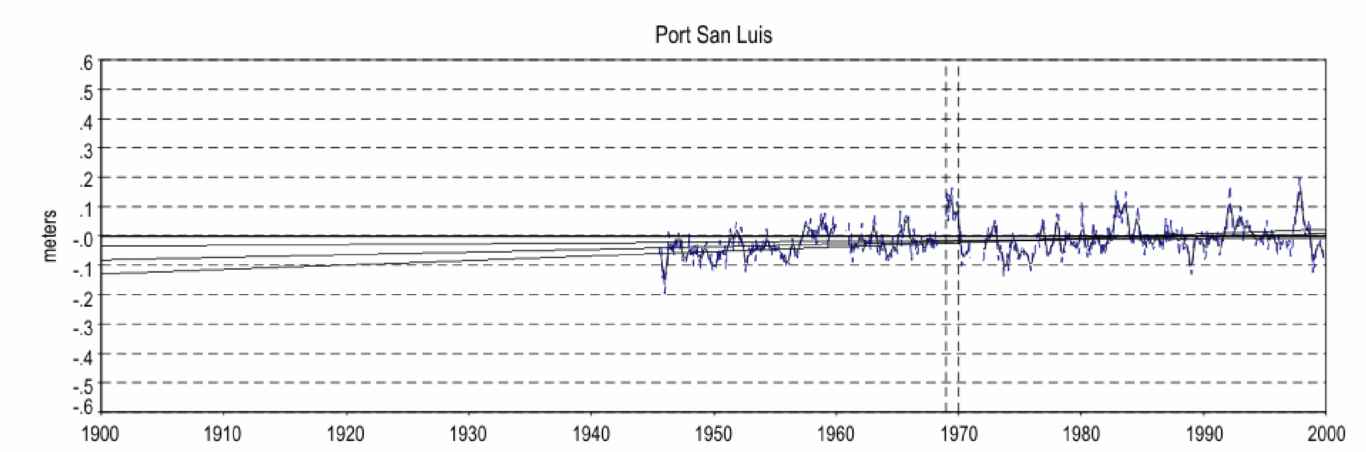



Gauge No. 9414750--Alameda. The mean sea level trend is 0.89 millimeters/year (0.29 feet/century) with a standard error of 0.32 mm/yr based on monthly mean sea level data from 1939 to 1999.

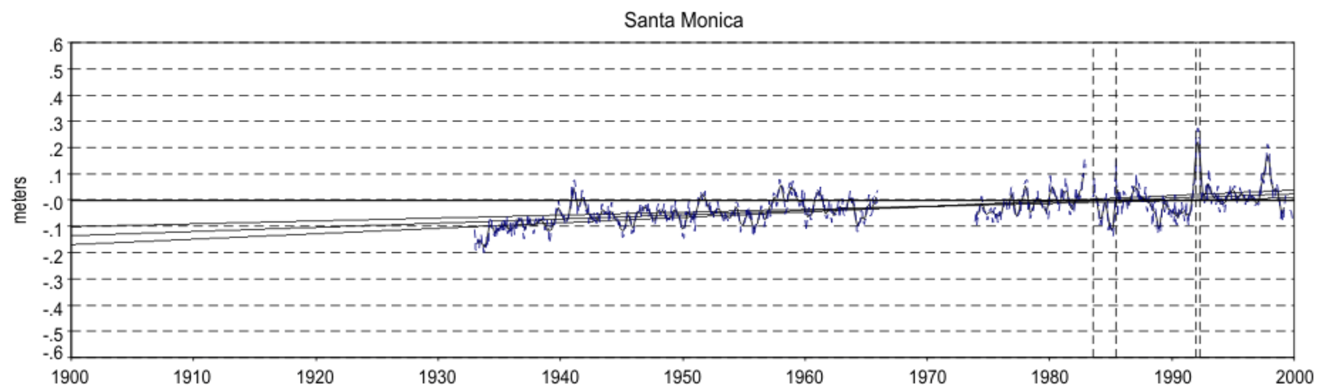



Gauge No. 9414290--San Francisco. The mean sea level trend is 2.13 millimeters/year (0.70 feet/century) with a standard error of 0.14 mm/yr based on monthly mean sea level data from 1906 to 1999.

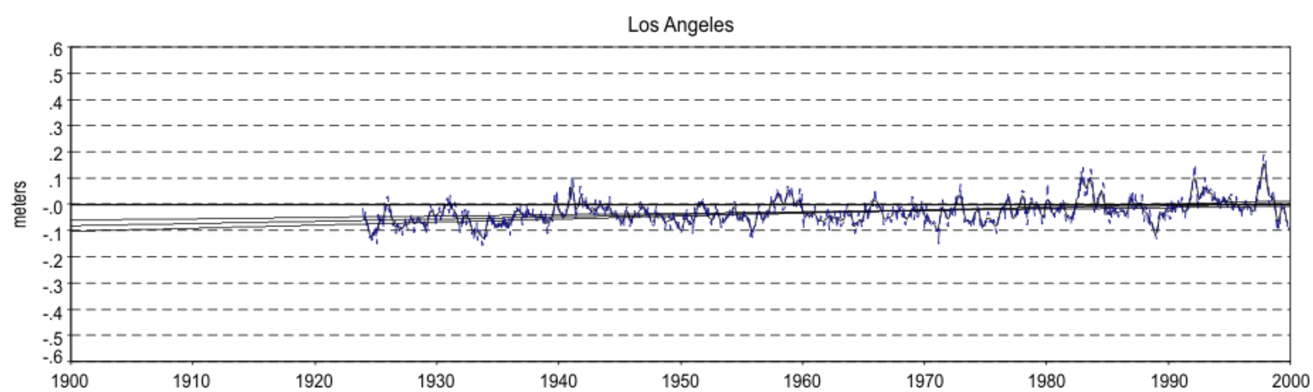
**Figure 2-25 Relative Sea Level Trends for Eight Tide Gauges along California's Coast (part 1 of 3)**




Gauge No. 9412110--Port San Luis**.** The mean sea level trend is 0.9 millimeters/year (0.30 feet/century) with a standard error of 0.32 mm/yr based on monthly mean sea level data from 1945 to 1999.

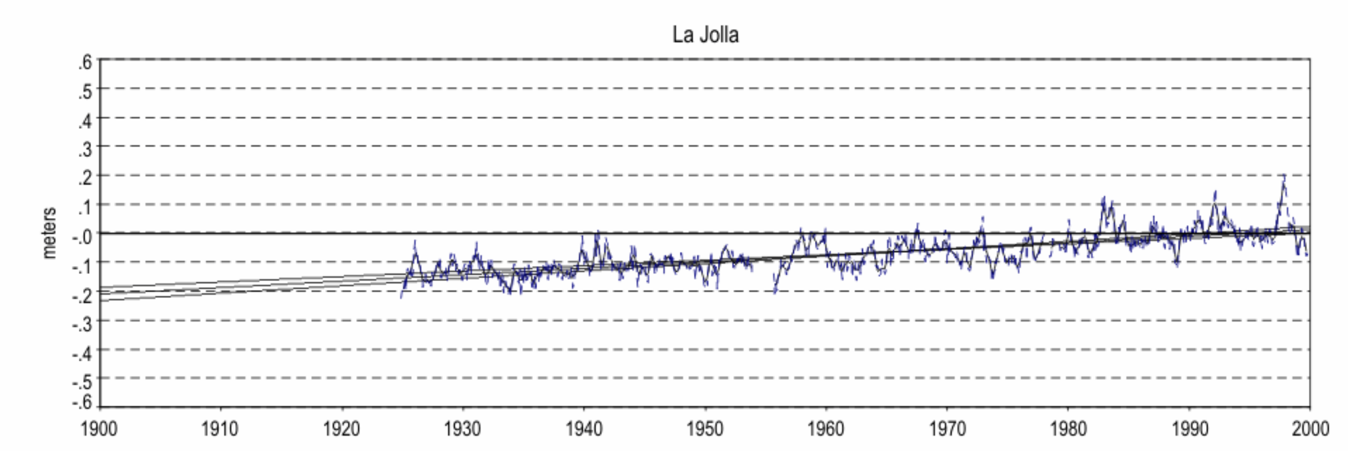



Gauge No. 9410840--Santa Monica. The mean sea level trend is 1.59 millimeters/year (0.52 feet/century) with a standard error of 0.25 mm/yr based on monthly mean sea level data from 1933 to 1999.

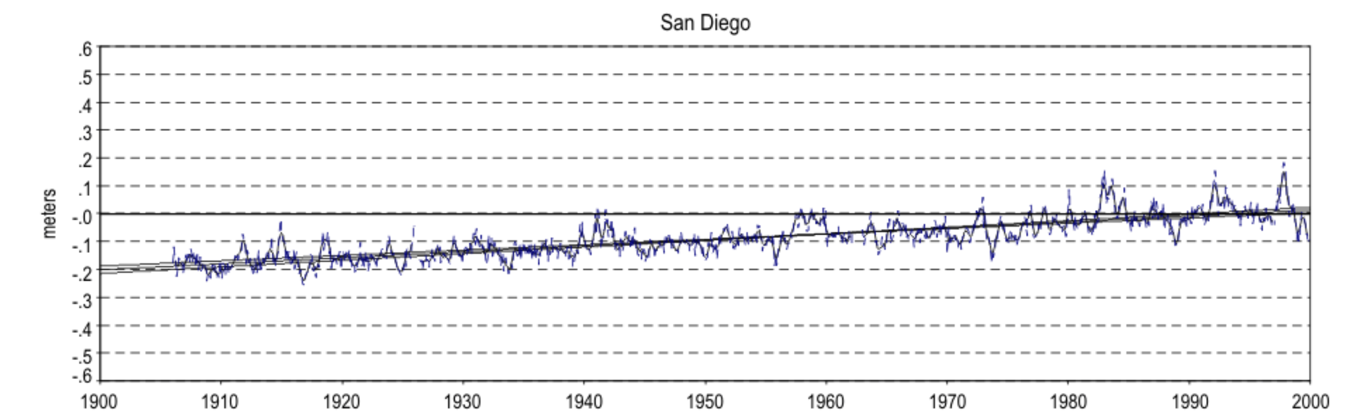



Gauge No. 9410660--Los Angeles. Mean sea level trend is 0.84 millimeters/year (0.28 feet/century) with a standard error of 0.16 mm/yr based on monthly mean sea level data from 1923 to 1999.

**Figure 2-25 Relative Sea Level Trends for Eight Tide Gauges along California's Coast (part 2 of 3)**




Gauge No. 9410230--La Jolla. The mean sea level trend is 2.22 millimeters/year (0.73 feet/century) with a standard error of 0.17 mm/yr based on monthly mean sea level data from 1924 to 1999.




Gauge No. 9410170--San Diego. The mean sea level trend is 2.15 millimeters/year (0.71 feet/century) with a standard error of 0.12 mm/yr based on monthly mean sea level data from 1906 to 1999.

**Figure 2-25 Relative Sea Level Trends for Eight Tide Gauges along California's Coast (part 3 of 3)**

Explanation: Solid blue curve is the five-month running average of monthly mean sea level with the average seasonal cycle removed. Linear trend lines illustrate 95 percent confidence interval after accounting for the average seasonal cycle. For most stations, the plotted values are relative to the 1983-2001 mean sea level datum recently established by the National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products (CO-OPS). Solid vertical lines indicate the occurrence of any major earthquakes in the vicinity of the gauge. Dashed vertical lines bracket any periods of questionable data.

Source: Graphs and explanations derived from National Oceanic and Atmospheric Administration, National Ocean Service, Center for Operational Oceanographic Products and Services' website at: http://co-ops.nos.noaa.gov/sltrends/sltrends_states.shtml?region=ca

**Table 2-6 Relative Sea Level Trends for Eight Tide Gauges Along the Coast of California with 50 Years or More of Record**

| CO-OPS Gauge Number--Name | Sea Level Trend [illegible] |
|---|---|
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |
| [illegible] | [illegible] |

Figure 2-25 and Table 2-6 show relative sea level along the coast of California is rising at all but one of the coastal gauges with 50 years or more of record. The one gauge showing a drop in relative sea level is at Crescent City. The apparent drop in sea level there is likely due to land-mass uplift given the gauge's proximity to the Mendocino Triple Tectonic Plate Junction. Information about this tectonic junction can be found at: http://pubs.usgs.gov/publications/text/Farallon.html.

The rate of relative sea level rise at the seven gauges with 50 years or more of record is fairly consistent with the worldwide sea level rise trend of 0.3 to 0.6 of a foot over the past century. Differences in the rate of rise at the various gauges may be due, at least in part, to changes in land mass elevation.

### 2.6.1.3 Projected Sea Level Rise

The Intergovernmental Panel on Climate Change projects worldwide average sea level to rise about 0.3 of a foot to 2.9 feet from 1990 to 2100 (IPCC, 2001a). The range in the projections reflects the results of multiple climate models for multiple greenhouse gas emission scenarios. Figure 2-26 depicts the varying sea level rise projections. A study by the U.S. Environmental Protection Agency published in 1995 assigned probability estimates for various magnitudes of sea level rise (Titus, 1995).

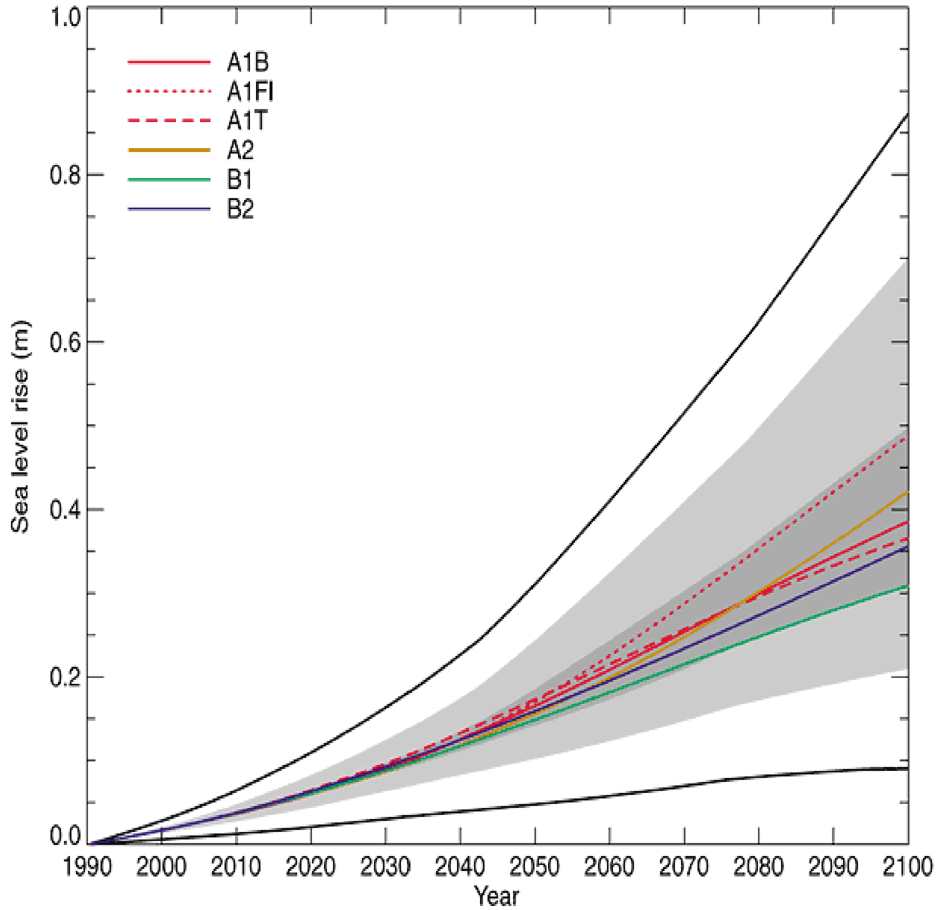



**Figure 2-26 Projected Rise in Global Average Sea Level from 1900 to 2100**

Source: Adapted from IPCC, 2001a (http://www.grida.no/climate/ipcc_tar/wg1/fig11-12.htm)
Explanation: Global average sea level rise from 1990 to 2100 for the SRES (Special Report on Emission Scenarios; IPCC 2000) scenarios and seven climate models. The region in dark shading shows the range of the average of models for all 35 SRES scenarios. The region in light shading shows the range of all models for all 35 scenarios. The colored lines in the key and in the graph represent the average of modeling results for six GHG emission scenarios. The region delimited by the outermost black lines shows the range of all models and scenarios including uncertainty in land-ice changes, permafrost changes and sediment deposition. This range does not allow for uncertainty relating to ice-dynamic changes in the West Antarctic ice sheet For additional explanation of this figure see IPCC, 2001a (http://www.grida.no/climate/ipcc_tar/wg1/index.htm).

As can be noted from Figure 2-26, many of the model projections for sea level rise show an acceleration in the rate of rise over that observed during the past century. This projected acceleration generally follows the projected acceleration in the rate of global average temperature rise by some climate models for some greenhouse gas emission scenarios (see section 2.4). As mentioned earlier, the rate of relative sea level rise experienced at many locations along California's coast is somewhat consistent with the worldwide average rate of rise observed over the past century. Therefore, it may be reasonable to expect that changes in worldwide average sea level through this century will also be experienced by California's coast.

As mentioned at the beginning of this section, sea level rise poses a significant threat for California. Perhaps the most noteworthy effect of sea level rise on California's water resources will be to the Sacramento-San Joaquin River Delta. Sea level rise over the next century will likely have a significant effect on the Delta's ecosystem, land uses and water supply function, even if the rate of rise over this century is about the same as that observed during the past century. Increased rates of rise, such as those projected for the highest levels of future greenhouse gas emissions and temperature rise could have profound effects on the Delta.

#### 2.6.1.4 Short-Term Changes in Sea Level

Sea level rise at any given location is a function of changes in worldwide average sea level; however, local and regional effects superimposed on global trends can be significant. Rising or falling land elevations can affect what levels an area experiences. Land masses can rise or fall relative to the center of the Earth through tectonic movement. Changes in the elevation of a land mass can also occur due to the activities of humans, such as the extraction of petroleum or groundwater. For example, significant amounts of coastal land subsidence (up to 3 meters) have occurred on the coast of Texas near Houston and Galveston due to petroleum extraction. Groundwater extraction along the Texas coast has also caused subsidence (Gibeaut, 2000). In California, petroleum extraction in Long Beach has resulted in coastal subsidence, but in a limited area. Some coastal area subsidence has also occurred in the Santa Clara Valley south of San Francisco Bay as the result of groundwater extraction (DWR, 1998).

Changes in land elevation as the result of tectonic movement typically occur very slowly (relative to a human timescale), although local land masses have been observed to rise or sink rapidly as the result of seismic activity. As discussed earlier, coastal land masses that are subsiding (sinking) will tend to experience sea levels that appear to be rising faster than the worldwide rate of sea level rise. Coastal areas that are undergoing uplift (rising) will tend to experience sea levels that appear to be going up more slowly than the worldwide average, or will experience sea levels that appear to be declining or not changing compared to worldwide trends.

While rising worldwide average sea level and land mass elevation changes play a long-term role in sea levels experienced at a particular location, other effects can play an important role in the short term. Such effects include:

- gravitational effects of the sun and moon (astronomical tides)
- dynamic interaction of tides with coastlines
- ocean currents
- hydraulic and salinity changes caused by rivers (especially in bays and estuaries)
- barometric pressure
- interannual and decadal changes in ocean temperatures, such as the El Nino Southern Oscillation and the Pacific Decadal Oscillation[3], as well as periodic ocean temperature changes on other timescales
- waves and storm surge

[3] For more information concerning short-term changes in ocean temperature visit: (http://topex-www.jpl.nasa.gov/science/pdo.html)

Of these factors, all but the first two could be affected by climate change. Figure 2-27 and Figure 2-28 illustrate the variability of annual average relative sea level at the San Francisco and La Jolla tide gauges, respectively. These figures also show the 19-year running average of annual average sea level at each gauge for comparison. The 19-year running average was selected since all significant variations in the relative movements of the earth, moon and sun that affect astronomical tides complete their full cycle about every 18.6 years. The San Francisco tide gauge is located a short distance inside of the Golden Gate Bridge on the shore of the San Francisco Presidio. The La Jolla gauge is located at the end of the Scripps Institution of Oceanography pier in La Jolla.

Short-term changes in sea level at a particular location can be quite significant, especially when superimposed on long-term changes. The combined effect could place California's coastal resources and the Delta at an even greater risk than worldwide changes in sea level alone.

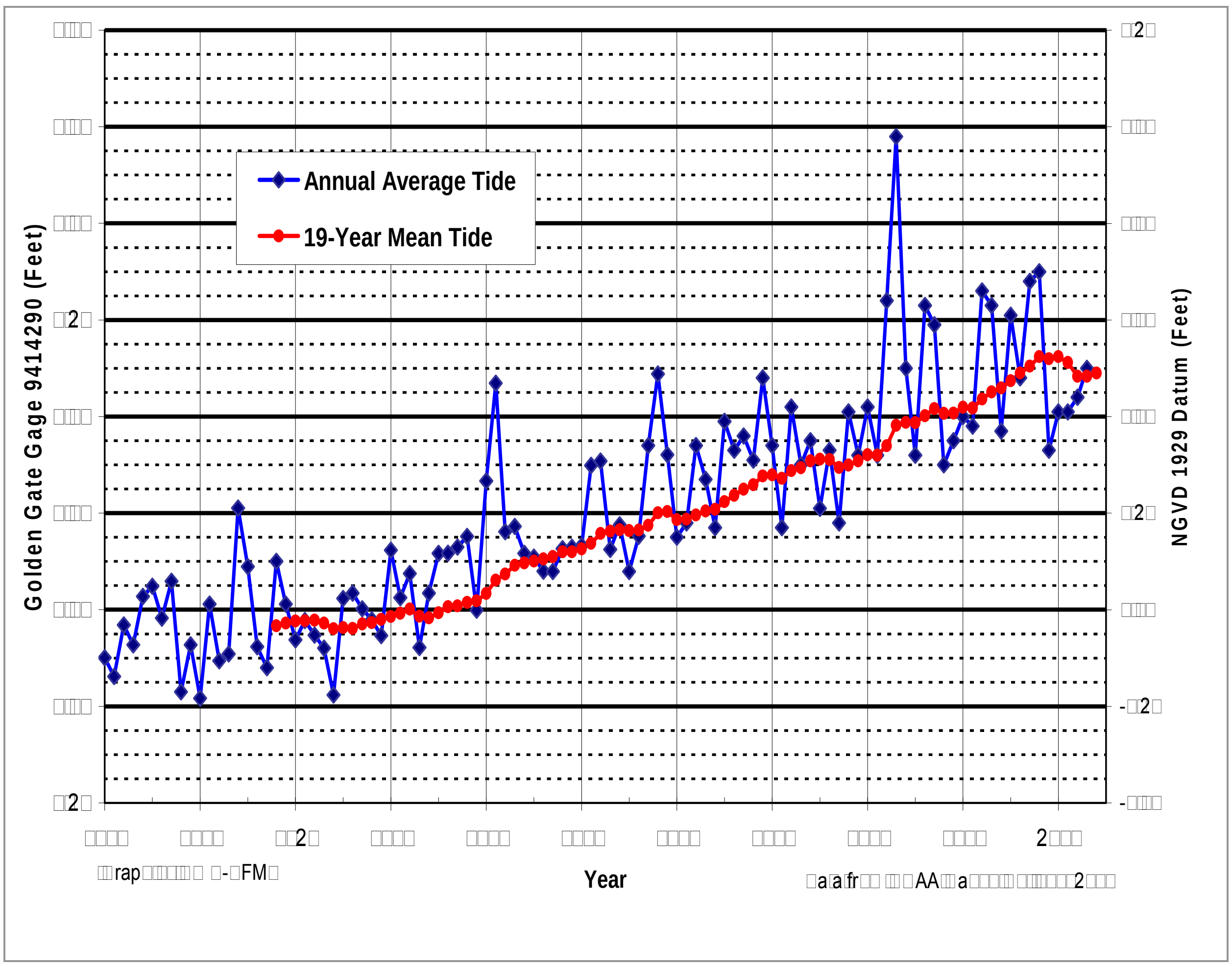



**Figure 2-27 Graph of Annual Average Relative Sea Level and the 19-Year Running Average Sea Level at the San Francisco Tide Gauge**

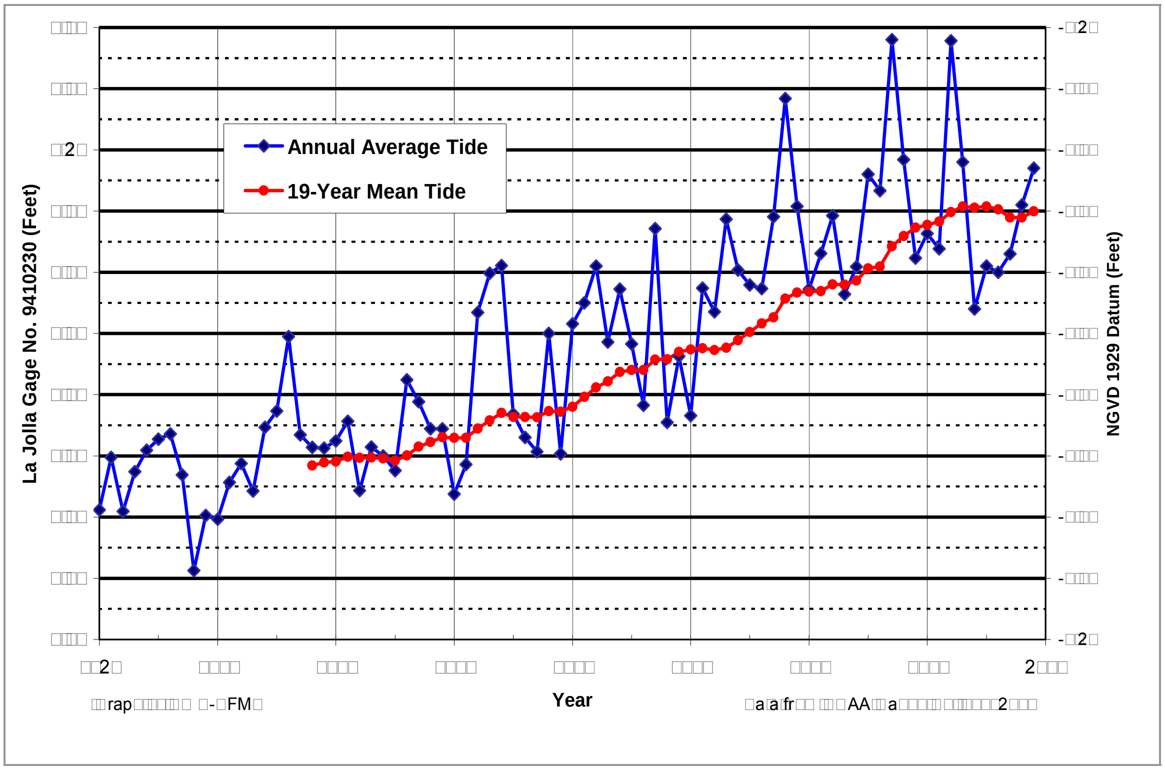



**Figure 2-28 Graph of Annual Average Relative Sea Level and the 19-Year Running Average Sea Level at the La Jolla Tide Gauge**

## 2.6.2 Consequences of Sea Level Rise

### 2.6.2.1 Sea Water Intrusion into Estuaries and River Systems

As mentioned previously, sea level rise during this century will cause increased sea water intrusion into California's coastal marshes and estuaries. Increased intrusion will likely disrupt marsh and estuary ecosystems, especially at the higher projections of sea level rise. Sea water intrusion into the Sacramento - San Joaquin River Delta could cause negative effects on fishes, as discussed in Section 2.9 and increase Delta salinity levels, as discussed in Chapter 5, Section 5.5. Increased salinity levels in the Delta would have a detrimental effect on Delta water supply operations if existing operations in the Delta remain the same and the Delta's configuration is not changed.

### 2.6.2.2 Sea Water Intrusion into Groundwater

Groundwater plays a significant role in providing California's water supply. In an average year, groundwater meets about 30 percent of California's urban and agricultural water demand. This percentage increases to more than 40 percent during drought years. In 1995, an estimated 13 million Californians, nearly 43 percent of the State's population, were served by groundwater. The demand on groundwater will likely increase as California's population grows (DWR, 2003).

Most of the State's groundwater is produced from alluvial groundwater basins. Alluvial basins are typically valleys that have been partially filled with sediment. Coarser sediment, such as sand, serves to store and transmit significant quantities of water to wells. Layers of finer sediment, such as clay, tend to restrict the movement of groundwater.

DWR has delineated 431 groundwater basins in California beneath about 40 percent of the State's surface area (DWR, 2003). The locations of these basins are illustrated in Figure 2-29.

More than 200 groundwater basins have been identified along the coast of California. Many of these basins play, or could potentially play a significant role in providing a local water supply. Many of California's larger urban areas, including the Los Angeles metropolitan area, overly coastal groundwater basins and derive a significant potion of their supply from groundwater. Regionally and nationally-significant agricultural areas that overlay coastal groundwater basins include the Salinas Valley, Santa Maria Valley and the Ventura-Oxnard Plain.

While most groundwater produced in coastal areas is derived from groundwater basins, groundwater is also produced from mountain and hillside areas underlain by rock, old marine deposits, or volcanic deposits. Such areas typically produce small quantities of groundwater compared to alluvial basins.

Figure 2-30 is a simple illustration of a cross-section of a coastal groundwater basin. The deposits of some coastal groundwater basins in California extend a significant distance beyond the coastline and contain saline ocean water. Under natural conditions, fresh water in coastal aquifers flows toward the ocean keeping saline ocean water from moving inland. However, if inland groundwater levels are lowered through pumping, ocean water may move inland.

Many groundwater basins along California's coast are very susceptible to sea water intrusion, or the intrusion of brackish water from bays and estuaries. Sea water intrusion into California's coastal aquifers was first noted in the 1930s and 1940s. Some of the earliest observations were in Los Angeles and Orange counties. Other areas where a significant amount of seawater intrusion has occurred include Ventura, Santa Cruz and Monterey counties, and some areas around San Francisco Bay and the Sacramento-San Joaquin River Delta. (DWR, 1958; DWR, 1975; DWR, 2003). Sea water intrusion in the Salinas Valley has been observed as far as 5 miles inland (DWR, 1994).

Rising sea level increases the potential for sea water intrusion into coastal groundwater aquifers and other coastal groundwater resources by increasing the pressure of ocean water exerted against water-bearing deposits extending inland from the coast. Rising sea level can also increase the potential for intrusion of sea water into coastal groundwater basins through the inundation of areas that were formerly above sea level.

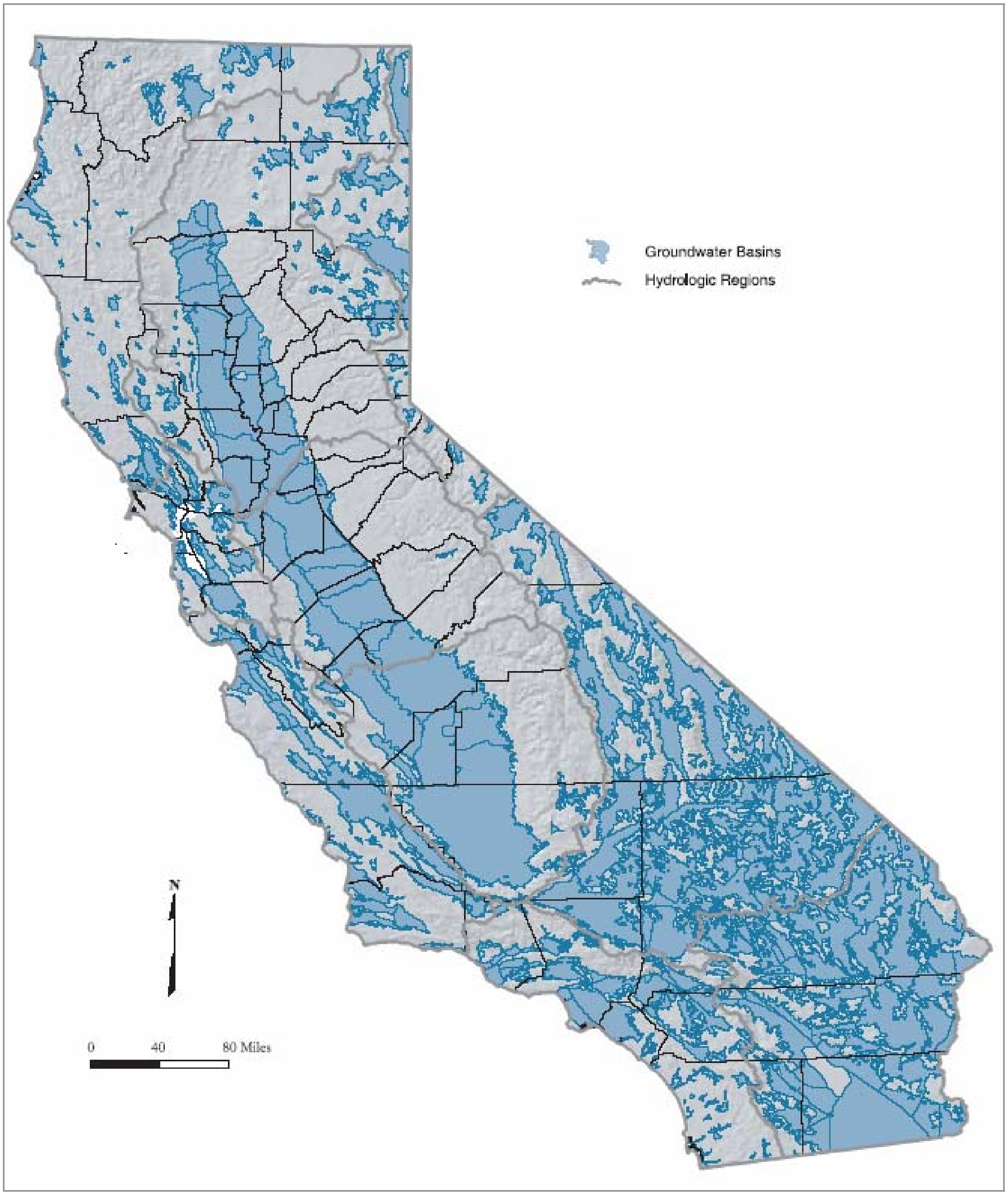



**Figure 2-29 California's Groundwater Basins**

Source: DWR, 2003

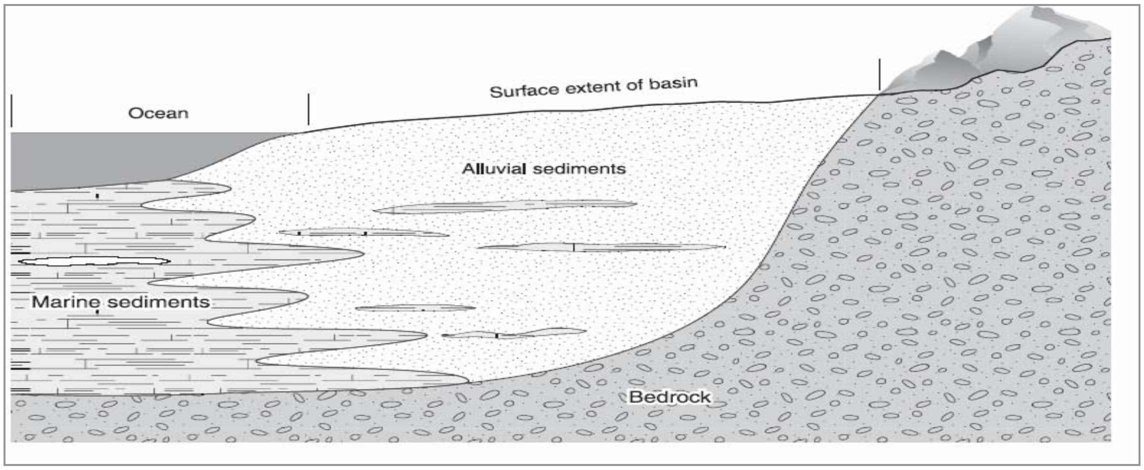



**Figure 2-30 Simplified Cross-Section of a Coastal Aquifer**
Source: DWR, 2003

The threat posed to coastal groundwater resources by sea level rise can be lessened by various means including controls on well construction and groundwater production, and the operation of hydraulic barrier projects. Hydraulic barrier projects typically involve the injection of treated wastewater or imported water into coastal aquifers to prevent ocean water from moving inland.

The threat to groundwater from the inundation of land by sea level rise can be lessened through shoreline engineering, such as the installation of sea walls. It is anticipated that shoreline engineering projects will be undertaken along many low-lying areas of California's coast to protect areas with high real estate values. Shoreline engineering may be difficult, impractical, or environmentally unacceptable for some of California's bays, estuaries and coastal marshes. Some of these areas might be subject to uncontrolled inundation due to sea level rise.

### 2.6.2.3 Flooding Risk in the Sacramento-San Joaquin River Delta

The Sacramento-San Joaquin River Delta is highly susceptible to flooding. The Delta includes 70 islands and tracts. Most have land surfaces at or below mean sea level. Land surface on some Delta Islands is as much as 25 feet below mean sea level (DWR, 2005a). The location of the Delta is depicted in Figure 2-19, and a detailed view of the Delta and its islands is shown in Figure 2-31.

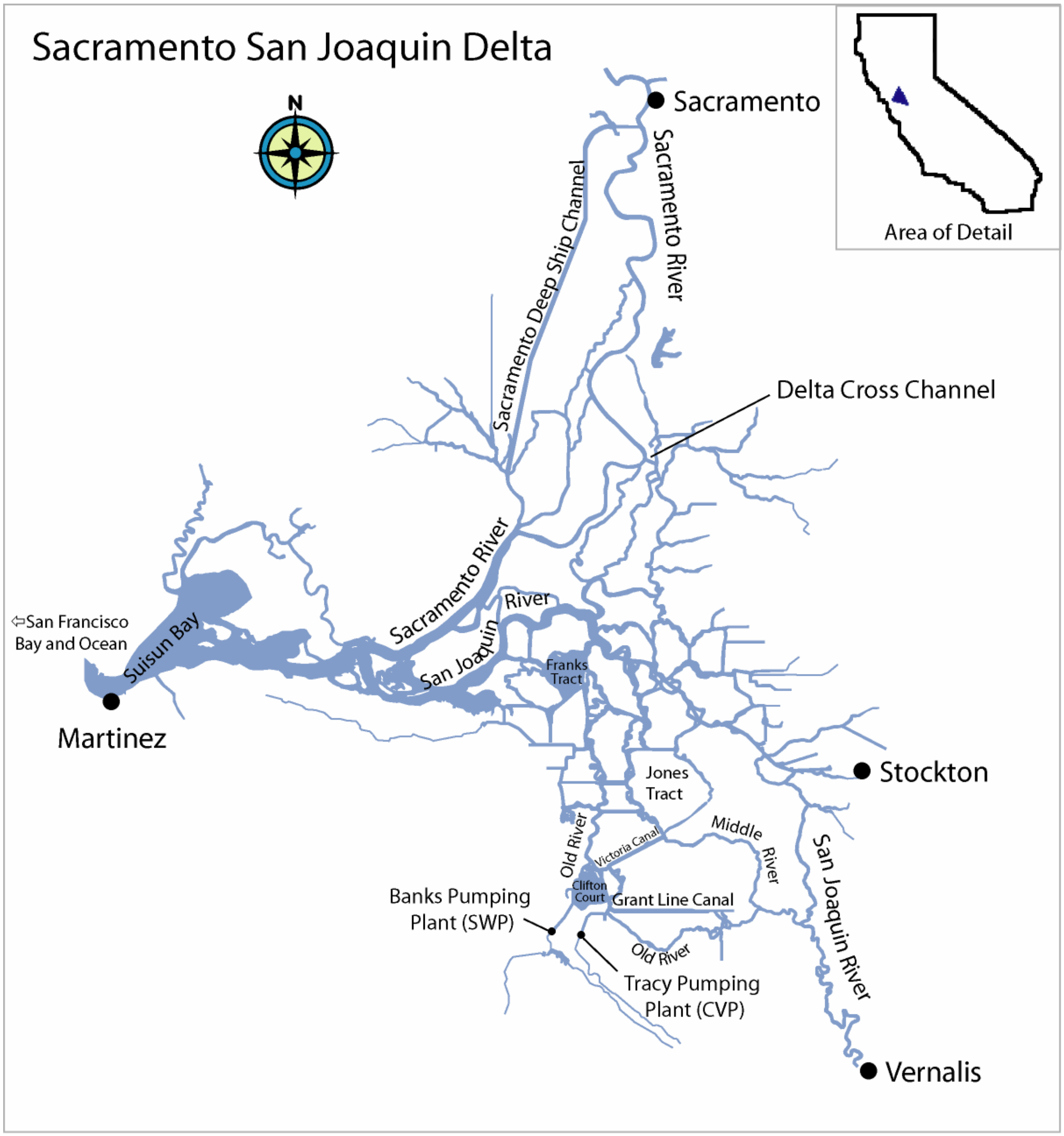



**Figure 2-31 Sacramento-San Joaquin River Delta**

The islands and tracts of the Delta are protected from the constant threat of inundation by about 1,100 miles of levees. Levee failure can occur due to seepage, piping, slippage, subsidence, sloughing or earthquakes, even during dry weather. Levee failure impacts include potential loss of human life, irreparable harm to the Delta's fragile ecosystem and its listed and endangered species, disruption of utilities and highways and water supply disruption. Water supply disruption can occur when levee failure and island flooding cause salinity levels in the Delta to increase to unacceptable levels due to:

- large amounts of saline ocean water to being drawn into the Delta from the San Francisco Bay, and
- increases in the volume of the Delta's tidal prism and resultant increases in the tidal exchange of saline water in the Delta.

Once a levee fails in the Delta and island flooding occurs, salinity conditions can take weeks or even months to return to normal, depending on the amount and location of levee failures and hydrologic conditions.

#### 2.6.2.3.1 Future Increased Risk of Flooding in the Delta Due to Land Surface Subsidence and Climate Change

Flood risk in the Delta is increasing with time due to land surface subsidence and sea level rise. Land subsidence and sea level rise also increase the consequences of levee failure.

As mentioned earlier, worldwide average sea level rise is projected to be about 0.3 of a foot to 2.9 feet from 1990 to 2100 (IPCC, 2001a). Rising sea levels are likely to have a direct effect on water levels in the Delta because the bottom of essentially all Delta channels and waterways are at or below current mean seal level. Rising sea level will cause backwater effects upstream of the Delta.

Global sea level rise combined with short-term or episodic factors that increase sea level and water levels in the Delta will reduce available levee freeboard unless levees are raised. Short-term and episodic increases in water levels in the Delta include high river flows, ocean/atmosphere phenomena such as El Nino's, storm surge, barometric high tides and high astronomical tides (particularly during perigee, perihelion, and either new or full moon). Figure 2-32 illustrates the relative impact that sea level rise will have on astronomical tides in the Delta. An especially high level of risk would occur if several periodic events were to occur at the same time in the Delta.

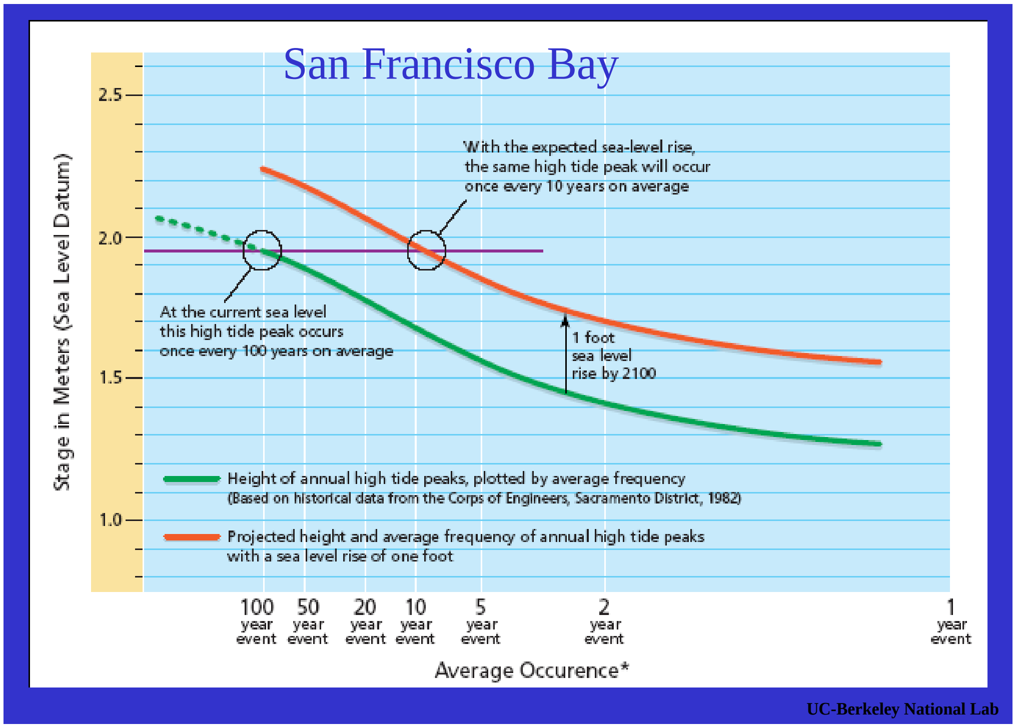



**Figure 2-32 Impact of One Foot of Sea Level Rise on the Relative Effect of Astronomical Tides in the Delta**

Source: Lawrence Berkeley National Lab (Miller, 1998).

Climate change may affect the magnitude and frequency of flood flows entering the Delta. In their paper on the potential impacts of climate change on California hydrology, Miller and others (2003) present peak river flow data based on climate change simulations. These data show an increased probability of higher annual peak flows for Central Valley rivers. These potential increased flows have yet to be quantified with any confidence. Higher flows will lead to higher water surface elevations in the Delta, especially in its upper reaches.

Ocean temperature anomalies, such as an El Nino, can cause a short-term rise in sea level along California's coast and thus increase water levels in the Delta. For example, the maximum water surface anomaly associated with the 1997-1998 El Nino event increased the level of the ocean along California's coast between about 0.6 to 0.8 of a foot during January 1998 (Bromirski, 2005). This level of rise was due to a combination of steric effects and poleward propagating, coastally-trapped waves. Climate change may increase the frequency or duration of El Nino events (Wara, 2005), although there is a significant amount of uncertainty about possible changes in the nature and occurrence of temperature anomalies in the Pacific as the result of climate change (Kerr, 2005).

Wind driven storm surge can also increase water surface elevations in the Delta. Stronger winds associated with some winter storms would lead to even greater changes in water surface elevations. Such changes are a function of channel geometry and the distance of open water with respect to wind direction, referred to as "fetch."

Subsidence also must be considered as a risk to Delta levees. The surfaces of many of the Delta's islands and tracts are dominated by soils rich in peat. Peat is a complex organic material that is principally composed of degraded plant matter. Subsidence in the Delta primarily occurs when peat soils are exposed to oxygen and undergo microbial decomposition due to agricultural practices. Subsidence also occurs when peat soils are lost by wind erosion and occasional peat fires. The peat soils of the Sacramento-San Joaquin Delta have subsided at rates of up to about 2 inches per year in the past. Subsidence rates have been the highest in the central Delta islands (Mount, 2004).

Subsidence increases the threat of flooding in the Delta by increasing the differential forces that levees experience. Subsidence also increases the volume of water that can inundate an island or tract when a levee fails. Together, the continued subsidence of Delta islands and rising sea level pose a double-sided threat for Delta levees and flooding. Other factors such as possible increases in peak river flows as the result of climate change further increase the threat to Delta levees.

## 2.7 Future Water Demand

California's water supply future will be determined by two principal factors, the condition of the State's water resources and water demand. Climate change will likely have a significant effect on California's future water resources, as discussed elsewhere in this report. Climate change will likely also have an effect on future water demand. However, many other factors such as population, land development and economic conditions that are not directly related to climate change will also affect future demand. Table 2-7 provides a summary of some of the potential effects of climate change on future water demand. Table 2-8 lists selected factors that could affect future water demand that will not be directly affected by climate change.

Today there is much uncertainty about future water demand, especially those aspects of future demand that will be directly affected by climate change and warming. While climate change is expected to continue through at least the end of this century, the magnitude and, in some cases, the nature of future changes are uncertain. This uncertainty serves to complicate the analysis of future water demand, especially where the relationship between climate change and its potential effect on water demand is not well understood.

Of the water demand factors that could be directly affected by climate change, potential changes in evapotranspiration, agronomic practices, and environmental water demand might be the most significant for California. Of the changes in demand not directly affected by climate change, changes in demand related to population growth and technological innovation could be the most significant. The following discussion is mostly limited to these aspects of future water demand. Chapter 7 provides additional discussion on evapotranspiration and possible changes in evapotranspiration due to climate change.

**Table 2-7 Summary of the Potential Effects of Climate Change on Future Water Demand**

| Type of Demand | Potential Effect |
|---|---|
| Crop Irrigation | Increasing temperatures will increase evapotranspiration rates and related water demand where all other factors remain unchanged. Increasing concentrations of atmospheric carbon dioxide may act to reduce increases in plant transpiration (a component of evapotranspiration) in response to increased temperatures. Other factors related to climate change, such as possible changes in humidity, cloudiness and wind could also affect evapotranspiration rates.<br><br>Evaporation rates from soil and plant surfaces may rise due to temperature increase, depending on changes in other factors that affect evaporation rates. Increased evaporation rates could increase salt accumulation on plant surfaces, especially where overhead irrigation is used. Salt accumulation in surficial soils could also increase. Additional irrigation water demand may result because of possible increased salt control requirements.<br><br>Some changes in crop type, planting cycles, time of planting, and crop productivity will likely occur as the result of increased temperatures. Statewide and regional irrigation water demand may increase or decrease as the result of these changes.<br><br>Use of water for frost protection will likely be reduced with increasing temperatures and projected reductions in the annual number of days when frost occurs. Frost protection is typically an important consideration for orchards and vineyards. |
| Landscape Irrigation | Increased temperatures, as well other atmospheric/climatic factors related to climate change, will affect landscape irrigation in manner similar to that described for crop irrigation, above. |
| Domestic Water Uses (excluding landscape irrigation) | Domestic water use typically increases with increasing temperature. Increased water demand can occur due to the use of evaporative cooling, increased laundering of clothing, increased bathing, increased drinking water requirements for humans and pets and recreational uses of water. |

**Table 2-7 Summary of the Potential Effects of Climate Change on Future Water Demand (continued)**

| Type of Demand | Potential Effect |
|---|---|
| Commercial and Industrial Water Use (including agro-industrial facilities such as dairies, poultry farms, packing plants, etc.) | Commercial and industrial water use will likely increase as the result of warming due to such factors as increased evaporative cooling demand. Increased consumption of water by concentrated animal feeding facilities, such as dairies and poultry farms, would also likely occur. |
| Evaporation Losses from Natural Water Bodies and Open Water Storage and Conveyance Facilities | Evaporation losses from water bodies and open conveyances will probably increase as the result of rising temperatures especially in arid portions of the State with low humidity and limited cloud cover. |
| Environmental Water Requirements | Delta outflow requirements will likely increase to maintain Delta salinity conditions in response to sea level rise; if the Delta's existing configuration, operation of its water supply facilities, and its ecosystem conditions are to remain as they are now.<br><br>Higher temperatures will likely result in increased environmental water demand for controlling water temperatures for sensitive aquatic species, including anadromous fish. Increased use of reservoir storage and thermal control releases from reservoirs will be required for controlling aquatic habitat temperatures. |

**Table 2-8 Selected Factors Affecting Future Water Demand in California that are Not Directly Related to Climate Change**

| Factor | Potential Effect |
|---|---|
| Population Change | Future increases in population will affect water demand, depending on the location and types of development needed to support an increased population. The conversion of agricultural lands into housing and related community development may not result in a significant increase in water use for a given area, depending on the agricultural use(s) that existed prior to land conversion, and on the type of housing and other facilities constructed. Redevelopment and densification of existing urban land may result in increased water demand in some areas. Development of raw, uncultivated land will directly increase water demand. In general, increases in California's population will tend to increase future water demand. |
| Changes in Agriculture | Changes in the type and amount of crops grown due to changes in agricultural markets and government crop subsidy programs may help increase or decrease agricultural water demand. |
| Changes in Landscaping Practices | Changes in consumer preferences and changes in land use ordinances relating to landscaping may affect future landscape water demand. |
| Changes in Environmental Water Use Requirements | The findings of continuing scientific research related to the condition and preservation of aquatic ecosystems in the State, including the Delta, may affect environmental water demand. |
| Water Law and Policy | Changes in water law and policy could affect water demand. |
| Technological Innovation | Lowered consumption rates could result from improvements in water use efficiency for irrigation, domestic, commercial, and industrial uses. Increased reuse of wastewater could help reduce demand on existing and future sources of water. Advances in desalinization technology may reduce demands on the State's freshwater resources, especially in areas along the south coast. |

### 2.7.1 Evapotranspiration

The collective term *evapotranspiration* refers to the vaporization of water from soil and plant surfaces (i.e., evaporation) and vaporization that occurs in plant leaves with water diffusing through pores (stomata) to ambient air (i.e., transpiration). Transpiration is controlled by water availability from the soil, plant morphological and physiological characteristics, and atmospheric conditions which determine how much energy is available to vaporize water inside leaves. Climate and plant type are important determinants of evapotranspiration rates. Even small increases in evapotranspiration rates from crops and landscaping as the possible result of climate change could affect California's overall water demand. This is because of the relatively large amount of the State that is dedicated to irrigated agriculture and the significant amount of landscaping in urban areas.

Increased temperature and atmospheric carbon dioxide concentrations are the two most consistently projected aspects of climate change that will impact evapotranspiration rates for crops and landscaping in California. Hidalgo and others (2005) concluded that a temperature increase of 3 degrees Celsius will result in a 5 percent increase in plant transpiration, unless there is a compensating decrease in solar radiation or other component of the plant energy budget. Increasing carbon dioxide concentrations in the atmosphere may tend to reduce transpiration losses from plants. Other important factors affecting evapotranspiration include wind, dew point (humidity), cloudiness and minimum temperature.

A number of studies related to physiological, biochemical and phenological plant responses to increased atmospheric carbon dioxide concentrations have been published including those studies using data from the 18 free-air carbon dioxide enrichment research sites around the world (Long, 2004). Stomatal responses at elevated atmospheric carbon dioxide concentrations seem to decrease water vapor diffusion; however, more information is needed to better understand the effects of increasing concentrations of atmospheric carbon dioxide on transpiration.

Increased atmospheric carbon dioxide concentrations may also serve to increase vegetal production. Possible increases in production could, in turn, serve to increase total transpiration from individual plants, as well as increase the per-plant water demand for tissue production and direct evaporation from vegetal surfaces. Long and others (2004) found that carbon dioxide concentrations expected by mid-century would increase dry matter production about 20 percent and seed yield by 24 percent for some plant types, including most crops and trees.

Urbanization can affect local evapotranspiration rates through regional greenhouse gas emissions, increasing amounts of plant physiological stressors such as atmospheric ozone, and through higher temperatures associated with urban island heat effects. Slone and others (2005) reported that temperatures over urban centers can be elevated while temperatures over irrigated land tend to be lower than temperatures over undeveloped areas. A significant increase in urbanization in California is expected by the end of this century.

### 2.7.2 Agronomic Practices

As noted in Table 2-7, climate change and increasing temperatures can affect total crop water demand by inducing changes in crop type, planting cycles and time of planting. Few studies have assessed the possible impacts of climate change on crop patterns in California (Hayhoe, 2004).

Plant physiological responses to increasing temperature will be mixed, therefore there are likely to be varying agronomic responses to climate change. For example, fewer frost days would allow citrus production to extend to higher latitudes and elevations, including in the Central Valley. However, fewer frost days would be detrimental for tree crops having a chill requirement.

There has been a long-term shift toward planting permanent crops in many parts of California, such as trees and vines. Climate change may increase the variability in precipitation and increase the frequency of droughts. Since agricultural water supplies tend to be curtailed before urban supplies during droughts, the possible consequences of increased droughts for agriculture could become more severe because of increased planting of permanent crops. Droughts typically do not cause lasting damage where crops are planted annually.

### 2.7.3 Changes in Environmental Water Demand

Climate change could have a significant effect on environmental water demand in California. Two aspects of environmental water demand that will likely be impacted the most are salinity control requirements for the Sacramento-San Joaquin River Delta and temperature control demand for various rivers and the Delta.

#### 2.7.3.1 Delta Salinity Control

The Delta is a key component of California's water supply infrastructure. A major portion of the State's agricultural and urban water supply passes through the Delta to State Water Project and Central Valley Project water diversion facilities.

Salinity levels in the Delta depend on outflow from the Delta to the San Francisco Bay and Pacific Ocean. Saline water from the San Francisco Bay is pushed out of the Delta during periods of high Delta outflow. Saline water can enter the Delta and increase salinity a significant distance inland during low outflow.

Delta outflow primarily depends on the amount of freshwater entering the Delta and the diversion of water from the Delta for the Central Valley Project, the State Water Project, and in-Delta uses which collectively reduce outflow. Most of the inflow to the Delta comes from the Sacramento, Cosumnes, Mokelumne, and San Joaquin rivers. Flows from these rivers are typically highest during the winter and spring in response to annual precipitation and snowmelt. The lowest flows typically occur in the late summer and fall.

The greatest challenge for maintaining salinity levels in the Delta typically comes in the late summer and fall when natural Delta inflow is usually the lowest. Reservoir releases during this time help maintain river flows into the Delta in the absence of enough natural runoff. The rate of pumping from the Delta can be reduced during this period to help maintain Delta outflow and prevent salinity intrusion. Pumping operations have been severely cut back during dry years; especially when reservoir storage levels are very low due to drought.

As discussed in Section 2.5, climate change is expected to cause more precipitation in the form of rain rather than snow, reductions in water storage in annual snowpack, earlier snowmelt and sea level rise. Each of these factors could present significant reservoir management challenges, particularly for reservoirs in the Sierra foothills. These reservoirs will likely experience changes in the rate and timing of inflow. Changes in reservoir operations and reduced annual storage in snowpack could result in less water being available in the summer and fall to meet Delta outflow and salinity control requirements.

#### 2.7.3.2 Water Temperature Control

Increased air temperatures as the result of climate change will likely increase water temperatures in the State's lakes and waterways. Increased water temperatures pose a threat to aquatic species that are sensitive to temperature, including anadromous fish. Increased water temperatures will also cause decreased dissolved oxygen concentrations in water and other water quality changes, and will likely increase production of algae and some aquatic weeds.

Intermittent temperature problems now exist for some aquatic species in some Central Valley rivers and streams, and in portions of the Delta. Intermittent temperature problems also occur in other areas of the State; including in the Klamath, Eel, and Russian river basins. High water-temperature problems typically occur during the summer and early fall.

Water resource managers often release cold water stored in reservoirs to control downstream water temperatures for aquatic life. Most of the water held in the State's reservoirs is accumulated in the winter and spring when temperatures are lower than at other times of the year. Reservoirs that are downstream of significant snowpack receive cold water from snowmelt through the spring and sometimes into the summer.

Climate change and rising temperatures will increase demand for temperature control releases from many reservoirs. However, coldwater storage in reservoirs needed to supply releases may decrease as the result of climate change due to:

- diminished snowpack and less inflow of late-season cold snowmelt, especially for lower elevation reservoirs in the Sierra Nevada
- increased heating of reservoir inflow
- increase heating of reservoir content and releases
- possible loss of reservoir storage for thermal control releases due to changes in reservoir operations in response to changes in runoff timing

Increased temperature control requirements together with a possible decreased capacity to provide temperature control releases from reservoirs as the result of climate change, could pose a double-sided threat for some aquatic species.

### 2.7.4 Population

California has experienced rapid population growth since the mid 1800s. This growth is due in part to California's strong economy, natural beauty and relatively mild climate.

California's population is approaching 37 million. The California Department of Finance projects the State's population to be about 44 million by 2020 and about 55 million by 2050 (DOF, 2004). California's population could be as high as 90 million by the end of the century (Landis, 2003). Figure 2-33 depicts growth in the State's population from 1850 to 2005, and projected growth to 2050.

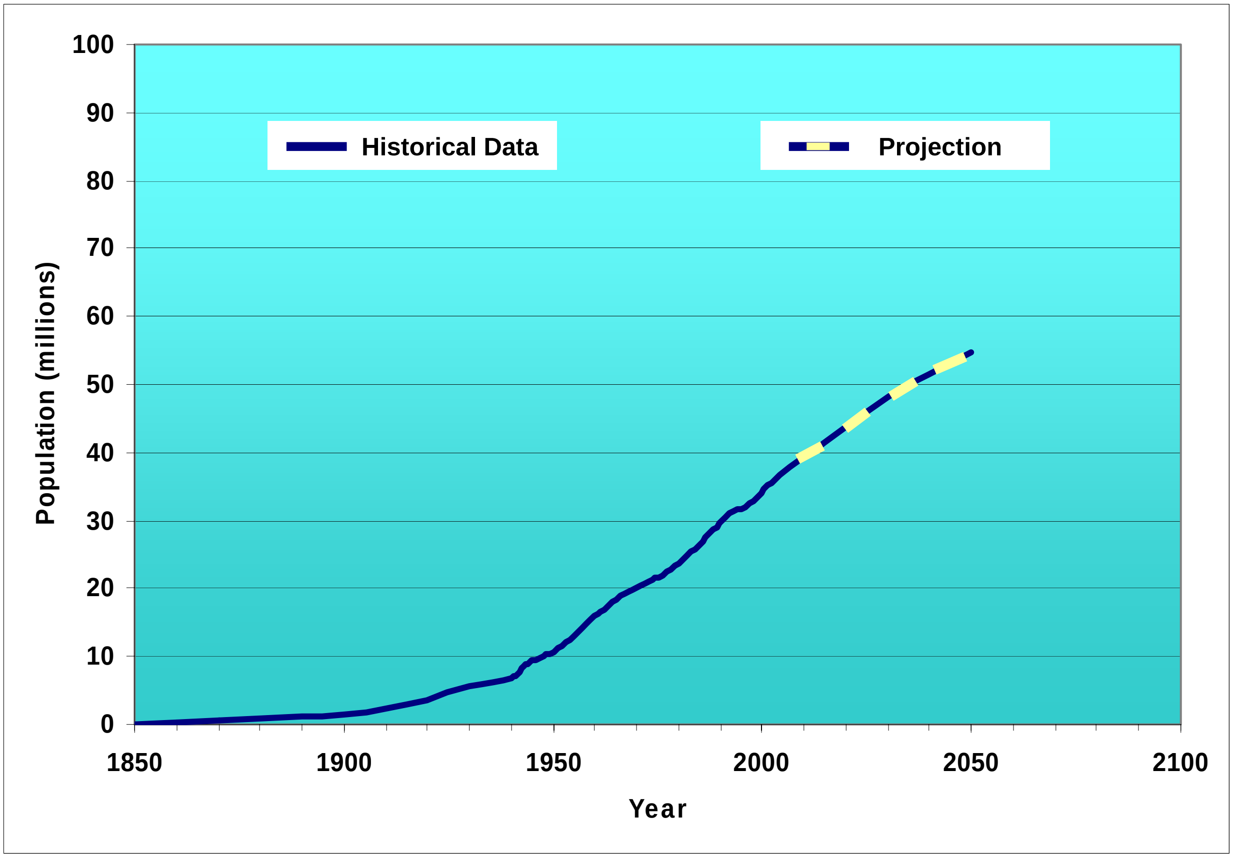



**Figure 2-33 Historical and Projected Future Population Growth in California**

Data source: DOF (2005)

Future increases in population will affect water demand, depending on the location and types of land development that occur to support an increased population. Much of California's future development is projected to occur on valley floor areas, including in the Central Valley along major transportation systems (Landis, 2003). While climate change is generally not expected to have a major effect on future population growth in California, it could have some effect on the where development occurs.

The conversion of agricultural lands into housing, commercial and industrial uses may not result in an increase in water use for a given area, depending on the agricultural use(s) that existed before conversion and on the specific type of development. Redevelopment and densification of existing urban land may result in increased water demand in some areas. Urbanization of undeveloped land will serve to increase water demand directly. While there is much uncertainty about California's future population growth and development, an increase in the State's population is generally expected to increase the State's total water demand, absent additional measures to conserve water.

### 2.7.5 Technological Innovation

Technological innovation could play a significant role in determining California's future water demand, as well as future supply. Innovation in water conservation practices could serve to reduce water demand by allowing water to be used more efficiently. Innovation in water resource management could allow California's water resource systems to be managed more efficiently and allow more water supply yield with the same or less environmental impact. Innovation in water resource management and water use would occur with or without climate change. However, given the potential impacts of climate change, there will be an increased impetus for innovation.

A key area for future technological innovation is agricultural water use efficiency. Tanaka and others (2005) have determined that by the year 2100, agricultural water use will fall by 24 percent, while loss of income from agriculture will decrease only 6 percent. This discrepancy between water use and income comes from a predicted shift to higher-value crops and more efficient use of water. A theoretical body of work suggests that horticultural breeding improvements alone can attain a maximum increase in water use efficiency of about 15 percent (Cowan, 1977).

An area of innovation that could affect future water supply conditions, at least in some parts of the State, is sea water desalinization. The unit cost of desalinization has fallen in recent years, however, desalinization remains a relatively expensive and energy-intensive means of obtaining water compared to other water sources. More improvements in desalinization technologies could reduce costs and energy requirements. Desalinization could become a more competitive source of water, especially in coastal areas of Southern California where water is often imported from long distances and at high cost partly because of energy requirements.

## 2.8 Colorado River Basin

This report is primarily focused on the potential effects of climate change on the Central Valley and associated water resource systems. This is because the Central Valley and its water resource systems supply most of California's water, and because much of the effort to assess the impacts of climate change on the State's water resources has been directed toward the Central Valley. Climate change will affect water resource systems that obtain water from areas outside of the Central Valley. While the timing and scope of this report preclude substantive discussion of most of these systems, it is important to mention the single largest source of water supply for California outside of the Central Valley, the Colorado River.

The Colorado River is an important source of water for Southern California. In the past, California has diverted as much as 5.3 million acre-feet annually from the Colorado River. This is in excess of the State's annual allotment of 4.4 million acre-feet. Even at the allotment of 4.4 million acre-feet per year, the River still supplies about half of Southern California's average annual net water use (DWR, 2005a).

California's diversions from the Colorado River are primarily through the All-American Canal and the Colorado River Aqueduct. The All-American Canal supplies water to cities and agriculture in the Imperial Valley, and to agriculture in the Coachella Valley. The Colorado River Aqueduct supplies water to agriculture and cities of the south coast. Figure 2-34 illustrates the location of the All-American Canal and the Colorado River Aqueduct, as well as the greater service areas for the two systems.

An overview of past, present, and future climate in the Colorado River Basin is presented in a 2005 DWR special report prepared for the Association of California Water Agencies and Colorado Water Users Association conferences (DWR, 2005b). The report discusses hydroclimatic issues for the Colorado River Basin and their implications for water users in the basin. Portions of that report are cited below.


**Figure 2-34 The Colorado River Aqueduct, All American Canal and Their Service Areas**

Source: California Department of Water Resources, http://www.crss.water.ca.gov/data/ca_service_area.cfm

### 2.8.1 Description of the Colorado River Basin and its Water Resources

The Colorado River Basin extends into seven western states and Mexico, each of which has strong interests in the river and its water. The states are Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming, as shown in Figure 2-35. While the volume of natural runoff in the basin is relatively small in comparison to its area, an average of about 15 million acre-feet of runoff is generated each year in the Colorado River Basin above Lees Ferry. Lees Ferry is labeled as "Compact Point" in Figure 2-35.

The Colorado River and its tributaries are the major source of water for many of the rapidly growing cities of the seven basin states and northern Baja California. The cities include Denver, Salt Lake City, Las Vegas, Phoenix, Tucson, Los Angeles and San Diego and other communities in south coastal California.

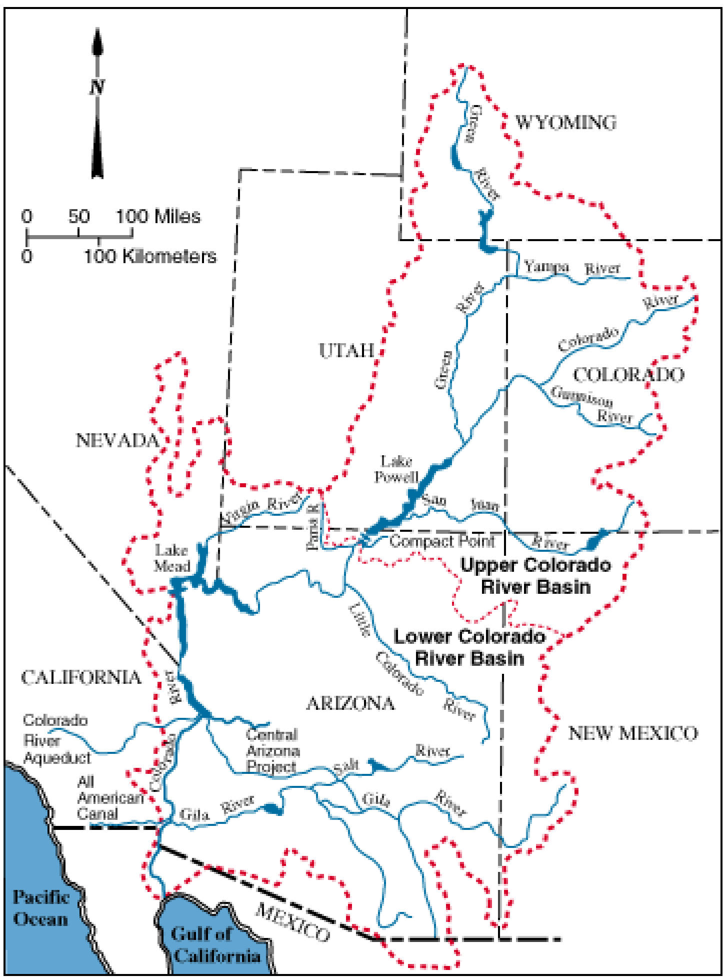



**Figure 2-35 Map of the Colorado River Basin**

Source: (Dettinger, 1995) http://geochange.er.usgs.gov/sw/changes/natural/codrought/

The Colorado River rises into the snow capped mountains of north central Colorado and flows southwesterly about 1,400 miles to Mexico and the Gulf of California. The River's major tributaries are the Green River, originating in the Wind River Mountains of southwest Wyoming, the Gunnison River from west central Colorado and the San Juan River from southwest Colorado.

The Colorado River basin is estimated to cover an area of about 244,000 square miles, about 8 percent of the land of the conterminous United States. About 2,000 square miles of the basin is in Mexico. The basin is typically considered to consist of two parts, an upper and lower basin, with the dividing point at the Lees Ferry gauging station in north-central Arizona, just downstream of Glen Canyon Dam and Lake Powell.

The upper Colorado River basin is nearly half the total drainage area of the entire basin or 109,300 square miles. Most of the water flowing in the Colorado River originates in the upper basin mountains, but significant tributaries also exist in the lower basin including the Little Colorado River in northeastern Arizona, the Virgin River in southwestern Utah and southeastern Nevada and the Gila River system of south central Arizona and extreme western New Mexico.

The Colorado River basin is one of the driest major watersheds in the United States. Average annual basin precipitation is 13.9 inches, with an annual average of 15.2 inches in the upper basin and 12.9 inches in the lower basin. Much of the Colorado River basin is desert receiving less than 10 inches of precipitation per year. High elevation areas receive significantly more precipitation, over 50 inches at some locations. The wetter areas of the Colorado River Basin consist of the Wind River Mountains in Wyoming, Rocky Mountains in Colorado, San Juan Mountains in southwest Colorado, the Uinta Mountains in northeast Utah and the Mogollon Rim in east central Arizona. The driest areas of the basin are in the basin's southwest corner near Yuma, Arizona. This area receives about 3 inches of annual precipitation. Figure 2-36 illustrates the distribution of average annual precipitation in the basin.

Most of the precipitation in the Colorado River basin is from winter storms originating in the Pacific Ocean. Most of the runoff from these storms comes from the high mountainous areas in the basin's upper reaches. These areas are favored by orographic precipitation and winter snowpacks. While these areas only constitute about 15 percent of the basin's entire area, they generate about 85 percent of its entire natural runoff.

Occasionally, more often in El Nino years, major winter storms from the Pacific Ocean move across Southern California and into the lower portions of the basin. These southern-track storms can provide heavy winter rainfall at low elevations in Arizona, and heavy snow in the San Juan Mountains of southwestern Colorado.

A major factor that sets the climate of the Southwest United States and southern part of the Colorado River Basin apart from the rest of the country is the North American monsoon system. Typically, during the months of July, August, and the first half of September, regional circulation patterns change and cause moisture-laden air to move into the Southwest from the Pacific Ocean, the Gulf of California, and the Gulf of Mexico. As this moist air moves into the southwest, a combination of orographic uplift and daytime heating from the sun causes thunderstorms to develop.

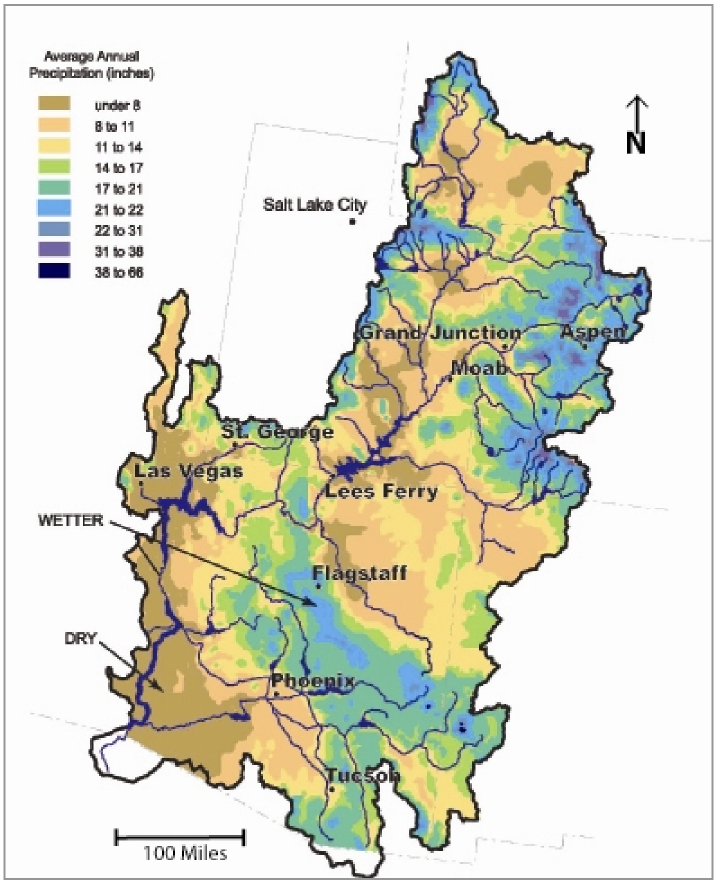



**Figure 2-36 Distribution of Average Annual Precipitation in the Colorado River Basin**
Adapted from The University of Arizona's Institute for the Study of Planet Earth CLIMAS
http://www.ispe.arizona.edu/climas/learn/swnutshell/sld004.htm

Summer monsoonal rainfall is an important fraction of the total annual precipitation received in southeastern Arizona, much of New Mexico, and southern Colorado. Most of the monsoonal rain is from thunderstorms and is highly localized and sometimes very intense. Although monsoonal rainfall is very important to nourishing watershed vegetation in parts of the southwest, and can cause local flooding, it does not contribute much to flows in the Colorado River or its major tributaries.

Finally, in the summer of some years, the remnants of a Pacific hurricane off the west coast of Mexico will move north over northwestern Mexico and into the Southwest United States. These tropical storms can produce regional rainfall over the desert and flash floods in some of the mountain watersheds.

Since the latter part of 1999, the upper Colorado River basin has experienced an extended severe drought. Water year 2005 saw improved hydrologic conditions in the basin. Figure 2-37 illustrates the volume of water stored in Lake Powell and Lake Mead since the construction of both reservoirs. The decline in reservoir storage after 1999 illustrates the significance of the recent drought. While hydrologic conditions improved in Water Year 2005 and the severity of drought conditions in the basin has eased somewhat, it is premature to declare that the drought in the upper basin is over (DWR, 2005b).

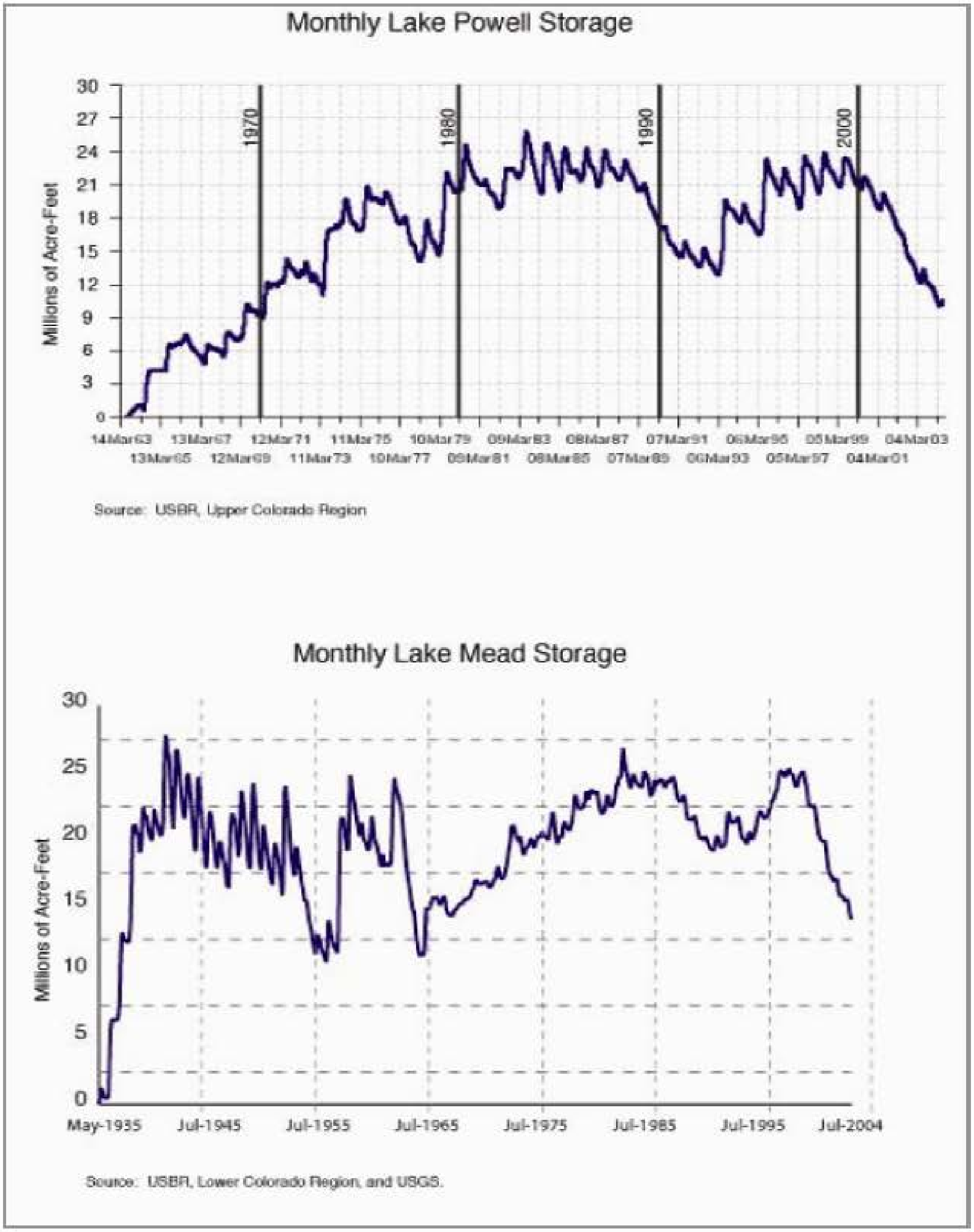



**Figure 2-37 Monthly Storage Volumes in Lake Powell and Lake Mead since their Construction**

### 2.8.2 Allocation of Water in the Colorado River Basin

The 1922 Colorado River Compact formally divided the Colorado River basin at Lees Ferry into two parts: an upper basin and lower basin, as described earlier. Each basin was apportioned 7.5 million acre-feet of Colorado River water annually for water supply purposes. A 1944 treaty between the United States and Mexico guarantees Mexico 1.5 million acre-feet annually. The burden of this guarantee is shared equally by the upper and lower basins.

The upper basin states allocated use among themselves in 1948. The allocation of water in the lower basin was decided by the U.S. Supreme Court in 1964. The court decided that the annual apportionment of 7.5 million acre-feet for the lower basin would be allocated as follows: 4.4 million acre-feet to California, 2.8 million acre-feet to Arizona, and 0.3 million acre-feet to Nevada. One of the salient points of the Supreme Court decree was that Arizona's use of Gila River water is not part of its 2.8 million acre-feet allocation. In addition, all lower basin states have the right to use tributary flows before they join the Colorado River without affecting their appropriation of Colorado River water.

### 2.8.3 Climate Change and the Colorado River Basin

Flows in the upper Colorado River basin are mostly a function of snowmelt. Warmer air temperatures as the projected result of climate change would tend to reduce the basin's middle elevation snowpack. Warmer air temperatures would also tend to cause earlier melting of annual accumulations of snow. Annual snowmelt could begin several weeks sooner than it does now, depending on the amount of warming that occurs.

Warming in the upper Colorado River Basin could cause an increase in winter runoff due to higher minimum snow elevations during winter storms and less precipitation falling and accumulating in the form of snow. Since reservoir storage in the Colorado River Basin is so large in comparison to average annual basin runoff (roughly four times average runoff), a change in the timing of annual runoff in the basin as the result of climate change would not be expected to significantly affect basin yield. Figure 2-38 illustrates locations of the larger reservoirs in the basin.

Recently completed climate model runs for the upcoming Intergovernmental Panel on Climate Change's 4th Assessment indicate a winter temperature increase of 1.1 to 2.0 degrees Celsius in the Colorado River basin by 2050, with continued temperature rise expected through the end of the century. Upper basin runoff from annual snowmelt would likely peak five to 25 days earlier than the average time of peak runoff for the 1951-80 historical period (Garfin, 2005).

Possible changes in amount of precipitation received by the Colorado River basin as the result of climate change could affect basin yield and thus are potentially of more concern for water supplies than predicted changes in the timing of runoff. As discussed previously, about 85 percent of upper basin runoff is contributed by its high elevation watersheds. Therefore, possible changes in high mountain watersheds and the amount runoff from them could be the most important. Although climate models provide precipitation projections, projections for a specific region, such as the Southwest, vary considerably between models and are probably not reliable (Garfin, 2005).


**Figure 2-38 Size and Locations of Reservoirs in the Colorado River Basin**

From http://www.water.utah.gov/interstate/thecoloradoriverart.pdf

Warmer temperatures from climate change could be expected to cause drying of water-producing areas of the vast Colorado River watershed somewhat sooner each year than what occurs today. One study indicates that a precipitation increase of 10 percent may be required to offset the drying effect of a 2 degree Celsius rise in temperature (Nash and Gleick, 1993).

More extreme precipitation events are generally expected to accompany increasing temperatures associated with climate change. More extreme precipitation events in the Colorado River watershed would in turn be expected to increase sediment production. Basin sediment production would also likely increase given that a higher percentage of the basin's precipitation would likely fall in the form of rain rather than snow due to increased temperatures. If more frequent wild fires were to occur because of earlier drying of watersheds, or simply because of increased summer temperatures, sediment production would be increased further. Increased sediment production would adversely affect water quality and increase the rate of reservoir capacity loss due to sedimentation.

There are likely to be changes in water demand in the Colorado River basin as the result of climate change. Changes in demand at any particular location will probably be small, however, the aggregate change for the basin could be significant since so much land is involved.

One of the key questions concerning possible changes in water demand is what effect climate change will have on evapotranspiration rates for crops and landscaping. Also of concern are possible changes in water use by water loving plants knows as phreatophytes along rivers and streams. Phreatophytes can cause a significant loss in stream flow and shallow groundwater.

As discussed in Section 2.7.1, evapotranspiration rates increase with temperature if other factors that effect evapotranspiration, such as cloudiness, humidity, and atmospheric carbon dioxide content remain the same. However, higher atmospheric carbon dioxide levels expected in the future will act to reduce water consumption by plants, as evidenced by laboratory tests.

Increasing temperatures in the Colorado River Basin will likely increase reservoir evaporation losses. Evaporative losses from open portions of conveyances such as the Central Arizona Project, Colorado River Aqueduct, and the All-American Canal would likely increase as well.

### 2.8.4 Summary

The Colorado River Basin provides water to Southern California. Expected changes to the Colorado River Basin associated with climate change include:

- Less precipitation falling as snow and an earlier snow melt
- Increased evaporation from reservoirs and conveyance facilities
- Increased sediment production due to more extreme events and more precipitation falling as rain than snow
- Changes in water demand

Changes in the amount of water available to California from the Colorado River Basin may change if long-term decreases in runoff occur.

## 2.9 Possible Effects on Fish

This section describes aspects of climate change that could affect the abundance of fish in California's inland waters. It focuses on a few key species that have major implications for water management, including rainbow trout, coho and Chinook salmon and Delta smelt. The analysis omits numerous fishes throughout the State for which the influence of climate change and its implications for water management seem less clear.

In California, the timing and amounts of water released from reservoirs and diverted from streams are limited by their effects on various native fishes, especially those that are listed as threatened or endangered under the federal and State endangered species acts. These include winter-run and spring-run Chinook salmon, coho salmon, coastal and Central Valley forms of steelhead rainbow trout, Lahontan cutthroat trout, razorback sucker and Delta smelt. California constitutes the warm, southern end of the geographic range of most of these species.

By 2100, climate change is expected to raise average air temperatures by about 1.4 to 5.8 degrees Celsius in California, raise stream water temperatures by at least as much, greatly reduce California's snowpack, shift the seasonal pattern of surface-water runoff to more in winter and less in spring and summer, and raise sea level by 0.3 of a foot to 2.9 feet (IPCCa, 2001). These physical changes are likely to influence the ecology of aquatic life in California and have several major effects -- all of them negative -- on cold-water fishes.

In many low- and middle-elevation California streams today, summer temperatures often come close to the upper tolerance limits for salmon and trout. Thus, anticipated climate change that raises air temperatures a few degrees Celsius may be enough to raise water temperatures above the tolerance of salmon and trout in many streams, favoring instead non-native fishes such as carp and sunfish.

Unsuitable summer temperatures are a problem because many of the threatened and endangered fishes spend the summer in cold-water streams, either as adults, juveniles, or both. Adults of some populations, such as spring-run Chinook, spend the summer near their upstream spawning grounds waiting for conditions suitable for spawning in fall or winter. Chinook salmon and steelhead, for example, prefer temperatures of less than 18-20 degrees Celsius in mountain streams, although they may tolerate higher temperatures for short periods (Moyle, 2002).

### 2.9.1 Regional Effects

The specific nature of ecological effects on fishes will differ among regions of the State. The following three regions are important for water supply and will see major effects from climate change:

- Region 1 – Basins with snowpack. River basins that drain the Sierra Nevada and Cascade Range and store water as snowpack;
- Region 2 – Basins without snowpack. River basins without significant snowpack, including all coastal streams south of the Klamath River basin; and
- Region 3 - The Sacramento-San Joaquin River Delta.

Streams on the eastern slope of the Sierra Nevada and in Southern California, as well as the Colorado River, are also important for water supply, but the effects of climate change on fishes there are less clear.

Winter-run and spring-run Chinook salmon, coho salmon, and coastal and Central Valley steelhead trout spawn in Region 1. Coho salmon and steelhead trout occupy coastal streams in the second region. Delta smelt spend their entire lives in the third region, while steelhead trout and Central Valley Chinook salmon migrate through it. All of these fishes are listed under the federal Endangered Species Act.

#### 2.9.1.1 Region 1- Basins with Snowpack

The Sierra-Cascade basins are predicted to get less snow and more rain, more winter and less spring and summer runoff, and warmer runoff. Spring-run Chinook salmon and steelhead trout in some streams migrate upriver into the foothills and mountains early in the year, spend the summer in deep, cold pools, and spawn the following fall (salmon) or winter (steelhead). Adult survival over the summer depends upon the availability of cold water. The combination of streams being both warmer and shallower in the summer due to climate change may diminish most summer habitat for steelhead and potentially all such habitat now used by spring-run salmon.

Many salmon and rainbow trout spawn and rear below dams, or at hatcheries associated with dams. Climate change could reduce the volume of cold water in foothill reservoirs since they would receive less snowmelt and have reduced carryover storage. Thus, releases of cold water to support fish spawning and rearing below such reservoirs may decline and fish production could also decline.

#### 2.9.1.2 Region 2 - Basins without Snowpack

Streams in basins without significant snowpack will likely be warmer in the dry season than now (as well as in the winter), matching the expected rise in air temperature. Warmer inland areas as the result of climate change may increase summer coastal fog which could provide mitigating effects for coastal areas and streams.

Juvenile coho salmon and coastal steelhead trout remain in fresh water through the summer. Climate change could make coastal streams too warm for coho salmon in the summer, especially for the more extreme projections of temperature rise. Steelhead trout could disappear from the more southerly streams in their current range (in Central and Southern California), and would probably be less abundant elsewhere.

#### 2.9.1.3 Region 3 - Sacramento-San Joaquin River Delta

The Sacramento-San Joaquin Delta will become saltier if sea level rise predictions are correct, Delta operations remain the same and the Delta retains its present physical configuration. The predicted decline in natural runoff during the spring, summer and fall could make the Delta even saltier, and over a larger area. River water at the upstream end of the Delta will still be fresh in summer, but is likely to be warmer than now if measures are not taken.

The Delta smelt occurs in the Sacramento-San Joaquin Estuary and nowhere else. During periods of drought, its center of abundance has been the channel of the Sacramento River in the upstream part of the Delta (Moyle, 2002). Delta smelt rarely occur in waters above 24 degrees Celsius and cannot survive long in water above 25 degrees Celsius (Swanson and others, 2000). Current peak temperatures in the lower Sacramento River at Hood and Rio Vista, for example, are already within a few degrees of these temperature thresholds (CDEC).

In short, a possible result of climate change is that Delta smelt will have little or no suitable habitat in summer. Waters in the lower Delta may be too salty and lacking in food, while fresh water in the upper Delta may be too warm. Thus, the species may become much less numerous or may even go extinct.

### 2.9.2 Summary

As evident from the above discussion, climate change could have a significant impact on threatened and endangered fish in California. Climate change could also have serious implications for fish that are not now identified as threatened and endangered, but might be affected to a point where they become designated as such.

## 2.10 Sudden Climate Change

Most global climate models predict that climate change due to human causes will be a continuous and somewhat gradual process through the end of this century. With proper foresight, planning and action, water managers will likely be able to help California adapt to many of the water supply challenges posed by climate change, even at some of the higher projections for change. However, sudden and unexpected changes in climate could leave water managers unprepared and could, in their extreme, have serious implications for California and its water supplies.

Sudden climate change could occur if progressive changes in the earth's climate cause a physical threshold or "trigger point" to be reached where one of the earth's major atmospheric or oceanic systems changes significantly, or ceases to function. One possible example of this that has received a significant amount of attention is a possible change in the global thermohaline circulation system depicted in Figure 2-39.

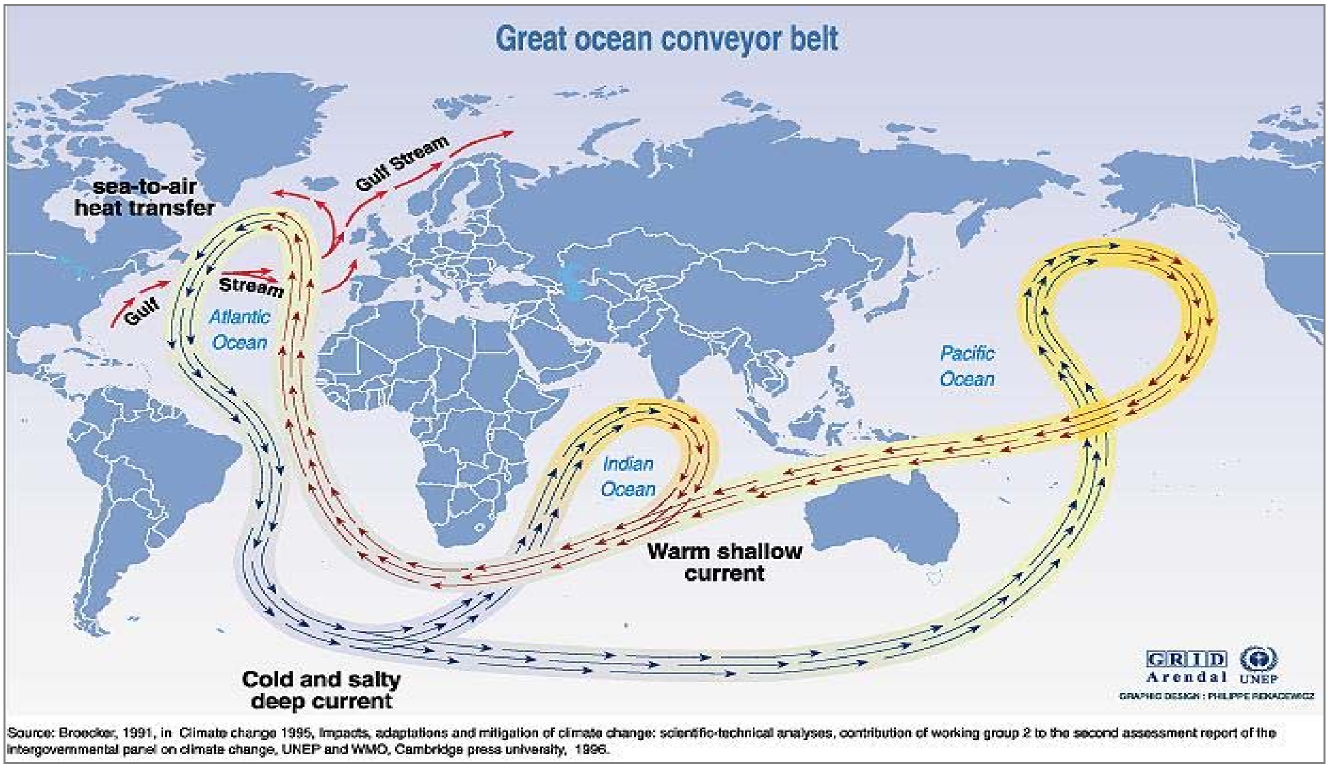



**Figure 2-39 The Global Thermohaline Circulation System**
Source: GRIDA, 2005.

There is evidence that circulation in the North Atlantic Ocean in relation to the global thermohaline system is slowing (Nature, 2005). While the complete shutdown of the system would likely lead to relatively rapid and significant changes in the earth's climate, such a scenario is considered by most scientists to be unlikely to occur in the next 50 years. The IPCC reports that none of the climate models it used in its evaluations project the complete shutdown of the system before 2100 (IPCC, 2001a).

Relatively sudden and often short-term changes in the climate of California and the western United States have occurred during at least the past 2000 years, as evidenced by precipitation and streamflow measurements over about the past 100 years and paleoclimatological information derived from physical evidence such as annual growth rings in trees. Of particular concern are extreme droughts, some of which appear to have occurred over large areas of the western United States and extended over several decades (MacDonald, 2005, Woodhouse, 2005). The exact cause of these events is unknown. However, there is speculation that some of the more recent droughts may have been due, at least in part, to oscillating conditions in the world's oceans.

Finally, other phenomena that could cause sudden and unexpected changes in the earth's climate include volcanic activity and the impact of meteorites or other extraterrestrial matter with the earth's surface. Large volcanic eruptions during recorded history have been observed to have caused temporary regional and sometimes global-scale cooling from one to several years (Kelly, 1996). While both volcanic eruptions and the impact of large extraterrestrial objects with the

Earth could suddenly affect the State's climate and water resources, the frequency of their occurrence together with their projected effects are extremely difficult to predict.

## 2.11 Summary

As discussed in previous sections, climate change could cause significant impacts on California's water resources and water demand. Changes in temperature and precipitation patterns in the State have been observed over the past century. Further changes are expected over the next century due to climate change. Changes in sea level are also expected to occur in response to the changing climate. These changes in precipitation and temperature patterns across the State may have profound impacts on ecologic and water resources systems in the State.

There is a significant amount of uncertainty about the magnitude of climate change that will occur over this century. It is unlikely that this level of uncertainty will diminish significantly in the foreseeable future (Dettinger, 2005b). There is also uncertainty about changes in hydrologic conditions, aquatic ecosystems and water demand that could occur as the result of various amounts of climate change. In the following chapters of this report, an initial attempt is made to quantify the impacts of climate change on some aspects of California's water resources.

## 2.12 References

Sources for illustrations are referenced below each illustration. References cited in the chapter text are listed below.

Bromirski (2005). Dr. Peter Bromirski, Assistant Project Scientist, Scripps Institute of Oceanography, La Jolla, CA, personal communication 10-10-2005.

CDEC [California Data Exchange Center]. California Department of Water Resources.

CRU (2000). Climatic Research Unit, School of Environmental Sciences University of East Anglia, United Kingdom Website. http://www.cru.uea.ac.uk/cru/info/thc/ November 30, 2005.

Cayan (2001). Changes in the Onset of Spring in the Western United States.[Cayan, D.R., Susan A. Kammerdiener, Michael D. Dettinger, Joseph M. Caprio, and David H. Peterson ] Bulletin of the American Meteorological Society. Vol. 82, No. 3, March 2001.

Cowan, (1977). *Stomatal diffusion in relation to leaf metabolism and environment*. [Cowan, I.R. and Farquhar, C.D.] Symp. Soc. Exp. Biol. 31, 471-505. 1977.

DOF (2005). *Data File: Historical and Projected Population for California*. California Department of Finance.

DWR (1951). Water Resources of California [California Water Resources Board (now California Department of Water Resources)].

DWR (1958). Sea-Water Intrusion in California, Bulletin 63. [California Department of Water Resources]. November, 1958.

DWR (1975). Sea-Water Intrusion in California, Inventory of Coastal Ground Water Basins, Bulletin 63-5. [California Department of Water Resources]. October, 1975.

DWR (1994). The California Water Plan Update, Bulletin 160-93. [California Department of Water Resources]. October, 1994.

DWR (1998). California Water Plan Update, Bulletin 160-98. [California Department of Water Resources]. 1998.

DWR (2003). *California's Groundwater; Bulletin 118, Update 2003.* [California Department of Water Resources].

DWR (2005a). California Water Plan, Update 2005 (Draft). [California Department of Water Resources]. Final Draft.

DWR (2005b). Special Publication for Association of California Water Agencies and Colorado River Water Users Association Conferences, prepared by the California Department of Water Resources, Sacramento. November, 2005.

DWR (2005c). Water Conditions in California, *California Cooperative Snow Surveys Bulletin 120*. [California Department of Water Resources].

Dettinger (2005a). Changes in Streamflow Timing in the Western United States in Recent Decades. [Michael D. Dettinger] U.S. Geological Survey. Fact Sheet, *http://pubs.usgs.gov/fs/2005/3018/pdf/FS2005_3018.pdf*

Dettinger (2005b). From climate-change spaghetti to climate-change distributions for 21st Century California. [Michael D. Dettinger] San Francisco Estuary and Watershed Science. Vol. 3, Issue 1 (March 2005), Article 4. http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4

Easterling, (2000). *Observed Variability and Trends in Extreme Climate Events: A Brief Review.* [D.R. Easterling, J.L. Evans, P. Ya. Groisman, T.R. Karl1, K.E. Kunkel, P. Ambenje] Bulletin of the American Meteorological Society, **81**, March 2000, 417-425. http://www.ncdc.noaa.gov/oa/pub/data/special/extr-bams2.pdf

Freeman (2002). Looking for Recent Climatic Trends and Patterns in California's Central Sierra. [Gary J. Freeman]. 2002 PACLIM Conference Proceedings.

Garfin (2005). *Climate and Hydrology in the Colorado River Basin, September 2005 (advance copy)* . [Greg Garfin, University of Arizona].

Gibeaut, J. C. (2000). *Texas Coastal Hazards Atlas Volume 1*. Bureau of Economic Geology, University of Texas, Austin.

Givati (2004). *Quantifying Precipitation Suppression Due to Air Pollution* . [Amir Givati and Daniel Rosenfeld, The Hebrew University of Jerusalem ] Journal of Applied Meteorology: Vol. 43, No. 7, pp. 1038–1056.

GRIDA (2005). United Nations Environment Programme, Global Resource Information Database-Arendal (GRIDA) Website at: http://www.grida.no/climate/vital/32.htm. November 30, 2005.

Groisman (2005). *Changes in precipitation distribution spectra and contemporary warming of the extratropics: implications for intense rainfall, droughts, and potential forest fire danger.* [ Pavel Ya. Groisman, NOAA/NESDIS/NCDC, Asheville, NC; and R. W. Knight, D. R. Easterling, D. Levinson, R. R. Heim, Jr., T. R. Karl, P. H. Whitfield, G. C. Hegerl, V. N. Razuvaev, B. G. Sherstyukov, J. G. Enloe, and N. S. Stroumentova]. Preceedings of the 16th Conference on Climate Variability and Change, 85th American Meterological Society Meeting, San Diego, CA, January 2005. http://ams.confex.com/ams/Annual2005/techprogram/paper_85857.htm

Hayhoe (2004). *Emissions pathways, climate change, and impacts onCalifornia.* [Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville] Proceedings of the National Academy of Sciences of the United States of America 101:12422-12427.

Hidalgo (2005). Sources of variability of evapotranspiration in California. [Hidalgo, H.G., Cayan, D.R., Dettinger, M.D.] J. Hydrometerology. 6, 3-19.

Hulme (1995). *Estimating Global Changes in Precipitation.* Weather, Vol. 50, No. 2, February 1995.

Inman, et. al. (2002). *Facing the Coastal Challenge: Modeling Coastal Erosion in Southern California, October 27, 2002* [Douglas L. Inman, Patricia M. Masters, Scott A. Jenkins, Coastal Morphology Group Integrative Oceanography Division Scripps Institution of Oceanography University of California, San Diego.] (http://repositories.cdlib.org/sio/cmg/12/)

IPCC (2001a). *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*.[ Houghton, J.T.,Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K.Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp. ISBN 0521 80767 0. http://www.grida.no/climate/ipcc_tar/wg1/index.htm

IPCC (2001b). *Climate Change 2001: Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T. and the Core Writing Team (eds.)]. Cambridge University Press, Cambridge,United Kingdom, and New York, NY, USA, 398 pp.

IPCC (2000). Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios, Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. pp 570, http://www.grida.no/climate/ipcc/emission/.

Kerr (2005). *El Niño or La Niña? The Past Hints at the Future.* [Richard A Kerr]. Science Vol. 309, 29 July 2005. www.sciencemag.org

Kelly (1996). "The Spatial Response of the Climate System to Explosive Volcanic Eruptions." [Kelly, P. M., Jones, P. D., and Jia Pengqun,] International Journal of Climatology 16 (5), 537-550.

Knowles (2002). *Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary.* [Knowles, N., and D. R. Cayan]. Geophys. Res. Lett., 29(18), 1891, doi:10.1029/2001GL014339.

Lempert (2003). *Shaping the Next One-Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis* [ Lempert, R. J., S.W. Popper and S.C. Bankes], RAND Corporation, ISBN 0-08330-3275-5. 2003.

Landis (2003). *How We Will Grow: Baseline Projections of the Growth of California's Urban Footprint through the Year 2100* (August 1, 2003). [John D. Landis and Michael Reilly] Institute of Urban & Regional Development. IURD Working Paper Series. Paper WP-2003-04. http://repositories.cdlib.org/iurd/wps/WP-2003-04 ,

Long (2004). *Rising atmospheric carbon dioxide: plants FACE the future.* [Long, S.P., Ainsworth, E.A., Rogers, A. and Ort, D.R.] (2004) Annu. Rev. Plant Biol. 55, 591-628.

MacDonald (2005). *Southern California and the "Perfect Drought"* [MacDonald G., S. Rian and H. Hildalgo]. Special Publication for Association of California Water Agencies and Colorado River Water Users Association Conferences, November, 2005.

Miller (2003). Miller, N.L., K.E. Bashford, E. Strem, 2003: Potential Impacts of Climate Change on California Hydrology, J. Amer. Water Resoures Assoc., 771-784.

Miller (1998). Climatically Sensitive California: Past, Present, and Future Climate. Presentation at California Workshop on Regional Climate Variability and Change, Santa Barbara, CA 9-11 March 1998

Mote (2005). *Declining mountain snowpack in western North America.* [Mote, P. W., A. F. Hamlet, M. Clark, and D. P. Lettenmaier] Bulletin of the American Meteorological Society 86(1):39-49

Mount (2004). Subsidence, Sea Level Rise, Seismicity in the Sacramento-San Joaquin Delta: Report to the Levee Integrity Subcommittee of the California Bay-Delta Authority Independent Science Board, December 2004. [Jeffery Mount and Robert Twiss, members of the CalFED Independent Science Board]. http://science.calwater.ca.gov/pdf/isb/ISB_subcom_levee_report_120104.pdf#search='mount%20%26%20twiss

Moyle (2002). Inland Fishes of California. University of California Press.

Munk (2002). Twentieth Century Sea Level: An Enigma. [Walter Munk] Proceedings of the National Academy of Sciences, Vol. 99, No. 10, pp. 6550-6555, May 14, 2002.

NOAA (2005). Global Warming, FrequentlyAsked Questions. [ National Oceanic and Atmospheric Administration , National Climatic Data Center]. http://lwf.ncdc.noaa.gov/oa/climate/globalwarming.html#Q5 October 23, 2005

NWS (2005). National Weather Service, Climate Prediction Website. December 12, 2005. http://www.cpc.ncep.noaa.gov/charts.shtml

Nash and Gleick (1993). The Colorado River Basin and Climatic Change: The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation. [Nash, L. and P. Gleick.] U.S. Environmental Protection Agency, EPA230-R-93-009, Washington, D.C. 121 pp.

Nature (2005). *Oceanography: The Atlantic heat conveyor slows.* [Detlef Quadfasel], Nature, Volume 438 Number 7068. December 1, 2005.

PASSC (2005). *Earth Impact Database.* University of New Brunswick, Planetary and Space Science Centre http://www.unb.ca/passc/ImpactDatabase/index.html. December 1, 2005.

Roos (1989). *Possible Climate Change and its Impact on Water Supply in California.* Oceans '89 Conference. [Maurice Roos, California Department of Water Resources]. Institute of Electrical and Electronic Engineering; Seattle, Washington.

Sloan (2005). L. C. Sloan, L. Kueppers, M. Snyder, D. Cayan, M. Tyree, M. Kanamitsu, H. Kanamaru, N. Miller, J. Jin, G. Franco, B. Weare. Have urban and agricultural land use changes affected California's climate? 2nd Annual Climate Research Conference and First Scientific Conference West Coast Governors' Global Warming Initiative. http://www.climatechange.ca.gov/events/2005_conference/presentations/2005-09-14/2005-09-14_SLOAN.PDF

Swanson (2000). Comparative environmental tolerances of threatened delta smelt (Hypomesus transpacificus) and introduced wakasagi (H. nipponensis) in an altered California estuary. [Swanson, C., T. Reid, P.S. Young, and J.J. Cech, Jr.] Oecologia 123: 384-390.

Tanaka (2005). Climate Warming and Water Management Adaptation for California. [Tanaka, S.K., Zhu, T, Lund, J.R., Howitt, R.E., Jenkins, M.W., Pulido, M.A., Tauber, M., Ritzema, R.S., Ferreira, I.C.]. Climatic Change, (in press).

Titus (1995). *The probability of sea level rise.* [ James G. Titus, Vijay K. Narayanan]. Washington, D.C.: U.S. Environmental Protection Agency. 186 pp. EPA 230-R95-008. (http://yosemite.epa.gov/OAR/globalwarming.nsf/content/ResourceCenterPublicationsProbability.html)

USDA (2003). *California Agricultural Statistics 2003,* U.S. Department of Agriculture, 2003. .

Wara (2005). *Permanent El Nino–Like Conditions During the Pliocene Warm Period.* [Michael W. Wara, Ana Christina Ravelo, and Margaret L. Delaney]. Science Vol.309, 29 July 2005. www.sciencemag.org

Woodhouse (2005) *Paleoclimate Overview* [Connie Woodhouse]. Special Publication for Association of California Water Agencies and Colorado River Water Users Association Conferences, November, 2005.

**Progress on Incorporating Climate Change into Management of California's Water Resources**

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# Chapter 3:
# DWR Climate Change Studies

**Author:**

[illegible]
[illegible]
Sacra[illegible]

**Contributors:**

[illegible]
[illegible]

[illegible]
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Sacra[illegible]

# 3 DWR Climate Change Studies

## 3.1 Introduction

This chapter provides an overview of climate change studies being conducted by the California Department of Water Resources (DWR). DWR is doing the studies to determine potential effects of climate change on management of California's water resources in support of the governor's Executive Order S-3-05 described below. This chapter explains the background and approach for conducting these climate change studies. It also describes the specific climate change scenarios selected for study. Subsequent chapters of this report will present the results of the studies.

## 3.2 Background

In June 2005, Gov. Arnold Schwarzenegger issued Executive Order S-3-05 on climate change. It set future greenhouse gas emissions targets for California. It also requires reports every two years on climate change impacts to five areas including water resources. The first of those reports is due to the governor in January 2006. To comply with the Executive Order a Climate Action Team (CAT) was formed with representatives from various state agencies, including the Resources Agency. A subcommittee of the CAT selected four climate change scenarios for analysis for the initial climate change report. The California Energy Commission (CEC) is coordinating the publication of that report.

This report is supplemental and complementary to the CEC report. This report focuses only on water resources. DWR staff has conducted preliminary studies on incorporating climate change into the planning and management of California's water resources. Whenever appropriate, the four climate change scenarios selected by the CAT were used in the DWR studies. DWR has coordinated efforts with other groups conducting modeling studies of climate change impacts on water resources. The groups include the University of California, Berkeley, (CalSim-II); University of California, Davis, (CALVIN); and the Natural Heritage Institute (WEAP).

In addition to these DWR studies for the governor, the California Water Plan Update 2005 includes a qualitative discussion of the possible statewide effects of climate change (DWR, 2005). An expanded, more quantitative discussion of statewide impacts will be included in future Water Plan Updates and will use information from the studies described in this report and other studies done outside DWR.

## 3.3 Climate Change Scenarios

The four climate change scenarios selected by the CAT were chosen from among several available scenarios compiled for the United Nation's Intergovernmental Panel on Climate Change's (IPCC's) Fourth Assessment Report which is due out in 2007. The four climate change scenarios consist of two greenhouse gas (GHG) emissions scenarios, A2 and B1, each represented by two different Global Climate Models (GCMs), the Geophysical Fluid Dynamic Lab model (GFDL) and the Parallel Climate Model (PCM). The four climate change scenarios are:

- GFDL A2
- PCM A2
- GFDL B1
- PCM B1

The A2 emissions scenario assumes high growth in population, regional based economic growth, and slow technological changes, which results in significantly higher greenhouse gas emissions. The B1 scenario represents low growth in population, global based economic growth and sustainable development that results in the lowest increase of greenhouse gas emissions of the IPCC scenarios. Both the GFDL and PCM models project future warming. The GFDL model indicates a greater warming trend than the PCM model.

Among the criteria used to select these climate change scenarios were ability of the models to represent El Niño events and availability of the data for analysis to meet the January 2006 governor's deadline for the report (Cayan, 2005). In addition, both models estimated historical climate trends reasonably well. The emissions scenarios and models are described further in later sections of this report.

### 3.3.1 Emissions Scenarios

The World Meteorological Organization and the United Nations Environment Programme formed the Intergovernmental Panel on Climate Change (IPCC) to periodically evaluate the science, impacts, and socioeconomics of climate change including adaptation and mitigation options. In order to conduct climate change studies, the IPCC has developed scenarios of future greenhouse gas emissions. The first set of IPCC emissions scenarios was released in 1990 and 1992. In 1994, those emissions scenarios were evaluated. And in 1996 a 50-member team representing 18 countries began updating the emissions scenarios. The updated emissions scenarios are documented in the 2000 IPCC Special Report on Emissions Scenarios (SRES).

The SRES emissions scenarios were developed and peer-reviewed using an open process with six major steps (IPCC, 2000):

1. Literature review of existing scenarios

2. Analysis of major scenario characteristics, driving forces, and their relationships

3. Formulation of four narrative scenario storylines to describe alternative futures

4. Quantification of each storyline using a variety of modeling approaches

5. An open review of the resulting emission scenarios and their assumptions

6. Three revisions of the scenarios and the report after the open review: the formal IPCC Expert Review and the final combined IPCC Expert and Government Review

To encompass the vast uncertainty about what may happen by the year 2100, the IPCC developed four storylines. Each story reflects different directions of major greenhouse gas emissions influences, including population, technology and economic factors. Each story evolves dynamically over time. The divergent visions for the future world are intended to represent different combinations of the main greenhouse gas sources, thus spanning the relevant ranges of greenhouse gas emissions. The four stories are referred to as A1, A2, B1 and B2, and the major characteristics of each storyline are summarized below (IPCC, 2000):

A1: The A1 story is about a future with low population growth, rapid economic growth, and rapid introduction of new and more efficient technologies. Other characteristics of the story include convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income.

A2: The A2 story is about a heterogeneous future with high population growth, regional economic growth, and fragmented technological changes. Self reliance and preservation of local identities are major themes in the A2 story.

B1: The B1 story is about a convergent future with low population growth, rapid economic growth, and sustainable technology. Economic growth moves rapidly towards a service- and information-based economy. Use of natural resources is reduced, and clean and resource-efficient technologies are introduced. The B1 storyline emphasizes global solutions to economic, social, and environmental sustainability.

B2: The B2 story envisions a future with moderate population growth, intermediate levels of economic growth, and less rapid and more diverse technological development than the A1 and B1 stories. Local solutions to economic, social, and environmental sustainability are emphasized.

Based on the four stories, the IPCC used six models and various approaches to quantify the characteristics of each story. A total of 40 scenarios were developed, each of which represents an alternative interpretation and quantification of one of the stories. All of the scenarios based on a given story are known as a scenario family. None of the scenarios include future policies that explicitly address climate change such as the United Nations Framework Convention for Climate Change or the Kyoto Protocol greenhouse gas emissions targets. However other policies included in the scenarios may affect greenhouse gas emissions. Disaster scenarios were not considered. The likelihood of each scenario was not evaluated, and thus no SRES scenario was identified as the best-guess or business-as-usual scenario.

The IPCC objectively presents the scenarios by not indicating a preference for any scenario, nor do they assign probabilities of occurrence to any of the scenarios. The IPCC intended for the scenarios to be widely used for climate change assessment: "*We recommend that the new scenarios be used not only in the IPCC's future assessments of climate change, its impacts, and adaptation and mitigation options, but also as the basis for analyses by the wider research and policy community of climate change and other environmental problems*" (IPCC, 2000).

The Climate Action Team has selected scenarios from the A2 and B1 storylines for water resources impact analysis. For these scenarios global population estimates in the year 2100 range from 7 billion people for the B1 scenario to 15 billion people for the A2 scenario (IPCC, 2001). The A2 scenario results in the highest greenhouse gas emissions, and the B1 scenario results in the lowest greenhouse gas emissions of the SRES scenarios (Figure 3.1).

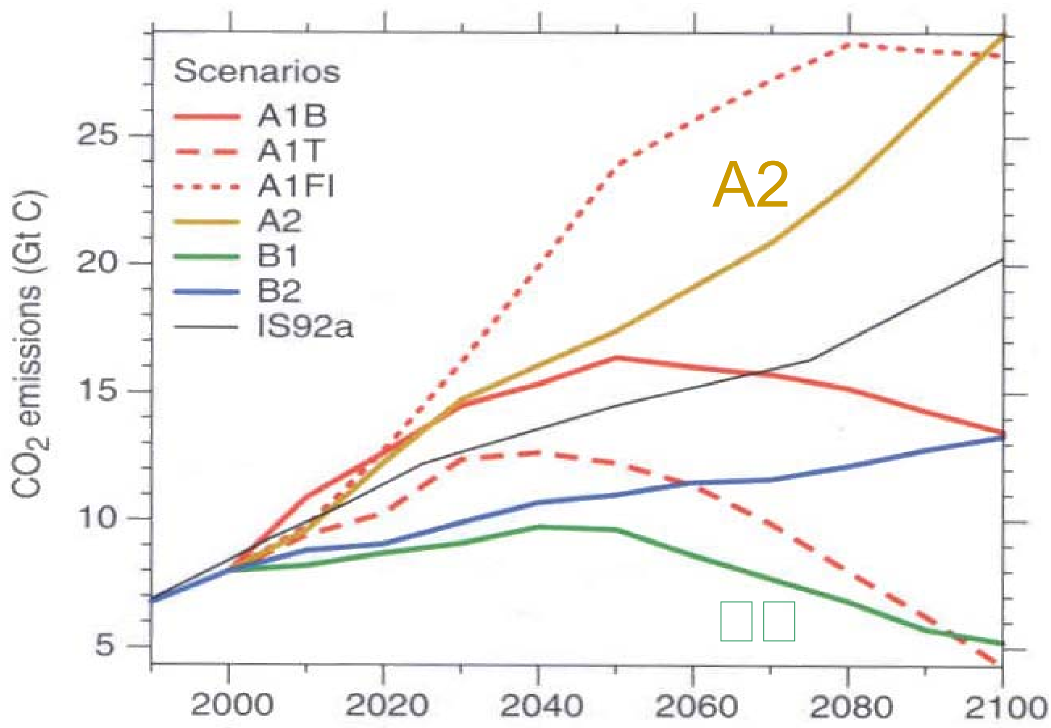


**Figure 3.1 Emissions of $CO_2$ from Human Activities for IPCC's SRES Scenarios**
Adapted from Technical Summary Figure 17 (IPCC, 2001)

### 3.3.2 Global Climate Models

Six Global Climate Models were used to develop IPCC's SRES emissions scenarios. The Climate Action Team (CAT) has selected the A2 and B1 emissions scenarios, each represented by two different global climate models, the Geophysical Fluid Dynamics Lab climate model (GFDL) and Parallel Climate Model (PCM). The Geophysical Fluid Dynamics Lab is part of the National Oceanic and Atmospheric Administration (NOAA). The PCM model was developed by the National Center for Atmospheric Research. The model versions, scenario name and run numbers for the four selected scenarios are given in Table 3.1. For this report, the four scenarios will be referred to by the model and scenario name.

**Table 3.1 Model and Emissions Scenario Labels for Four Climate Change Scenarios**

| Scenario Label for this Report | GCM and SRES Scenario Description |
|---|---|
| GFDL A2 | GFDL version2.1 SRESA2 run1 |
| PCM A2 | NCAR PCM version 1 SRESA2 run1 |
| GFDL B1 | GFDL version2.1 SRESB1 run1 |
| PCM B1 | NCAR PCM version 1 SRESB1 run2 |

The GFDL and PCM models are both state-of-the-art global climate models that represent linked oceanic, land, and atmospheric processes, including realistic representations of changes in sea surface temperatures due to the El Niño Southern Oscillation (ENSO). The climate processes in a global climate model are driven by factors known as forcings. The forcings used in these two models are summarized in Figure 3.2. Both models include forcings from greenhouse gas emissions, ozone, direct effects of sulfate aerosols, solar irradiance, and volcanic aerosols. In addition, the GFDL model includes forcings from black and organic carbon and land use or land cover. The GFDL model has a resolution of 2.0 degrees latitude by 2.5 degrees longitude, and the PCM model has a resolution of 2.8 degrees latitude by 2.8 degrees longitude. Both models were used to simulate 21st century climate change scenarios for the IPCC fourth assessment report, known as AR4, which is due out in 2007. Those simulations are archived at Lawrence Livermore National Lab's (LLNL's) Program for Climate Model Diagnosis and Intercomparison (PCMDI). The PCMDI website is http://www-pcmdi.llnl.gov/.

Model results and information for the four climate change scenarios selected by the CAT were made available for analysis on the California Climate Change Center's Web site managed by Scripps Institute for Oceanography, http://meteora.ucsd.edu/cap/cccc_model.html. Data are provided for the following variables:

- Surface latent heat flux; W/m$^2$
- Specific humidity at 925mb and 850mb
- Surface specific humidity; g/kg
- Total precipitation; mm/day
- Sea level pressure; mb
- Downward shortwave at the surface; W/m$^2$
- Upward shortwave at the surface; W/m$^2$
- Air temperature at 925mb, 850mb and 500mb; Kelvin
- Surface (2m) air temperature, Kelvin
- Maximum and minimum surface air temperature; Kelvin
- Zonal (east/west) wind at 925mb, 850mb and 500mb; m/s
- Surface (10m) zonal (east/west) wind; m/s
- Meridional (north/south) wind at 925mb, 850mb and 500mb; m/s
- Surface (10m) meridional (north/south) wind; m/s

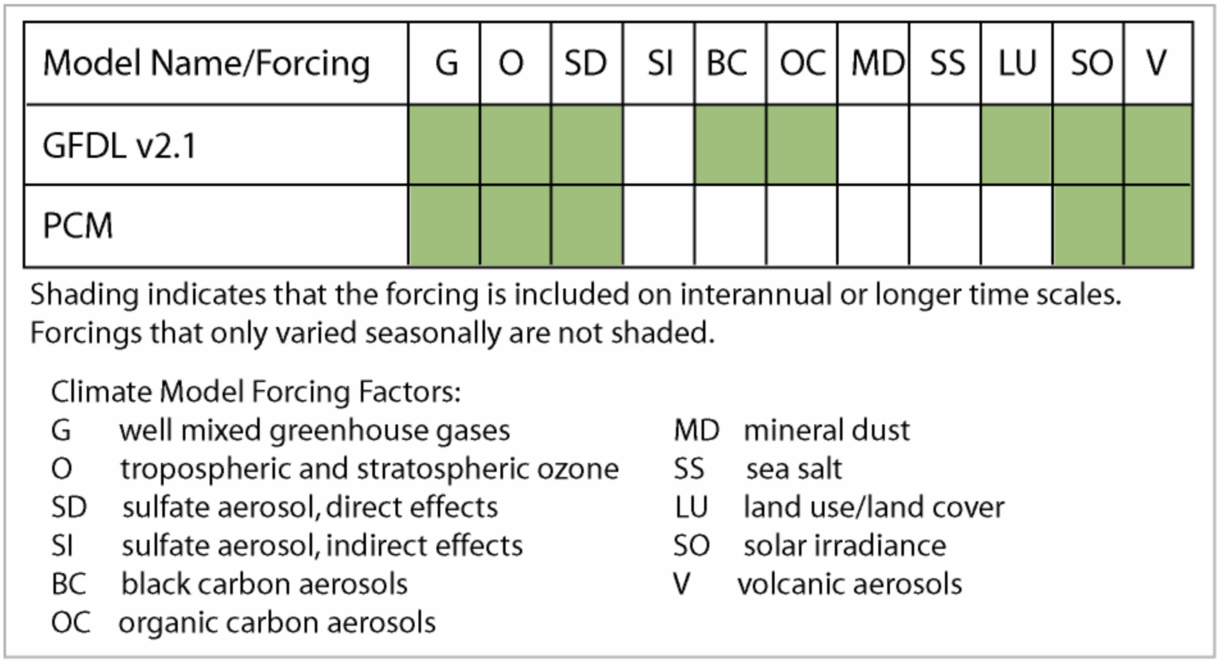


**Figure 3.2 Climate Model Forcings used for Climate Change Studies**
Adapted from Table 5.2 (Santer et al., 2006)

A summary of the general air temperature and precipitation trends for the four climate change scenarios at the end of the 21$^{st}$ century is presented in Table 3.2. All four scenarios show an increase in air temperature. The PCM B1 scenario is the only scenario that shows an increase in precipitation.

For the climate change studies presented in this report, a 2050 projection level was used to reflect a water resource planning horizon. For each global climate model, projection data were available at two data points in California (Table 3.3). Average air temperature and precipitation values were computed from the global climate model results for a 30-year historical period from 1961-1990 and for a 30-year future projection period centered around 2050 (2035-2064) (Table 3.4 to Table 3.7). For comparison purposes, average historical air temperature and precipitation data for the 30 year historical period from 1961-1990 are also shown. The historical average values are based on the nearest two data stations for each site. The historical air temperature values were greater than the simulated values since the elevations of the data stations were lower than the elevations of the global climate model output locations (Table 3.3). Thus a temperature correction was applied to the historical average air temperature to adjust the value to a value that corresponds to the elevation of each global climate model output location. The historical average air temperature values for the global climate model output are within acceptable lapse rate (change of temperature with elevation) values for adjusting observed historical values (Table 3.4 and Table 3.5). The precipitation values were not adjusted for elevation since there is no straight forward correlation between precipitation and elevation.

Looking at the 2050 projections increases in air temperature range from 0.8ºC to 2.4ºC (Table 3.4 and Table 3.5). For most scenarios, warming is slightly higher in Northern California than Southern California. Projected changes in precipitation for 2050 are typically less than an inch per year. Values for both the air temperature and the precipitation projections were more dependent on the global climate model used to represent the emissions scenario than on the emissions scenario. In other words, the projected values from a given global climate model, GFDL or PCM in this case, were closer to each other than the values for a given emissions scenario, A2 or B1 in this case. Additional global climate model results are presented in chapters 2 and 6.

**Table 3.2 Air Temperature and Precipitation Trends for Climate Change Scenarios**

| Scenario | End of 21st Century Projection Trends |
|---|---|
| GFDL A2 | Relatively strong warming<br>Modest drying |
| PCM A2 | Modest warming<br>Modest drying |
| GFDL B1 | Modest warming,<br>Modest drying |
| PCM B1 | Weak temperature warming<br>Weak precipitation increase |

Source: Cayan, 2005.

**Table 3.3 GCM Grid Points in California**

| Location | Latitude degrees | Longitude degrees | Elevation m | Avg. Elevation Historical Data m |
|---|---|---|---|---|
| **Northern California** | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM | [illegible] | [illegible] | [illegible] | [illegible] |
| **Southern California** | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 3.4 Air Temperature Projections for Northern California, °C**

| Northern CA | 1961-1990 Average | | 2035-2064 Average | Difference |
|---|---|---|---|---|
| Historical Average | 13.2 | | N/A | N/A |
| Corrected for Elevation | 9.5 GFDL | 8.9 PCM | | |
| GFDL A2 | 9.5 | | 11.8 | 2.3 |
| GFDL B1 | | | 11.6 | 2.1 |
| PCM A2 | 8.2 | | 9.5 | 1.3 |
| PCM B1 | | | 9.0 | 0.8 |

**Table 3.5 Air Temperature Projections for Southern California, °C**

| Southern CA | 1961-1990 Average | | 2035-2064 Average | Difference |
|---|---|---|---|---|
| Historical | 16.2 | | N/A | N/A |
| Corrected for Elevation | 13.6 GFDL | 14.5 PCM | | |
| GFDL A2 | 12.4 | | 14.7 | 2.3 |
| GFDL B1 | | | 14.5 | 2.1 |
| PCM A2 | 14.5 | | 15.7 | 1.2 |
| PCM B1 | | | 15.4 | 0.9 |

**Table 3.6 Precipitation Projections for Northern California, in/yr**

| Northern CA | 1961-1990 Average | 2035-2064 Average | Difference |
|---|---|---|---|
| Historical | 27.46 | N/A | N/A |
| GFDL A2 | 36.56 | 35.81 | -0.75 |
| GFDL B1 | | 36.31 | -0.25 |
| PCM A2 | 25.03 | 24.41 | -0.62 |
| PCM B1 | | 25.86 | 0.83 |

**Table 3.7 Precipitation Projections for Southern California, in/yr**

| Southern CA | 1961-1990 Average | 2035-2064 Average | Difference |
|---|---|---|---|
| Historical | 14.24 | N/A | N/A |
| GFDL A2 | 17.92 | 17.70 | -0.22 |
| GFDL B1 | | 16.15 | -1.77 |
| PCM A2 | 11.36 | 12.06 | 0.70 |
| PCM B1 | | 11.28 | -0.08 |

### 3.3.3 Regional Downscaling

In order to conduct water resources impact analyses for climate change scenarios, the coarse spatial representation of the global climate model data must be refined in a process called downscaling. For the scenarios selected by the CAT, the regional climate data were produced by statistical downscaling of the global climate model output using the Variable Infiltration Capacity (VIC) model. The VIC model provides monthly output at 1/8$^{th}$ degree latitude/longitude resolution for the entire state of California. Daily data were computed by perturbing a historical data set based on the monthly computed climate change data from VIC. For hydrologic analysis, the VIC model output also provides stream flow, snow pack, snowmelt timing and soil moisture content (Maurer and Duffy, 2005; Maurer, 2005). Information on obtaining the downscaled data is available at the California Climate Change Center's Web site http://meteora.ucsd.edu/cap/cccc_model.html. Available climate data for a simulation period from 1950-2100 are:

- Precipitation
- Air temperature
- Wind speed
- Surface air humidity
- Soil moisture in three layers

Stream flow data for the simulation period 1950-2100 are available at the following locations:

- Smith River at Jedediah Smith State Park
- Sacramento River at Shasta Dam
- Feather River at Oroville
- North fork of the American River at North Fork Dam
- American River at Folsom Dam
- Yuba River system outflow at Marysville
- Sacramento River at the Delta
- Stanislaus River at New Melones Dam
- Tuolumne River at Don Pedro
- Merced River at Lake McClure
- King River at Pine Flat Dam

Results of the downscaled climate change data are presented in chapters 2 and 6.

## 3.4 Water Resources Impacts Approach

As the title of this report suggests, its main goal is to present initial methodologies and results for incorporating climate change into management of California's water resources. This report presents preliminary studies using existing analysis tools at DWR to quantify potential water resources related effects of climate change. Whenever appropriate, studies focus on the four climate change scenarios selected by the CAT (Figure 3.3). The climate change scenario data were developed by experts in the field of climate change. The goal of DWR staff is to develop methods for incorporating that data into water resources planning and management, not to make predictions about future climate conditions. These initial studies focus on potential effects of climate change to four main California water resources areas:

- State Water Project (SWP) and Central Valley Project (CVP) operations
- Delta water quality including possible increases in sea level
- Flood management and water supply forecasting
- Changes in evapotranspiration rates and thus consumptive use of irrigation water

Each of these topics is covered in detail in separate chapters of this report.

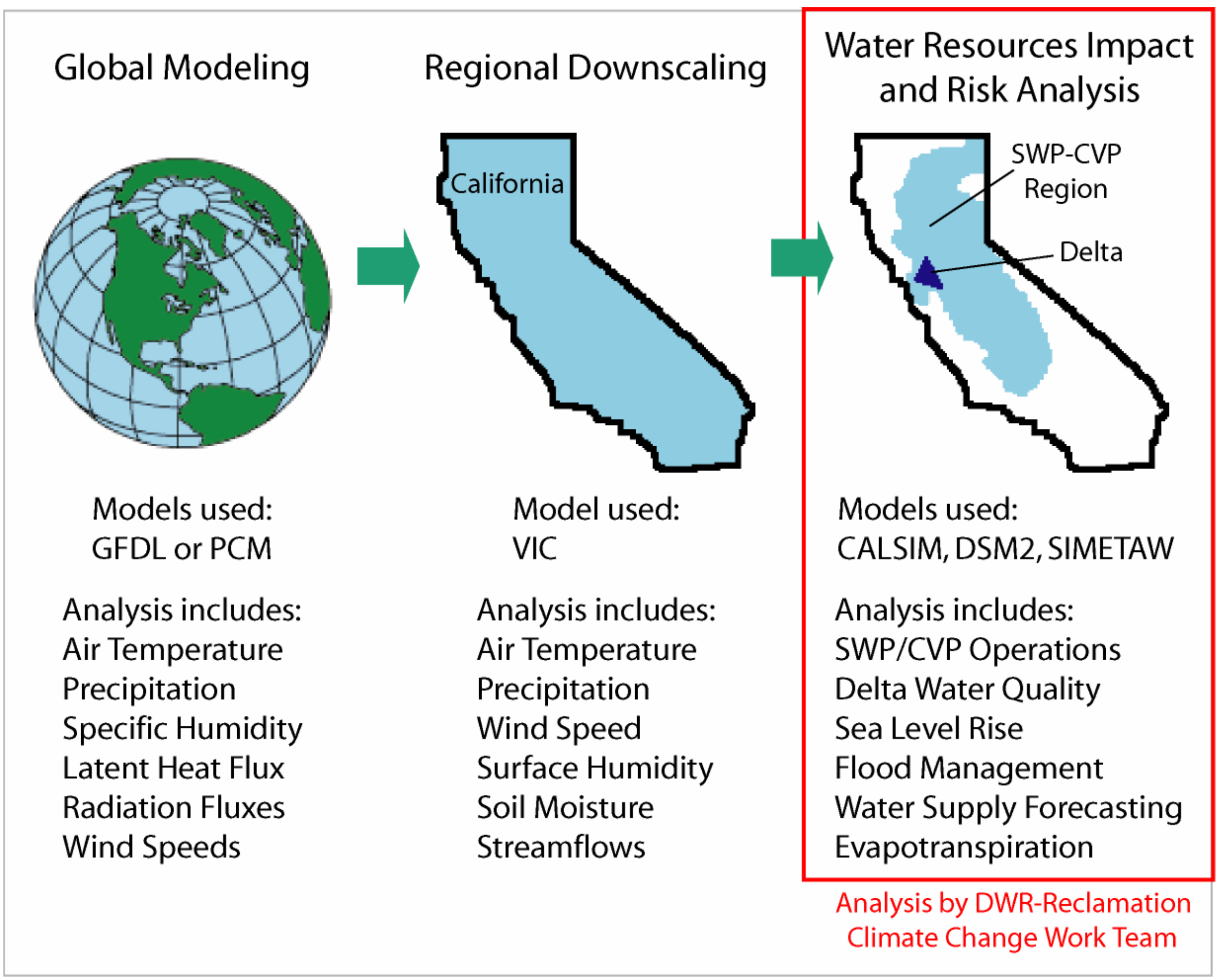


**Figure 3.3 Approach for Analyzing Potential Water Resources Impacts of Climate Change**

## 3.5 Acknowledgements

Internal review of this chapter was provided by Rich Juricich.

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VIC data were produced by Ed Maurer at the Santa Clara University.

Information on the Global Climate Model models and emissions scenarios were provided by Dan Cayan from Scripps Institution of Oceanography and Mike Dettinger from the U.S. Geological Survey and Scripps Institution of Oceanography.

## 3.6 References

Cayan, D., 2005. E-mail dated posted on California Climate Change Center website discussing climate change scenario selection by the CAT. July 25, 2005. http://meteora.ucsd.edu/cap/cccc_model_prelim.html#dan25jul

DWR, 2005. California Water Plan Update 2005, Volume 1-Stategic Plan, Chapter 4: Preparing for an Uncertain Future, California Department of Water Resources, Sacramento, CA, Public Review Draft. http://www.waterplan.water.ca.gov/cwpu2005/index.cfm

IPCC, 2000. Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios, Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. pp 570, http://www.grida.no/climate/ipcc/emission/.

IPCC, 2001. Intergovernmental Panel on Climate Change, Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC, J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), Cambridge University Press, UK. pp 944. http://www.grida.no/climate/ipcc_tar/wg1/index.htm

Maurer, E.P., 2005, Uncertainty in hydrologic impacts of climate change in the Sierra Nevada Mountains, California under two emissions scenarios, Climatic Change (submitted 29 April 2005)

Maurer, E.P. and P.B. Duffy, 2005, Uncertainty in Projections of Streamflow Changes due to Climate Change in California, Geophys. Res. Let. 32(3), L03704 doi:10.1029/2004GL021462

Santer, B.D., J.E. Penner, and P.W. Thorne, 2006: How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes? In: Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA (in press).

## 3.7 List of Abbreviations

AR4-IPCC Fourth Assessment Report

CalSim - II-Operations model of the State Water Project and Central Valley Project

CALVIN-Economics driven optimization model of State Water Project and Central Valley Project operations

CAT-Climate Action Team

CEC-California Energy Commission

DWR-California Department of Water Resources

ENSO-El Niño Southern Oscillation

GCM-Global Climate Model

GFDL-Geophysical Fluid Dynamic Lab model

GHG-Greenhouse Gas

IPCC-Intergovernmental Panel on Climate Change

LLNL-Lawrence Livermore National Lab

NCAR-National Center for Atmospheric Research

NOAA-National Oceanic and Atmospheric Administration

PCM-Parallel Climate Model

PCMDI-Program for Climate Model Diagnosis and Intercomparison

SRES-Special Report on Emissions Scenarios [IPCC, 2000]

VIC-Variable Infiltration Capacity Model

WEAP-Water Evaluation and Planning Program

**Progress on Incorporating Climate Change into Management of California's Water Resources**

**1st Progress Report**
**July 2006**

# Chapter 4:
# Preliminary Climate Change Impacts Assessment for State Water Project and Central Valley Project Operations

**Authors:**

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[illegible]
[illegible]

[illegible]
[illegible]

**Peer Reviewers:**

[illegible]

[illegible]

# 4 Preliminary Climate Change Impacts Assessment for State Water Project and Central Valley Project Operations

## 4.1 Introduction

Planning and design of the Central Valley Project (CVP) and State Water Project (SWP) has, for the most part, assumed an unchanging climate. Of course, it was always accepted that, in California, there would be years of plentiful precipitation followed by years of scarcity; that there would be wet, cool winters followed by hot, dry summers. Weather was expected to change. In fact, it was to overcome these changing weather patterns that the CVP and SWP were primarily built; the people of California needed flood protection during the wet periods and water during the dry. But at a climactic timescale of 30 years or more, it was assumed that the average of the weather patterns would remain about the same; the frequency and severity of future droughts would be much like that of the past; precipitation would continue to fall as winter snow, and the snow would continue to melt in the spring and early summer to fill our reservoirs. That was the assumption, and a changing climate may threaten to destabilize the infrastructure and operations dependent on that assumption.

As titled, this chapter discusses a preliminary assessment of climate change impacts on the SWP and CVP. Impacts were quantified for four scenarios predicted by two global climate models at two carbon dioxide emission rates (see Table 4.1). All four climate scenarios predict a warming trend for California. The effect on annual average precipitation is varied: Three of the scenarios predict a modestly drier climate and one predicts a weak increase in precipitation. The significant change is in the timing of runoff. Most precipitation that feeds the SWP and CVP falls in the Sierra Nevada and the southern end of the Cascades that border the eastern and northern boundaries of the Central Valley. Much of it comes as snow. A warming climate will result in a greater share of rainfall and a more rapid melt of the snowpack. As such, more runoff will occur in the winter and early spring and less during the late spring and early summer.

**Table 4.1 Air Temperature and Precipitation Prediction Trends for Four Scenarios**

| Selected Climate Model | Emission Scenario | Description |
|---|---|---|
| PCM | B1 | Weak temperature warming<br>Weak precipitation increase in California |
| PCM | A2 | Modest warming<br>Modest drying |
| GFDL v2.0 | B1 | Modest warming,<br>Modest drying |
| GFDL v2.0 | A2 | Relatively strong warming<br>Modest drying |

The focus of this chapter is impacts on water supply. Flood control is only discussed with respect to its operational conflicts with water supply goals. Of course, the SWP and CVP do more than provide water and flood protection to California; among other things, the projects generate and use large quantities of power; they control river temperatures to protect Chinook salmon and steelhead. Climate change effects on these operations will also be discussed.

It is important to note that this is just a starting point for analyzing climate change impacts on SWP and CVP operations. Current management practices and existing system facilities were used in the analysis for this report. No changes were made to lessen the effects of climate change or sea level rise. Only four scenarios are included, and we have not addressed the likelihood of one scenario over another. Furthermore, as will be discussed in the following sections, we have not included all of the ways in which climate change may impact water supply. Therefore, what is written here is not sufficient, by itself, to make final policy decisions. Its sole intent is to introduce readers to the methods of analysis and the potential significance of climate change impacts on CVP and SWP water supply.

## 4.2 Description of the CVP and SWP

The CVP, operated and maintained by the U.S. Bureau of Reclamation (Reclamation), is the largest surface water storage and delivery system in California, with a geographic scope covering 35 of the state's 58 counties. Authorized project purposes include flood control, navigation, agricultural and domestic water supply, fish and wildlife protection, and power generation. The CVP is composed of some 20 reservoirs with more than 11 million acre-feet (MAF) of storage capacity, 11 power plants, and over 500 miles of major canals and aqueducts. Within the Sacramento Basin, the CVP operates Shasta and Folsom reservoirs, among others. Water is imported from the Trinity River into the Sacramento Basin through Clear Creek Tunnel. Tracy Pumping Plant exports water from the Sacramento-San Joaquin Delta for storage in San Luis Reservoir and delivery to contractors in the San Joaquin Valley. The CVP also operates New Melones Lake on the Stanislaus River and Millerton Lake on the San Joaquin River, and it exports water from the San Joaquin Basin to the Tulare Basin through the Friant-Kern Canal. Overall, the project supplies water to 250 long-term water contractors in the Central Valley, Santa Clara Valley, and the San Francisco Bay Area. Key CVP reservoirs and their storage capacities are listed in Table 4.2.

**Table 4.2 Key CVP Reservoirs**

| Reservoir | Capacity (MAF) |
|---|---|
| Trinity | [illegible] |
| Shasta | [illegible] |
| Folsom | [illegible] |
| San Luis CVP Share | [illegible] |
| New Melones | [illegible] |
| Millerton | [illegible] |

The SWP is operated by DWR. It consists of 32 storage facilities, 660 miles of aqueducts and pipelines, 17 pumping plants, and eight hydroelectric powerplants. Using these facilities, the SWP provides urban and agricultural water supply, flood control, recreation, fish and wildlife enhancement, power generation, and salinity-control in the Sacramento-San Joaquin Delta. The project delivers water to over two-thirds of California's population and approximately 600,000 acres of farmland through 29 urban and agricultural water districts. These agencies have long-term water supply contracts totaling 4.2 million acre-feet per year. The principal storage facility for the SWP is Lake Oroville on the Feather River in the Sacramento Valley. Banks Pumping Plant exports water from the Sacramento-San Joaquin Delta for storage in San Luis Reservoir and delivery to water contractors in the San Francisco Bay Area, San Joaquin Valley, Central Coast, and Southern California. Key SWP reservoirs and their capacities are listed in Table 4.3.

**Table 4.3 Key SWP Reservoirs**

| [illegible] | Capac[illegible] ([illegible]AF[illegible]) |
|---|---|
| [illegible] | [illegible] |
| Sa[illegible] S[illegible] P[illegible]ar[illegible] | [illegible] |

## 4.3 Modeling Methodology for Quantifying Climate Change Impacts on CVP and SWP Operations

Traditionally, planning simulation models have been used to measure the effects of hydrologic, structural, or regulatory changes on SWP and CVP operations. A base case is simulated to establish expected annual average deliveries and carryover storage if no change is made. Study scenarios are then run by incorporating the expected changes to hydrology, such as those caused by climate change, or planned changes in facilities or project regulations. The impacts of the changes can then be determined by comparing base case operational statistics with those of the study scenarios.

The DWR and Reclamation have jointly developed computer model CalSim-II that simulates much of the water resources infrastructure in the Central Valley of California and Delta region. CalSim-II models all areas that contribute flow to the Delta. The geographical coverage includes: The Sacramento River Valley; the San Joaquin River Valley; the Sacramento-San Joaquin Delta; the Upper Trinity River and the CVP and SWP service areas. CalSim-II simulates operation of the CVP-SWP system for 73 years using a monthly time step. The model assumes that facilities, land use, water supply contracts, and regulatory requirements are constant over this period, representing a fixed level of development. The historical flow record October 1922-Septrember 1994, adjusted for the influence of land-use change and upstream flow regulation, is used to represent the possible range of water supply conditions.

CalSim-II uses optimization techniques to route water through a CVP-SWP system network representation. The network includes over 300 nodes and over 900 arcs, representing 24 surface reservoirs and the interconnected flow system. A linear programming (LP)/mixed integer linear programming (MILP) solver determines an optimal set of decisions for each time period given a set of weights and system constraints. The physical description of the system is expressed through a user interface with tables outlining the system characteristics. The priority weights and basic constraints are also entered in the system tables. The programming language used, Water Resources Engineering Simulation Language (WRESL), serves as an interface between the user and the LP/MILP solver, time-series database, and relational database. Specialized operating criteria are expressed in WRESL.

The hydrology in CalSim-II was developed jointly by DWR and Reclamation. Water diversion requirements (demands), stream accretions and depletions, rim basin inflows, irrigation efficiency, return flows, non-recoverable losses, and groundwater operation are components that make up the hydrology used in CalSim-II. Demands are preprocessed independent of CalSim-II and vary according to the specified level of development (e.g., 2001, 2020) and according to hydrologic conditions. Agricultural land-use-based demands are calculated from an assumed cropping pattern and a soil moisture budget. Urban demands are typically set to contract amount, but with reductions in wet years based on recent historical data. Both land-use-based demands and contract entitlements serve as upper bound on deliveries. Environmental demands such as minimum reservoir storage requirements, minimum in-stream flows and deliveries to national wildlife refuges, and wildlife management areas are as stipulated in current regulatory requirements and discretionary interagency agreements. Sacramento Valley and tributary rim basin hydrologies are developed using a process designed to adjust the historical sequence of monthly stream flows to represent a sequence of flows at a future level of development. Adjustments to historic water supplies are determined by imposing future level land use on historical meteorological and hydrologic conditions. San Joaquin River basin hydrology is developed using fixed annual demands and regression analysis to develop accretions and depletions. The resulting hydrology represents the water supply available from Central Valley streams to the CVP and SWP at a future level of development. Groundwater has only limited representation in CalSim-II. This resource is modeled as a series of interconnected lumped-parameter basins. Groundwater pumping, recharge from irrigation, stream-aquifer interaction and interbasin flow are calculated dynamically by the model.

CalSim-II uses DWR's Artificial Neural Network (ANN) model to simulate the flow-salinity relationships for the Delta. The ANN model correlates DSM2 model-generated salinity at key locations in the Delta with Delta inflows, Delta exports, and Delta Cross Channel operations. The ANN flow-salinity model estimates electrical conductivity at the following four locations for the purpose of modeling Delta water quality standards: Old River at Rock Slough, San Joaquin River at Jersey Point, Sacramento River at Emmaton, and Sacramento River at Collinsville. In its estimates, the ANN model considers antecedent conditions up to 148 days, and considers a "carriage-water" type of effect associated with Delta exports.

CalSim-II uses logic for determining deliveries to north-of-Delta, and south-of-Delta CVP and SWP contractors. The delivery logic uses runoff forecast information, which incorporates uncertainty and standardized rule curves (i.e. Water Supply Index versus Demand Index Curve). The rule curves relate forecasted water supplies to deliverable "demand," and then use deliverable "demand" to assign subsequent delivery levels to estimate the water available for delivery and carryover storage. Updates of delivery levels occur monthly from January 1 through May 1 for the SWP and March 1 through May 1 for the CVP as runoff forecasts become more certain. The south-of-Delta SWP delivery is determined based on water supply parameters and operational constraints. The CVP system wide delivery and south-of-Delta delivery are determined similarly upon water supply parameters and operational constraints with specific consideration for export constraints.

## 4.4 Generating CalSim-II Input from Global Climate Model Output

To simulate the proposed climate change scenarios, CalSim-II climate change input was needed. At a minimum, the input had to represent climate change effects on rainfall and snowmelt runoff. Global climate models (GCMs), listed previously in Table 4.1, provided projected climate data, however, the GCM data were not suitable for direct CalSim-II input for two reasons. First, CalSim-II needed streamflow data whereas the GCMs provided precipitation data. Second, CalSim-II needed data at specific locations, such as inflows to major reservoirs, whereas the GCMs provide data at a coarse resolution of only about six grid points over all of California. In other words, the type and scale of GCM output did not fit as CalSim-II input. An intermediate hydrologic model was needed.

Fortunately, such a hydrologic simulation was available. Ed Maurer, of the University of Santa Clara, had run the GCM results of interest through a macro-scale hydrologic model called the Variable Infiltration Capacity or VIC model. VIC converted the GCM precipitation data into runoff data at a 1/8$^{th}$ degree grid. Both rainfall and snowmelt runoff were represented in this model. The runoff data was further processed by SCRIPPS to produce regional scale streamflow data centered on the following locations:

1) Smith River at Jedediah Smith State Park
2) Sacramento River at Shasta Lake
3) Feather River at Lake Oroville
4) Yuba River
5) North Fork of the American River
6) American River at Folsom Lake
7) Stanislaus River at New Melones Reservoir
8) Tuolumne River at New Don Pedro Reservoir
9) Merced River at Lake McClure
10) Kings River at Pine Flat Reservoir

Thus, streamflow data was available, but the regional scale of the data was still too coarse for direct CalSim-II input.

Miller, et al (2001) proposed using perturbation ratios to transfer regional scale climate change behavior to local scale historic data. This technique was used to transfer average climate change effects observed in VIC regional runoff to historic CalSim-II reservoir inflows. First, historic and projected time references were selected – 1976 and 2050 respectively. VIC monthly streamflows were averaged around these years. To adequately represent the effects of climate change, the period of average was thirty years - a recognized climatological time-scale – centered on the reference year; 1976 average monthly streamflows were calculated using the 1961-1990 VIC data, and 2050 average monthly streamflows were calculated using the 2035-2064 VIC data. Finally, perturbation ratios were calculated by dividing the 2050 VIC average monthly streamflows by their respective 1976 VIC average monthly streamflows. The results are listed in Table 4.4, Table 4.5, Table 4.6, and Table 4.7.

Let's consider the GFDL A2 results listed in Table 4.4. The June perturbation ratio for the Smith River region was 0.62. This shows that, on average, 2050 June streamflows in this region are projected to be 38 percent less (0.62 – 1 = -0.38) than the historic reference 1976 streamflows. For comparison, consider the June perturbation ratio in the Smith River region for scenario PCM B1 – the mildly wetter climate change scenario. Results for this scenario are listed in Table 4.7. A ratio of 0.85 is listed indicating a 15 percent reduction in average streamflow in 2050 as compared to 1976. So while PCM B1 is mildly wetter than current conditions, there is still a projected reduction in runoff in the Smith River region during the late spring.

**Table 4.4 Streamflow Perturbation Ratios for Scenario GFDL A2**

| | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Smith R at Jed Smith State Park | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Stanislaus R at New Melones Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Kings R at Pine Flat Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Merced R at Lake McClure | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Yuba R System Outflow | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| NF American R at NF Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Sacramento R at Shasta Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Feather R at Oroville | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| American R at Folsom Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Tuolumne R at New Don Pedro | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 4.5 Streamflow Perturbation Ratios for Scenario PCM A2**

| | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Smith R at Jed Smith State Park | 0.65 | 0.88 | 0.90 | 0.91 | 1.09 | 1.12 | 0.87 | 0.79 | 0.73 | 0.76 | 0.95 | 1.14 |
| Stanislaus R at New Melones Dam | 0.95 | 1.12 | 0.72 | 1.05 | 1.31 | 1.11 | 1.11 | 0.85 | 0.81 | 0.75 | 0.87 | 0.92 |
| Kings R at Pine Flat Dam | 0.96 | 1.13 | 0.83 | 1.00 | 1.42 | 1.19 | 1.22 | 1.02 | 0.81 | 0.69 | 0.79 | 0.89 |
| Merced R at Lake McClure | 0.99 | 1.69 | 0.84 | 0.93 | 1.33 | 1.18 | 1.21 | 0.88 | 0.70 | 0.60 | 0.71 | 0.89 |
| Yuba R System Outflow | 0.69 | 1.10 | 0.82 | 0.95 | 1.25 | 1.14 | 0.95 | 0.74 | 0.67 | 0.67 | 0.91 | 0.91 |
| NF American R at NF Dam | 0.58 | 1.19 | 0.71 | 1.00 | 1.26 | 1.14 | 0.91 | 0.69 | 0.61 | 0.49 | 0.90 | 0.90 |
| Sacramento R at Shasta Dam | 0.86 | 1.02 | 0.95 | 0.86 | 1.06 | 1.05 | 0.91 | 0.78 | 0.86 | 0.89 | 0.94 | 0.96 |
| Feather R at Oroville | 0.81 | 1.00 | 0.93 | 0.90 | 1.24 | 1.13 | 1.00 | 0.79 | 0.73 | 0.85 | 0.93 | 0.93 |
| American R at Folsom Dam | 0.69 | 1.13 | 0.65 | 1.01 | 1.35 | 1.05 | 0.91 | 0.65 | 0.68 | 0.68 | 0.92 | 0.93 |
| Tuolumne R at New Don Pedro | 0.98 | 1.17 | 0.75 | 1.02 | 1.27 | 1.11 | 1.15 | 0.93 | 0.71 | 0.81 | 0.90 | 0.92 |

**Table 4.6 Streamflow Perturbation Ratios for Scenario GFDL B1**

| | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Smith R at Jed Smith State Park | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Stanislaus R at New Melones Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Kings R at Pine Flat Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Merced R at Lake McClure | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Yuba R System Outflow | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| NF American R at NF Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Sacramento R at Shasta Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Feather R at Oroville | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| American R at Folsom Dam | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| Tuolumne R at New Don Pedro | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 4.7 Streamflow Perturbation Ratios for Scenario PCM B1**

| | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Smith R at Jed Smith State Park | 0.99 | 0.90 | 0.90 | 1.06 | 1.00 | 1.37 | 1.12 | 1.02 | 0.85 | 0.85 | 0.95 | 1.23 |
| Stanislaus R at New Melones Dam | 0.96 | 1.19 | 0.73 | 1.26 | 1.18 | 1.28 | 1.20 | 0.95 | 0.81 | 0.83 | 0.92 | 0.93 |
| Kings R at Pine Flat Dam | 0.94 | 1.13 | 0.78 | 1.16 | 1.15 | 1.13 | 1.12 | 1.06 | 0.81 | 0.85 | 0.86 | 0.91 |
| Merced R at Lake McClure | 0.95 | 1.45 | 0.64 | 1.20 | 1.21 | 1.32 | 1.19 | 0.96 | 0.73 | 0.80 | 0.86 | 0.90 |
| Yuba R System Outflow | 0.92 | 1.09 | 0.69 | 1.26 | 1.10 | 1.38 | 1.19 | 0.94 | 0.82 | 0.85 | 0.97 | 0.97 |
| NF American R at NF Dam | 0.86 | 1.23 | 0.60 | 1.34 | 1.08 | 1.47 | 1.21 | 0.92 | 0.73 | 0.75 | 0.96 | 0.94 |
| Sacramento R at Shasta Dam | 1.14 | 0.94 | 0.90 | 1.10 | 0.97 | 1.30 | 1.17 | 1.02 | 0.97 | 0.98 | 0.99 | 1.00 |
| Feather R at Oroville | 0.99 | 0.94 | 0.78 | 1.18 | 1.11 | 1.29 | 1.17 | 0.97 | 0.90 | 0.95 | 0.99 | 0.99 |
| American R at Folsom Dam | 0.86 | 1.21 | 0.60 | 1.38 | 1.21 | 1.40 | 1.20 | 0.88 | 0.74 | 0.84 | 0.97 | 0.97 |
| Tuolumne R at New Don Pedro | 0.98 | 1.18 | 0.73 | 1.21 | 1.16 | 1.24 | 1.21 | 1.03 | 0.75 | 0.89 | 0.93 | 0.93 |

The CalSim-II climate change scenario input was produced using the above listed perturbation ratios. Base CalSim-II reservoir inflows were generated from the WY1922-1994 historical record. For each climate change scenario, the historical inflows were perturbed or altered by multiplying the historical inflow timeseries with corresponding perturbation ratios obtained from the VIC streamflow analysis; perturbation ratios were matched with CalSim-II inflow timeseries data based on month and geographic proximity.

The reservoir inflows that constitute the bulk of water supply for the State Water Project (SWP) and the Central Valley Project (CVP) are limited in number. They include the Sacramento River at Shasta, the Feather River at Oroville, the American River above Folsom, all in the Sacramento Valley, and the Stanislaus, the Tuolumne, the Merced and the San Joaquin Rivers in the San Joaquin Valley. These and others, such as the Trinity River and Yuba River, are the historical inflows that were perturbed for each climate change scenario. Focusing on Sacramento Valley impacts, average monthly Shasta, Oroville and Folsom inflows for the Base and four climate change scenarios are compared in Figure 4.1, Figure 4.2, and Figure 4.3 respectively. The period of average is WY1922-1994. As shown, the climate change perturbations generally resulted in higher flows in the winter and lower in the spring and early summer as expected.

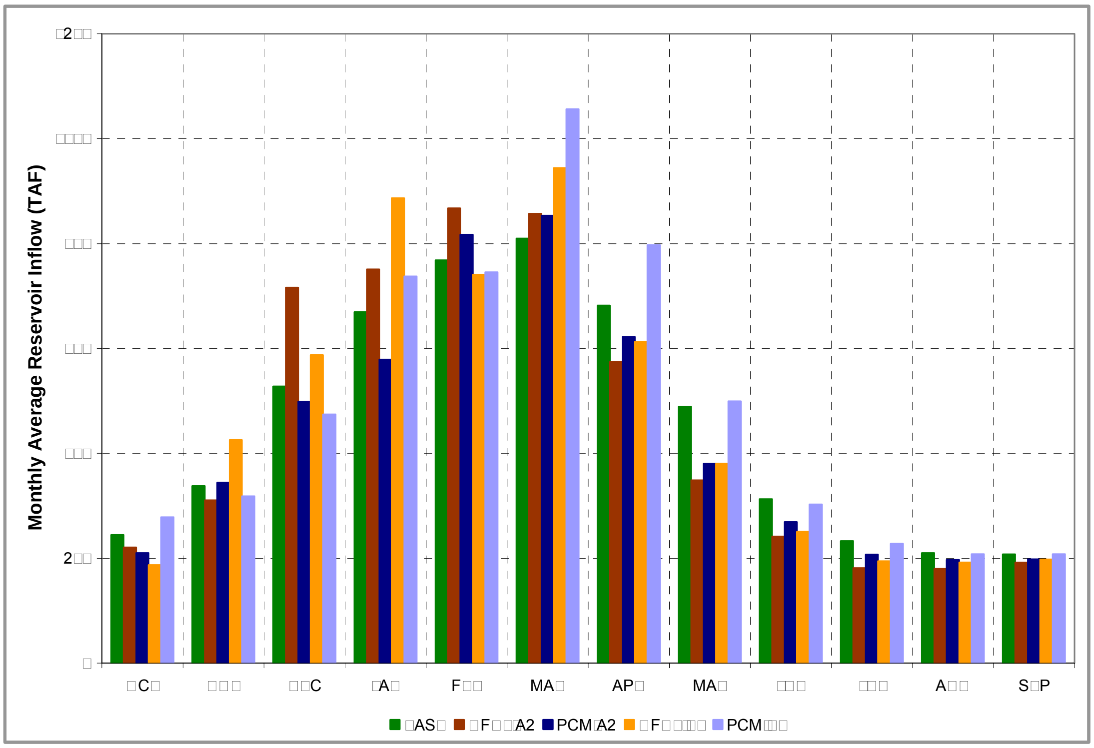


**Figure 4.1 Lake Shasta Average Monthly Inflow (1922-1944)**

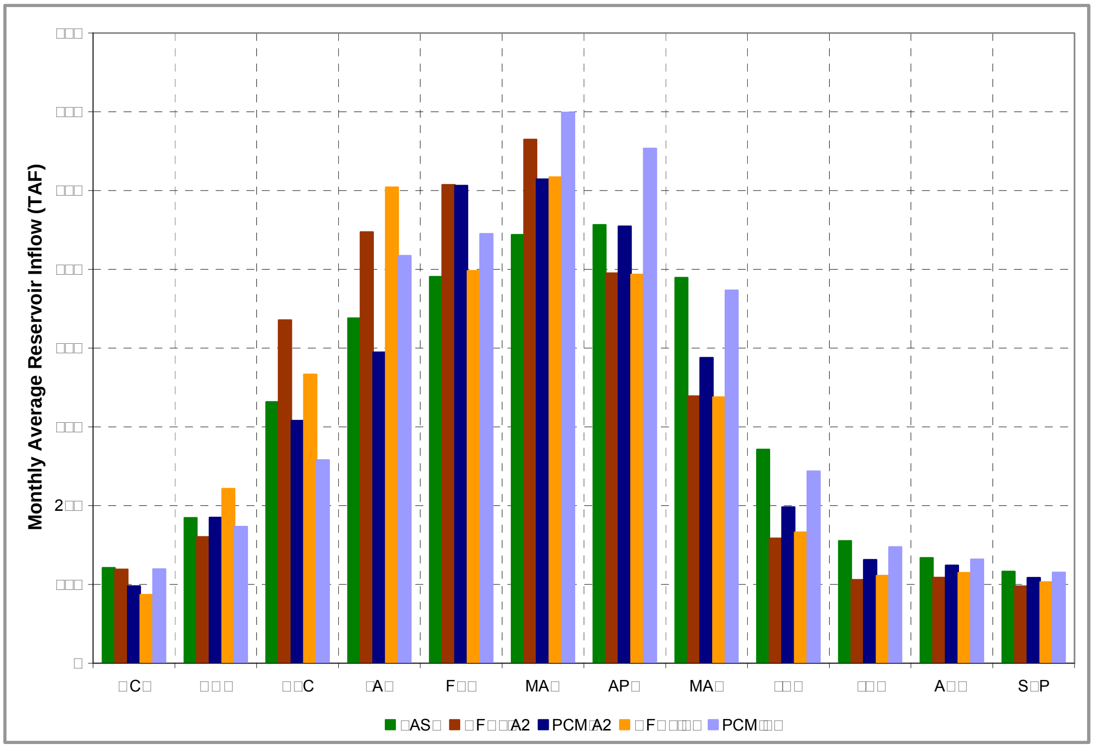


**Figure 4.2 Lake Oroville Average Monthly Inflow (1922-1994)**

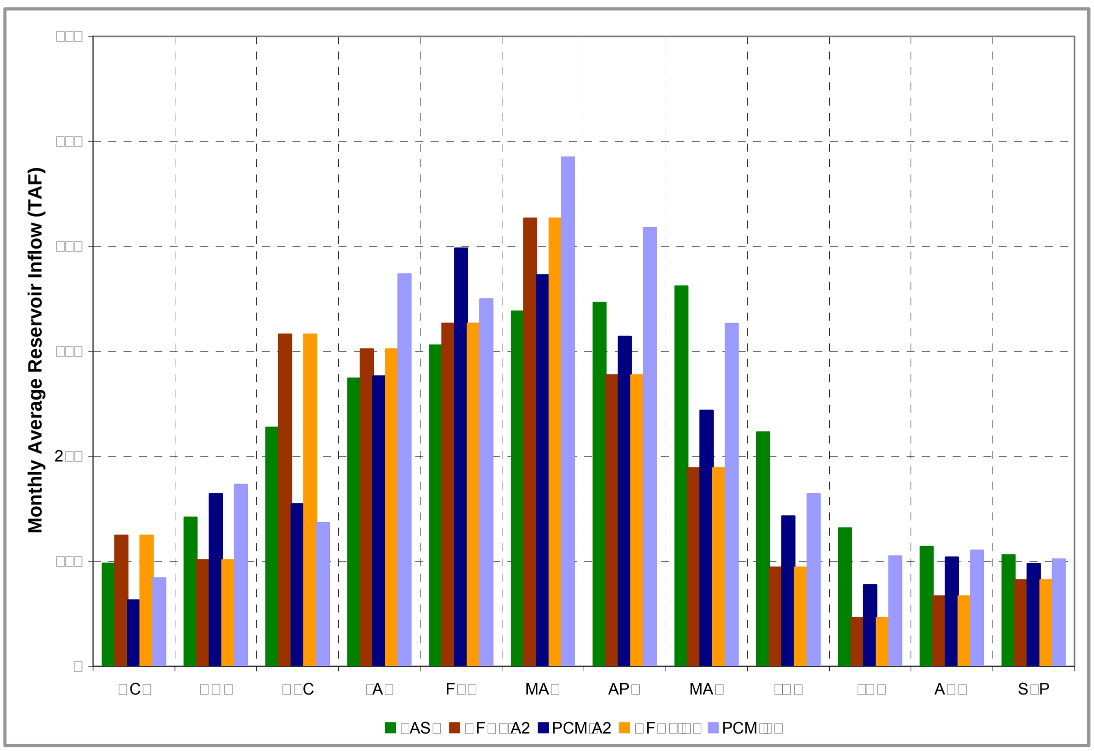


**Figure 4.3 Folsom Lake Average Monthly Inflow (1922-1994)**

Annual average Shasta, Oroville, and Folsom inflows are listed in Table 4.8, Table 4.9, and Table 4.10. The annual average flows for the climate change scenarios were calculated from the perturbed CalSim-II timeseries input. Inflows were averaged over the 1922 – 1994 historical period, the 1928 – 1934 and 1986 – 1992 droughts, and the 1981 – 1983 wet period.

**Table 4.8 Lake Shasta Annual Average Inflow (TAF)**

| | | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|---|
| Long-term (1922 – 1994) | Value | 5492 | 5442 | 5177 | 5601 | 5854 |
| | Change | -- | -51 | -315 | 109 | 362 |
| May 1928 - Oct 1934 | Value | 3332 | 3227 | 3114 | 3321 | 3545 |
| | Change | -- | -106 | -219 | -12 | 213 |
| WY 1987 - WY 1992 | Value | 3817 | 3720 | 3603 | 3859 | 4115 |
| | Change | -- | -97 | -214 | 42 | 299 |
| WY 1980 - WY 1983 (Wet Period) | Value | 7582 | 7599 | 7223 | 7829 | 8143 |
| | Change | -- | 17 | -359 | 247 | 561 |

**Table 4.9 Lake Oroville Annual Average Inflow (TAF)**

| | | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|---|
| Long-term (1922 – 1994) | Value | 3833 | 3840 | 3712 | 3722 | 4079 |
| | Change | -- | 6 | -122 | -111 | 245 |
| May 1928 - Oct 1934 | Value | 2174 | 2109 | 2061 | 2038 | 2282 |
| | Change | -- | -66 | -113 | -136 | 108 |
| WY 1987 - WY 1992 | Value | 2002 | 2032 | 1968 | 1964 | 2163 |
| | Change | -- | 30 | -34 | -38 | 161 |
| WY 1980 - WY 1983 (Wet Period) | Value | 6064 | 6170 | 5936 | 5995 | 6465 |
| | Change | -- | 106 | -128 | -69 | 401 |

**Table 4.10 Folsom Lake Annual Average Inflow (TAF)**

| | | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|---|
| Long-term Annual Average | Value | 2670 | 2355 | 2410 | 2368 | 2829 |
| | Change | -- | -315 | -260 | -302 | 159 |
| May 1928 - Oct 1934 | Value | 1519 | 1281 | 1321 | 1277 | 1552 |
| | Change | -- | -238 | -198 | -242 | 33 |
| WY 1987 - WY 1992 | Value | 1355 | 1225 | 1237 | 1239 | 1479 |
| | Change | -- | -130 | -117 | -116 | 125 |
| WY 1980 - WY 1983 (Wet Period) | Value | 4470 | 4022 | 4109 | 4057 | 4802 |
| | Change | -- | -449 | -361 | -414 | 332 |

So through a sequence of global climate models (GFDL and PCM), a regional hydrologic model (VIC), derivation of climate change runoff perturbation ratios, and, finally, applying those perturbation ratios to CalSim-II historic reservoir inflows, the CalSim-II climate change scenario input was created. The sequence of models is illustrated in Figure 4.4.

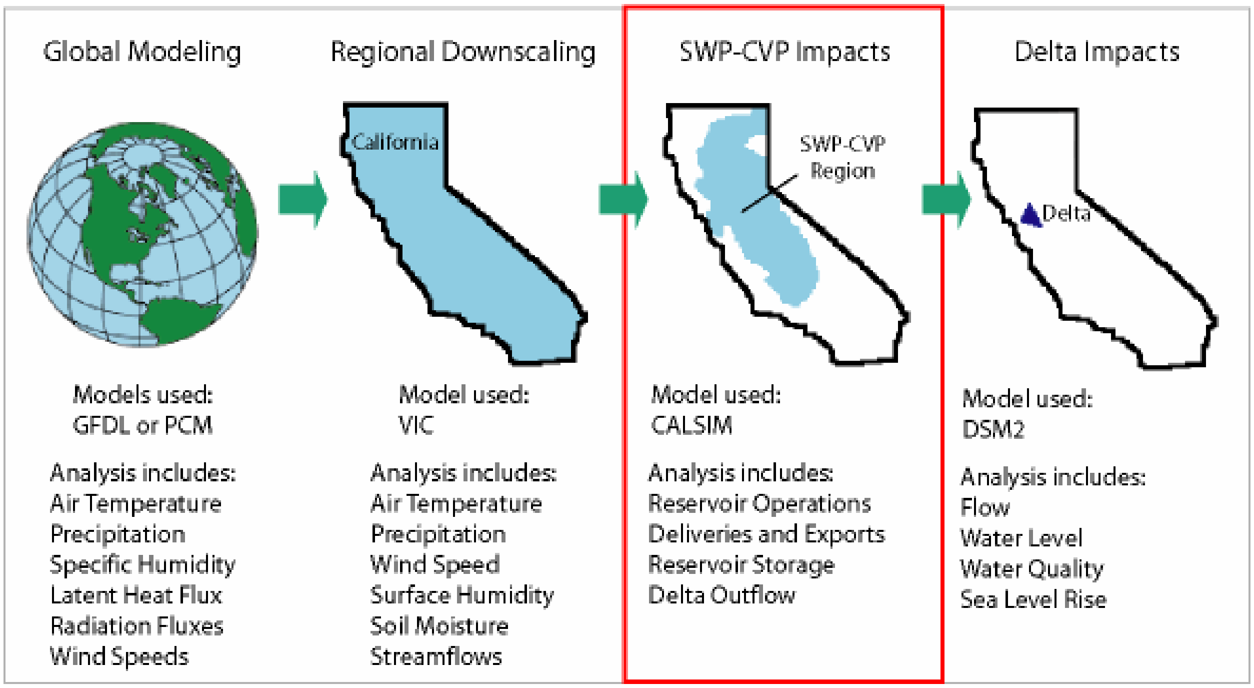


**Figure 4.4 Modeling Sequence for Generating CalSim-II Climate Change Scenarios**

## 4.5 Study Scenarios

### 4.5.1 Base Scenario

The base CalSim-II simulation was adapted from one of the studies presented in 2004 by the Bureau of Reclamation in support of its latest Operations Criteria and Plan (OCAP). Table 4.11 lists project and non-project demand assumptions by region. Regulatory standards and operations criteria are listed in Table 6-2 of Chapter 6 of the report *Long-Term Central Valley Project Operations Criteria and Plan* (USBR 2004). The specific study used from the OCAP analysis was Study D at a 2020 level of development. Some key regulatory and operational assumptions in this study are:

1) Delta exports, outflow and water quality are regulated according to the State Water Resources Control Board D1641 and the Water Quality Control Plan.
2) CVPIA 3406 (b)(2) is NOT included.
3) The Environmental Water Account (EWA) is NOT included.

**Table 4.11 Demand Assumptions for the Base Scenario**

| | **Base Condition** |
|---|---|
| **Period of Simulation** | 73 years (1922-1994) |
| **HYDROLOGY**<br>**Level of Development (Land Use)** | 2020 Level, DWR Bulletin 160-98 |
| **Demands** | |
| **North of Delta (exc American R)** | |
| CVP | Land Use based, limited by Full Contract |
| SWP (FRSA) | Land Use based, limited by Full Contract |
| Non-Project | Land Use based |
| **CVP Refuges** | Firm Level 2 |
| **American River Basin** | |
| Water rights | 2020, Sacramento Water Forum[1] |
| CVP | 2020, Sacramento Water Forum[2] |
| **San Joaquin River Basin** | |
| Friant Unit | Regression of historical |
| Lower Basin | Fixed annual demands |
| Stanslaus River Basin | New Melones Interim Operations Plan |
| **South of Delta** | |
| CVP | Full Contract |
| CCWD | 195 TAF/YR |
| SWP (w/ North Bay Aqueduct) | 3.4-4.2 MAF/YR |
| SWP Article 21 Demand | MWDSC up to 50 TAF/month, Dec-Mar, others up to 84 TAF/month |

[1] Sacramento Water Forum 2025 Level Demands defined in the Sacramento Water Forum's EIR
[2] Same as footnote 1
[3] Delta diversions include operations of Los Vaqueros Reservoir operations

### 4.5.2 Climate Change Scenarios

Four climate change scenarios were simulated for this analysis: GFDL A2, PCM A2, GFDL B1, and PCM B1. GFDL and PCM are the global climate models that generated the climate scenarios. A2 and B1 indicate the different assumed rates of carbon loading in each scenario (see Table 4.1). Global climate model results were downscaled for input as CalSim-II inflow as described in Section 4.4.

The following monthly inflows were perturbed with the factors listed in Table 4.4 - Table 4.7:

1) Trinity River at Trinity Lake
2) Sacramento, McCloud, and Pit Rivers at Shasta Lake
3) Feather River at Lake Oroville
4) Yuba River upstream of the confluence with the Feather River
5) North and South Forks of the American River at Folsom Lake
6) Stanislaus River at New Melones Lake
7) Tuolumne River at New Don Pedro Reservoir
8) Merced River at Lake McClure
9) San Joaquin River at Millerton Lake

Since the monthly perturbation factors repeat themselves on an annual basis, the annual hydrology of both base and climate change scenarios maintain the same pattern of wet years and droughts. Specifically, the droughts of 1929-1934, 1976-1977, and 1987-1992 are preserved and, overall, a wet year in the base is a wet year in the climate change scenarios; there is just modestly less or more precipitation on an annual basis depending on the scenario.

The significant change in inflows between the base and climate change scenarios was in the seasonal distribution of runoff. Generally, as shown in Figure 4.1 - Figure 4.3, more runoff occurred from December through March while less came in the remainder of the year. This seasonal change in runoff was most significant in scenarios GFDL A2 and GFDL B1. It was least significant in PCM B1, and PCM A2 lies somewhere in between. A simple explanation for the change in seasonal runoff patterns is that more precipitation will fall as rain than snow in a warmer climate. More rainfall leads to more runoff in the wet months whereas less snowfall results in a smaller snowpack and less snowmelt in the dry months.

What wasn't changed between the base and climate change scenarios? There were no structural changes – no added storage, pumping, and canal capacity. No changes were made to system regulations. The CVP and SWP continued meeting minimum in-stream flow requirements. The projects continued meeting the Delta outflow and water quality standards established by the State Water Resources Control Board in Decision 1641 and the Water Quality Control Plan. Water use remained at a year 2020 level of development, and operational rules such as flood control and delivery allocations are applied consistently in base and climate change scenarios.

> Current management practices and existing system facilities were used in the analysis for this report. No changes were made to lessen the effects of climate change or sea level rise.
>
> No changes were made to:
>
> - System structures, such as added water storage, pumping, or canal capacity
> - Reservoir operating rules, such as changing the space required for flood control
> - Streamflow requirements
> - Water quality standards
> - Delta outflow requirements
> - Operations to account for sea level rise

### 4.5.3 Climate Change Impacts Not Considered in the Study Scenarios

There are also some key climate change impacts that were not considered in the study scenarios. With changing rates of evapotranspiration, it is expected that urban (landscaping) and agricultural demand for CVP and SWP water will change accordingly, but no changes in demand were included in the climate change scenarios. Another anticipated result of a warming climate is a rising sea level. While the climate change scenarios are held to the same

Delta salinity standards as in the base scenario, the effect of a rising sea level on the projects' ability to meet those standards was not accounted for; it is assumed in all scenarios that sea level remains unchanged. Future work will include development of a tool for modifying system operations to maintain Delta water quality standards under sea level rise conditions. Note that sea level rise scenarios discussed in Chapter 5 section 5.5 use operations based on present sea level.

Furthermore, the method of downscaling global climate model information for CalSim-II input only captures the general trends of average rainfall and seasonal shifts in runoff. There is no information included about changes in weather variability. In each of the scenarios, the frequency and length of the droughts remained the same. If climate change influences these underlying weather phenomena, then we are missing important information necessary to determine impacts to CVP and SWP operations.

## 4.6 Results

Results of the CalSim-II base and climate change scenarios are presented and compared in this section. Given that the primary purpose of the CVP and SWP is water supply, the key CVP and SWP operational measures presented are water shortages, contractor deliveries, and carryover storage. Then, to begin the search for operational flexibility in dealing with climate change impacts on water supply, the significance of various operational constraints was analyzed. Of course, the CVP and SWP have other important responsibilities such and fish and wildlife enhancement and power supply. Therefore, at the end of the section, climate change impacts on in-stream temperatures and power supply are also discussed.

Before reviewing the results, though, please note that the purpose of this report is to demonstrate how various analysis tools currently used by DWR could be used to address issues related to climate change. The methods and results presented in this report could be used to guide future climate change analysis and to identify areas where more information is needed. All results presented in this report are preliminary, incorporate several assumptions, reflect a limited number of climate change scenarios, and do not address the likelihood of each scenario. Therefore, these results are not sufficient by themselves to make policy decisions.

### 4.6.1 Shortages

To discuss CalSim-II shortages, we must first discuss water use priorities. There are many competing demands for the water that flows into the Central Valley. They include farm irrigation, urban and industrial use, ecosystem protection and restoration, and reservoir storage for hydropower production, recreation or for later use in the next inevitable drought. In CalSim-II, distribution of water is prioritized as listed in Table 4.12.

**Table 4.12 CalSim-II Water Use Prioritization**

| | |
|---|---|
| First Priority | prior right water users, minimum in-stream flow requirements, WQCP requirements |
| Second Priority | SWP Table A contractors, CVP contractors |
| Third Priority | reservoir storage for the next year (carryover) |
| Fourth Priority | SWP Article 21 deliveries |

While CVP and SWP contractor deliveries take precedence over next year's storage, a balance between the two is struck in the allocation decision. During the winter and spring, the SWP and CVP decide how much of contractor demand can be met for the year based on available storage and forecasted runoff. Part of the allocation decision is to ensure that enough water is left in storage at the end of the year in case of impending drought. Once the allocation decision is made though, deliveries to meet that allocation take priority over maintaining the storage carryover target.

Given this simple explanation of prioritization, there are two types of shortages in CalSim-II. One is an acceptable, though not desirable, result of making water allocations based on imperfect forecasts. In wetter years, the SWP and CVP sometimes allocate more south-of-Delta (SOD) deliveries than can be delivered through the pumps due to various export constraints. For the base and four climate change scenarios, this type of shortage is infrequent and, compared to total annual deliveries, insignificant. This type of shortage is also implicitly included in the delivery analysis; if it's not delivered, we don't count it.

The other type of shortage is usually unacceptable. This is when the first priority obligations – prior right contracts, minimum in-stream flow requirements, Delta requirements – are not met. The only way for this shortage to occur in CalSim-II is for one or more North-of-Delta reservoirs to be drawn down to dead storage. At this point, the model has lost control of meeting the watershed's most basic needs not to mention the lawful obligations of the CVP and SWP. Such a simulation is broken. The lower priority metrics are questionable: Could the shortage of high priority water uses be avoided at the expense of lower priority uses through some simple changes in operating rules? And the results of a broken simulation can not be confidently compared to an unbroken simulation.

Table 4.13 shows that Shasta and Folsom reservoirs were at dead storage for a significant number of months in scenarios GFDL A2, PCM A2, and GFDL B1. These months are all concentrated in the critical year of 1924 and the droughts of 1929-1934, 1976-1977, and 1987-1992. During these months, streamflow requirements were not met on the Sacramento and American rivers and the CVP was unable to contribute its Coordinated Operation Agreement defined share of in-basin use. The base scenario had one month of shortage on the American and Sacramento rivers – October 1977. Due to the severity of the 1976-1977 drought, this is frequently unavoidable in CalSim-II simulations.

**Table 4.13 Months of Critical Shortages (Storage at Dead Pool)**

| | Shasta [illegible] | Oroville [illegible] | Folsom [illegible] |
|---|---|---|---|
| BASE | [illegible] | [illegible] | [illegible] |
| GFDL A2 | [illegible] | [illegible] | [illegible] |
| PCM A2 | [illegible] | [illegible] | 22 |
| GFDL B1 | [illegible] | [illegible] | [illegible] |
| PCM B1 | [illegible] | [illegible] | [illegible] |

The length of shortages in GFDL A2, PCM A2, and GFDL B1 indicate that the delivery results presented for these scenarios in the next section are not always reliable. Too much risk was taken in the delivery allocation decisions of these three scenarios and not enough storage was carried into the drought periods as a result. In future climate change simulations, modifications to the rule that divides available water into delivery and carryover should be investigated as a means to prevent these shortages. Since CVP allocations are dependent on Shasta and Folsom storage, such modifications will likely alter the resulting delivery capability of the CVP as compared to the results presented in the next section.

### 4.6.2 Delivery and Storage Analysis

As shown previously in Figure 4.1, Figure 4.2, and Figure 4.3, the general effect of climate change on runoff is that more comes in the winter, when we don't need it, and less comes in spring and summer, when we do need it. One would expect that this shift in runoff will make it more difficult for the CVP and SWP to capture water and deliver it to their customers. The resulting annual average deliveries to Table A contractors listed in Table 4.14 fit these expectations for three of the four climate change scenarios. GFDL B1, with 2,861 TAF annual average deliveries, was 10.2 percent less than the Base scenario annual average of 3,186 TAF. PCM A2 and GFDL A2 also reduced Table A deliveries below the Base. On the other hand, in PCM B1, the scenario that was slightly wetter than the Base, the SWP managed to make 1.2 percent more Table A deliveries on an annual average basis – increasing deliveries from 3,186 to 3,224 TAF. The dry year samples of Table A deliveries listed in Table 4.14 show that the SWP did better in the Base scenario than in GFDL A2, PCM A2, and GFDL B1 in most instances. The exception was the single dry year of 1977 – no doubt the result of the higher Table A allocation in the Base scenario for the first year of the 1976-1977 drought. PCM B1 results in higher dry year Table A deliveries than the Base in all instances except for the 1976-1977 drought.

**Table 4.14 SWP average and dry year Table A deliveries (TAF)**

| | *Average* | *Single dry year 1977* | *2-year drought 1976-1977* | *4-year drought 1931-1934* | *6-year drought 1987-1992* | *6-year drought 1929-1934* |
|---|---|---|---|---|---|---|
| BASE | [illegible] | 222 | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL B1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM B1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

While Table 4.14 contrasts annual average deliveries of the Base and climate change scenarios, a more useful comparison is delivery capability. This comparison was made using delivery exceedance probability curves which show the likelihood that some quantity of water or more was delivered in a given scenario. Each curve was assembled from the 73-year annual delivery sample provided by the CalSim-II simulation. For instance, let's say that in one simulation SWP Table A contractors were delivered more than 4 million acre-feet of water in 16 of the 73-year simulation. Therefore, one point on the curve would match the 78 percent (16/73 = 78 percent) probability of exceedance with a delivery of 4 million acre-feet.

Figure 4.5 shows the exceedance probability curves for SWP Table A deliveries. GFDL A2, PCM A2, and GFDL B1, all with slightly drier climates and significant shifts in seasonal runoff, resulted in consistently lower delivery capability. It does not matter whether the deliveries are low or high. PCM B1, with the slightly wetter climate and no significant reduction in runoff in the late spring and summer, resulted in higher delivery capability for SWP Table A contractors at the lower end of the delivery spectrum and roughly equivalent capability at the higher end. This is consistent with the results shown in the dry-period analysis of Table 4.14. The 50 percent exceedance level delivery represents the median delivery of the 73-year simulation. As shown in Figure 4.5, the Base scenario delivery with a 50 percent probability of exceedance was highest at 3551 TAF. PCM B1 was close behind. GFDL A2 has the lowest delivery at 50 percent exceedance; at 3,154 TAF, it is 11.2 percent less than the base scenario.

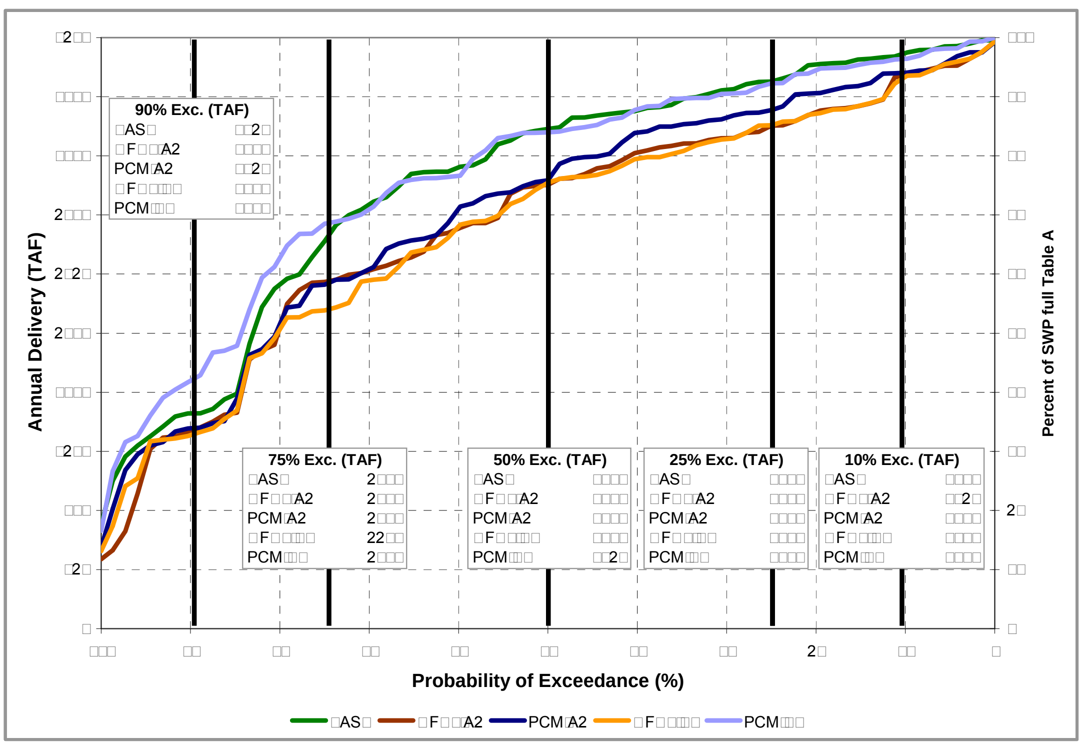


**Figure 4.5 Exceedance Probability Plot of SWP Table A Deliveries**

Carryover storage was analyzed in a similar fashion. SWP carryover storage is the sum of Oroville storage and SWP San Luis storage on September 30 – the end of the water year. Figure 4.6 shows the probability of exceedance plot for SWP carryover storage. Again, this is constructed from the 73-year simulation sample. As shown, the persistence of SWP carryover storage in scenarios GFDL A2, PCM A2, and GFDL B1 was consistently lower than the Base. The greatest difference was at the 10 percent exceedance level; GFDL B1, at 2,677 TAF carryover, is 28 percent less than the SWP carryover of 3,718 TAF for the Base scenario. However, during the dry years, the SWP was able to change operations and allocations sufficiently to make up for this carryover deficit and avoid unnecessary shortages. Note the convergence of the SWP carryover exceedance curves as you go from 10 percent probability to 90 percent. Base and GFDL A2 carryover were respectively 1,342 TAF and 1,202 TAF at the 90 percent exceedance level. This is a 10 percent reduction in carryover as compared to the 28 percent reduction at the 10 percent exceedance level. Overall, with the drier climate scenarios, less water was delivered to Table A contractors and more risk with SWP carryover storage was taken to do it. The SWP carryover storage in scenario PCM B1 tended to be slightly more dependable than the base for carryover under 2,250 TAF and slightly less dependable than the base for carryover greater than 2,250 TAF. This is also consistent with results shown earlier. The wetter climate of PCM B1 paid off during the drought periods when plenty of storage was available to dampen the added seasonal variability. The SWP was able to capture and deliver this water during the droughts. During the wetter periods though, the storage capacity wasn't available to capture the larger winter runoff. To maintain deliveries, carryover was then reduced.

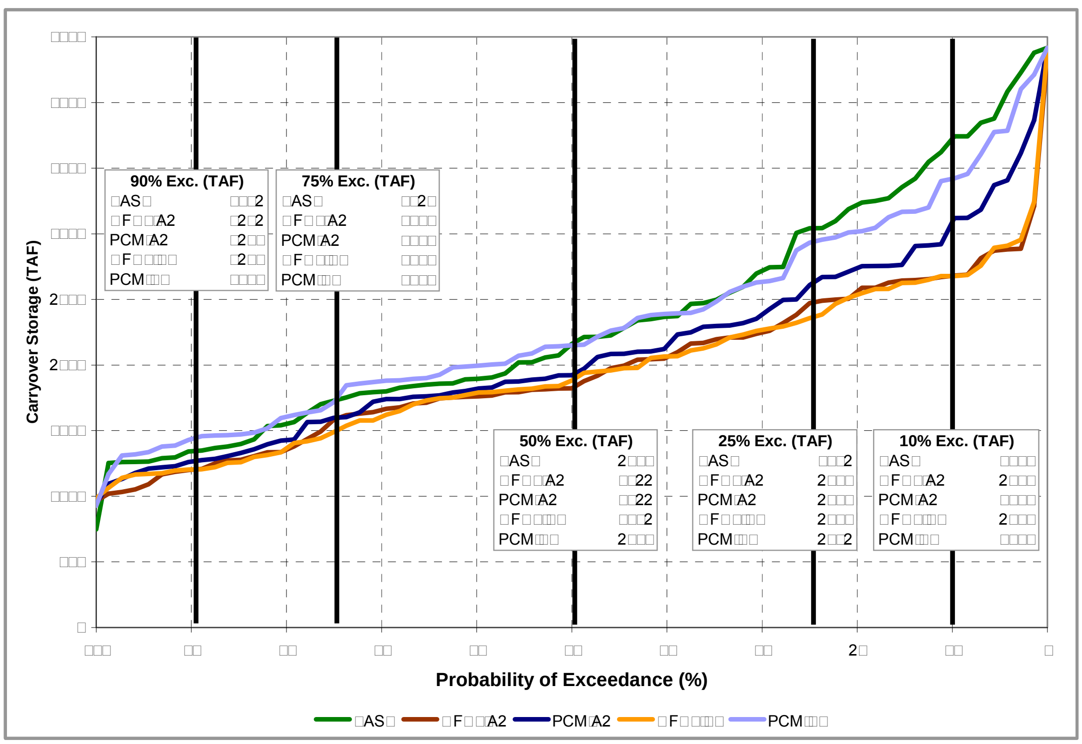


**Figure 4.6 Exceedance Probability Plot of SWP Carryover Storage**

SWP Article 21 deliveries were not affected by climate change in the same way as Table A deliveries. Having a lower priority than storage, as discussed in Section 4.6.1, Article 21 deliveries were only made when San Luis was full and Delta surplus and Banks pumping capacity were available. Whereas the bulk of Table A deliveries came in the summer and are dependent on the storage of winter precipitation, Article 21 deliveries were primarily made in the winter when surplus conditions existed. The larger winter runoff and lower Table A allocations resulted in higher average Article 21 deliveries for scenarios GFDL A2, PCM A2, and GFDL B1 as shown in Table 4.15. GFDL A2 annual average Article 21 deliveries were increased by 7 TAF from the Base – 99 to 106 TAF. In contrast, GFDL A2 annual average Table A deliveries were decreased 307 TAF from the Base – 3,186 to 2,879 TAF (see Table 4.14). Table 4.15 shows that PCM B1 annual average Article 21 deliveries were reduced in comparison to the Base scenario by 11 TAF. During the 1929-1934 drought, Article 21 contractors lost 69 TAF in scenario PCM B1 as compared to the Base scenario. This happened because higher Table A deliveries were made during this drought in PCM B1 than in the Base. Table 4.14 shows that PCM B1 and Base annual average Table A deliveries during the 1929-1934 drought were 1,949 TAF and 1,679 TAF respectively – a difference of 270 TAF. With higher Table A deliveries, San Luis did not fill as frequently resulting in less Article 21 delivery opportunities.

**Table 4.15 SWP average and dry year Article 21 deliveries (TAF)**

| | *Average* | *Single dry year 1977* | *2-year drought 1976-1977* | *4-year drought 1931-1934* | *6-year drought 1987-1992* | *6-year drought 1929-1934* |
|---|---|---|---|---|---|---|
| [illegible]AS[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible]F[illegible]A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] |
| [illegible]F[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2 | [illegible]2 |
| PCM[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2 |

Article 21 delivery capability is illustrated for the Base and climate change scenarios in Figure 4.7. As shown, in all scenarios, no Article 21 deliveries were made in more the 40 percent of the 73 years of simulation. PCM B1 had no Article 21 deliveries in 50 percent of the years. The drier climate change scenarios – GFDL A2, PCM A2, and GFDL B1 – resulted in more frequent Article 21 deliveries. Yet, at the lower probabilities of exceedance, such as 5 percent and 10 percent, the Base and PCM B1 scenarios tended to produce larger Article 21 deliveries.

As expected, the shift in seasonal runoff and slightly drier climate of scenarios GFDL A2, PCM A2 and GFDL B1 reduced annual average deliveries to CVP South-of-Delta contractors. Table 4.16 lists CVP SOD deliveries. The annual average deliveries in the Base and GFDL A2 scenarios were 2,716 and 2,435 TAF respectively – a 10.3 percent reduction. Just as with SWP Table A deliveries, scenario PCM B1 increased annual average CVP SOD deliveries as compared to the Base. The increase was 69 TAF – 2.5 percent of Base CVP SOD deliveries. With the drier climates, less was delivered to CVP SOD contractors during each of the droughts in scenarios GFDL A2, PCM A2, and GFDL B1. Drought CVP SOD deliveries were larger in PCM B1 than in the base in all instances except for 1976-1977.

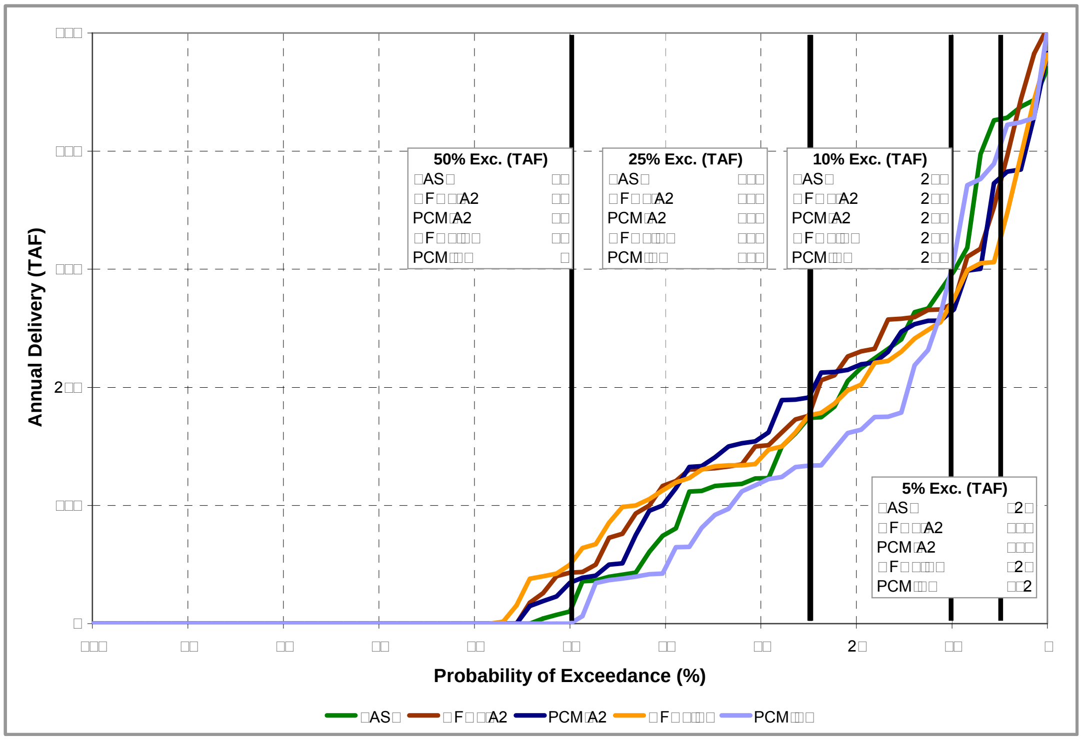


**Figure 4.7 Exceedance Probability Plot of SWP Article 21 Deliveries**

**Table 4.16 CVP South-of-Delta contractor deliveries (TAF)**

| | *Average* | *Single dry year 1977* | *2-year drought 1976-1977* | *4-year drought 1931-1934* | *6-year drought 1987-1992* | *6-year drought 1929-1934* |
|---|---|---|---|---|---|---|
| □AS□ | 2□□□ | □□□□ | □□□□ | □□□2 | □□□□ | □□□□ |
| □F□□A2 | 2□□□ | □□□□ | □□□□ | □2□□ | □□2□ | □□2□ |
| PCM□A2 | 2□□□ | □2□□ | □□□□ | □22□ | □□□□ | □□□□ |
| □F□□□□ | 2□□□ | □2□□ | □□□□ | □2□□ | □□□□ | □□□□ |
| PCM□□ | 2□□□ | □□□□ | □□□□ | □□□□ | □□□□ | □□□□ |

Capability of CVP SOD deliveries decreased for the drier scenarios both at the high and low ends of the probability spectrum. Figure 4.8 shows that the Base median (50 percent exceedance) CVP SOD delivery was 2,963 TAF. The median delivery of scenario GFDL A2 is 2,533 TAF. This equals a 14.5 percent reduction in delivery capability at a 50 percent probability of exceedance. PCM B1 shows more capability than the base in the 60 percent-100 percent exceedance probability range. Annual deliveries of this size (1,500 TAF – 2,750 TAF) typically occurred in the drier years. As such, the higher capability of CVP SOD deliveries in PCM B1 as compared to the base conforms to the higher dry year deliveries shown in Table 4.16.

CVP carryover storage was reduced in the in the drier scenarios and increased in the wetter scenario as compared to the Base. Figure 4.9 plots exceedance probability for CVP carryover storage – defined as the sum of Trinity, Shasta, Folsom, and CVP San Luis storage on September 30, the end of the water year. For GFDL A2, PCM A2, and GFDL B1, higher risks of shortage were taken (lower carryover) and still resulted in lower SOD CVP deliveries. With PCM B1, carryover was more dependable and helped the CVP increase deliveries in the droughts.

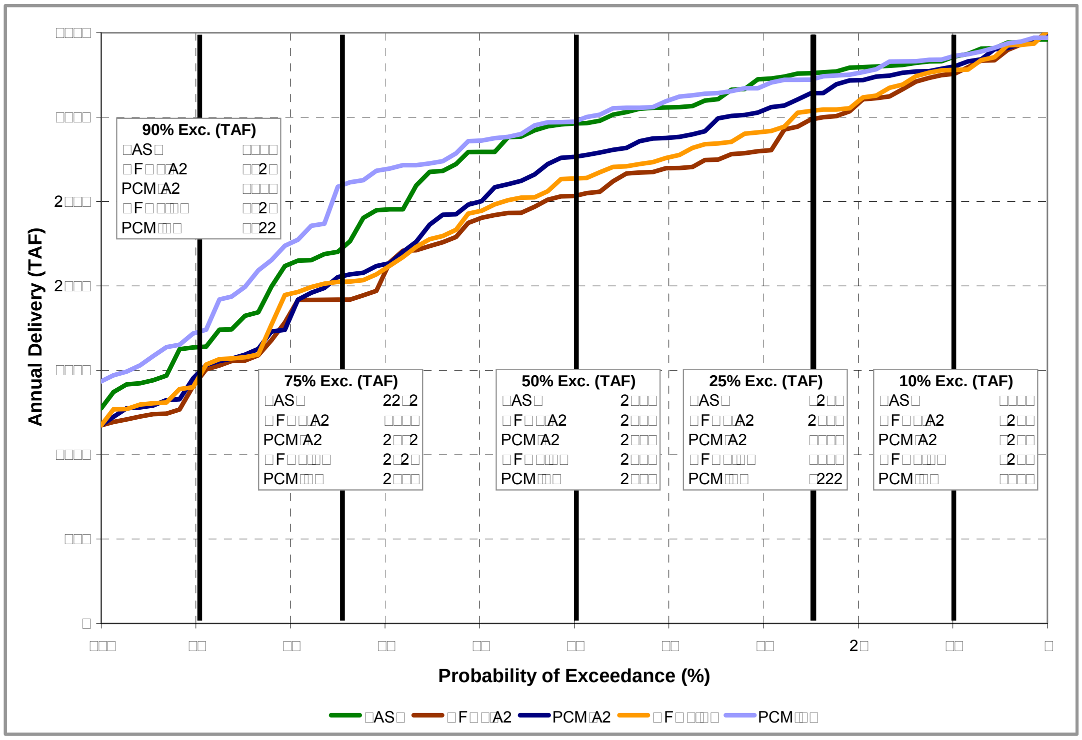


**Figure 4.8 Exceedance Probability Plot of CVP South-of-Delta Deliveries**

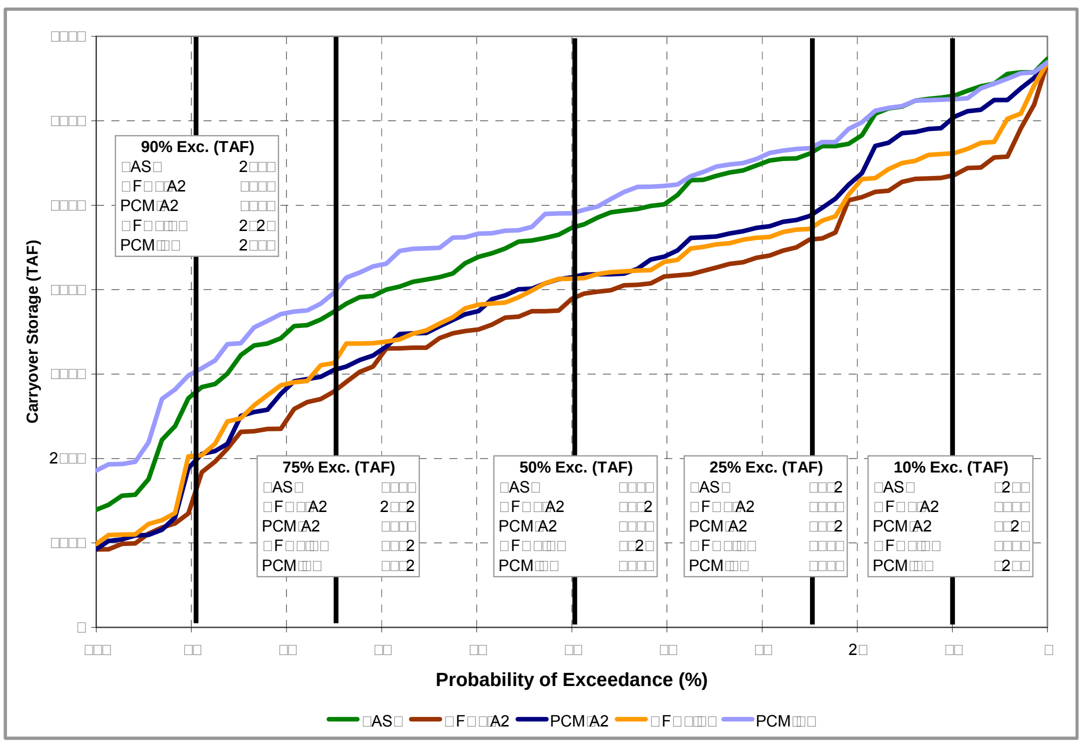


**Figure 4.9 Exceedance Probability Plot of CVP Carryover Storage**

Table 4.17 shows the annual average CVP north-of-Delta (NOD) deliveries were not as significantly affected by climate change as the CVP SOD deliveries. Base and GFDL A2 annual average CVP NOD deliveries were 2,251 and 2,181 TAF respectively. This equals a 3.1 percent reduction. In contrast, GFDL A2 CVP SOD deliveries were reduced 10.3 percent. There were some significant changes in CVP NOD deliveries during the dry periods. For instance, as shown in Table 4.17, Base and GFDL A2 annual average CVP NOD deliveries during the 1929-1934 drought were 1,940 TAF and 1,742 TAF respectively – a decrease of 10.2 percent. However, this decrease was less of a result of lowered allocations as it was of the critical shortages at Shasta and Folsom. When these reservoirs were drawn down to dead storage during the drought, settlement contractors and refuges were shorted their promised supply. These shortages are reflected in the annual average deliveries presented in Table 4.17.

**Table 4.17 CVP North-of-Delta contractor deliveries (TAF)**

| | *Average* | *Single dry year 1977* | *2-year drought 1976-1977* | *4-year drought 1931-1934* | *6-year drought 1987-1992* | *6-year drought 1929-1934* |
|---|---|---|---|---|---|---|
| [illegible]AS[illegible] | 22[illegible] | [illegible] | 2[illegible] | [illegible] | 2[illegible] | [illegible] |
| [illegible]F[illegible]A2 | 2[illegible] | [illegible] | 2[illegible]2[illegible] | [illegible] | [illegible] | [illegible]2 |
| PCM[illegible]A2 | 22[illegible] | [illegible] | 2[illegible] | [illegible]2 | [illegible] | [illegible] |
| [illegible]F[illegible] | 22[illegible] | [illegible]2[illegible] | 2[illegible] | [illegible] | 2[illegible]2[illegible] | [illegible]2[illegible] |
| PCM[illegible] | 22[illegible] | [illegible] | 2[illegible] | [illegible] | 2[illegible] | [illegible] |

Why were CVP NOD deliveries not as affected by climate change as CVP SOD deliveries? The reason is that different classes of water contracts have different allocation rules. Over 80 percent of CVP NOD deliveries were for settlement contracts or refuges, and delivery allocations for these water users were independent of available storage. NOD settlement contractors and refuges receive 100 percent of contract demand in all years except Shasta critical years; in these years, 75 percent of contract demand is met. (Shasta critical years are defined as years in which Shasta natural inflow totaled less than 3.2 million acre-feet, or as years where the two year total Shasta natural inflow was less than 7.2 million acre-feet and the previous years natural inflow was less than 4 million acre-feet.) SOD exchange contracts and refuges are allocated water in the same way, but these water users represent only around 34 percent of SOD demand. In the Base scenario, nine of the 73 years were Shasta critical. From analysis of Shasta inflow, drier scenarios GFDL A2 and GFDL B1 have exactly the same distribution of Shasta critical years as the Base, drier scenario PCM A2 would add only a single Shasta critical year, and wetter scenario PCM B1 would reduce the number of Shasta critical years by three. For purposes of this study, though, it was assumed that the distribution of Shasta critical years in each climate change scenario remained unchanged from the Base. In the years this assumption was false – one in PCM A2, three in PCM B1 – only small changes in Shasta inflow would be required for the exact definition of Shasta critical to be met. Therefore, the assumption is reasonable. With no change in the number or order of Shasta critical years, water allocations for 80 percent of CVP NOD deliveries and 34 percent of CVP SOD deliveries were the same for the Base and climate scenarios. On the other hand, 66 percent of CVP SOD deliveries and only 20 percent of CVP NOD deliveries were exposed to allocation cuts due to climate change effects on available storage. Thus, total CVP SOD deliveries were more exposed to the negative effects of climate change than CVP NOD deliveries.

Figure 4.10 shows the CVP NOD delivery capability curves for all five scenarios. Capability of these deliveries in the climate change scenarios closely tracked that of the Base in the 0 percent to 90 percent exceedance probability range. No critical shortages occurred in the years that fall in this range. Given that settlement contract and refuge deliveries were equal in all five scenarios during these years and that these types of deliveries make up more than 80 percent of the total, the fact that the capability curves for CVP NOD deliveries track so closely is expected. In the 0 percent to 90 percent exceedance probability range, GFDL A2, PCM A2, and GFDL B1 have slightly lower deliveries than the Base or PCM B1. This is due to the less than 20 percent of deliveries that are subject to allocation decisions based on available storage. The divergence of the capability curves in the 90 percent to 100 percent exceedance probability range reflects the years of shortage. GFDL A2 shorted settlement contractors and refuges the most. The Base and PCM B1 scenarios continue to track closely in the 90 percent to 100 percent range because neither experienced extreme shortages.

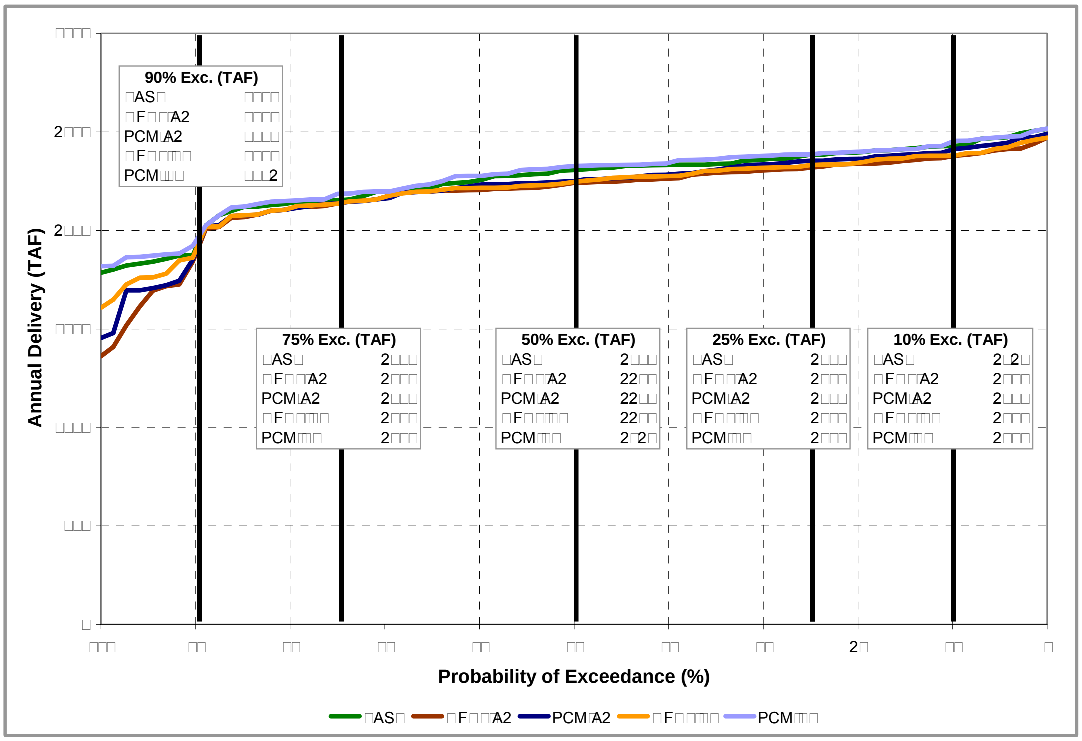


**Figure 4.10 Exceedance Probability Plot of CVP North-of-Delta Deliveries**

As shown in the above delivery and storage analysis, SWP Table A deliveries and CVP SOD deliveries were negatively affected by the drier climate change scenarios – GFDL A2, PCM A2, and GFDL B1. Carryover was also reduced in these scenarios. With less annual average runoff and a shift in seasonal flows, both projects were less effective capturing, storing, and delivering water. The wetter scenario, PCM B1, had an opposite effect despite the seasonal shift in runoff. During droughts, the additional water was readily captured and delivered with available storage and export capacity. Obviously, the likelihood of a wetter or drier climate will be an important consideration in climate change planning studies. In this case, PCM B1 is the outlier. Does this mean the wetter scenario is less probable than a drier scenario? That is a question that must be addressed.

### 4.6.3 North-of-Delta Operations Analysis

The purpose of this section is to discuss the interaction between some basic North-of-Delta operational constraints, the climate changed runoff, and impacts to water supply. The constraints of focus are flood control storage and minimum in-stream flow (MIF) requirements. Maintaining flood pool storage in reservoirs during the winter months reduces water supply capacity. Therefore, flood control operations could limit the projects' ability to capture the increased reservoir inflow due to climate change. On the other hand, MIF requirements draw water from NOD storage during extended dry periods. This can lead to a NOD-SOD storage imbalance which adds to the risk of critical NOD shortages like those that occurred in scenarios GFDL A1, PCM A1, and GFDL B1.

Figure 4.11, Figure 4.12, and Figure 4.13 show the monthly frequency that flood pool capacity limited the capture of water for long-term storage in Shasta, Oroville, and Folsom reservoirs respectively. In these frequency plots, flood control included instances that flood pool capacity is zero and the reservoirs were full -- typically in late spring and early summer. It also included late summer and early fall releases to initially free up flood pool capacity. The flood control frequency plots have nothing to do with flooding downstream; they simply show the probability that water was released from a reservoir to preserve flood pool capacity or overtopping of the reservoir in the case that the reservoir was full.

The climate change scenarios, as compared to the Base, increased inflows to Shasta, Oroville and Folsom over the December to March flood season. Shasta and Oroville reserve most of their capacity for water supply, while Folsom's primary function is flood control. It is expected that flood control frequency of Folsom will be greater than that of Shasta or Oroville. As shown in Figure 4.11, Shasta was at flood control capacity less than 40 percent of the time in December and January in all scenarios; therefore, Shasta had a better than 60 percent chance of being able to capture the additional flows in these months. In February, Shasta storage was limited by flood pool less than 45 percent of the time in the five scenarios. While in March, the presence of the flood pool becomes more significant in the GFDL B1 and PCM B1 scenarios with an approximately 50 percent control frequency. Scenarios Base, GFDL A2, and PCM A2 have a Shasta flood control frequency of around 40 percent in March.

Figure 4.12 shows that Oroville is likely to have available capacity to capture increased inflows in December, January, and February in all four climate change scenarios. Only in March does the flood control frequency of Oroville rise above 50 percent for three of the climate change scenarios; at 63 percent flood control frequency, Oroville was least effective capturing the PCM B1 increased inflows in March.

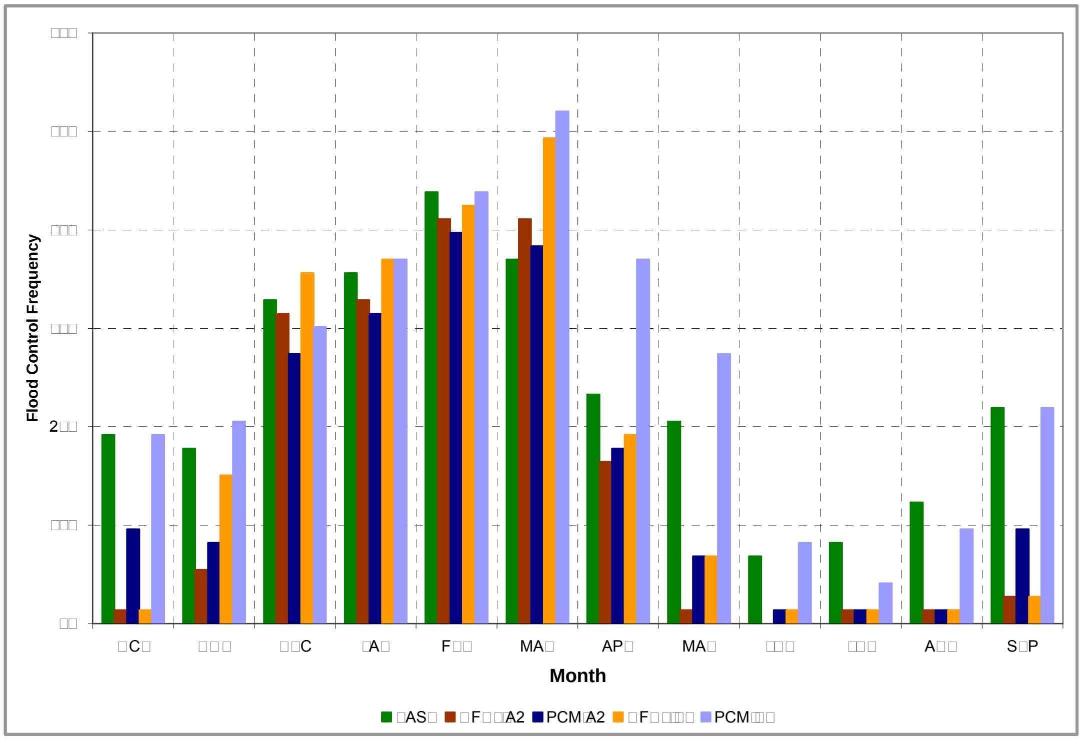


**Figure 4.11 Monthly flood control frequency of Lake Shasta**

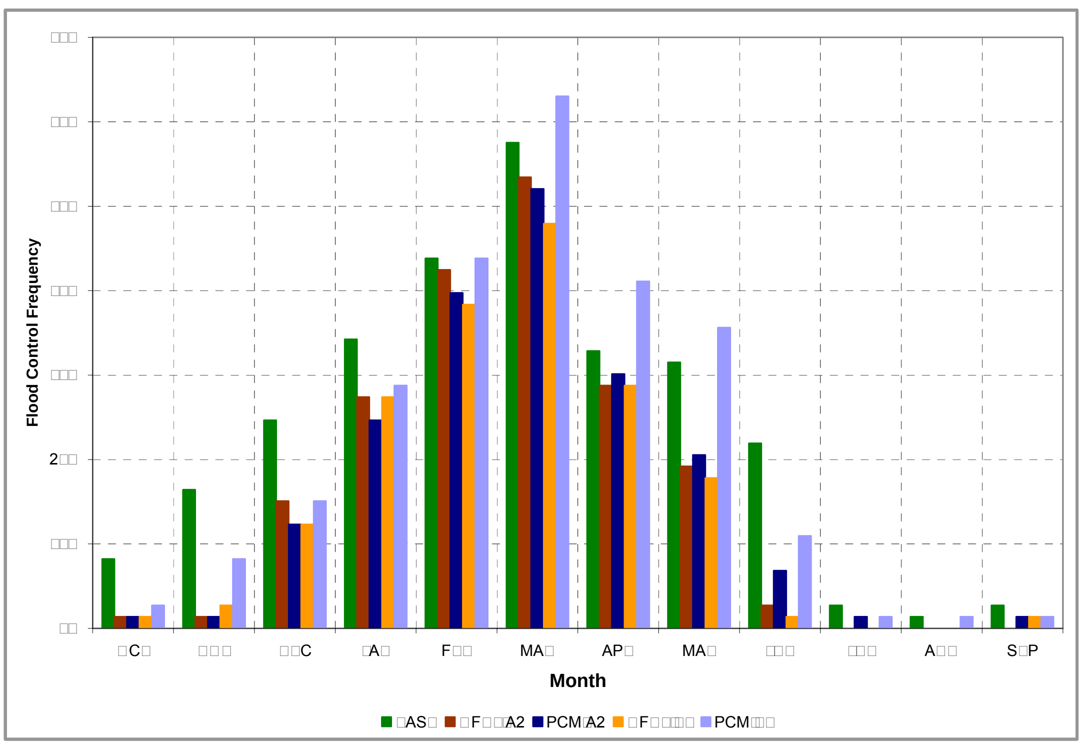


**Figure 4.12 Monthly flood control frequency of Lake Oroville**

Folsom was the least able of the three reservoirs to capture increased winter inflows. Figure 4.13 shows that in January, February, and March, the Folsom flood control frequency approached or surpassed 70 percent in the four climate change scenarios. PCM B1 reaches nearly 80 percent in February and March. The analysis assumes that flood pool operations will remain consistent with historical rules. However, with increased winter runoff, demands for greater flood protection may further encroach on water supply storage.

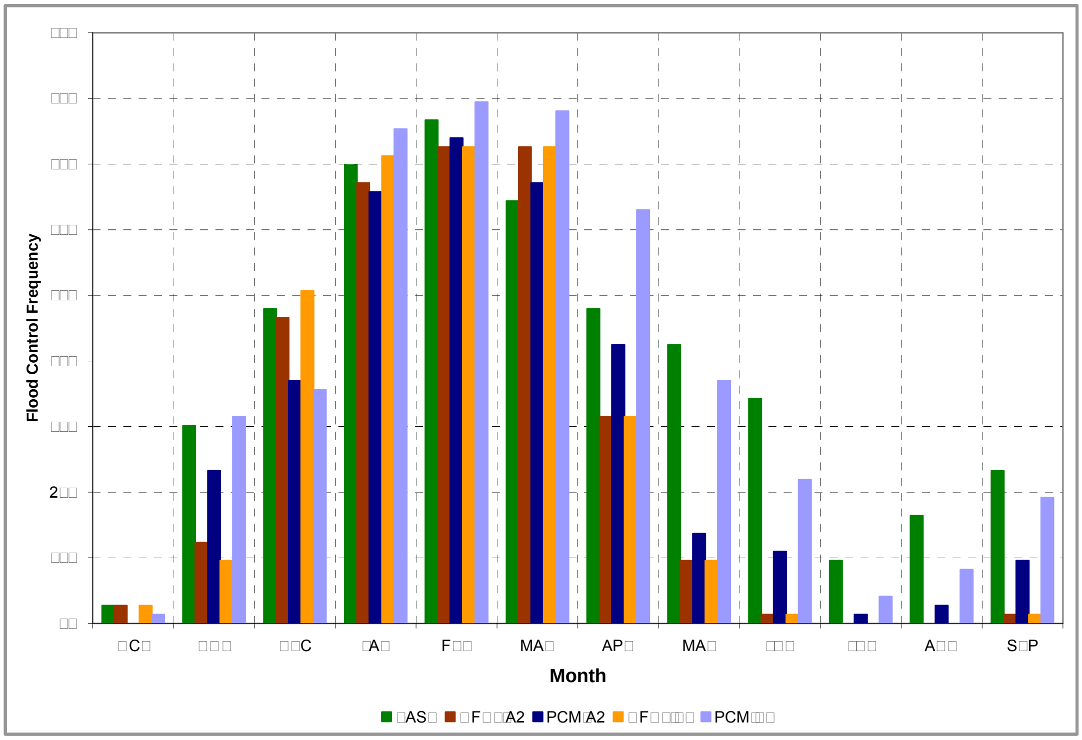


**Figure 4.13 Monthly flood control frequency of Folsom Lake**

While flood control operations may prevent the capture of increased winter runoff, MIF requirements downstream of the reservoirs will draw down NOD storage when reservoir inflows are low. Figure 4.14, Figure 4.15, and Figure 4.16 show the dry-period frequency that Shasta, Oroville, and Folsom releases are controlled by MIF requirements on the Sacramento, Feather, and American rivers respectively. Each river has 2 to 3 MIF requirements at different locations. When flow is reduced to one of the MIF requirements, reservoir releases on that river have reached a minimum and the MIF requirement is effectively controlling operations.

The reason the control frequency plots for MIF requirements focus on the dry periods – 1924, 1929-1934, 1976-1977, and 1987-1992 – is that those are the periods where there are critical shortages in Shasta and Folsom in the GFDL A2, PCM A2, and GFDL B1 scenarios. Figure 4.14 and Figure 4.16 show that MIF requirements are largely responsible for draining these reservoirs during the dry periods. Of course, there are downstream Delta requirements that are being met by these releases also. One can conclude that changes in SOD delivery allocations during the dry periods will not likely alleviate all of the Shasta and Folsom shortages. The water will have to be released during these years whether it's going South-of-Delta or not. The only way to prevent the shortages with changes in allocation rules is to reduce deliveries in the wet years preceding a drought in hopes of enough carryover storage to get the project through.

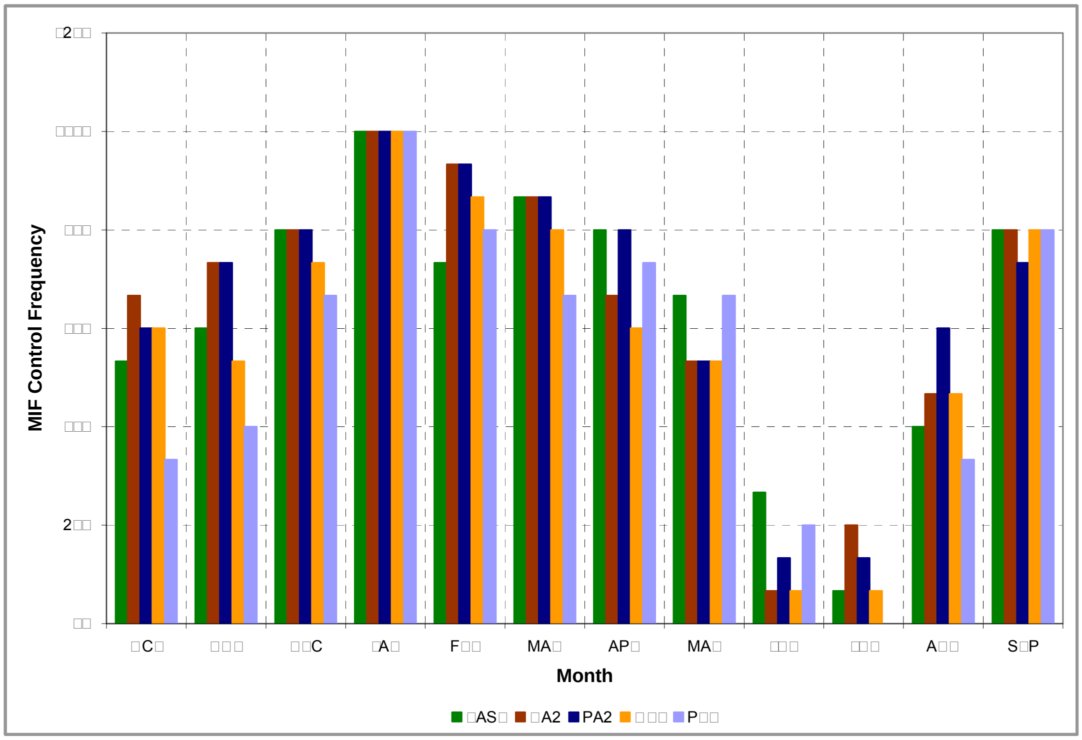


**Figure 4.14 MIF requirement control frequency on the Sacramento River during dry periods (1924, 1929-1934, 1976-1977, 1987-1992)**

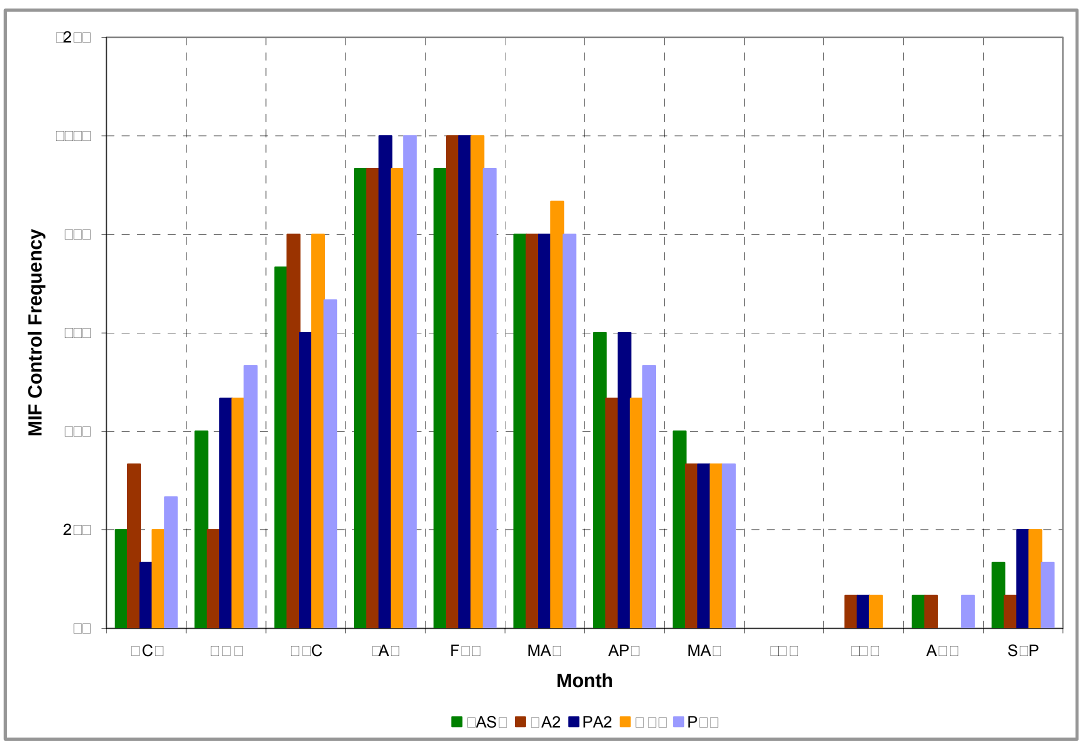


**Figure 4.15 MIF requirement control frequency on the Feather River during dry periods (1924, 1929-1934, 1976-1977, 1987-1992)**

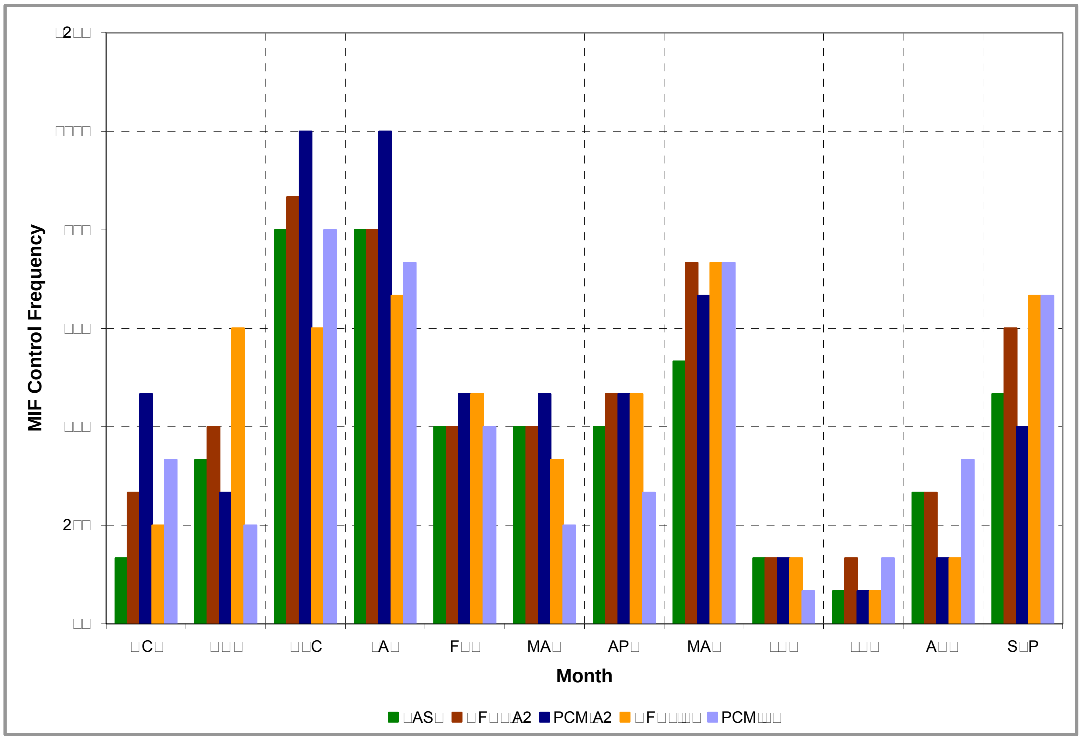


**Figure 4.16 MIF requirement control frequency on the American River during dry periods (1924, 1929-1934, 1976-1977, 1987-1992)**

### 4.6.4 Delta Operations Analysis

The CVP and SWP have three mechanisms to operate, or control, the Sacramento-San Joaquin Delta – NOD reservoir releases to the Sacramento River, the Delta Cross Channel, and Tracy and Banks exports. NOD storage releases can be increased to meet Delta outflow requirements, improve water quality, or increase exports. The Delta Cross Channel gates are opened during certain periods of the year to reduce salinity in the Delta interior with water from the Sacramento River and closed for certain periods of the year to prevent migrating fish from getting lost in the interior. Exports can be reduced to protect water quality, fish, or to maintain Delta outflow requirements or increased to capture available surplus water that would otherwise flow out to the San Francisco Bay. Delta locations of the Sacramento River inflow, Cross Channel, and the Banks and Tracy pumping plants are shown in Figure 4.17.

Operation of the Delta Cross Channel gates is largely pre-processed in CalSim-II. The only dynamic decision in the model with respect to the gates is to keep them closed when Delta inflow on the Sacramento River exceeds 25,000 cubic feet per second. While this is a frequent condition, it does not cause many differences in Delta Cross Channel gate operations when comparing the Base and climate change scenarios. There are occasions when the gates are closed in one scenario and open in another, but this is an infrequent occurrence.

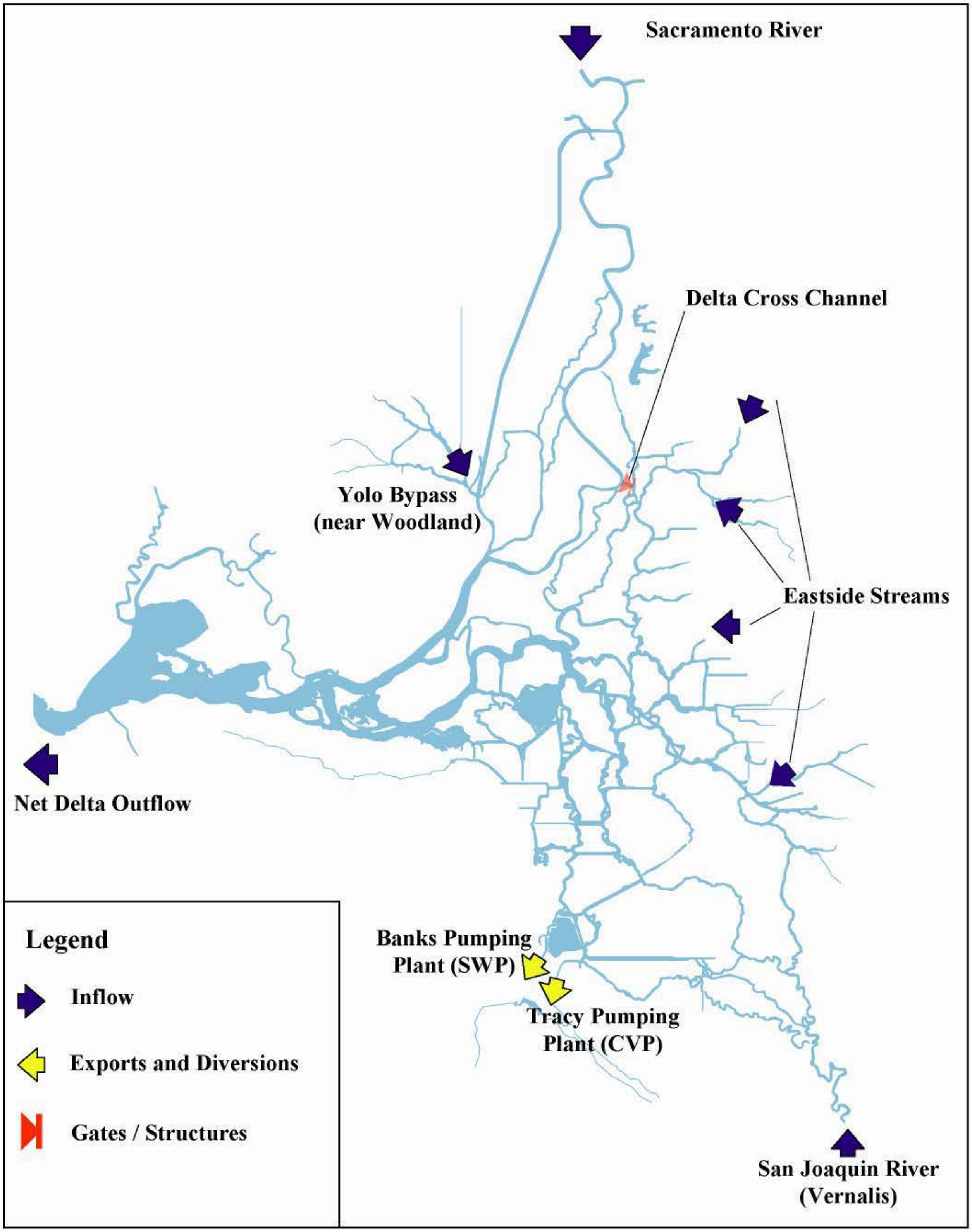


**Figure 4.17 Map of the Sacramento – San Joaquin Delta**

Annual average changes in Delta inflow are listed in Table 4.18. Total Delta inflow includes the Sacramento River, Yolo Bypass, Eastside streams, San Joaquin River (SJR), and Marsh Creek. Inflow from the Eastside streams and Marsh Creek do not change from the Base to the climate change scenarios. Changes in inflow are centered on the San Joaquin River, Sacramento River, and Yolo Bypass.

**Table 4.18 Annual Average Delta Inflow (WY1922-1994)**

| Scenario | San Joaquin River | | | Sacramento River and Yolo Bypass | | | Total Delta Inflow | | |
|---|---|---|---|---|---|---|---|---|---|
| | Annual Average Inflow (TAF) | Change from Base (TAF) | Change from Base (%) | Annual Average Inflow (TAF) | Change from Base (TAF) | Change from Base (%) | Annual Average Inflow (TAF) | Change from Base (TAF) | Change from Base (%) |
| BASE | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| GFDL B1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | -2… | [illegible] | [illegible] | [illegible] |
| PCM B1 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

So far, there has been no discussion of effects in the San Joaquin basin due to the altered reservoir inflows under the climate change scenarios. That will have to wait for another report. However, with respect to Delta operations, it's important to look at the changes in Delta inflow on the San Joaquin River. In the dry months, where SJR Delta inflow is reduced, either exports must be reduced or more NOD storage releases must be made to support Banks and Tracy pumping. Furthermore, Banks permitted pumping capacity is dependent on SJR Delta inflow at Vernalis from December 15 to March 15. During this period, Banks permitted capacity is 6,680 cfs when SJR inflow is at or below 1,000 cfs. One-third of SJR inflow is added to permitted capacity if SJR inflow exceeds 1,000 cfs. Given Banks physical capacity is approximately 8,500 cfs, this permitted capacity condition is significant when SJR monthly inflows are within the range of 60 to 330 TAF per month. Figure 4.18 shows the monthly SJR Delta inflows as averaged over WY1922-1994. From December to March, monthly average inflow falls within this range.

Figure 4.19 shows combined monthly Sacramento River and Yolo Bypass Delta inflows as averaged over WY1922-1994. Average inflows of the climate change scenarios tend to be higher than the base scenario December through March. This is due to increased NOD reservoir inflow in these months when flood control operations were in effect and storage capacity was not available. During the summer and early fall months, Sacramento inflows for scenarios GFDL A2, PCM A2, and GFDL B1 are lower than in the Base. One explanation is that in the Base scenario larger NOD reservoir releases must be made to support the higher exports and SOD deliveries.

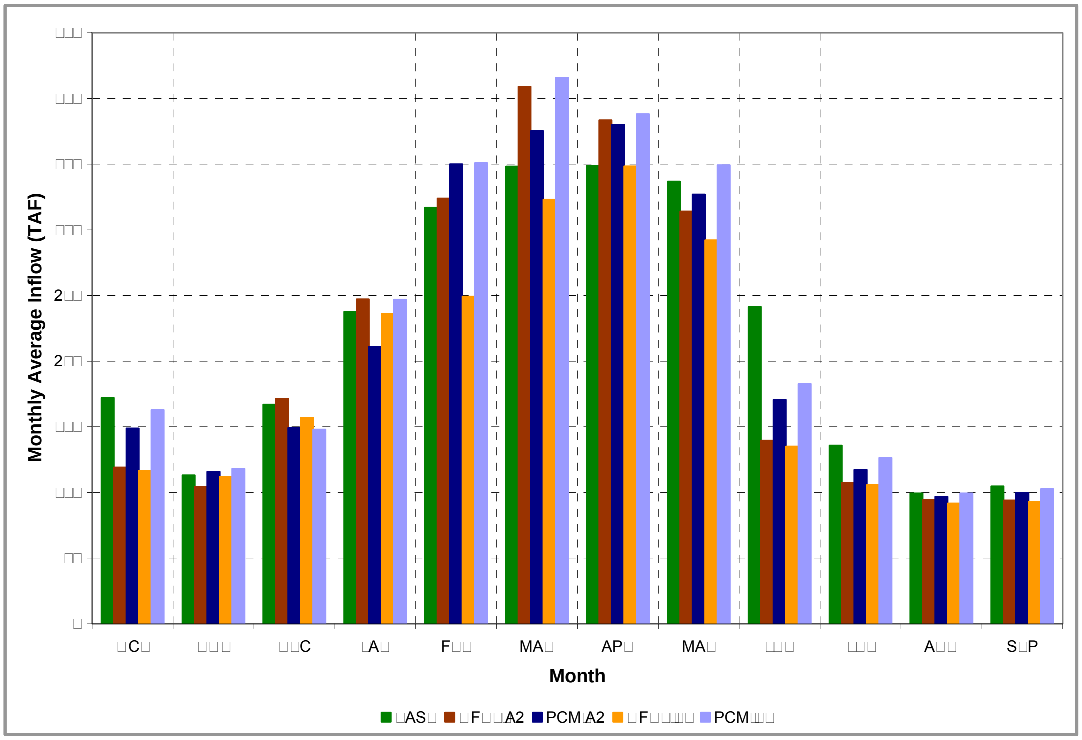


**Figure 4.18 Monthly average San Joaquin River Delta inflow at Vernalis (WY1922-1994)**

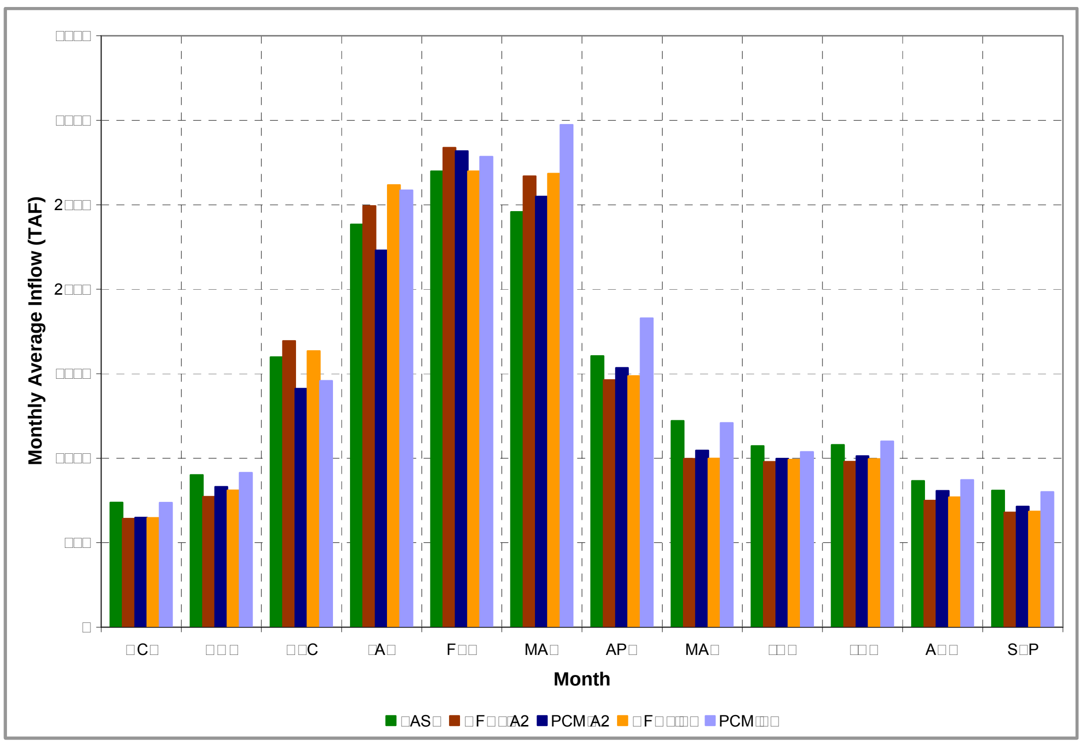


**Figure 4.19 Monthly average Sacramento River--Yolo Bypass Delta inflow (WY1922-1994)**

Changes in required, surplus, and total Delta outflow, as compared to the Base are listed in Table 4.19. Required Delta outflow is defined in Table 3 of the Water Quality Control Plan (WQCP). It also includes outflow necessary to maintain water quality standards as set in the WQCP. As shown, there are no significant changes in required Delta outflow on an annual average basis. Surplus Delta outflow is where the changes are concentrated. This outflow typically comes in the winter and spring due to rain and snowmelt runoff. In PCM A2, Surplus Delta outflow decreases by 7 percent as compared to the base scenario, while in PCM B1, it increases by 11 percent on average.

**Table 4.19 Annual Average Delta Outflow (WY1922 – 1994)**

| [illegible] | [illegible] | | | [illegible] | | | [illegible] | | |
|---|---|---|---|---|---|---|---|---|---|
| | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| PCM [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

Figure 4.20 shows monthly Delta outflow as averaged over WY1922-1994. Notice that outflows for the base and climate change scenarios are roughly equivalent on average July-November. As set in Table 3 of the WQCP, required Delta outflow in these months will not change from scenario to scenario. Little surplus would be expected in these months also. The slight increases in base outflows during these months were attributed to maintaining water quality standards with higher exports. This, at times, required higher Delta outflows. In the winter, Delta outflows of the climate change scenarios tended to be higher than those of the base. Given higher Delta inflows during this period and limited pumping capacity, this pattern was expected.

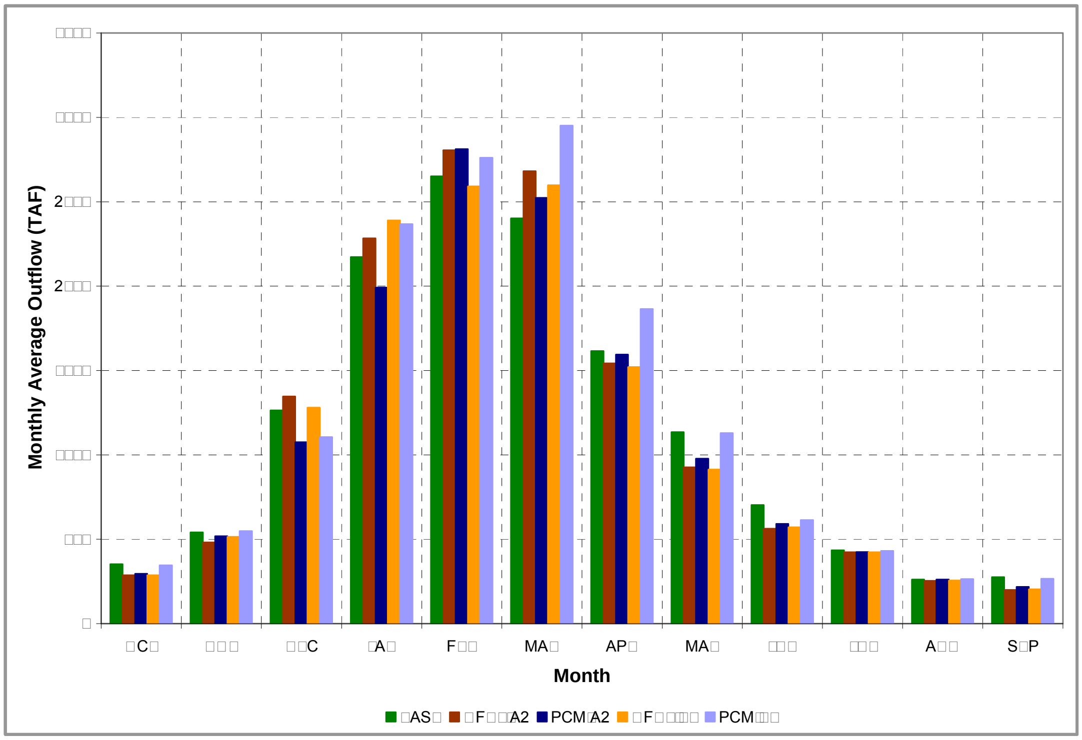


**Figure 4.20 Monthly average Delta outflow (WY1922-1994)**

Previously, it was shown that the combined SWP and CVP SOD deliveries in the drier climate change scenarios were consistently less than the base scenario. It was expected that SOD exports would decrease also. Table 4.20 lists annual average exports and calculates changes with respect to the base. Total exports in GFDL A2, PCM A2, and GFDL B1 decrease by 10 percent, 6 percent, and 9 percent respectively. Overall, SOD deliveries were increased for the SWP and CVP in scenario PCM B1. A corresponding 2 percent increase in total exports is shown in Table 4.20.

**Table 4.20 Annual Average Delta Exports**

| S□□d□ | □rac□□□p□r□□ | | | □a□□□□□p□r□□ | | | □□a□□□p□r□□ | | |
|---|---|---|---|---|---|---|---|---|---|
| | A□□□a□ A□□ra□□ □□p□r□□ □□AF□ | C□a□□□ fr□□ □a□□ □□AF□ | C□a□□□ fr□□ □a□□ □□ □ | A□□□a□ A□□ra□□ □□p□r□□ □□AF□ | C□a□□□ fr□□ □a□□ □□AF□ | C□a□□□ fr□□ □a□□ □□ □ | A□□□a□ A□□ra□□ □□p□r□□ □□AF□ | C□a□□□ fr□□ □a□□ □□AF□ | C□a□□□ fr□□ □a□□ □□ □ |
| □AS□ | 2□□□ | □ | □□ | □□□□ | □ | □□ | □□□□ | □ | □□ |
| □F□□A2 | 22□□ | -2□□ | -□□□ | □□□□ | -□□□ | -□□ | □□□2 | -□□□ | -□□□ |
| PCM□A2 | 2□□□ | -□□□ | -□□ | □□□□ | -22□ | -□□ | □□22 | -□□□ | -□□ |
| □F□□□□□ | 2□□□ | -□□□ | -□□ | □□2□ | -□2□ | -□□□ | □□□□ | -□□□ | -□□ |
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Figure 4.21 shows monthly total Delta exports as averaged over WY1922-1994. During the winter, average exports were not significantly changed from the base to the climate change scenarios. Even with the added Delta inflow of the climate change scenarios during the wet months, exports at Tracy and Banks were unable to capture most of it because of a combination of permitted pumping capacity, physical pumping capacity, SOD conveyance constraints, and the export to inflow ratio of the WQCP. Base and PCM B1 exports were significantly higher in the summer and fall months as compared to the drier climate change scenarios. The higher exports were to support the higher delivery allocations in the Base and PCM B1 scenarios.

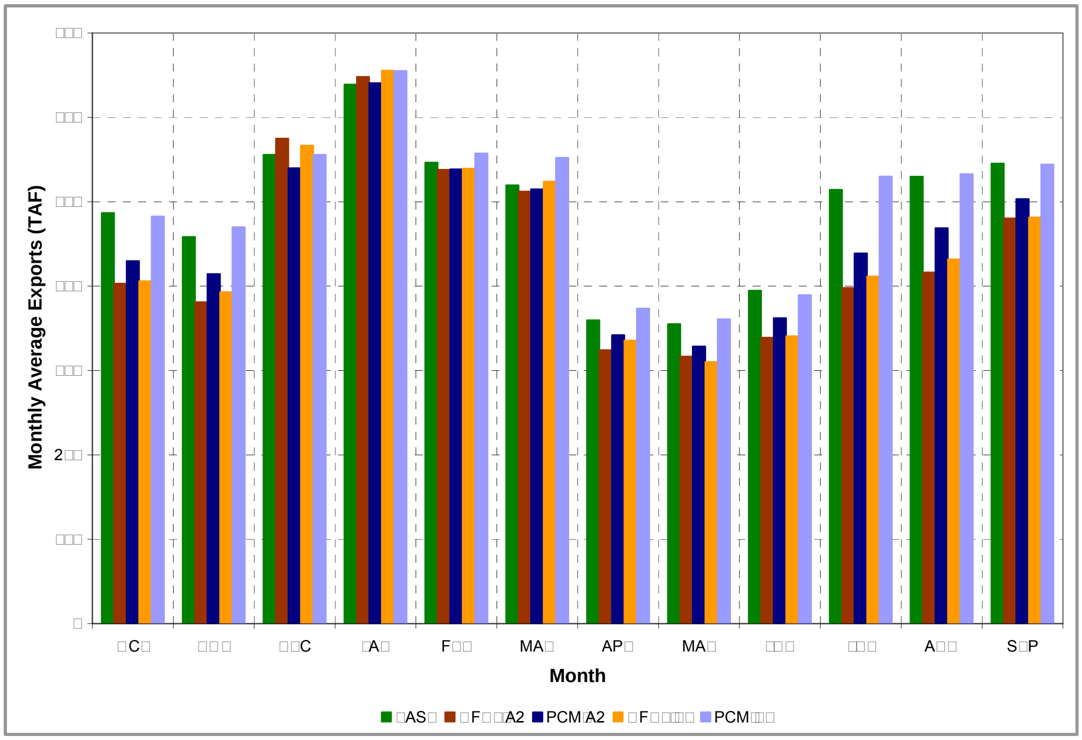


**Figure 4.21 Monthly average total Delta exports (WY1922-1994)**

There are a number of system constraints, physical and regulatory, that inhibit SWP and CVP Delta exports to SOD contractors. They include:

1) Permitted and physical pumping capacity
2) SOD conveyance capacity including storage capacity, channel and pumping capacity, and contractor demand
3) April-May SJR pulse flow limits on exports (April 15-May15)
4) WQCP water quality standard limits on exports as calculated using ANN
5) WQCP export-inflow ratio

The frequency that these export constraints control exports was quantified for the Base and climate change scenarios. For Banks, the frequency that permitted or physical pumping capacity was reached on a monthly basis is shown in Figure 4.22. This constraint is most significant in

January when surplus Delta outflow was likely. Figure 4.23 shows that SOD conveyance constraints are most likely to constrain exports in March. The April-May pulse flow export limits were applied from April 15 to May 15. Since the simulation time-step is one month, the simulated constraint was actually a day-weighted average of the pulse flow constraint and permitted capacity. As shown in Figure 4.24, the simulated April-May export constraint controlled Banks pumping about 90 percent of the time in these two months in all scenarios. Figure 4.25 shows the frequency that exports are constrained in each simulation by the various WQCP water quality standards; while frequency of water quality constraints varies significantly from month to month and scenario to scenario, November is the month where water quality was most likely to control Banks exports in all five simulations. The frequency that the export-inflow ratio controls Banks is shown in Figure 4.26

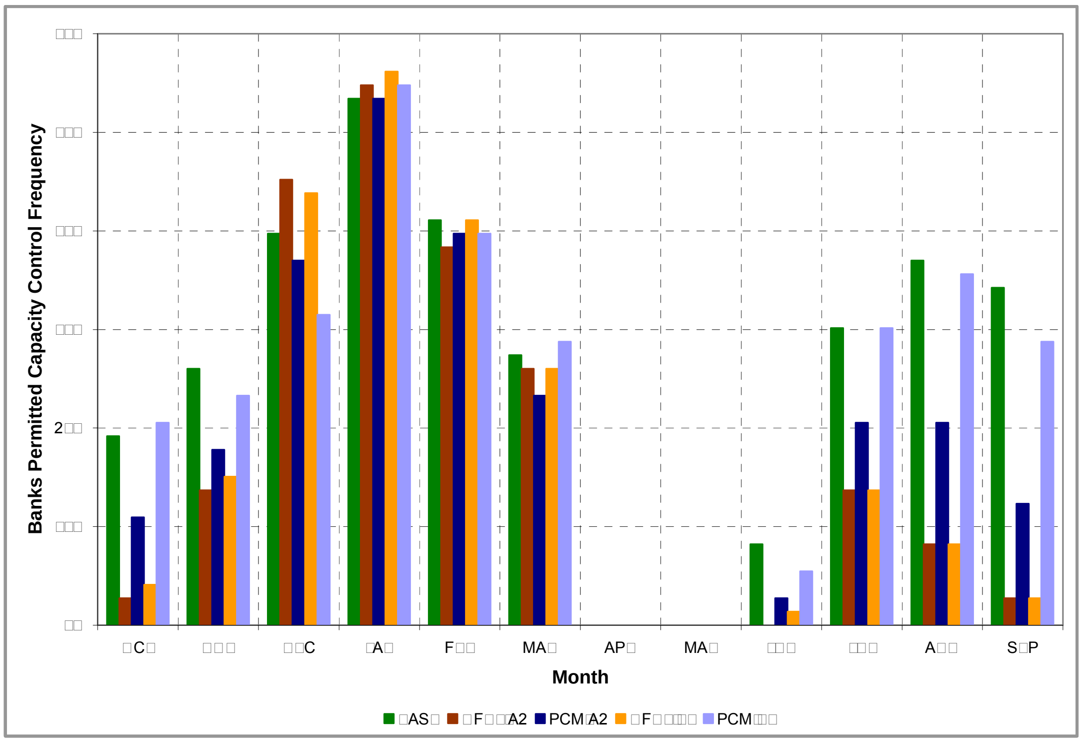


**Figure 4.22 Operational control frequency of Banks permitted capacity**

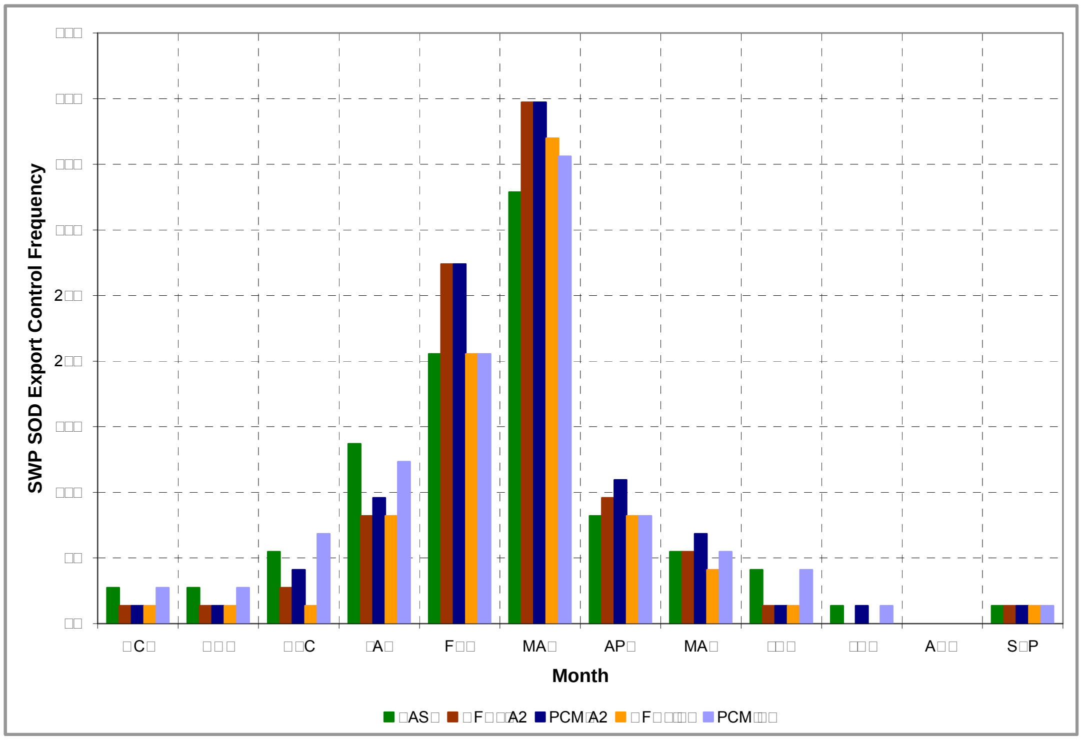


**Figure 4.23 Operational control frequency of SWP SOD conveyance capacity on Banks exports**

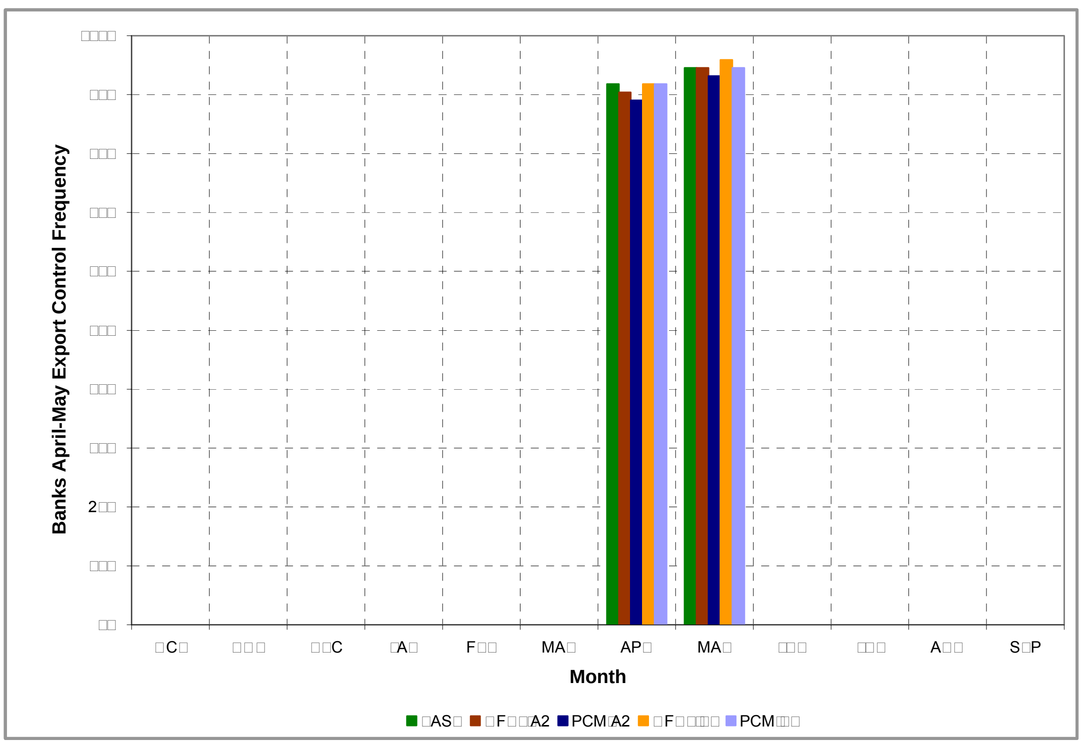


**Figure 4.24 Operational control frequency of the April-May San Joaquin River pulse flow export constraints on Banks pumping**

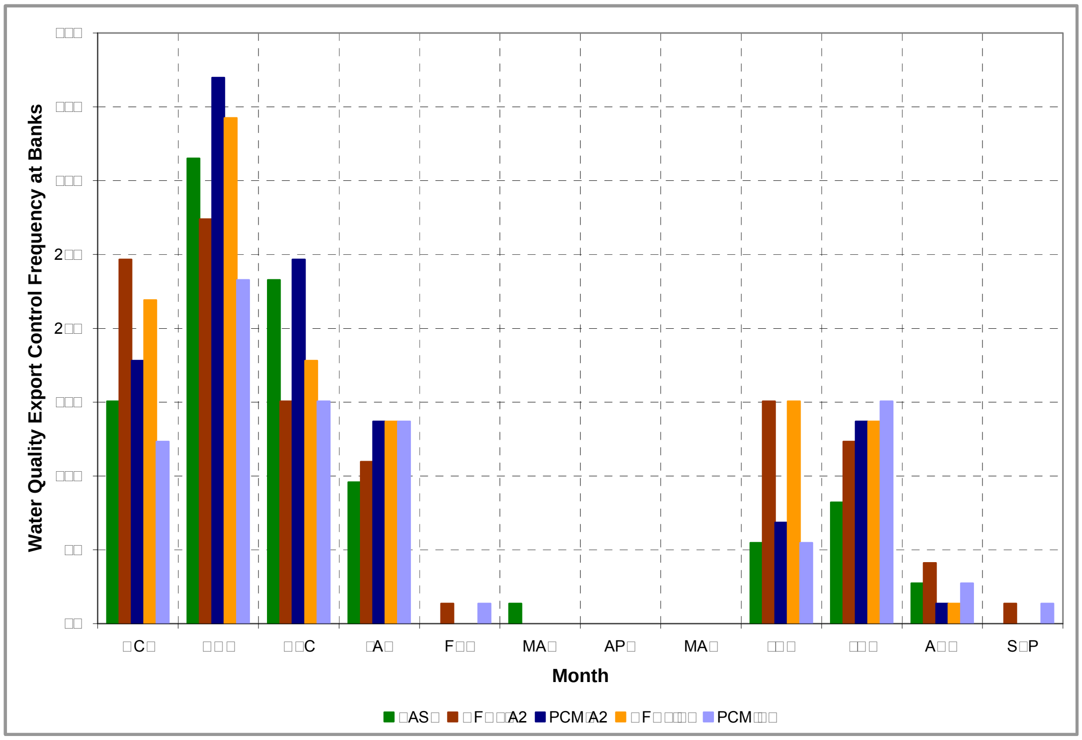


**Figure 4.25 Operational control frequency of Delta water quality standards on Banks pumping**

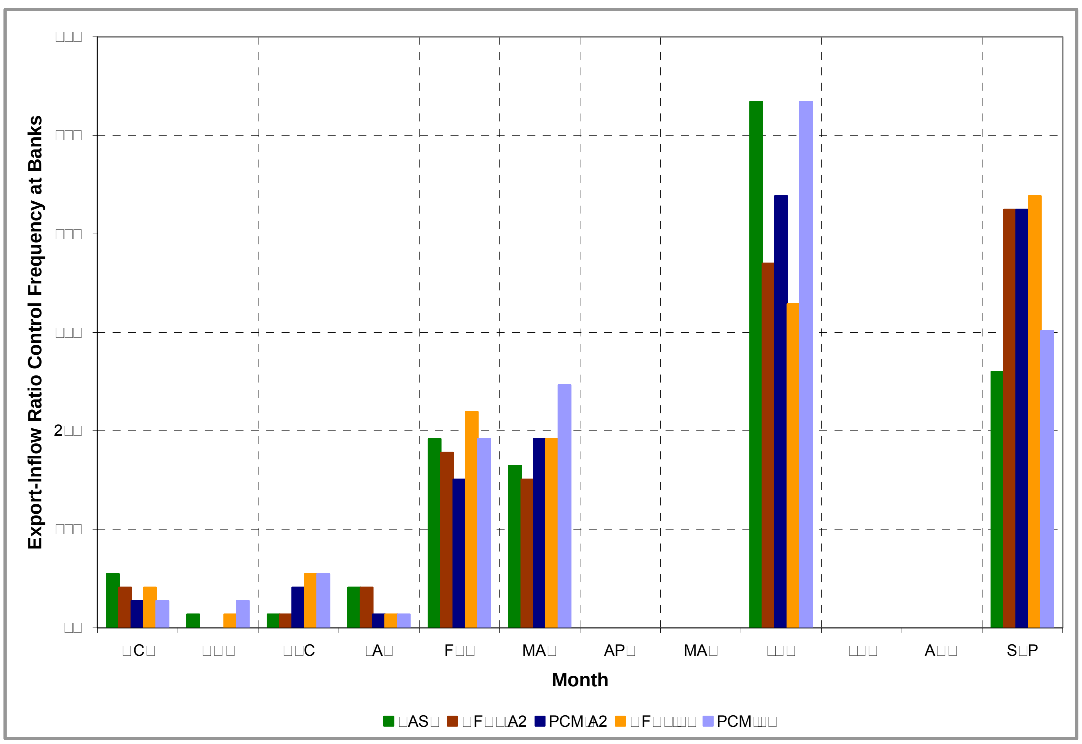


**Figure 4.26 Operational control frequency of Banks pumping by the export-inflow ratio**

With increased Delta inflow from December to March in the climate change scenarios, it would be useful, from a water supply standpoint, to capture some of the surplus Delta outflow. From the operational control frequency information contained in Figure 4.22 to Figure 4.26, the key constraint in this period was Banks permitted and physical capacity. In March, SWP SOD conveyance often becomes the constraining parameter. This suggests that changes in Banks permitted capacity and SWP SOD conveyance capacity – surface storage, canals, pumps, groundwater banking – should be tested for its potential to compensate for climate change impacts on SOD water supply.

Figure 4.27 shows the frequency that Banks exports are not constrained by physical or permitted capacity, SOD conveyance capacity, April-May export restrictions, water quality, or the export-inflow ratio. In this case, a decision was made to preserve Oroville storage at the expense of San Luis storage. As expected, the least flexibility in Banks pumping is in December-March when it is most needed to capture the additional Delta inflow in the climate change scenarios. Due to decreased exports, there is some unused summer Banks capacity in the drier climate change scenarios as compared to the Base. Would it be helpful to increase San Luis carryover at the expense of Oroville? It is possible that greater available capacity in Oroville would help to capture the increased winter runoff, but no conclusions could be made without further tests. Special Feather River fish criteria from October 15 to November 30 limit Oroville releases for Delta export. So even though there is a high frequency of no export controls in these months, it is likely that Oroville releases could not be made to take advantage. The CVP could take advantage of available Banks capacity for delivery to Cross Valley Canal in the summer and fall. However, given the critical shortages on Shasta and Folsom in the drier climate change scenarios, it is not clear that the CVP would want to release additional water from these reservoirs.

Tracy Pumping Plant has a physical capacity of 4,600 cfs with exports further limited to a range of 4,200 cfs – 4,600 cfs by a constriction on the upper Delta-Mendota canal. Figure 4.28 shows the frequency that the combined physical pumping capacity and upper DMC constraint limit Tracy exports. Sometimes, typically in the winter, there is no place SOD for the CVP to put the water. Figure 4.29 shows the frequency that this occurs. As shown in Figure 4.30, the April-May export constraint regularly limits Tracy exports in these months – just as it did with Banks. However, the April-May constraint does not control Tracy as frequently as Banks because of CVP SOD conveyance limits. Figure 4.31 shows the regularity that the WQCP water quality standards limit Tracy pumping, and Figure 4.32 shows the same information for the export-inflow ratio.

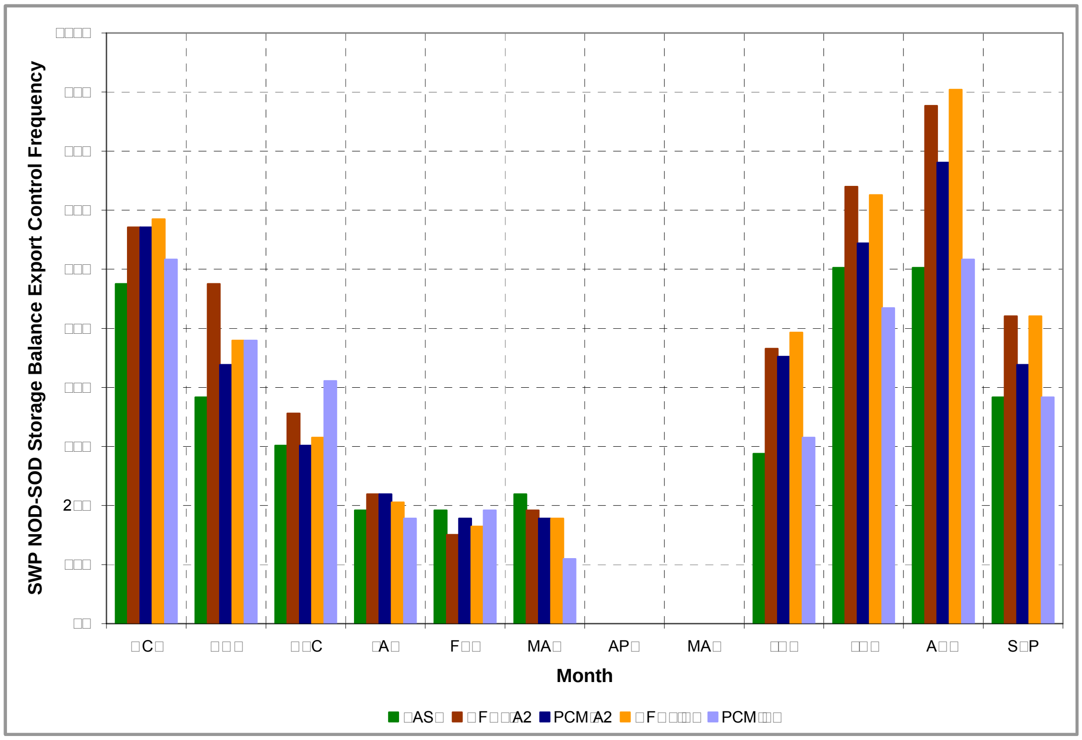


**Figure 4.27 Frequency of the decision to favor SWP NOD storage over SWP SOD storage by limiting Oroville releases and Banks pumping**

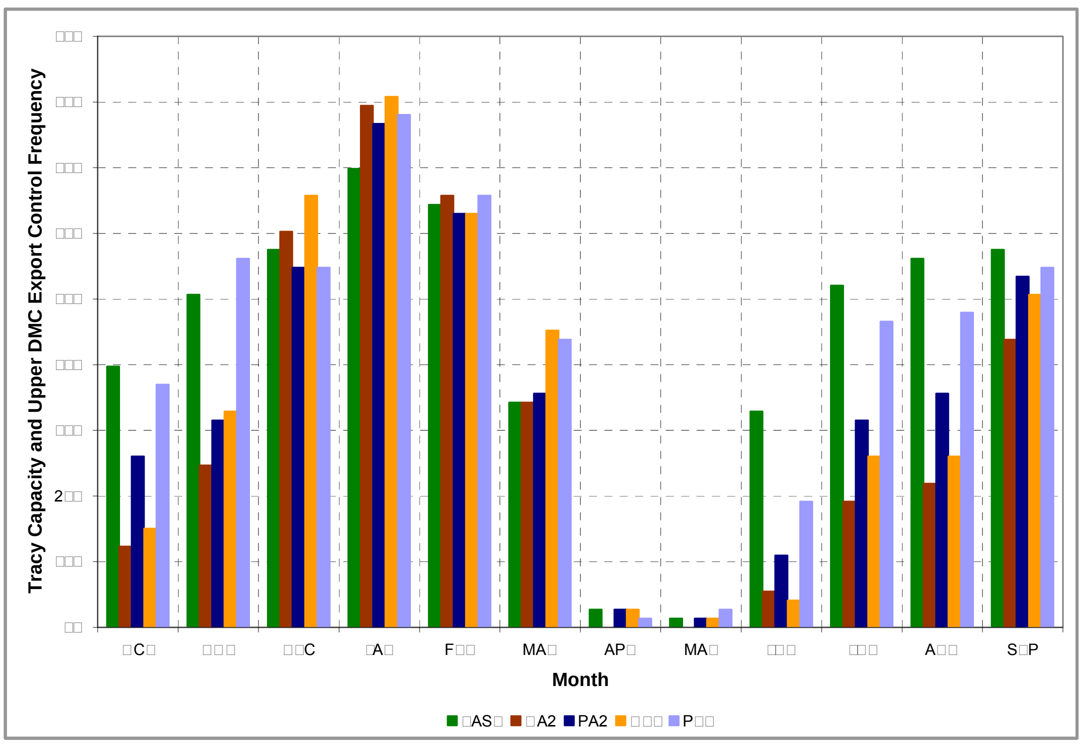


**Figure 4.28 Operational control frequency of Tracy pumping capacity and upper Delta-Mendota Canal conveyance capacity**

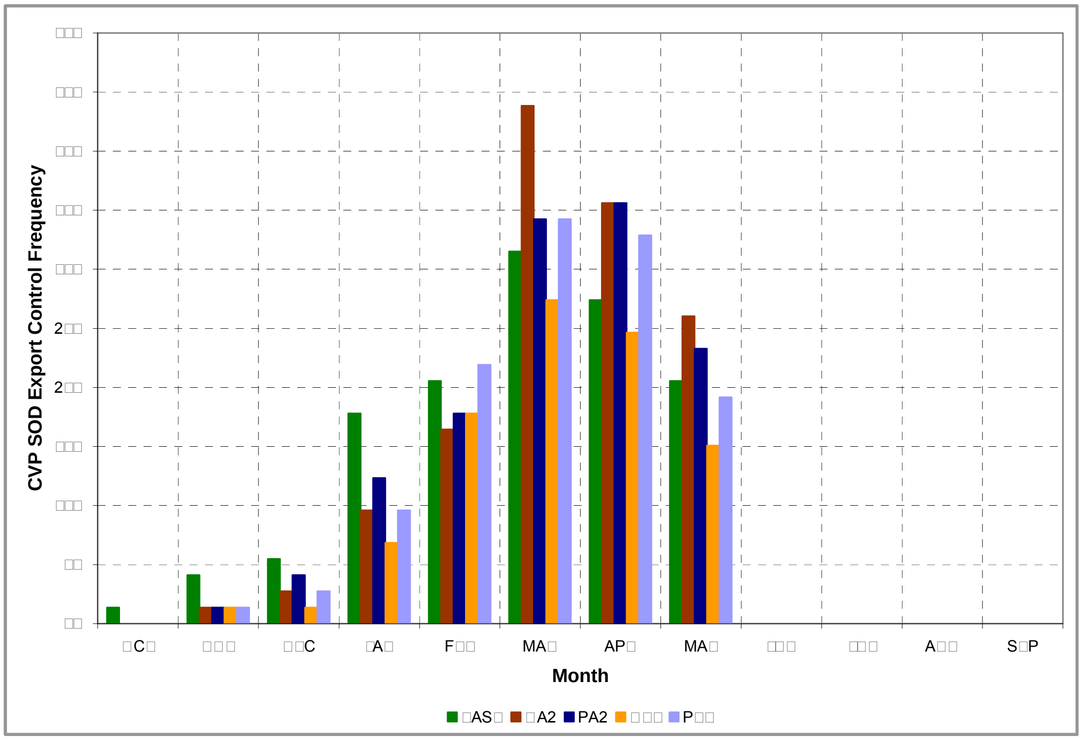


**Figure 4.29 Operational control frequency of CVP SOD conveyance capacity on Tracy exports**

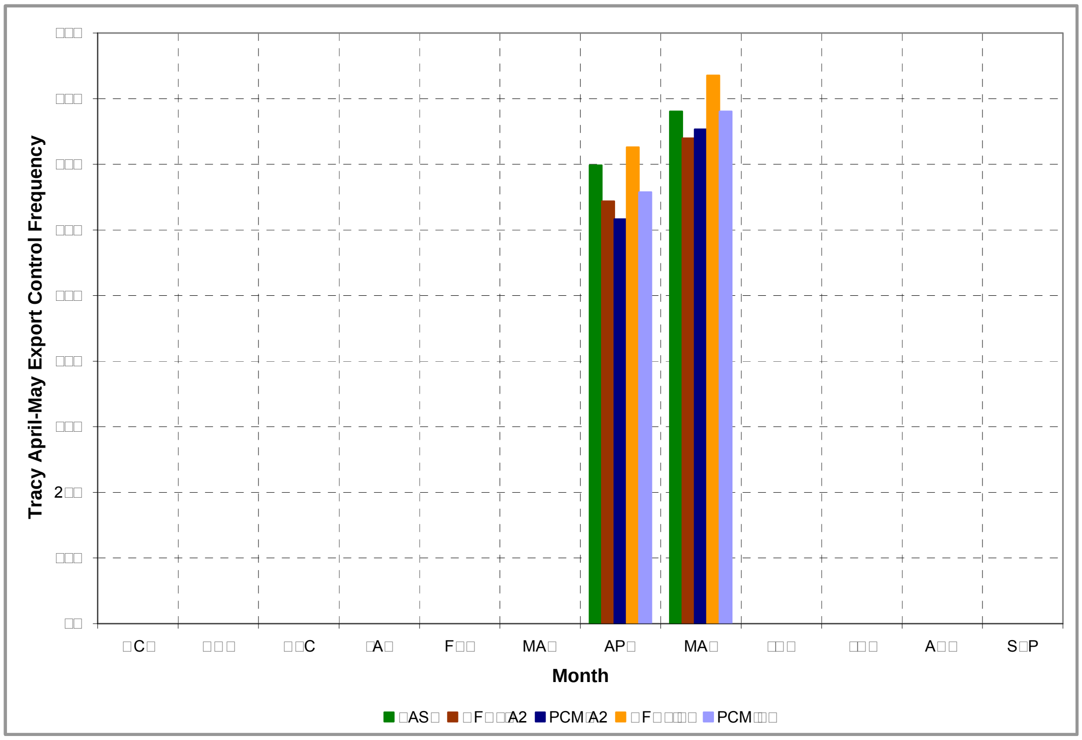


**Figure 4.30 Operational control frequency of the April-May San Joaquin River pulse flow export constraints on Tracy pumping**

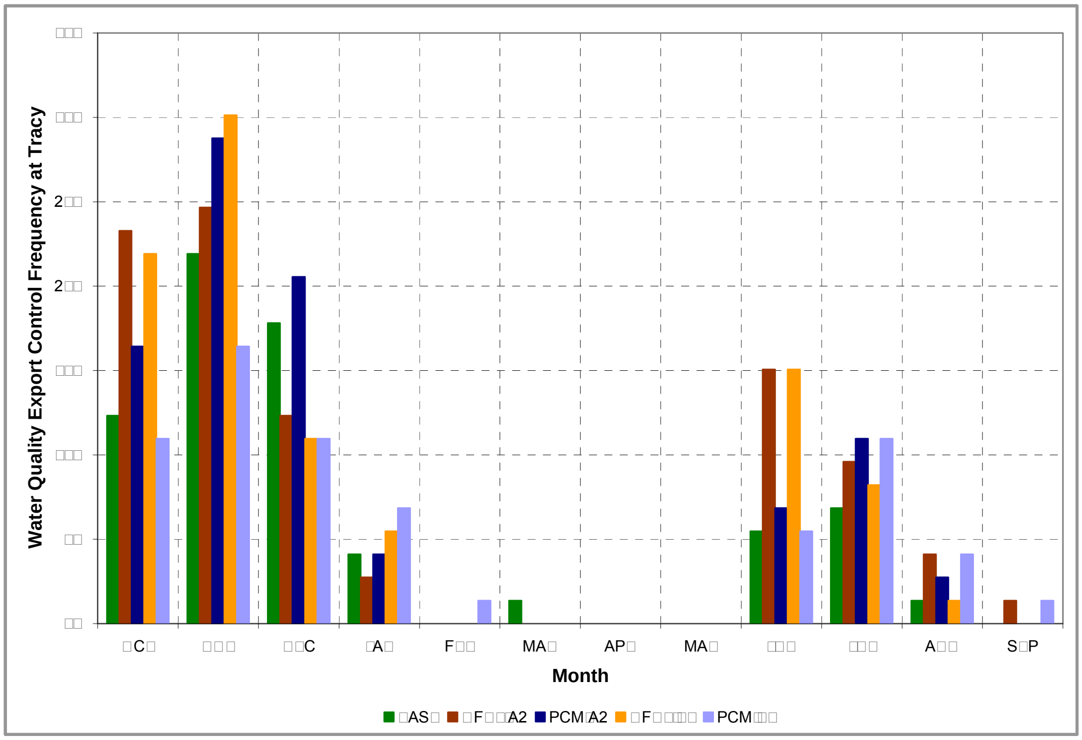


**Figure 4.31 Operational control frequency of water quality standards of Tracy pumping**

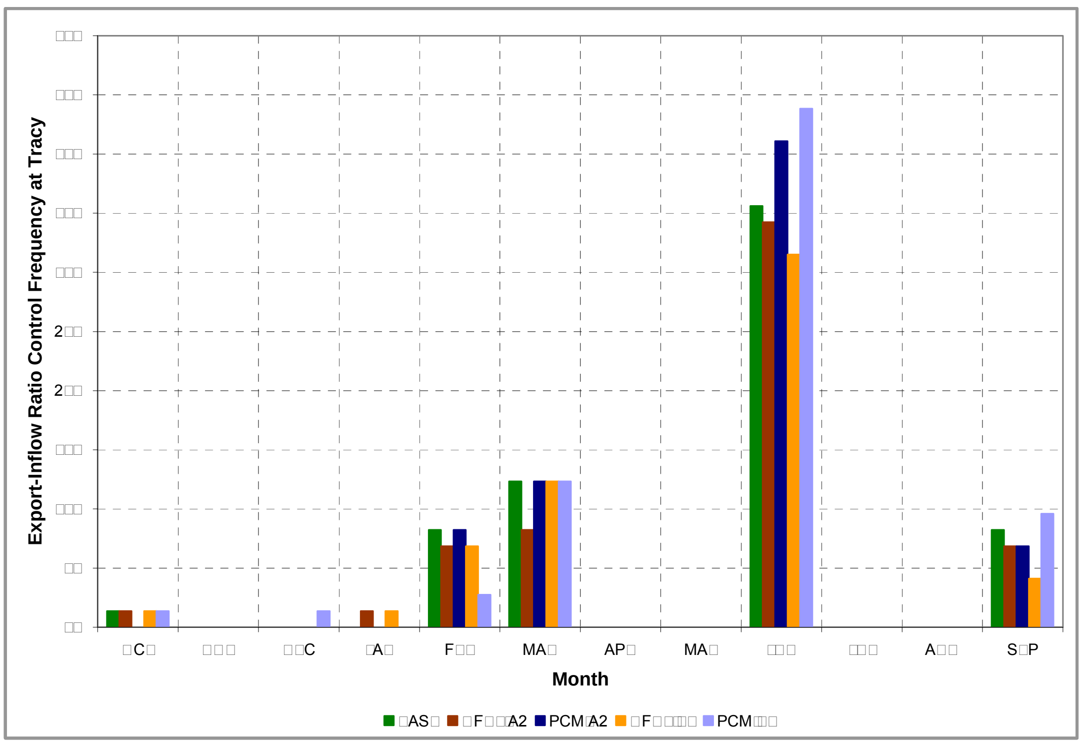


**Figure 4.32 Operational control frequency of the export-inflow ratio of Tracy pumping**

In the key months of December through March, Tracy exports were most frequently limited by pumping capacity or the upper Delta-Mendota Canal constriction as shown in Figure 4.27. It has been proposed to install an intertie between the Delta-Mendota Canal (DMC) and the California Aqueduct. This would relieve the upper DMC constraint and would be worth more study in the context of climate change.

Figure 4.33 shows the frequency that Tracy Pumping Plant has remaining export capacity -- none of the above mentioned constraints are controlling Tracy exports. Just as with Banks, Tracy is less likely to have available export capacity in the December – March period when it is most needed. In the drier climate change scenarios, there is some flexibility for higher Tracy exports in the summer and fall. However, given the shortages in Shasta and Folsom in these drier scenarios, it is doubtful that higher releases from these reservoirs to support higher exports would be beneficial.

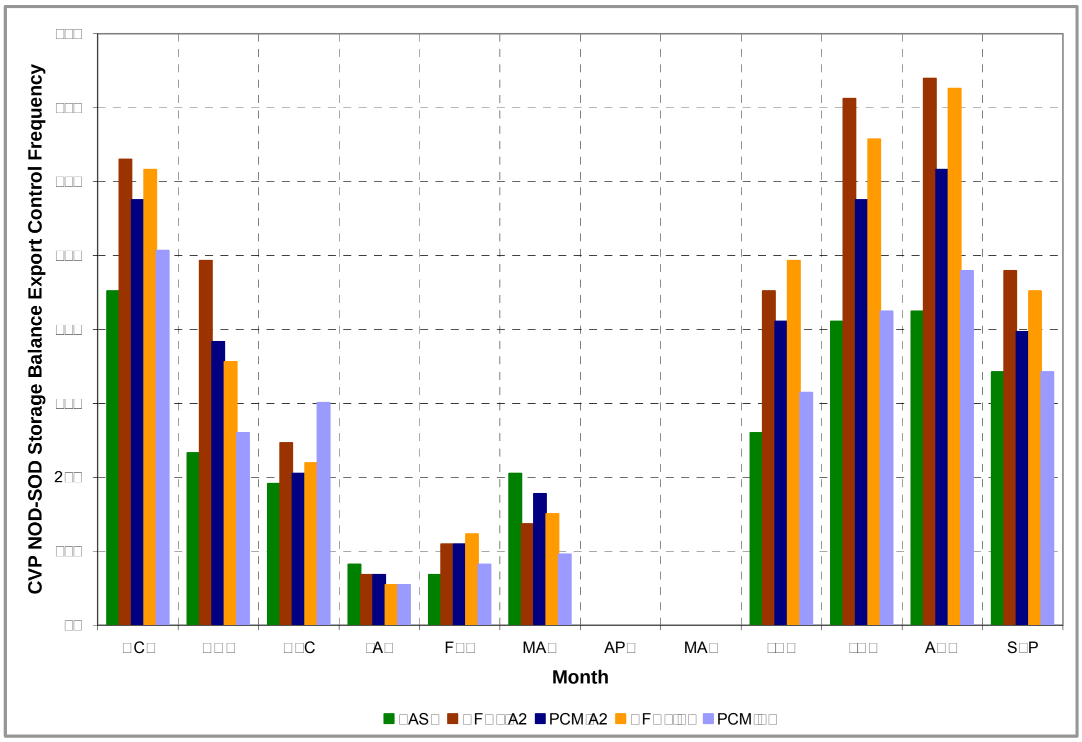


**Figure 4.33 Frequency of the decision to favor CVP NOD storage over CVP SOD storage by limiting Shasta and Folsom releases and Tracy pumping**

### 4.6.5 Power Supply

Climate change impacts to CVP and SWP power supply were calculated using Bureau of Reclamation and DWR spreadsheet models. These models estimate monthly power generation using reservoir storage and release data from CalSim-II, and they estimate monthly power loads based on CalSim-II pumping rates. The CVP and SWP facilities included in the power supply analysis are listed in Table 4.21.

Estimates of the average annual SWP power generation and load for each study are compared to the base study in Table 4.22. The summary includes the long-term period of 1922-1993 as well as two six-year droughts. The negative values for net generation indicate that the SWP consumes more power than is generated. For the period 1922-1993, the GFDL A2, PCM A2 and GFDL B1 studies show a decrease in net generation ranging from 7 percent to 11 percent while the PCM B1 study has a smaller decrease of 1 percent. The SWP net power generation effects for the drought of 1929-1934 ranges from a decrease of 11 percent for the PCM A2 study to an increase of 14 percent for the PCM B1 study. For 1987-1992, the GFDL A2, PCM A2 and GFDL B1 studies have a decrease in net generation ranging from 8 percent to 21 percent while the PCM B1 study is only 1 percent less than the base study.

Estimates of the average annual CVP power generation and load for each study are compared to the base study in Table 4.23 for the long-term period of 1922-1994 and the two six-year droughts. For 1922-1994, the GFDL A2, PCM A2 and GFDL B1 studies show a decrease in net generation ranging from 6 percent to 10 percent while the PCM B1 study increases net generation by 6 percent. The CVP net power generation effects for the drought of 1929-1934 ranges from a decrease of 15 percent for the GFDL A2 study to an increase of 7 percent for the PCM B1 study. For 1987-1992, the GFDL A2, PCM A2 and GFDL B1 studies have a decrease in net generation ranging from 3 percent to 12 percent while the PCM B1 study is 8 percent greater than the base study.

**Table 4.21 Generation and Load Facilities Included in Power Supply Analysis**

| S□ P□Fac□□□□ | | C□P□Fac□□□□ | |
|---|---|---|---|
| □ □□□ra□□□ | □□ad | □ □□□ra□□□ | □□ad |
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| □ a□□□□ | □ □□□a□□ | Spr□□□Cr□□□ | C□□□ra□C□□a |
| A□a□ □ | □ a□□□□ | S□a□a | □ □ □□□ |
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| Ca□□a□c | □□□□a□ □□a | □□□ M□□□□□□ | F□□□□ |
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| | | | M□c□□a□□□□□ |

### Table 4.22 Annual Average SWP Power Generation and Load

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| | PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] |
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### Table 4.23 Annual Average CVP Power Generation and Load

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| | PCM A2 | [illegible] | [illegible] | [illegible] | [illegible] |
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A comparison of monthly average SWP power generation and load and CVP power generation and load are presented in Figure 4.34, Figure 4.35, Figure 4.36 and Figure 4.37, respectively. For the drier scenarios, SWP power generation decreases in all months compared to the Base with the exception of scenario GFDL A2 which has a slight increase in March. The largest decrease occurs in May. For the wetter scenario, PCM B1, SWP power generation increases in February through September and decreases in October through January. The largest increase in SWP power generation occurs in March.

SWP power load decreases in all months for the drier scenarios because of reduced water deliveries. With the wetter scenario, SWP power load increases in all months except January and February.

For the drier scenarios, CVP power generation decreases in all months compared to the Base with the exceptions of scenario GFDL A2 which has a slight increase in March and scenario GFDL B1 which has slight increases in January and March. The largest decreases in CVP power generation occur in September and October when storage impacts are greatest. For the wetter scenario, PCM B1, CVP power generation increases in all months except June and December which have slight decreases. The largest increase in CVP power generation occurs in March.

For the drier scenarios, CVP power load increases slightly in January through March due to higher exports and decreases in other months due to reduced deliveries. With the wetter scenario, there are slight increases in CVP power load in all months except October.

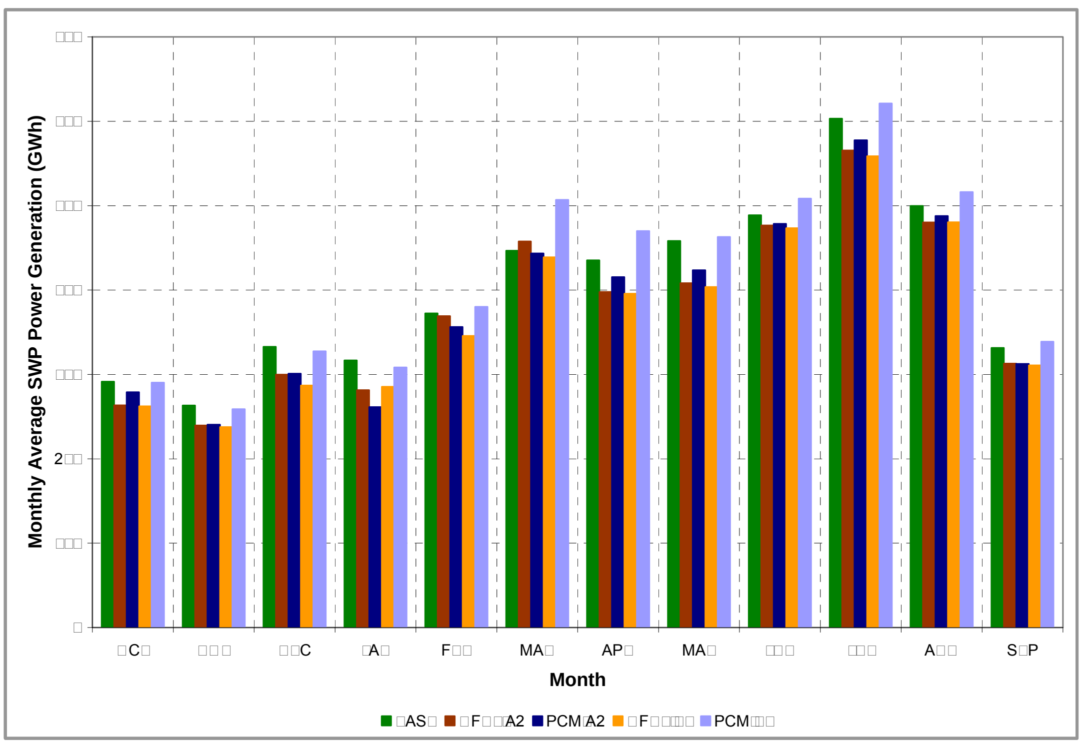


**Figure 4.34 Monthly Average SWP Power Generation**

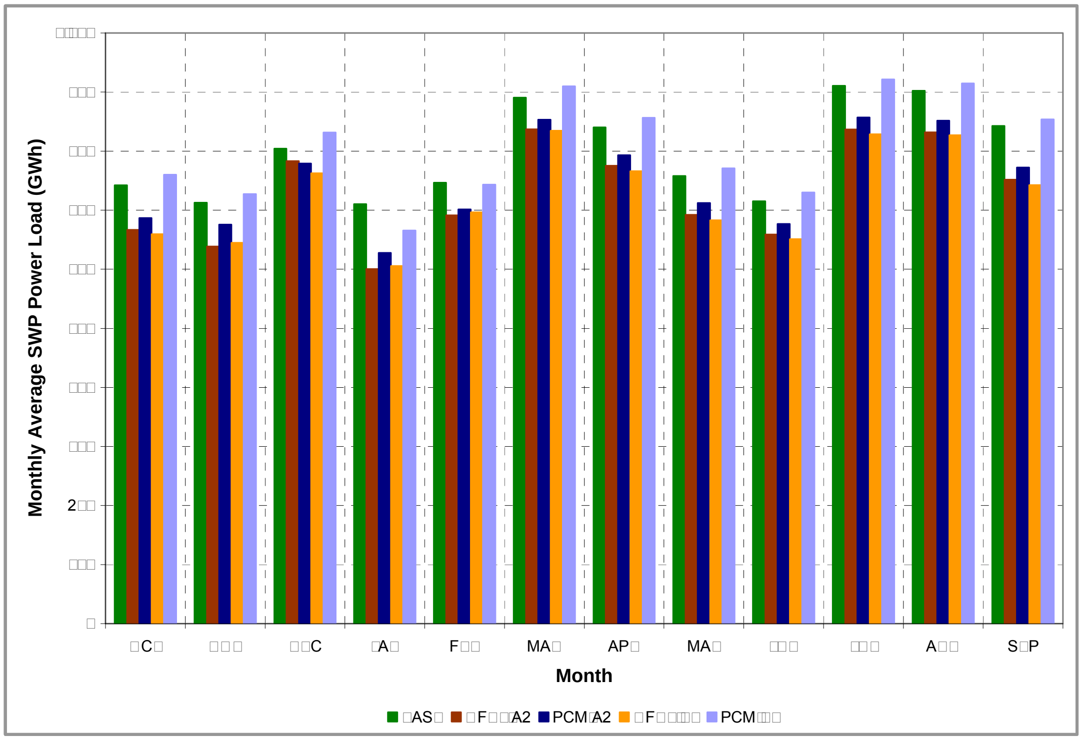


**Figure 4.35 Monthly Average SWP Power Load**

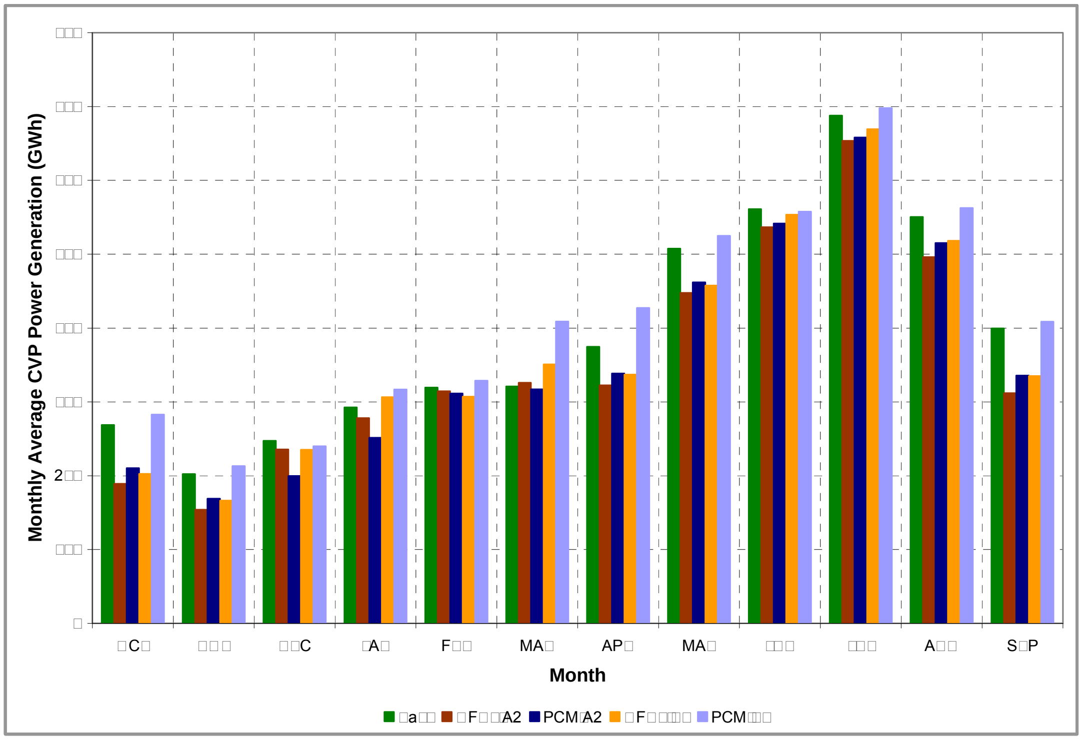


**Figure 4.36 Monthly Average CVP Power Generation**

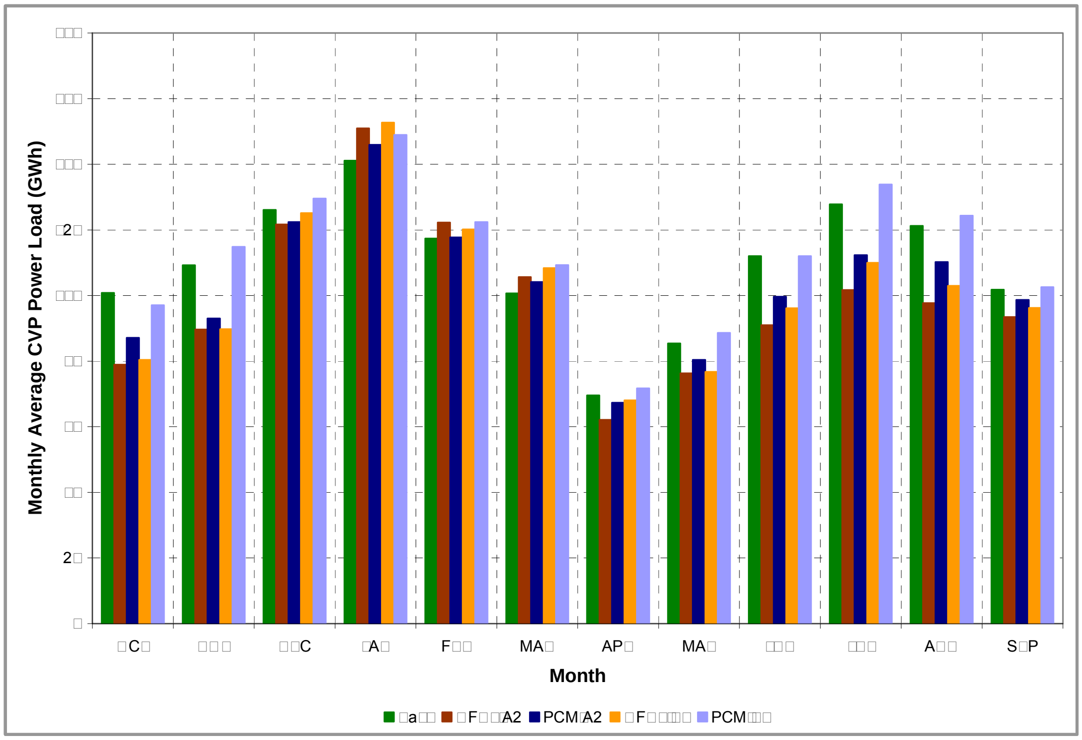


**Figure 4.37 Monthly Average CVP Power Load**

### 4.6.6 In-Stream Temperature Analysis

Water temperature has been recognized as key to the habitat needs of steelhead and Chinook salmon in the rivers of the Central Valley. River temperatures that are too high can kill salmon and steelhead by impairing metabolic function, or indirectly by increasing the probability of disease, predation, or other secondary mortality factors. Temperature tolerances also vary by life stage.

The water temperature of the river is a result of several factors: the temperature of water released from the major dams (Shasta, Oroville and Folsom) in the Sacramento Valley (a function of temperature stratification within each reservoir); the depths from which dam releases are made; the seasonal management of the deep cold-water pool reserves; ambient seasonal air temperatures and other climatic conditions; tributary accretions and water temperatures; and residence time in the re-regulating reservoirs downstream of each major dam, and in the river itself. To assist with downstream temperature control, temperature control devices (TCD) were installed at Shasta, Oroville, and Folsom dams. The TCDs can selectively withdraw water from different reservoir levels. The TCDs are generally operated to conserve cold water for the summer and fall months, when river temperatures become critical for fisheries. Therefore, the TCD is operated to make upper-level releases in the winter and spring, mid-level releases in the late spring and summer, and low-level release in the late summer and fall.

To assist in the water temperature impact evaluations of the various climate change scenarios, the Bureau of Reclamation temperature model was used to estimate temperatures in the Trinity, Sacramento, Feather, American, and Stanislaus river systems. The reservoir component of the temperature model simulates TCD operation. The joint DWR/Bureau of Reclamation simulation model, CALSIM-II, provided monthly CVP/SWP operations input to the temperature model for a 72-year hydrologic period from1922 to 1993.

The climate change scenario impacts on the distribution and volume of reservoir inflow, and its resulting effect on seasonal reservoir storage, influence the cold-water pool volume. Three of the four climate change scenarios indicate an average reduction in reservoir storage, and therefore a corresponding reduction in cold-water pool volume. In addition, all four climate change scenarios show an expected increase in air temperature. This increase is reflected in increased river temperature. A summary of river temperatures at several key locations along the Sacramento River is shown in Table 4.24. Increased air temperature in the winter and early spring is especially important since inflow and air temperature during this period drive accumulation of the cold-water pool.

**Table 4.24 Average Water Temperatures along the Sacramento River**

| | [illegible] | | [illegible] A2 | | [illegible] PCM A2 | | [illegible] | | [illegible] PCM [illegible] | |
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## 4.7 Conclusion

The purpose of this report was to provide a preliminary assessment of climate change impacts on CVP and SWP operations. Results of four climate change scenarios from global climate models GFDL and PCM were downscaled to regional hydrologic data using VIC. The regional streamflows were used to determine average monthly changes in reservoir inflows at a 2050 climate (2035 to 2064) as compared to a historical 1976 climate (1961 to 1990). The resulting perturbation factors were superimposed on historical reservoir inflows to create input for the four climate change simulations of CVP and SWP operations. The perturbed reservoir inflows were input into CalSim-II – the current planning simulation model for the CVP and SWP. Simulation results of the four climate change scenarios were compared to a historic climate simulation scenario in order to determine changes in water deliveries and carryover storage.

### 4.7.1 Study Limitations

There were some limitations in our analysis. First, the only representation of climate change in the CalSim-II simulations was the perturbed reservoir inflows. No consideration was given in these scenarios to heightened water demand due to changes in evapotranspiration or rainfall; nor was consideration given to increased Delta salinity due to a rising sea level. Both could significantly impact delivery capability.

Also, the method of downscaling global climate model information for CalSim-II input only captures the general trends of average rainfall and seasonal shifts in runoff. There is no information included about changes in weather variability. In each of the scenarios, the frequency and length of the droughts remained the same. If climate change influences these underlying weather phenomena, then we are missing important information necessary to determine impacts to CVP and SWP operations.

Another analytical limitation of our simulated results was the critical shortages of water in Shasta and Folsom during the droughts in scenarios GFDL A2, PCM A2, and GFDL B1. When these reservoirs were at dead storage, the simulated CVP operation was allowed to break rules and contracts that the Base and PCM B1 scenarios otherwise weren't. The result is that CVP deliveries reported for scenarios GFDL A2, PCM A2, and GFDL B1 are likely inaccurate. Alterations to CVP allocation rules governing the balance between deliveries and carryover may be necessary to prevent these shortages.

Given these and other analytical limitations, the results presented in this report are strictly preliminary. They are intended to be used to guide future climate change analysis and to identify areas where more information is needed. The results are not sufficient by themselves to make policy decisions.

### 4.7.2 Results

While there were limitations to our analysis, the results were nevertheless significant. General shifts in seasonal and annual average runoff, as predicted by the climate change scenarios, resulted in considerable impacts to SWP and CVP delivery capabilities, especially in the drier scenarios. Annual average SWP Table A deliveries were reduced by 10.2 percent in GFDL B1, while GFDL A2, the driest scenario, reduced annual average CVP SOD deliveries by 10.3 percent. SWP Article 21 deliveries tended to be slightly higher in the dry scenarios as compared to the Base because San Luis storage was less aggressively used for Table A and more Delta surplus was available in the winter; as such, San Luis was more likely to fill and the conditions for Article 21 deliveries -- full San Luis, Delta surplus, available Banks capacity -- were more likely to be met. However, the increased Article 21 deliveries did not offset reductions to Table A deliveries. PCM B1, the wetter climate change scenario, generated slightly higher SWP Table A and CVP SOD deliveries and slightly lower Article 21 deliveries; the difference between PCM B1 and the Base was most significant in the dry periods when storage capacity was available to make use of the extra water.

In response to climate change, California will need to search for physical, regulatory, and operational flexibilities in the SWP and CVP systems to maintain project delivery capabilities. With more runoff in the winter, there is likely to be a heightened conflict between the water supply and flood control uses of North-of-Delta reservoirs. Better storm forecasting technology, allowing for earlier flood releases, or increased storage capacity could reduce the conflict. With higher Delta inflows in the winter months, greater winter SOD exports are desirable. For Banks Pumping Plant, permitted capacity and SOD conveyance including storage, pump, and channel capacity often limited exports from December to March. Therefore, future studies on changes in Banks permitted capacity should consider including climate change scenarios for estimating potential water supply benefits. Tracy exports were often limited by the upper Delta-Mendota Canal constriction. As such, it would be useful to simulate the proposed DMC-California Aqueduct intertie in the context of a climate change scenario.

CalSim-II results were processed to produce net impacts to SWP and CVP power generation. The SWP, using more power than it generates, increased its net load on an annual average basis by 11 percent in both GFDL simulations. The CVP, a net power generator, lost 10 percent of its power production on an annual average basis in both GFDL scenarios. Power generation on average increased for the CVP in scenario PCM B1. Of course, annual average changes in power generation are not as telling as seasonal changes. For the drier climate scenarios, lower storage resulted in reduced SWP and CVP power generation during the key summer months. Summer power generation was slightly higher for PCM B1.

Base and climate change scenario results were input into the Bureau of Reclamation temperature model for in-stream temperature analysis. High temperatures can be hazardous to salmon and steelhead. Therefore, downstream temperature controls are part of CVP and SWP operations of Shasta, Oroville, and Folsom. According to Table 4.24, the climate change scenarios resulted in warming of river temperatures at several key locations on an annual average basis. The timing of impacts will have to be explored in future studies.

As stated in the introduction, this is just the starting point for analyzing climate change impacts on SWP and CVP operations. There is still much work to be done to fully consider climate change effects in project planning studies. Furthermore, future studies should consider measures to relieve the negative effects of climate change. Analysis of the interaction of hydrologic changes and system constraints can suggest where more flexibility would be most useful. Eventually, the accumulated data and analysis can be used by our scientists, engineers, and political leaders to make sound policy decisions concerning the SWP, CVP, and climate change.

## 4.8 Acknowledgements

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## 4.9 References

Miller, Norman L., et al (2001). Climate Change Sensitivity Study of California Hydrology: A Report to the California Energy Commission, *LBNL Technical Report No. 49110*.

United States Bureau of Reclamation (USBR) (2004). Chapter 6: Analytical Approach and Methods. In: *Long-Term Central Valley Project Operations Criteria and Plan.* United States Bureau of Reclamation. Sacramento, CA.

## Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
**July 2006**

# Chapter 5:
# Preliminary Climate Change Impacts Assessment for the Sacramento-San Joaquin Delta


**Author:**
Jamie Anderson Ph.D., P.E.
California Department of Water Resources, Bay Delta Office, Modeling Support Branch, Sacramento.

**Contributor:**
Joel Dudas P.E.
California Department of Water Resources, Division of Flood Management, Delta-Suisun Marsh Office, Sacramento.

**Peer Reviewers:**
Paul Hutton, Ph.D., P.E., Metropolitan Water District of Southern California

Leah Orloff, Contra Costa Water District

KT Shum, East Bay Municipal Water District

# 5 Preliminary Climate Change Impacts Assessment for the Sacramento-San Joaquin Delta

## 5.1 Introduction

The Sacramento-San Joaquin Delta is a dynamic network of natural and man-made channels. Freshwater from the southward flowing Sacramento River and from the northward flowing San Joaquin River converge with salty tidal flows from San Francisco Bay (Figure 5.1). Historically the Delta was a vast marsh. After the Gold Rush, farmers began building levees in the Delta to reclaim farmland. After years of farming, many of the Delta islands have subsided and are currently below sea level. Today the Delta consists of 57 leveed islands and more than 700 miles of sloughs and channels. This complex ecosystem is home to more than 500 species, including 20 endangered species such as the Delta smelt and salt harvest Suisun Marsh mouse. The Delta is also part of the migration path of young salmon heading out to the ocean and for adult salmon returning to spawn in their natal streams.

The Sacramento-San Joaquin Delta can be considered the hub of California's water supply system. About two-thirds of Californians and millions of acres of farmland rely on water from the Delta. Pumping plants in the south Delta are integral components for water distribution to central and southern California from the State Water Project (SWP) and the federal Central Valley Project (CVP). The Delta also provides local water supply for municipal and industrial and agricultural uses. The Delta supports more than $500 million in annual crop production (DWR, 2006).

The Sacramento River provides most of the freshwater inflow into the Delta (Figure 5.2). From 1980-1991, on average nearly 25 percent of the freshwater inflows to the Delta were used for municipal, industrial and agricultural water supplies, while the remaining 75 percent flowed to San Francisco Bay as Delta outflow. The actual distribution of Delta inflows varies from year to year depending on factors such as the amount and timing of precipitation and operations of upstream reservoirs.

Climate change could affect the Delta water balance shown in Figure 5.2. Warmer air temperatures are expected to shift the timing and form -- rain or snow -- of winter precipitation (see Chapter 2 and Chapter 6). Less snowpack would lead to less spring runoff. These shifting precipitation and runoff patterns would affect reservoir operations and Delta exports (see Chapter 4). Since the major inflows into the Delta are controlled by reservoir releases, Delta inflow patterns would be affected as well. More changes to reservoir releases and Delta exports might be required for compliance with Delta water quality standards. Changes in crop evapotranspiration rates could affect the amount of water needed for agricultural uses (see Chapter 7).

Future projected sea level rise would also affect the Delta. Higher water levels could threaten Delta island levees. Increased saltwater intrusion from the ocean could require increased freshwater releases from upstream reservoirs to maintain compliance with Delta water quality standards.

This chapter presents an initial demonstration of modeling tools use to quantify potential impacts of climate change on Delta water quality and water levels. The results demonstrate advancements on incorporating climate change into existing modeling methodologies, however the results produced are not sufficient by themselves for making management decisions. All results are preliminary and are for illustration purposes only. Sections 5.3 and 5.4 present potential effects of shifting precipitation and runoff patterns on Delta inflows and diversions for present sea level conditions. Section 5.5 addresses potential effects of sea level rise alone and in conjunction with shifting precipitation and runoff patterns.

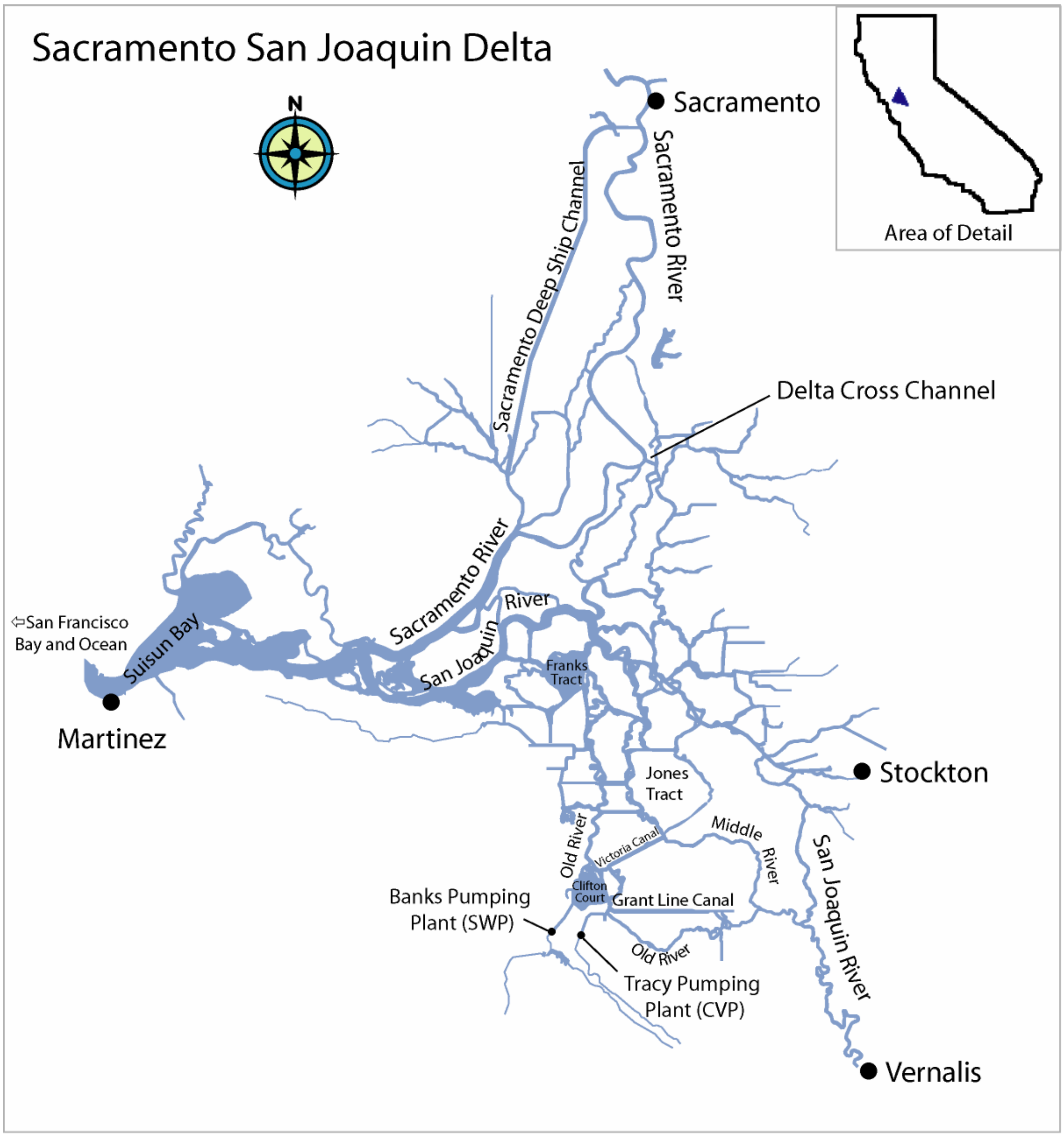



**Figure 5.1: The Sacramento-San Joaquin Delta**

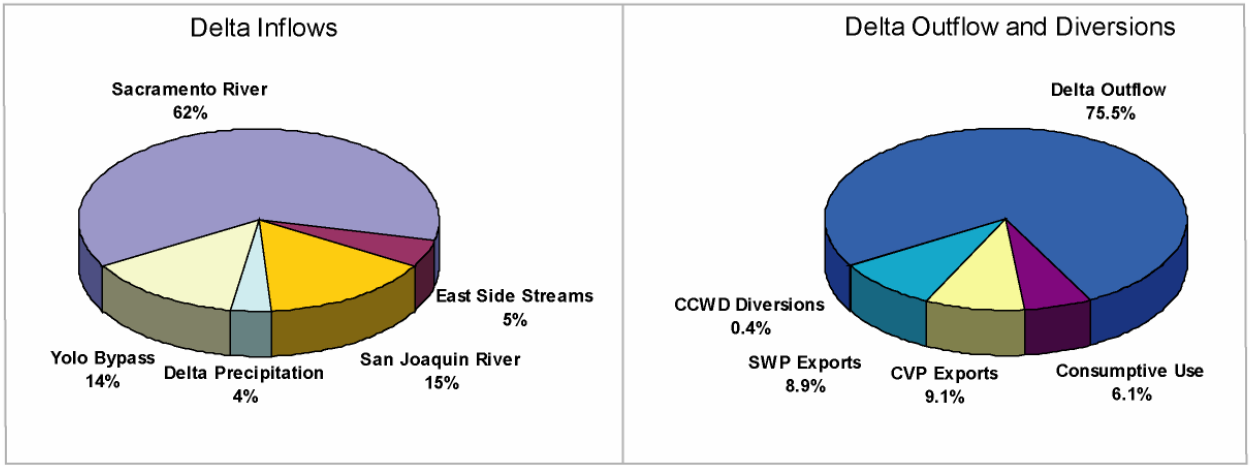



**Figure 5.2: Average Annual Delta Inflows, Outflow and Diversions from 1980-1991**
Adapted from Delta Atlas (DWR, 1995a)

## 5.2 Approach

A series of numerical models are being used for preliminary quantification of potential impacts of climate change on Delta flows, water levels and water quality (Figure 5.3). First, climate change scenarios are modeled using a Global Climate Model (GCM) to produce estimates of future air temperature and precipitation changes. These global scale changes are then reduced to a regional scale by a process called downscaling (see Chapter 3). The regional downscaling converts future projections of air temperature and precipitation into estimates of future streamflows. For these studies, the future streamflows are entered into a model, CalSim-II, which then simulates the operations of the SWP and CVP (see Chapter 4 and http://modeling.water.ca.gov/hydro/model/index.html). Using current management practices and existing system facilities, CalSim-II provides estimates of reservoir releases and Delta exports for each climate change scenario. The resulting Delta inflows and exports are then used to drive a model of the flows, water levels and water quality in the Delta, the Delta Simulation Model 2 (DSM2) (http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/models/dsm2/dsm2.cfm). Results of the Delta model are then analyzed for the potential effects on water quality at several key locations. DSM2 is also used to estimate impacts of sea level rise.

All results presented in this report are preliminary. These studies are a starting point for analyzing climate change impacts on Delta hydrodynamics and water quality. Current management practices and existing system facilities were used in the analysis for this report. No changes were made to lessen the effects of climate change or sea level rise. Only four climate change scenarios and one sea level rise scenario were examined, and the likelihood of each scenario was not addressed. Several assumptions were also included in the analyses (see Section 5.2.3). The results presented here are not sufficient by themselves for making final policy decisions. These results are intended to illustrate the application of CalSim-II and DSM2 for climate change impacts assessment. Future efforts will involve improvements of the models and the study assumptions, and will address the likelihood of various climate change scenarios.

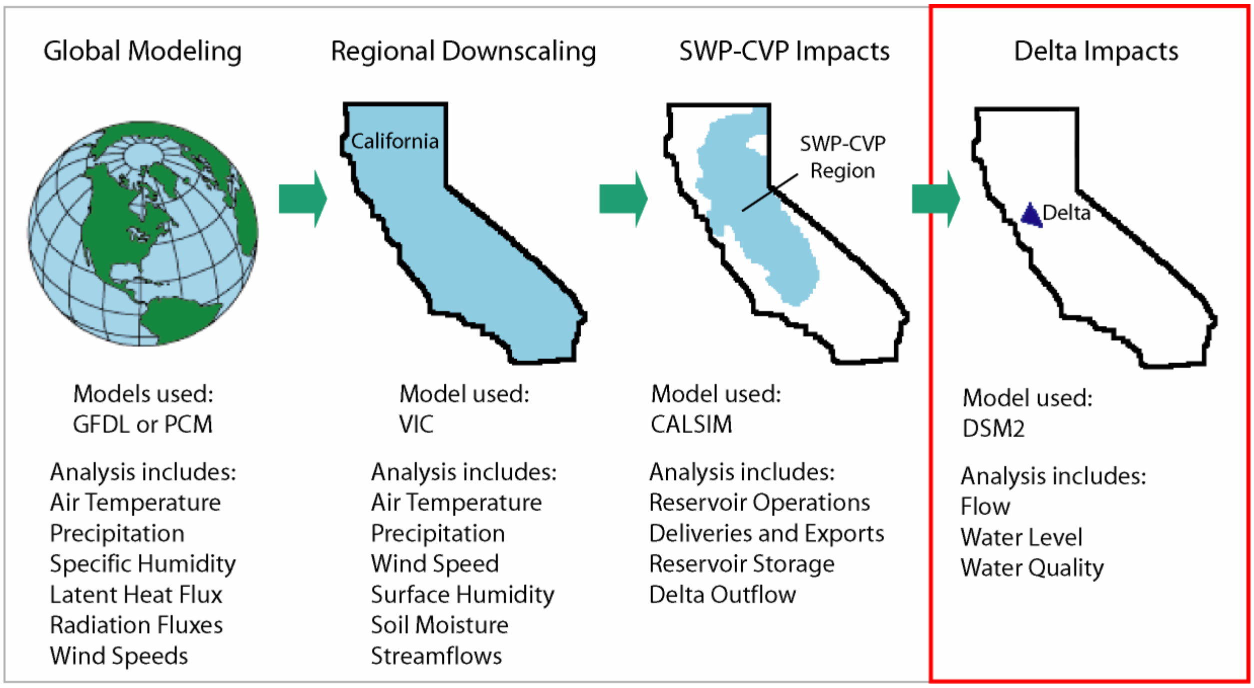



**Figure 5.3: Delta Impacts Analysis Approach**

### 5.2.1 Base Case

The base case for these studies is a 2020 level of development scenario using operations based on the "Long-Term Central Valley Project Operations Criteria and Plan" (USBR, 2004). Assumptions for the base case and climate change scenarios are presented later in Section 5.2.3.

### 5.2.2 Climate Change Scenarios

The studies presented in this report focus on the four climate change scenarios selected by the Climate Action Team appointed in response to the governor's Executive Order S-3-05 on climate change. The four climate change scenarios consist of two greenhouse gas (GHG) emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), known as A2 and B1, each represented by two different GCMs, the Geophysical Fluid Dynamic Lab model (GFDL) and the Parallel Climate Model (PCM) (see Chapter 3).

The A2 emissions scenario assumes high population growth, regional based economic growth, and slow technological changes that result in significantly higher GHG emissions. The B1 scenario represents low population growth, global based economic growth and sustainable development that result in the lowest increase of GHG emissions of the IPCC scenarios. Both the GFDL and PCM models project future warming, with GFDL indicating a greater warming trend than PCM. The PCM B1 scenario is the only scenario that shows a slight increase in precipitation. Precipitation is reduced in the other three scenarios.

Although the GCM models represent climate change through the end of the 21st century, the planning horizon for water resources is typically about 30 years. So the studies presented here focus on the climate change projections at about mid-century (Table 5.1). Thirty years of projected streamflows centered around the year 2050 (2035-2064) were used to develop the climate change influenced runoff patterns simulated in the SWP and CVP operations model, CalSim-II (see Chapter 4). However, land use projections were not available for 2050, so the climate change scenarios use land-use estimates for 2020. Thus when the climate change scenarios are described as being at the 2050 projection level, this refers to the runoff estimates only.

**Table 5.1: Air Temperature and Precipitation Projections for 2050**

| Scenario | Average Change in Air Temperature °C | | Average Change in Precipitation, in/yr | |
|---|---|---|---|---|
| | Northern CA | Southern CA | Northern CA | Southern CA |
| 2050 GFDL A2 | 2.3 | 2.3 | -0.75 | -0.22 |
| 2050 PCM A2 | 2.1 | 2.1 | -0.25 | -1.77 |
| 2050 GFDL B1 | 1.3 | 1.2 | -0.62 | 0.70 |
| 2050 PCM B1 | 0.8 | 0.9 | 0.83 | -0.08 |

### 5.2.3 Assumptions

Major assumptions made in these studies are summarized below:

**Runoff Estimations for Climate Change Scenarios (see Chapter 4 section 4.4)**

- ❑ Runoff estimates reflect 2050 projections.
- ❑ Climate change scenarios maintain historical hydrologic variability.

**CalSim-II Simulations of SWP and CVP Operations (see Chapter 4 section 4.5)**

- ❑ Simulations were run for a 73-year analysis period based on wy1922-1994.
- ❑ Operating rules were not modified for climate change scenarios.
- ❑ For climate change scenarios, reservoir inflows reflect 2050 projections.
- ❑ For all scenarios, land use and water demands represent a constant 2020 level of development. The level of development does not change as the simulation progresses through time.

Current management practices and existing system facilities were used in the analysis for this report. No changes were made to lessen the effects of climate change or sea level rise.

No changes were made to:

- ❑ System structures, such as added water storage, pumping, or canal capacity
- ❑ Reservoir operating rules, such as changing the space required for flood control
- ❑ Streamflow requirements
- ❑ Water quality standards
- ❑ Delta outflow requirements
- ❑ Operations to account for sea level rise

- Delta exports, outflow and water quality are regulated according to the State Water Resources Control Board Decision 1641 (D1641) and the Water Quality Control Plan.
- Meeting Delta water quality standards is the top priority when changing SWP and CVP operations. Climate change will make this a larger challenge in the future. (see Table 4.12 in Chapter 4).

**CalSim-II Simulations of SWP and CVP Operations (continued)**

- Regulations from the Central Valley Project Improvement Act (CVPIA) 3406 (b)(2) are not included.
- The Environmental Water Account (EWA) is not included.
- San Joaquin River hydrology, operations and water quality do not reflect recent improvements subjected to the 2005 California Water and Environmental Modeling Forum (CWEMF)/CALFED peer review.
- New Melones Reservoir operations are governed by the Interim Plan of Operations.
- Operations were not modified to reflect sea level rise conditions

**Delta Simulations**

- Simulations were run for a 16-year analysis period based on wy1976-1991.
- Delta inflows and exports provided by CalSim-II output were not further modified to try to mitigate for Delta water quality effects of climate change or sea level rise.
- Contra Costa Water District (CCWD) diversions from Old River at Rock Slough and Old River at Highway 4 were combined and diverted from Rock Slough since CalSim-II did not simulate the two diversions separately.
- Operations of south Delta temporary fish and agricultural barriers were not simulated.[1]
- Pulse flows in April and May for the Vernalis Adaptive Management Plan (VAMP) were not simulated.
- Delta Island Consumptive Use for the 2020 level of development was used for all scenarios.
- Delta island return flow water quality varies monthly in a given year, but does not vary from year to year.
- For one-foot sea level rise scenarios, sea level rise was assumed to affect tidal elevation only. Tidal period and amplitude were assumed to be unchanged.
- Martinez EC is either the same or is increased for sea level rise scenarios (see section 5.5.1.1)
- Vernalis EC is the same for present sea level and one-foot sea level rise scenarios.

[1] Barrier operations can significantly influence Delta water quality and circulation patterns. The intent of the preliminary studies was to focus on the effects of climate change without having to separate which impacts were due to climate change and which were due to barrier operations.

### 5.2.4 Delta Simulations

The base case and four climate change scenarios were evaluated using DSM2 to quantify effects on Delta water quality and water levels. Each scenario was simulated at present sea level and for a one-foot sea level rise. DSM2 is a one dimensional model of flow, water levels and conservative and non-conservative constituent transport. The boundaries of the Delta representation in DSM2 are the I Street Bridge in Sacramento on the Sacramento River, Vernalis on the San Joaquin River, and Martinez downstream of the confluence of the two rivers as they flow into San Francisco Bay (Figure 5.1). Tidal water level fluctuations, river inflows, Delta exports, and irrigation withdrawals and return flows are all represented in DSM2. To represent the effects of the tidal cycle, DSM2 uses a 15-minute computational time step.

For DSM2 planning studies, a 16-year study period based on water years (wy) 1976-1991 (Oct. 1, 1975 to Sept. 30, 1991) is used. The study period reflects the variability in California's hydrology and includes the wettest (wy1983) and driest (wy1977) periods on record.

Reservoir inflows for the study period were modified to reflect climate change by multiplying the base-case runoff by monthly adjustment factors for each climate change scenario (see Chapter 4). Thus these studies reflect potential changes in magnitude and timing of runoff, but they do not represent potential changes in hydrologic variability since the base case represents historical hydrologic variability. System operations were then simulated using CalSim-II. Monthly average results from the CalSim-II simulations provided the following major Delta inflows, exports and diversions (Figure 5.4):

**Delta Inflows**

- Sacramento River at I Street Bridge in Sacramento
- San Joaquin River at Vernalis
- Eastside Streams (combined Mokelumne and Cosumnes river flows)
- Calaveras River
- Yolo Bypass

**Delta Exports and Diversions**

- SWP at Banks Pumping Plant
- CVP at Tracy Pumping Plant
- Contra Costa Water District (combined diversions Old River at Rock Slough and at Hwy. 4)
- North Bay Aqueduct
- Vallejo

The Delta inflows, exports and diversions provided from CalSim-II already incorporate mitigation for climate change through system operations using present operating rules. Tidal fluctuations in water level at Martinez are represented in DSM2 on a 15-minute time step by an adjusted astronomical tide that is based on historical data and reflects the spring-neap tidal cycle (Ateljevich, 2001a). Delta Island Consumptive Use (DICU) is represented at more than 250 locations (DWR, 1995b). Delta Cross Channel operations are provided by CalSim-II and did not change for any of the scenarios.

For this study, water quality analysis focused on salinity. DSM2 simulates electrical conductivity (EC) directly. Other salinity constituents such as chlorides can be estimated from the EC concentrations using statistical regression equations. For the DSM2 simulations, EC values must be specified for all Delta inflows. For the Sacramento River, eastside streams, Calaveras River and Yolo Bypass, constant EC values for each location are used in all of the scenarios (Table 5.2). San Joaquin River EC at Vernalis is provided for each scenario from output from the CalSim-II simulations. EC at Martinez is estimated for each scenario using a regression relationship that correlates the astronomical tide and Delta outflow to salinity (Ateljevich, 2001b). Delta Island return flow quality estimates were made based on available field data (DWR, 1995c). The quality of the return flows varies monthly, but does not vary from year to year. The same return flow quality values were used for all scenarios.

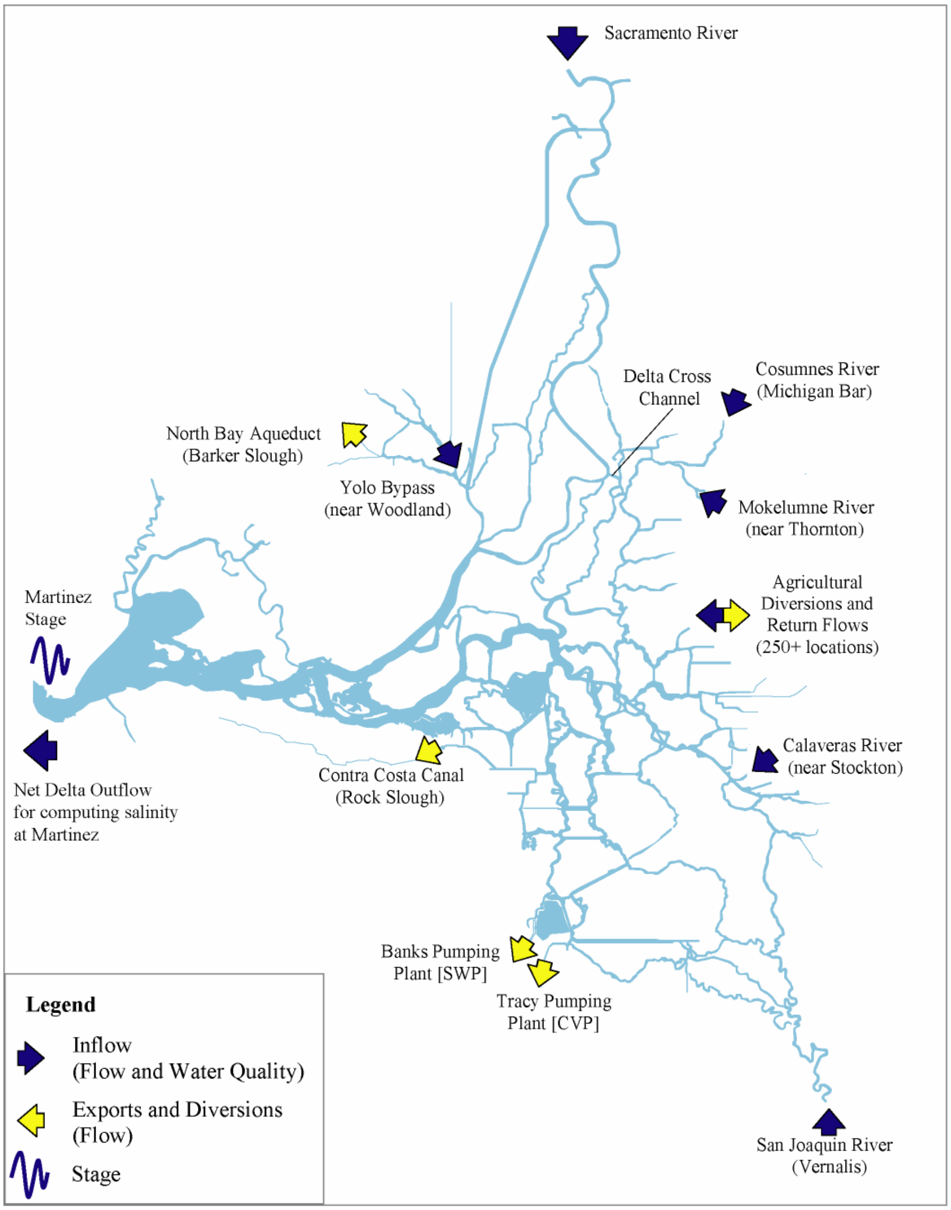



**Figure 5.4: Inflows, Exports, Diversions and EC Inputs for DSM2 Simulations**

**Table 5.2: Constant EC Concentrations for DSM2 Simulations**

| Location | EC, uS/cm |
|---|---|
| Sacramento River | 175 |
| Eastside Streams | 150 |
| Calaveras River | 150 |
| Yolo Bypass | 175 |

For sea level rise scenarios (see section 5.5), the tidal elevations at Martinez were raised uniformly by one-foot. This assumes that sea level rise does not affect the period of the tidal cycle. Estimates of additional salt transported from the ocean to Martinez under a one-foot sea level rise were not available. Due to time constraints, a preliminary approach for estimating salinity increases at Martinez for a one-foot sea level rise is applied only to the base case. In order to examine potential combined effects of sea level rise and climate change, scenarios that combined changes in Delta inflows and exports due to climate change with a one-foot sea level rise assumed that the salinity at Martinez for the one-foot sea level rise was the same as the Martinez EC for the present sea level version of that scenario. For example, the specified EC at Martinez was the same for the 2050 GFDL A2 present sea level and one-foot sea level rise scenarios. Since the salinity at Martinez would likely increase with rising sea levels, this assumption provides a lower bound for potential sea level rise effects on water quality for a one-foot rise in sea level. For these studies, system operations were not changed to try to lessen the increased salt intrusion for the sea level rise scenarios.

## 5.3 Climate Change Impacts on Delta Inflows and Exports for Present Sea Level Conditions

Output from CalSim-II provided Delta inflows and exports for DSM2 simulations of present sea level conditions for the base case and four climate change scenarios (Figure 5.5 to Figure 5.8). Tabular values of selected Delta inflows and exports are provided in the appendix in Section 5.11. Table 5.3 to Table 5.6 show monthly average changes in Delta inflows and exports for the climate change scenarios relative to the base case, and yearly changes are shown in Table 5.7 and Table 5.8. These results are preliminary representations of climate change impacts, and they reflect the assumptions listed in Section 5.2.3. See Chapter 4 for further information on climate change impacts to system operations.

Delta inflows tend to increase during the late winter and early spring and decrease during the summer and fall. The largest reductions in exports tend to occur in summer and fall. Inflows and exports are most sensitive to climate change during extremely wet or extremely dry periods. For example, the largest reduction in the magnitude of Delta inflows occurs during the summer of 1983 when base runoff was very high. For the climate change scenarios, the reduction in inflow for each month is determined by a monthly scaling factor as described in Chapter 4. For example, in the GFDL A2 scenario the June runoff into Shasta and Oroville is reduced by about 30 percent. Since the base runoff for 1983 was very high, the 30 percent reduction in the runoff resulted in the largest Delta inflow reduction. Contra Costa Water District (CCWD) diversions were the same for all scenarios since they receive a high priority when CalSim-II allocates water. See Chapter 4 for more details on effects of climate change on SWP and CVP operations.

**Table 5.3: Average Monthly Change in Sacramento River Inflow to the Delta, cfs**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GFDL A2 | -1,600 | -2,156 | -1,518 | 930 | 265 | 2,441 | -1,040 | -2,667 | -1,647 | -1,571 | -1,600 | -2,156 |
| PCM A2 | -294 | -1,056 | -1,515 | -910 | -57 | 811 | -1,010 | -2,168 | -841 | -1,104 | -294 | -1,056 |
| GFDL B1 | -1,175 | -1,719 | -1,611 | 1,547 | -369 | 2,456 | -728 | -2,605 | -1,540 | -1,205 | -1,175 | -1,719 |
| PCM B1 | 254 | -163 | -178 | 1,639 | 386 | 5,265 | 1,814 | 17 | -289 | 272 | 254 | -163 |

**Table 5.4: Average Monthly Change in San Joaquin River Inflow to the Delta, cfs**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GFDL A2 | -1,324 | -436 | 634 | 479 | 713 | 1,921 | 901 | -393 | -2,812 | -1,173 | -115 | -426 |
| PCM A2 | -410 | 296 | -592 | -404 | 1,447 | 980 | 813 | -110 | -1,847 | -705 | -67 | -196 |
| GFDL B1 | -1,362 | 208 | 82 | 364 | -1,773 | -175 | 288 | -870 | -2,866 | -1,159 | -136 | -422 |
| PCM B1 | -198 | 287 | -617 | 361 | 1,257 | 1,600 | 823 | 255 | -1,628 | -420 | -26 | -113 |

**Table 5.5: Average Monthly Change in SWP Exports, cfs**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GFDL A2 | -756 | -646 | -91 | -107 | -73 | -146 | -516 | -106 | -158 | -407 | -445 | -865 |
| PCM A2 | -630 | -12 | -338 | -292 | -57 | -167 | -284 | -69 | -142 | -351 | -10 | -626 |
| GFDL B1 | -756 | -489 | 107 | -160 | -131 | -152 | -417 | -454 | -382 | -382 | -433 | -999 |
| PCM B1 | -169 | 3 | -213 | -28 | -106 | 198 | -117 | 75 | -75 | 8 | 91 | -75 |

**Table 5.6: Average Monthly Change in CVP Exports, cfs**

| | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GFDL A2 | -474 | -36 | -266 | 126 | -444 | 149 | -303 | -235 | -690 | -1,143 | -867 | -305 |
| PCM A2 | -306 | -94 | -255 | 159 | -490 | 169 | -243 | -125 | -263 | -582 | -350 | -99 |
| GFDL B1 | -473 | -46 | -164 | 143 | -365 | 219 | -215 | -178 | -447 | -754 | -554 | -81 |
| PCM B1 | -16 | 245 | -269 | 125 | -71 | 130 | -48 | 63 | 55 | 122 | -4 | -37 |

**Table 5.7: Annual Change in Delta Inflows**

| Water Year | Year Type* | Base Flows TAF | | Change in Sacramento River Flows, TAF | | | | Change in San Joaquin River Flows, TAF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SAC River | SJR River | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
| 1976 | C | 9,322 | 1,345 | -1,011 | -611 | -933 | -198 | -148 | -88 | -154 | -41 |
| 1977 | C | 6,222 | 1,086 | -511 | -157 | -145 | 99 | -37 | -19 | -59 | -8 |
| 1978 | AN | 20,144 | 4,094 | 826 | -148 | 792 | 2,021 | -260 | -148 | -787 | -94 |
| 1979 | BN | 13,383 | 2,974 | -1,457 | -892 | -1,562 | 492 | -443 | -144 | -614 | 260 |
| 1980 | AN | 20,158 | 4,794 | -622 | -175 | -430 | 1,092 | 101 | 0 | -1,096 | 367 |
| 1981 | D | 11,976 | 1,840 | -922 | -866 | -693 | 251 | -343 | -38 | -360 | 45 |
| 1982 | W | 31,303 | 6,056 | -585 | -373 | -573 | 735 | 131 | 61 | -796 | 438 |
| 1983 | W | 35,501 | 13,934 | -5,199 | -3,185 | -4,618 | -130 | -1,874 | -838 | -2,971 | -148 |
| 1984 | W | 23,068 | 5,767 | 201 | 56 | 315 | 1,196 | 32 | 183 | -229 | 340 |
| 1985 | D | 12,050 | 1,556 | -588 | -183 | -286 | 78 | -204 | -56 | -216 | -10 |
| 1986 | W | 18,784 | 4,732 | -871 | -776 | -821 | 208 | 568 | 493 | -874 | 589 |
| 1987 | D | 9,765 | 1,333 | -1,008 | -828 | -988 | 353 | -115 | -93 | -119 | -44 |
| 1988 | C | 8,694 | 932 | -158 | -192 | -71 | 314 | -25 | -19 | -26 | -3 |
| 1989 | D | 12,086 | 973 | 756 | -426 | 838 | 2,093 | -29 | -10 | -36 | 4 |
| 1990 | C | 8,128 | 893 | -243 | -289 | -215 | -122 | -15 | -9 | -26 | 14 |
| 1991 | C | 7,611 | 965 | -535 | -145 | -136 | 333 | -21 | -12 | -26 | 8 |

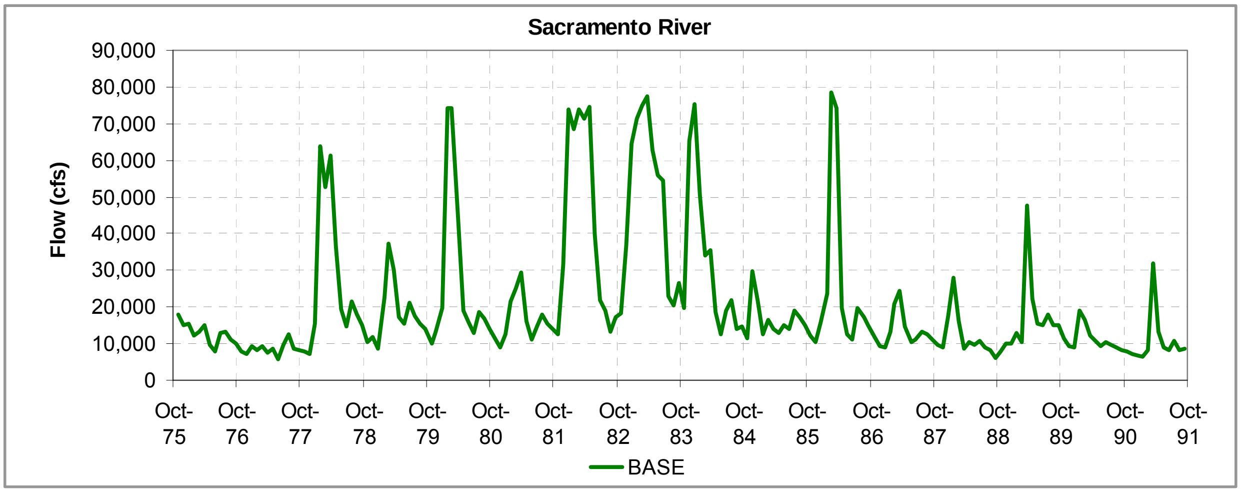
*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical

**Table 5.8: Annual Change in Delta Exports**

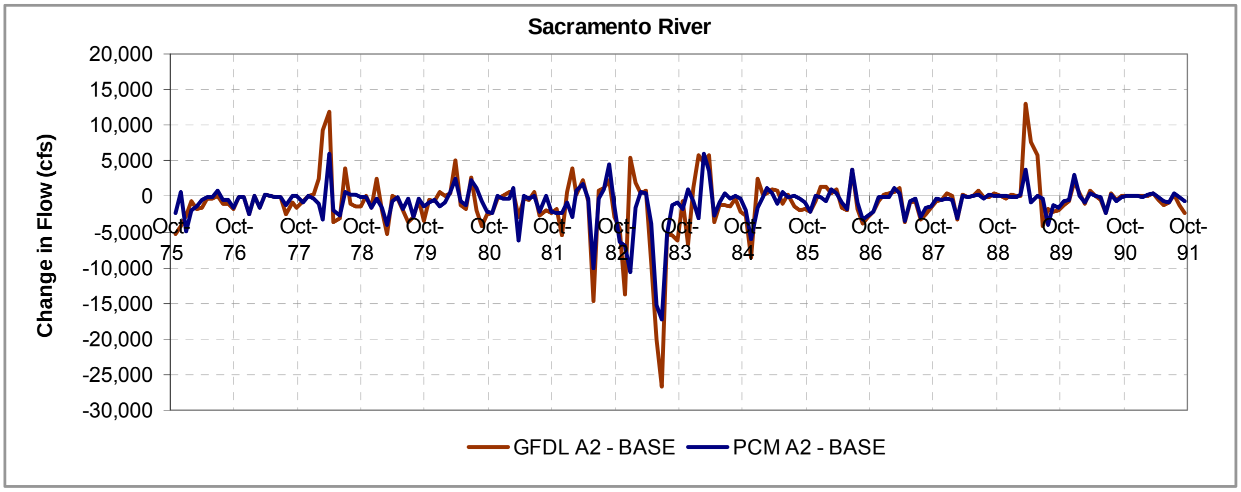
| Water Year | Year Type* | Base Exports TAF | | Change in SWP Exports TAF | | | | Change in CVP Exports, TAF | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | SWP | CVP | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
| 1976 | C | 2,967 | 2,158 | -635 | -385 | -588 | -229 | -23 | 45 | 22 | -34 |
| 1977 | C | 995 | 1,391 | -3 | -83 | -59 | 75 | -462 | -97 | -153 | 38 |
| 1978 | AN | 3,608 | 2,736 | -217 | -115 | -438 | -102 | -143 | -29 | -171 | 19 |
| 1979 | BN | 3,703 | 2,895 | -446 | -101 | -589 | 118 | -447 | -223 | -374 | 62 |
| 1980 | AN | 4,105 | 2,965 | -478 | -263 | -457 | 1 | -992 | -572 | -786 | -152 |
| 1981 | D | 3,326 | 2,748 | -674 | -558 | -716 | -167 | -195 | -71 | -128 | 8 |
| 1982 | W | 4,706 | 3,229 | 191 | 244 | 179 | 281 | -393 | -153 | -286 | -172 |
| 1983 | W | 3,676 | 2,827 | 34 | 0 | 29 | 0 | 176 | 15 | 168 | 14 |
| 1984 | W | 3,417 | 2,501 | -288 | -86 | -305 | -3 | -309 | -102 | -174 | -25 |
| 1985 | D | 3,516 | 2,869 | -239 | -189 | -278 | 76 | -415 | -11 | -169 | -42 |
| 1986 | W | 4,201 | 2,799 | -583 | -432 | -664 | 56 | -520 | -420 | -471 | -227 |
| 1987 | D | 2,570 | 1,904 | -903 | -770 | -972 | -284 | -377 | -239 | -277 | 395 |
| 1988 | C | 1,541 | 1,729 | 32 | -12 | 20 | 72 | -191 | -117 | -100 | 265 |
| 1989 | D | 2,723 | 2,248 | -382 | -194 | -344 | -71 | -299 | -289 | -162 | 99 |
| 1990 | C | 1,605 | 1,563 | -303 | -277 | -314 | -161 | -24 | -90 | -25 | -77 |
| 1991 | C | 1,110 | 1,495 | 162 | 63 | -17 | 161 | -574 | -143 | -149 | 103 |

*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical

a) Base Case Delta Inflows




b) Change in Inflow for Climate Change A2 Scenarios




c) Change in Inflow for Climate Change B1 Scenarios

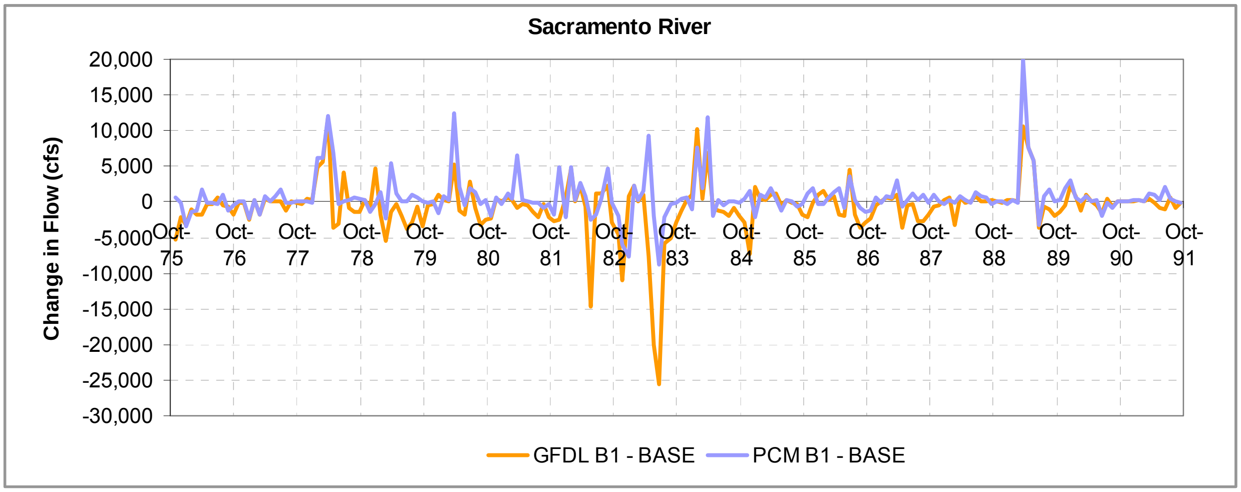
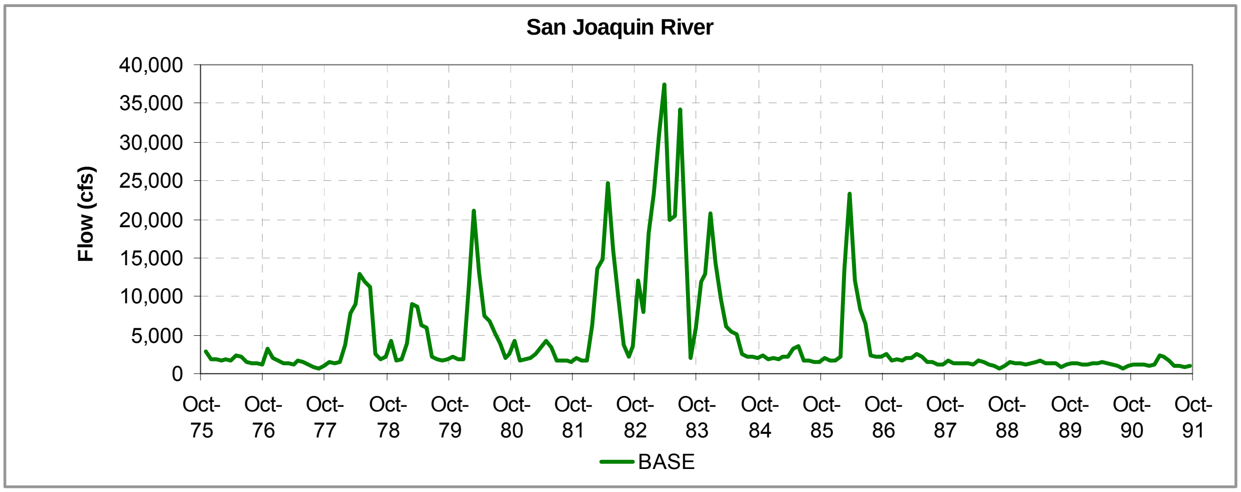
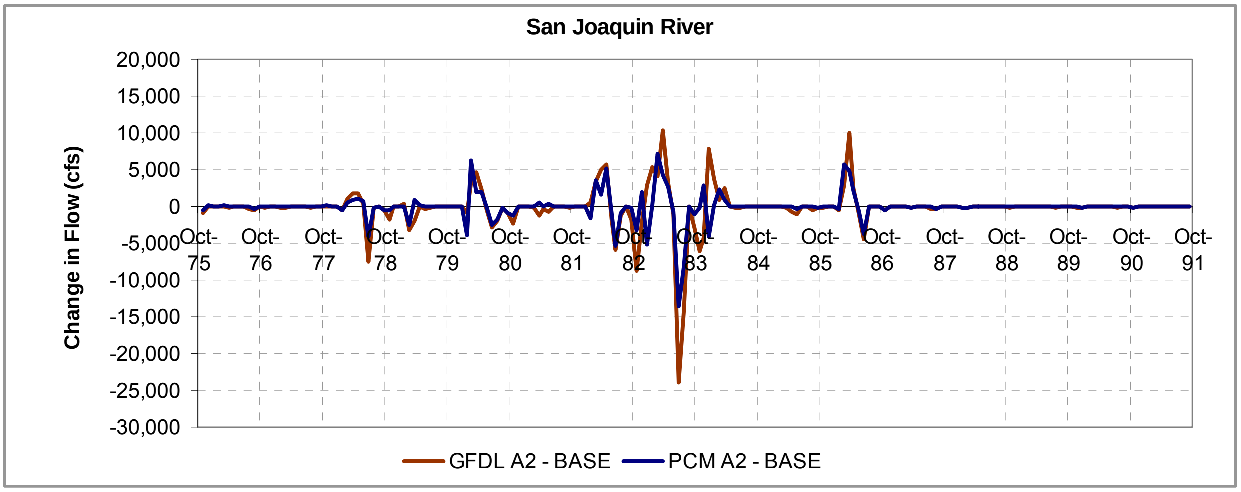



**Figure 5.5: Delta Inflows from the Sacramento River**

a) Base Case Delta Inflows




b) Change in Inflow for Climate Change A2 Scenarios




c) Change in Inflow for Climate Change B1 Scenarios

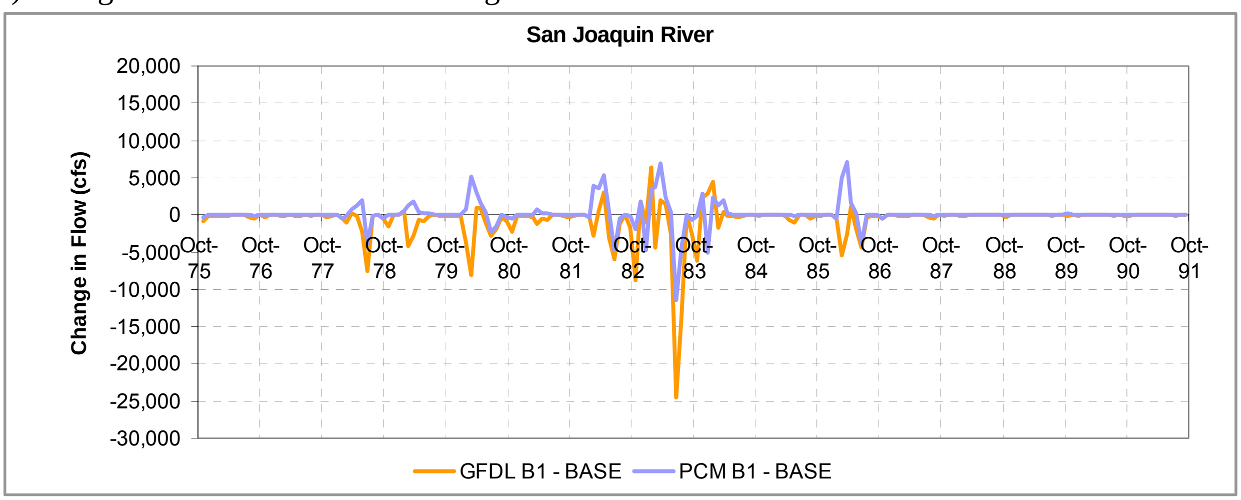
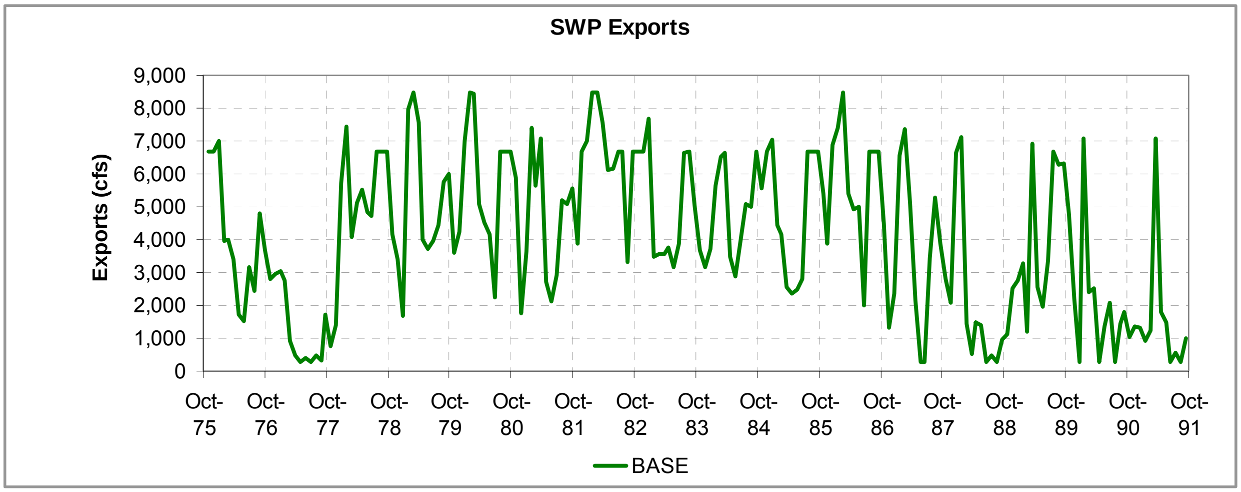
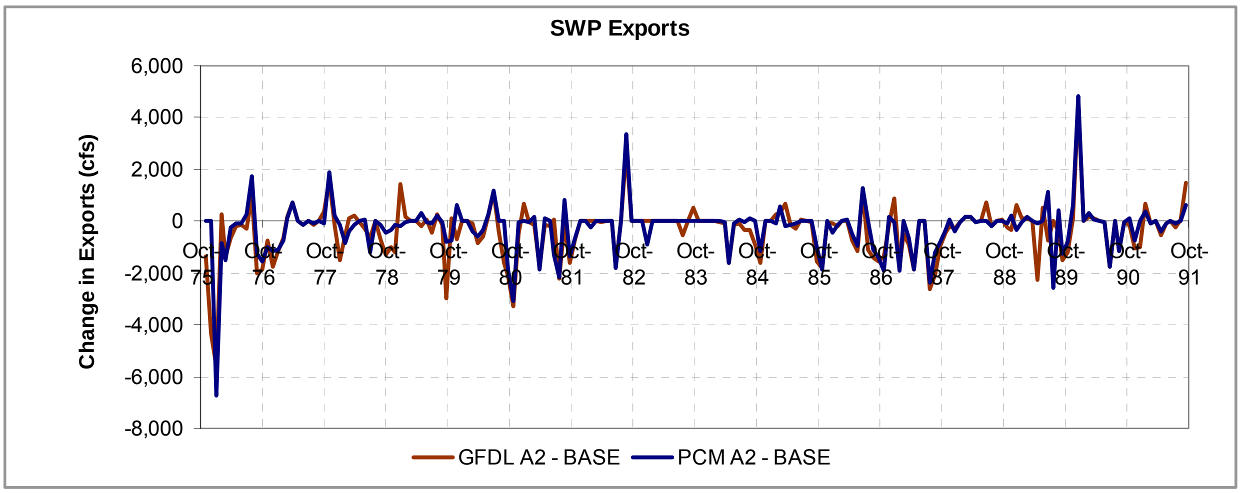



**Figure 5.6: Delta Inflows from the San Joaquin River**

a) Base Case Delta Exports




b) Change in Exports for Climate Change A2 Scenarios




c) Change in Exports for Climate Change B1 Scenarios

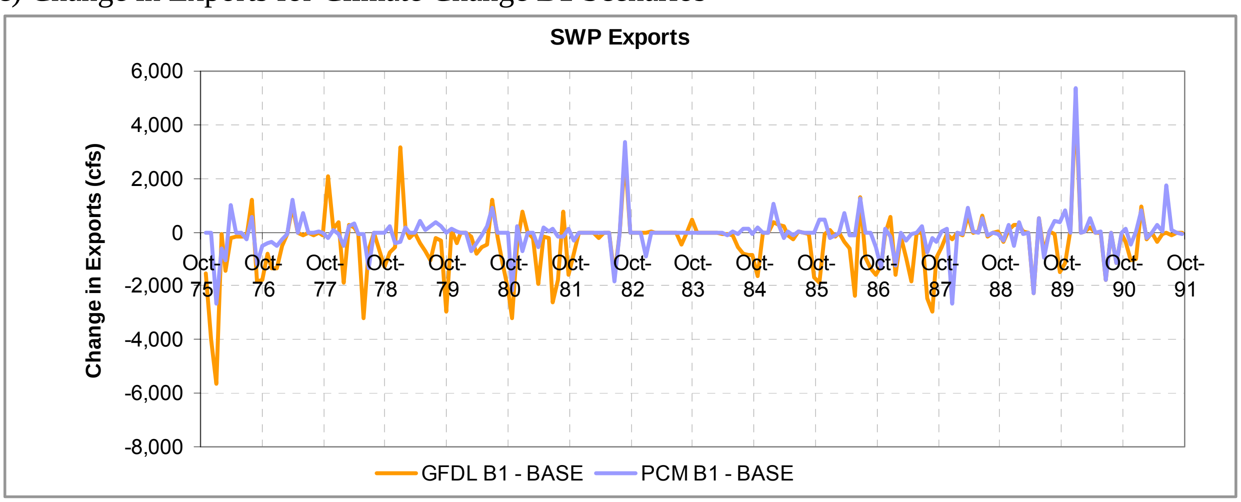
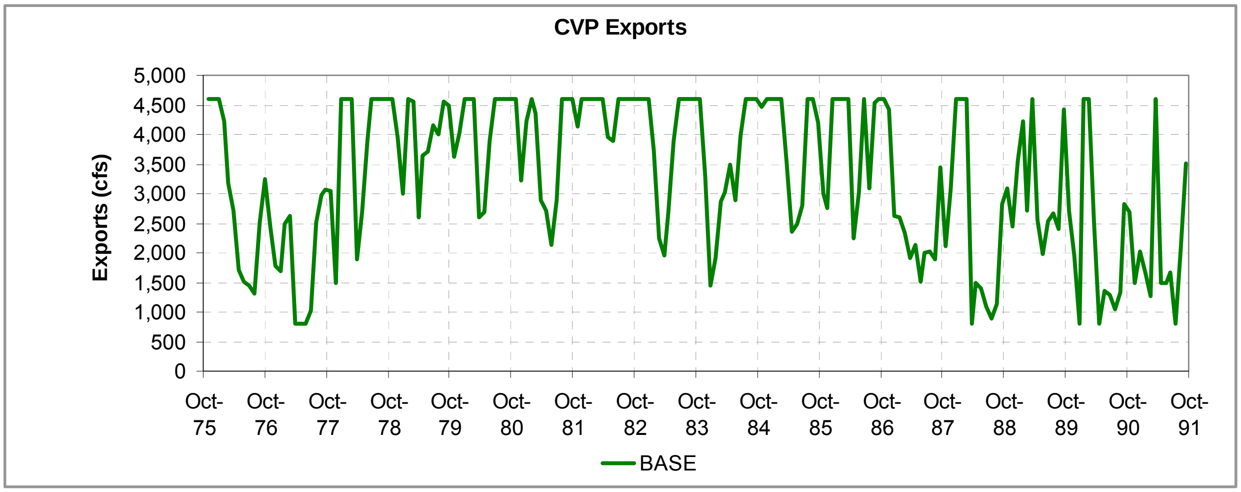
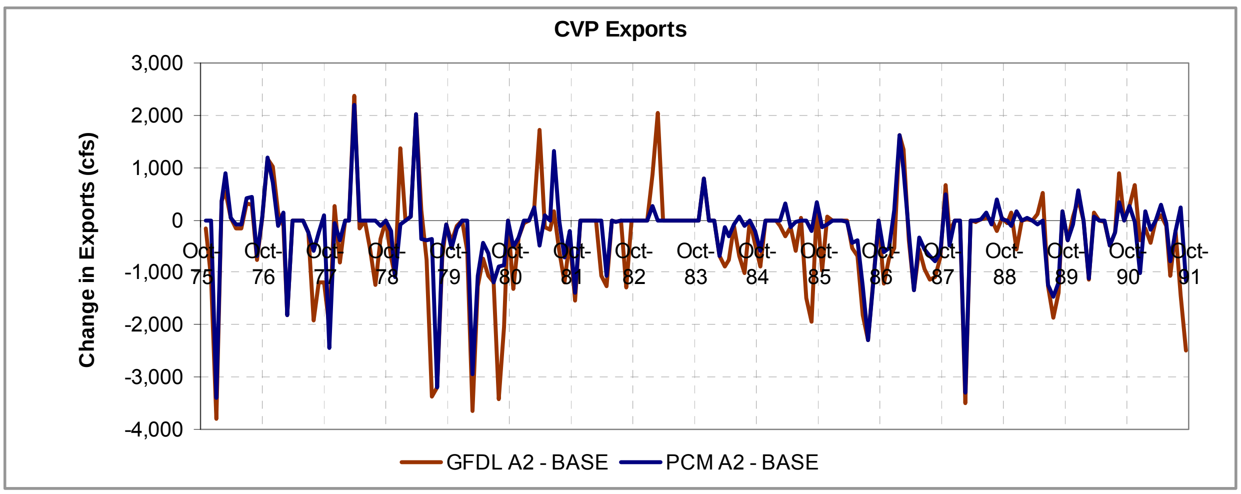



**Figure 5.7: Delta Exports from the State Water Project**

a) Base Case Delta Exports




b) Change in Exports for Climate Change A2 Scenarios




c) Change in Exports for Climate Change B1 Scenarios

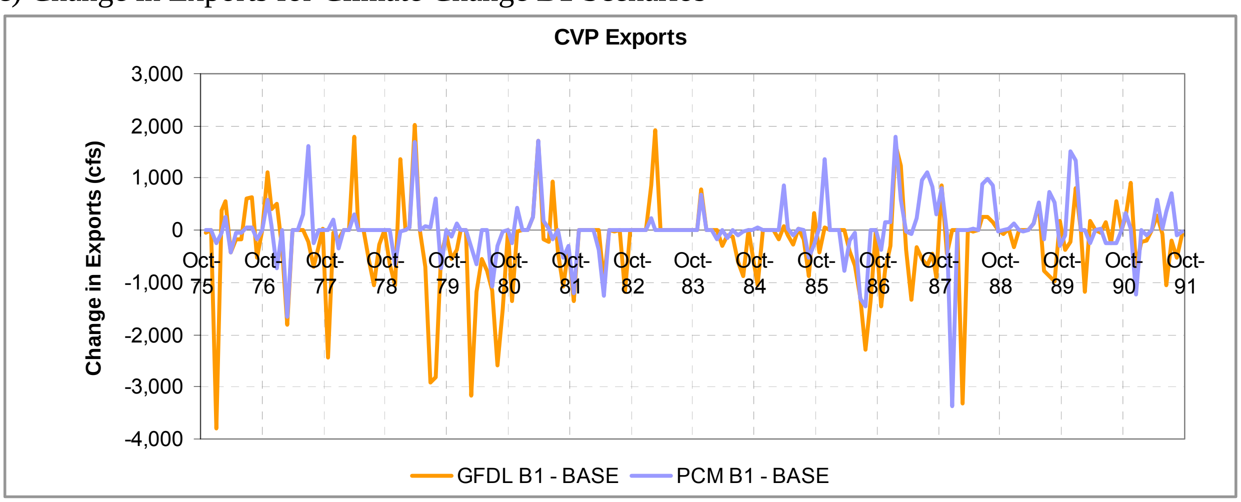



**Figure 5.8: Delta Exports from the Central Valley Project**

## 5.4 Climate Change Impacts on Water Quality for Present Sea Level Conditions

Initial analysis of potential impacts of climate change on Delta water quality for present sea level conditions focuses on compliance with selected Delta water quality standards from the Water Quality Control Plan and the State Water Resources Control Board Decision 1641 (D1641) (SWRCB, 1995). Analysis of other water quality parameters of concern, such as disinfection by-product formation potential is beyond the scope of this report. Initial analysis focused on specified limits for chloride concentrations (Table 5.9) at four municipal and industrial intake locations (Figure 5.9). Chloride mass loadings at each intake were also examined. All results are preliminary and incorporate several assumptions (see Section 5.2.3). These preliminary results are intended to illustrate the use of CalSim-II and DSM2 for climate change impacts assessment. The results are not sufficient by themselves for making policy decisions.

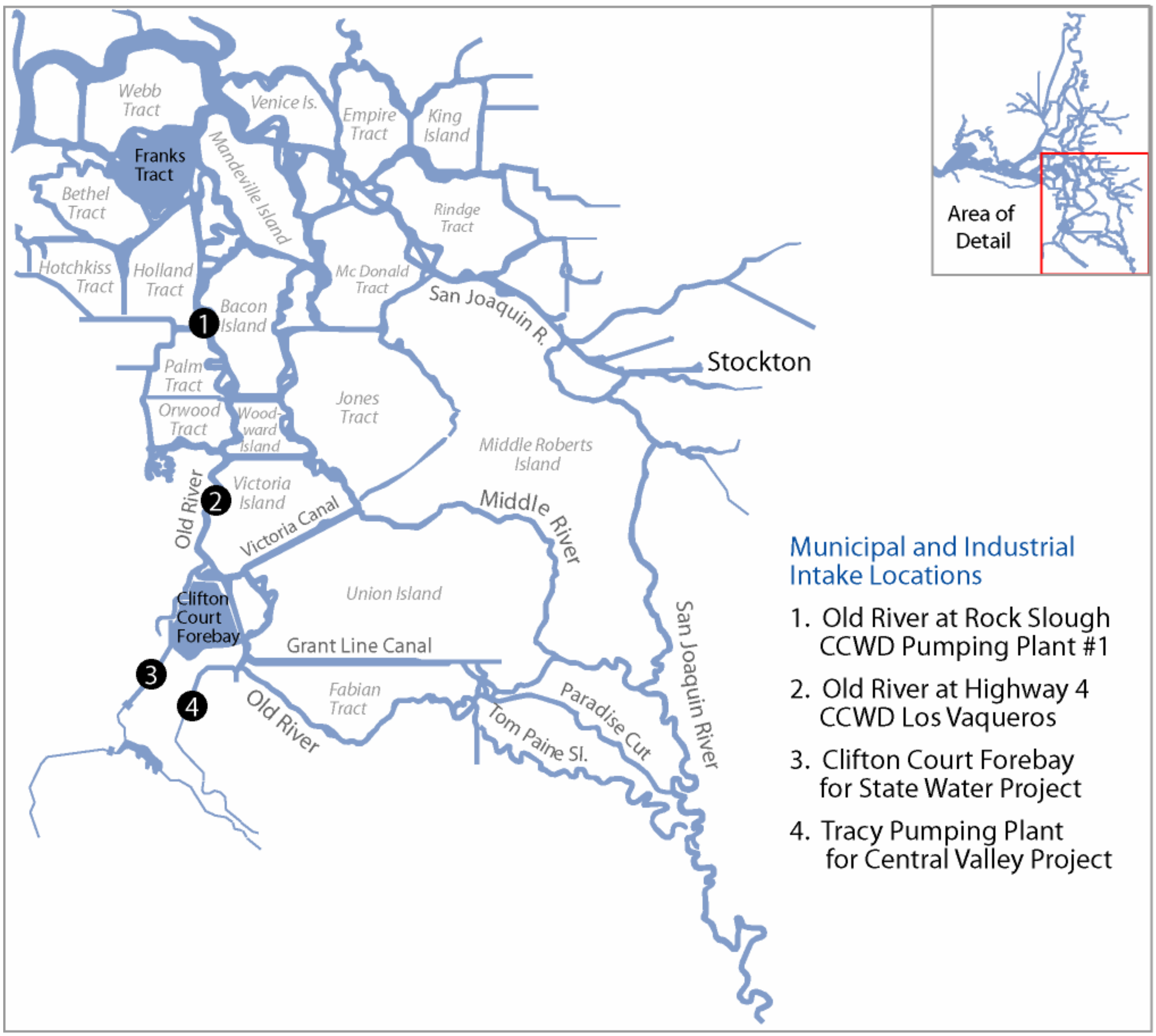



**Figure 5.9: Delta Water Quality Impact Analysis Locations**

**Table 5.9: Delta Water Quality Standards**

<table>
<tr><th></th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th></tr>
<tr><td>Municipal and Industrial Compliance Locations</td><td colspan="12">Daily average Cl < 250 mg/l</td></tr>
<tr><td>Contra Costa Pumping Plant #1</td><td colspan="12">Cl<150 mg/l for a required # of days based on year type</td></tr>
</table>

### 5.4.1 Municipal and Industrial Water Quality for Present Sea Level Conditions

For this study, two municipal and industrial chloride standards from D1641 (SWRCB, 1995) were examined. The first standard specifies that maximum allowable daily average chloride concentrations can not exceed 250mg/l (Table 5.9). The second standard states that daily average chloride concentrations must be less than 150 mg/l for a specified number of days per calendar year based on the water year type (Table 5.10). This second chloride standard also requires that chloride concentration must be less than 150 mg/l for two consecutive weeks before those days can be counted towards meeting the standard.

**Table 5.10: D1641 150 mg/l Chloride Standard**

| Water Year Type | Minimum Number of Days with Chloride Concentration ≤ 150 mg/l |
|---|---|
| Wet | 240 (60% of the time) |
| Above Normal | 190 (52% of the time) |
| Below Normal | 175 (48% of the time) |
| Dry | 165 (45% of the time) |
| Critical | 155 (42% of the time) |

*Chloride concentrations must be below 150 mg/l for at least two weeks before those days can be counted towards meeting the standard.

CalSim-II and DSM2 results were analyzed to determine compliance with the chloride standards at four municipal and industrial intakes (Figure 5.9) for the base and climate change scenarios:

- CCWD at Old River diversion at Rock Slough (for Contra Costa Canal)
- CCWD at Old River diversion at Highway 4 (for Los Vaqueros)
- SWP at Clifton Court Forebay
- CVP at Tracy

For these studies in both CalSim-II and DSM2, Contra Costa Water District's diversions were all withdrawn from Old River at Rock Slough[2]. This assumption could have local impacts on hydrodynamics and water quality. Although CCWD diversions were not simulated at Old River at Highway 4, water quality results are presented for that location since it is a potential diversion point.

In CalSim-II, the Artificial Neural Network (ANN) that represents Delta water quality provides chloride concentrations at a few Delta locations. The DSM2 simulations for this study determined EC concentrations throughout the Delta. These EC values can be converted to chloride concentrations using regression relationships based on field data (e.g. Suits, 2001 or Freeport, 2003[3]). For the analysis presented in this chapter, the simulated EC concentrations were converted to chlorides using the following equations from Suits (2001):

**Contra Costa Water District Old River Diversion at Rock Slough**

$$Cl = \frac{EC - 89.6}{3.73} \qquad \text{Eqn 5.1}$$

**Old River at Highway 4, SWP at Clifton Court and CVP at Tracy**

$$Cl = \frac{EC - 160.6}{3.66} \qquad \text{Eqn 5.2}$$

where,

Cl = chloride concentration in mg/l

EC = electrical conductivity in uS/cm

#### *5.4.1.1 250 mg/l Chloride Standard*

**Monthly Average Results**

One of the municipal and industrial beneficial use standards in D1641 specifies a maximum daily chloride concentration of 250 mg/l (Table 5.9). CalSim-II simulations attempt to meet this standard at Old River at Rock Slough. Monthly time step CalSim-II simulations represent this standard by setting a monthly average chloride target at Old River at Rock Slough of 225 mg/l. In CalSim-II the monthly average chloride concentrations at Rock Slough are determined by an ANN. CalSim-II tries to operate the system to meet the maximum allowable chloride standard at all time, but that isn't always possible (Table 5.11). For the base case, the 225mg/l chloride

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[2] CalSimII calculates CCWD's combined Old River at Rock Slough (Contra Costa Canal) and Old River at Highway 4 (Los Vaqueros) diversions. For DSM2 studies, these combined diversions are taken from Old River at Rock Slough. In order to represent the two diversions separately, it would be necessary to develop a series of rules to emulate the CCWD operation of those diversions.

[3] Examining long term average chloride concentrations at Old River at Rock Slough using two sets of regression relationships, chloride concentrations from the Suits (2001) regression equation were an average of about 15mg/l higher than chloride concentrations determined from the Freeport (2003) regression equations.

target was met about 92 percent of the time for the DSM2 analysis period of wy1976-wy1991. Times when the target maximum chloride concentration was not met occurred in November to January. For the four climate change scenarios, the percent time for meeting the maximum chloride concentration target was met differed from the base case by less than 2 percent.

**Table 5.11: Percent of Time Monthly Average Chloride Concentration <225mg/l**

| | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| CalSim-II results | 92.2 | 91.1 | 92.2 | 90.1 | 93.8 |
| DSM2 results | 92.7 | 95.3 | 94.8 | 95.8 | 93.8 |

Monthly system operations from CalSim-II are used to run the more detailed Delta model, DSM2. DSM2 runs on a 15-minute time step and includes physically-based descriptions of flow and water quality constituent transport. DSM2 represents the spring-neap tidal cycle and diversions to and return flows from Delta islands. Thus, chloride concentrations simulated by the physically-based model DSM2 can differ from those estimated by the correlation-based ANN in CalSim-II. For studies in this report, average differences in monthly average chloride concentration at Old River at Rock Slough were about 5mg/l lower for the DSM2 simulations than for the ANN results. For comparison purposes, the percent time that the monthly average chloride concentrations at Rock Slough were less than the 225 mg/l target for both CalSim-II and DSM2 results are shown in Table 5.11. Since the DSM2 simulations tend to have slightly lower chloride concentrations that those estimated by the ANN, the monthly average DSM2 simulation results are less than 225 mg/l a bit more frequently than the CalSim-II results.

### Daily Average Results

Daily average EC results from DSM2 for the 16-year simulation period were converted to daily average chloride concentrations using equations 5.1 and 5.2. Exceedance plots for daily average chloride concentrations at Rock Slough are shown in Figure 5.10. Percentiles and average chloride concentrations are shown in Table 5.12. Exceedance plots and percentile tables for other municipal and industrial intake locations are presented in the appendix in section 5.12. The distribution of chloride concentrations is similar for the base case and climate change scenarios at all four municipal and industrial intake locations.

Daily average chloride concentrations based on DSM2 simulation results can be used to examine compliance with the 250 mg/l maximum allowable daily average chloride concentration standard (Table 5.9). Compliance with the maximum daily average chloride concentration standard is given in Table 5.13. Increases in chloride standard compliance for the climate change scenarios relative to the base case are shown in Table 5.14. At Old River at Rock Slough, compliance with the 250 mg/l standard is at least 97 percent for all scenarios. Compliance was reduced in September through February of dry years when freshwater inflows to the Delta are low, which leads to higher salt intrusion from the ocean. Increased winter runoff for the climate change scenarios lead to slight improvements in compliance with the chloride standard at Old River at Rock Slough. There was complete compliance with the 250 mg/l standard for SWP and CVP intakes for all of the scenarios.

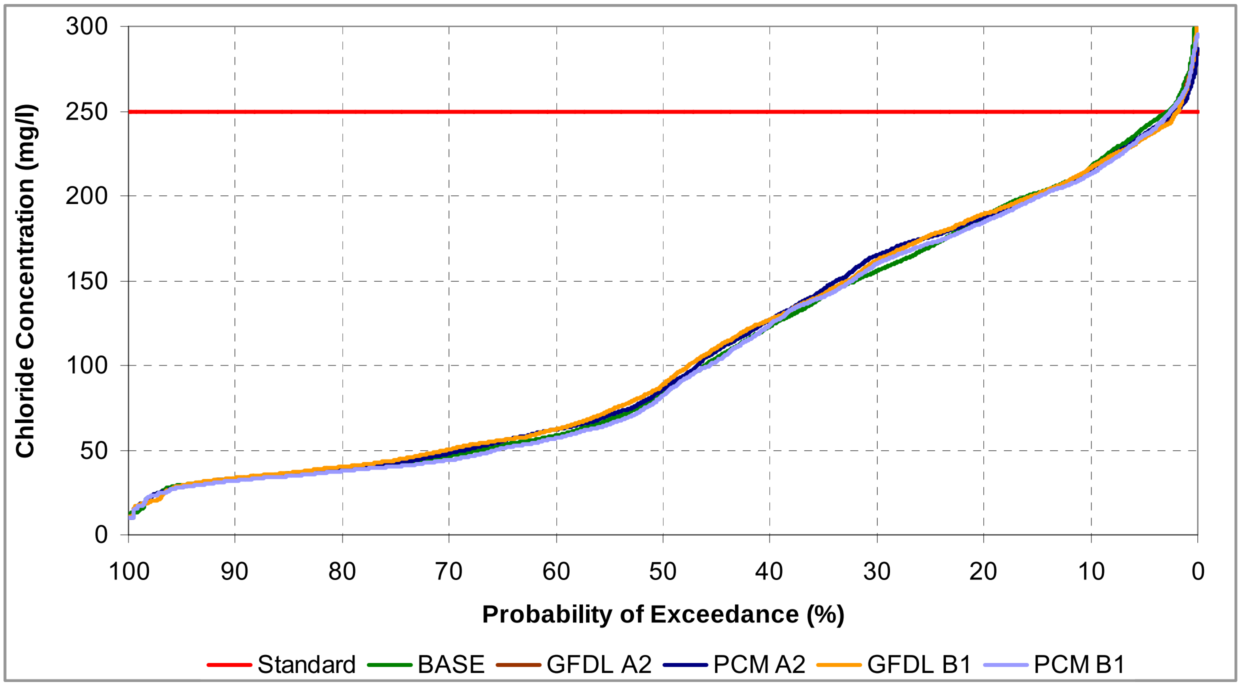


**Figure 5.10: Probability of Exceedance for Chlorides at Old River at Rock Slough**

**Table 5.12: Chloride Concentration Percentiles for Old River at Rock Slough (mg/l)**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 30 | 33 | 42 | 83 | 170 | 217 | 240 | 109 |
| GFDL A2 | 27 | 33 | 43 | 89 | 175 | 217 | 234 | 110 |
| PCM A2 | 29 | 33 | 43 | 86 | 176 | 216 | 236 | 110 |
| GFDL B1 | 29 | 34 | 44 | 89 | 177 | 216 | 234 | 111 |
| PCM B1 | 28 | 32 | 40 | 82 | 172 | 213 | 236 | 107 |

Examining the daily average chloride concentrations from DSM2 resulted in higher compliance values for the 250 mg/l maximum chloride concentration standard at Old River at Rock Slough (Table 5.13) than the estimated compliance from examining the monthly average results from CalSim-II relative to the target monthly average chloride concentration of 225mg/l (Table 5.11). For these studies, the 225 mg/l target monthly average chloride concentration in CalSim-II provides a conservative estimate of compliance with of the daily average 250 mg/l maximum chloride concentration standard.

Although the Contra Costa Water District intake at Old River at Highway 4 is not a D1641 compliance location, chloride concentrations were also examined at that location. At Old River at Highway 4, daily average chloride concentrations were less than 250 mg/l 99.9 percent of the time for the base case and 100 percent of the time for the four climate change scenarios. There was complete compliance with the 250 mg/l chloride standard at the SWP and CVP intakes for all scenarios. These results demonstrate that existing flexibility in the system was able to accommodate changing reservoir inflows due to climate change with only minor impacts to compliance with the 250 mg/l chloride standard.

**Table 5.13: Municipal and Industrial Intake Chloride Standard Compliance**

| Scenario/ Location | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| CCWD-Old River at Rock Sl. | 97.2% | 98.0% | 98.0% | 98.2% | 97.4% |
| CCWD-Old River at Hwy 4* | 99.9% | 100% | 100% | 100% | 100% |
| SWP-Clifton Court | 100% | 100% | 100% | 100% | 100% |
| CVP-Tracy | 100% | 100% | 100% | 100% | 100% |

* Contra Costa Water District's intake at Old River at Highway 4 is not a compliance location for D1641. It is shown for comparison purposes.

**Table 5.14: Change in Municipal and Industrial Intake Chloride Standard Compliance**

| Scenario/ Location | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|
| CCWD-Old River at Rock Sl. | 0.8% | 0.8% | 0.9% | 0.2% |
| CCWD-Old River at Hwy 4* | 0.1% | 0.1% | 0.1% | 0.1% |
| SWP-Clifton Court | 0.0% | 0.0% | 0.0% | 0.0% |
| CVP-Tracy | 0.0% | 0.0% | 0.0% | 0.0% |

* Contra Costa Water District's intake at Old River at Highway 4 is not a compliance location for D1641. It is shown for comparison purposes.

#### *5.4.1.2 150 mg/l Chloride Standard*

At Old River at Rock Slough, another water quality standard states that the daily average chloride concentration should be below 150 mg/l for a specified number of days per calendar year depending on the water year type (Table 5.9 and Table 5.10). This standard also states that chloride concentrations must be below 150mg/l for at least two weeks before those days can be counted towards meeting the standard. Daily average chloride concentrations were computed from DSM2 EC results using equation 5.1. There was complete compliance with this standard for the base case or the two A2 scenarios (Table 5.15). For the two B1 scenarios, compliance with the standard was reduced during a dry year. The values in Table 5.15 reflect the requirement that chloride concentrations be less than 150 mg/l for at least two weeks before those days can be counted toward the standard. For these studies, the compliance pattern does not change for any of the scenarios if all days with chloride concentrations less than 150 mg/l are considered. For the two cases that had non-compliance, the number of days with chloride concentrations less than 150 mg/l with and without the 2 consecutive week requirement is shown in Table 5.16. In most cases, existing system flexibility was able to adjust to climate change while maintaining compliance with the 150 mg/l chloride standard.

**Table 5.15: Old River at Rock Slough 150mg/l Chloride Standard Compliance**
**Number of days that chloride concentrations were below 150 mg/l for at least 2 weeks**

| Year | Yr. Type* | Standard: Min Days Cl≤150 mg/l | Base | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|---|---|
| 1976 | C | 155 | 177 | 168 | 169 | 167 | 178 |
| 1977 | C | 155 | 161 | 190 | 169 | 170 | 158 |
| 1978 | AN | 190 | 247 | 255 | 250 | 259 | 250 |
| 1979 | BN | 175 | 259 | 264 | 239 | 264 | 247 |
| 1980 | AN | 190 | 269 | 265 | 262 | 264 | 262 |
| 1981 | D | 165 | 260 | 275 | 261 | 257 | 261 |
| 1982 | W | 240 | 365 | 365 | 365 | 365 | 365 |
| 1983 | W | 240 | 365 | 365 | 365 | 365 | 365 |
| 1984 | W | 240 | 295 | 306 | 306 | 307 | 296 |
| 1985 | D | 165 | 216 | 211 | 199 | 215 | 223 |
| 1986 | W | 240 | 287 | 252 | 259 | 252 | 258 |
| 1987 | D | 165 | 176 | 196 | 187 | 197 | 217 |
| 1988 | C | 155 | 230 | 236 | 229 | 234 | 245 |
| 1989 | D | 165 | 184 | 169 | 170 | **153** | **139** |
| 1990 | C | 155 | 222 | 195 | 195 | 196 | 210 |

*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical
Gray shading and bold text indicate non-compliance with the standard.

**Table 5.16: Effect of 2 Week Requirement on 150mg/l Chloride Standard Compliance for Two Climate Change Scenarios at Old River at Rock Slough**

| | Year | Yr. Type* | Standard: Min Days Cl≤150 mg/l | Number of Days Cl≤150 mg/l | |
|---|---|---|---|---|---|
| | | | | GFDL B1 | PCM B1 |
| # Days with Cl≤150 mg/l for at least 2 weeks | 1989 | D | 165 | **153** | **139** |
| Total # Days with Cl≤150 mg/l | 1989 | D | 165 | **156** | **155** |

*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical
Gray shading and bold text indicate non-compliance with the standard.
Results are only shown for scenarios that did not comply with the standard (see Table 5.15)

### 5.4.1.3 Chloride Mass Loading Rates

Chloride mass loadings at municipal and industrial intakes were estimated using equation 5.3. The mass loading estimates for CCWD are based on the combined diversion rate for CCWD's Old River diversions at Rock Slough and Highway 4 and the chloride concentrations at Rock Slough (see footnote 2 on page 5-1 for explanation of combined diversions).

$$Cl\ MassLoading\,(metric\,tons/day) = Cl\,(mg/l) * Exports\,(cfs) * \underbrace{2.832x10^{-8}}_{\frac{mg}{l}\ to\ \frac{metric\ tons}{ft3}} * \underbrace{86{,}400}_{\frac{ft^3}{\sec}\ to\ \frac{ft^3}{day}} \qquad \text{Eqn 5.3}$$

Since the export rates at Old River at Rock Slough are the same for all of the scenarios (Table 5.39), the chloride mass loadings are similar for all of the scenarios (Table 5.17). Export rates for the SWP and CVP vary for each scenario (Table 5.37 and Table 5.38). Mass loadings for the SWP and CVP are an order of magnitude higher than those at Rock Slough because the export rates at those locations are also an order of magnitude higher (Table 5.37 and Table 5.38). For the SWP, average chloride mass loadings decrease by 4 percent-9 percent for the climate change scenarios relative to the base case (Table 5.18). For the CVP, the B1 scenarios show little change relative to the base case, while the A2 scenarios have about 5 percent lower chloride mass loadings than the base case (Table 5.19). Reduced chloride mass loadings for the climate change scenarios are due to reduced export rates for those scenarios.

**Table 5.17: Chloride Mass Loading Percentiles (metric tons/day) for Old River at Rock Slough**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 0* | 9 | 19 | 45 | 80 | 115 | 146 | 54 |
| GFDL A2 | 0 | 7 | 20 | 47 | 77 | 119 | 141 | 54 |
| PCM A2 | 0 | 9 | 20 | 47 | 77 | 113 | 145 | 54 |
| GFDL B1 | 0 | 8 | 20 | 47 | 78 | 119 | 140 | 55 |
| PCM B1 | 0 | 9 | 19 | 45 | 77 | 115 | 148 | 54 |

*Zero values reflect times when no diversions were made.

**Table 5.18: Chloride Mass Loading Percentiles (metric tons/day) for State Water Project**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 48 | 80 | 264 | 460 | 1086 | 1763 | 2068 | 711 |
| GFDL A2 | 48 | 73 | 247 | 480 | 923 | 1387 | 1713 | 646 |
| PCM A2 | 48 | 69 | 255 | 451 | 957 | 1560 | 1945 | 667 |
| GFDL B1 | 47 | 71 | 230 | 477 | 951 | 1495 | 1883 | 670 |
| PCM B1 | 47 | 75 | 265 | 459 | 1009 | 1660 | 1954 | 685 |

**Table 5.19: Chloride Mass Loading Percentiles (metric tons/day) for Central Valley Project**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 59 | 146 | 317 | 575 | 1037 | 1325 | 1540 | 686 |
| GFDL A2 | 56 | 145 | 271 | 534 | 1001 | 1260 | 1444 | 648 |
| PCM A2 | 53 | 142 | 314 | 532 | 1074 | 1305 | 1413 | 663 |
| GFDL B1 | 65 | 164 | 340 | 560 | 1050 | 1282 | 1475 | 686 |
| PCM B1 | 51 | 118 | 337 | 582 | 1056 | 1267 | 1491 | 688 |

## 5.5 Sea Level Rise

Historical records show that in the 20th century sea levels rose globally with an average increase ranging from 3.9 in to 7.9 in (IPCC, 2001). Over the past 100 years, sea level at Golden Gate has risen more than 8 inches (Figure 5.11) (Roos, 2004). Sea levels are expected to continue to rise under global warming due to thermal expansion of the ocean and melting of glaciers and polar ice caps. Simulations of future climate change for all of the Intergovernmental Panel on Climate Change's (IPCC's) emissions scenarios show increases in global sea levels ranging from 0.3 feet to 2.9 feet (IPCC, 2001).

For California's water supply, the largest effect of sea level rise (SLR) would likely be in the Sacramento-San Joaquin Delta (DWR, 2005). Rising sea levels would increase pressure on the levees that protect the Delta islands, many of which are below sea level. A one-foot increase in sea level is projected to increase the frequency of a 100-year peak tide to a 10-year event (DWR, 2005). Increased intrusion of salt water from the ocean into the Delta could degrade the quality of the freshwater that is pumped out of the Delta for municipal, industrial and agricultural purposes. This could lead to increased releases of water from upstream reservoirs or reduced pumping from the Delta to maintain compliance with Delta water quality standards. Salt water intrusion could also degrade groundwater aquifers. Additional information on sea level rise can be found in Chapter 2 in section 2.6.

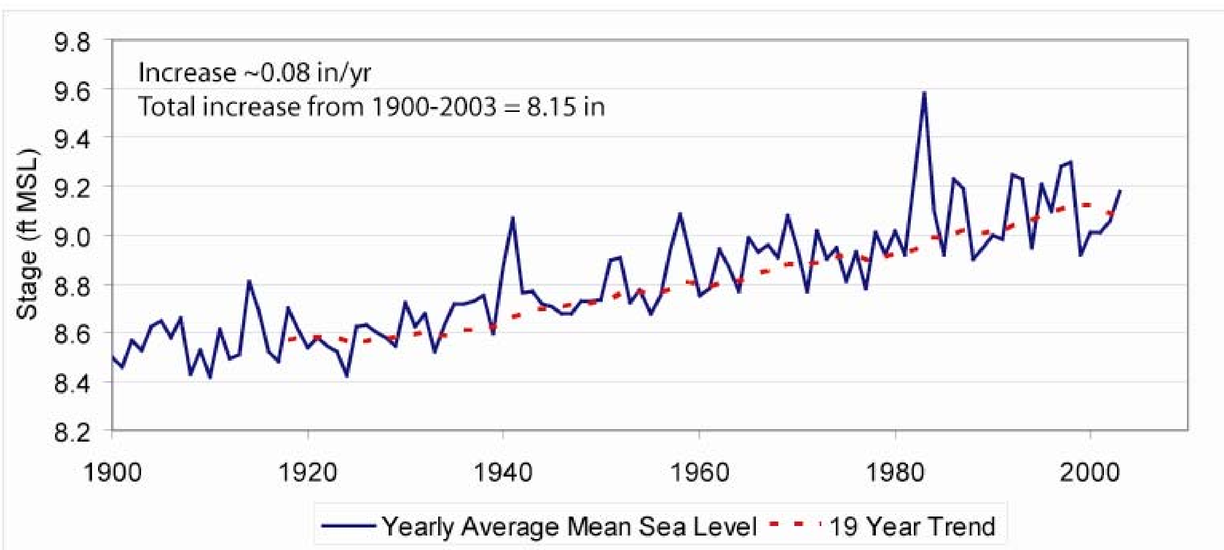


**Figure 5.11 Historical Annual Mean Sea Level at Golden Gate, 1900-2003**

### 5.5.1 Analysis Approach

In order to do a complete analysis of potential sea level rise impacts on the Delta, both increased salt intrusion and changes in system operations such as reservoir releases and Delta exports would need to be examined. Currently an analysis tool is not available to determine changes in system operations required to lessen the effects of increased salt intrusion due to sea level rise. However, existing tools can be used to quantify potential salt intrusion into the Delta for sea level rise with present system operations. The results of such studies improve understanding of the salinity transport in the Delta and provide an important starting point for the development of tools and analysis techniques for determining changes in system operations to maintain compliance with Delta water quality standards for sea level rise conditions. In this report water quality concentrations for a one-foot sea level rise without changes in system operations are compared to water quality standards. This information is presented as a surrogate for evaluating the effects of sea level rise on water project operations to meet existing standards.

This report provides preliminary assessments of potential impacts of sea level rise on Delta water quality and on levee overtopping potential assuming present system operations. Additional information on possible effects of sea level rise on the Delta, such as increasing the risk of levee failures, is presented in Chapter 2 in section 2.6. These studies are a first step in developing a more complete sea level rise analysis approach. All results are preliminary and are intended to illustrate the use of DSM2 for sea level rise analysis.

Preliminary modeling studies were conducted to assess potential effects of a one-foot rise in sea level on the Delta. DSM2 simulations were run for

- ❑ Present sea level with base case system operations (see section 5.4)
- ❑ Present sea level with system operations modified for climate change (see sections 5.4)
- ❑ One-foot sea level rise with base case system operations (see sections 5.5.2 and 5.5.4)
- ❑ One-foot sea level rise with system operations modified for climate change (see sections 5.5.3 and 5.5.4)

For all of the sea level rise scenarios, the tidal stage (water level) was increased uniformly by one-foot at the DSM2 downstream boundary at Martinez. This assumes that sea level rise does not change the tidal period or amplitude. Representation of Martinez EC for the sea level rise simulations is described in section 5.5.1.1. All other Delta inflows, exports and water quality boundary conditions were identical to the present sea level simulations (see sections 5.3 and 5.11). No operational changes were made to lessen potential effects of sea level rise.

Water quality analysis for the sea level rise scenarios focused on the comparisons of simulated constituent concentrations compared to standard thresholds for the municipal and industrial intakes (Table 5.9). These results are a demonstration of a preliminary application of DSM2 to access water quality changes for a one foot rise in sea level. The results do not reflect operations changes to try to reduce the effects of salt water intrusion from sea level rise, and therefore the results by themselves are not sufficient for making management decisions.

#### 5.5.1.1 Martinez Salinity for Sea Level Rise Scenarios

One area of uncertainty in modeling sea level rise conditions with DSM2 is the representation of salt water intrusion at Martinez, the downstream boundary for DSM2. For this report, two assumptions were used for estimating salinity at Martinez for a one-foot sea level rise (Anderson and Miller, 2005):

- Assume Martinez EC is the same as in the present sea level scenarios
- Increase Martinez EC based on a regression relationship (equation 5.4)

Comparing results for DSM2 studies using each of these assumptions for Martinez EC provides a range of potential effects of a one-foot rise in sea level.

**Assume Martinez EC Does Not Change**

The first method used to estimate Martinez EC for a one-foot rise in sea level was to assume that the EC is the same as in the present sea level scenario. This provides a lower-bound estimate of salt water intrusion into the Delta for a one-foot increase in sea level.

**Assume Martinez EC Increases**

The second method used to estimate Martinez EC for a one-foot rise in sea level was to use a preliminary regression relationship based on the Martinez EC for present sea level conditions (Anderson and Miller, 2005):

$$MartinezEC_{1\,ft\,SLR} = 1.0022 * MartinezEC_{\Pr esent\,Sea\,Level} + 840.87 \qquad \text{Eqn. 5-4}$$

This regression relationship was based on results from a preliminary one year (calendar year 1992) multi-dimensional modeling study using models from Resource Management Associates (RMA). Since the effects of sea level rise on EC at the DSM2 downstream boundary at Martinez had not been quantified, a multi-dimensional modeling study was done to represent flows and salt water intrusion from Golden Gate into the Delta for a one-foot sea level rise (Figure 5.12). Results from the RMA modeling studies at Martinez for base and one-foot sea level rise conditions were used to develop the regression relationship shown in equation 5-4 (Figure 5.13). This regression relationship can be used to estimate Martinez EC for a one-foot sea level rise for DSM2 simulations.

Equation 5-4 is only applicable for a one-foot rise in sea level. Since this relationship is linear with a coefficient of nearly 1 (1.0022), equation 5-4 indicates that a one-foot rise in sea level at Golden Gate corresponds to an approximate increase in EC at Martinez of 840 uS/cm. Therefore use of this regression equation to estimate the Martinez EC for a one-foot rise in sea level will provide a higher estimate of salt water intrusion than using the assumption that the Martinez EC does not change. An increase in EC of 840 uS/cm is relatively small during time periods when Martinez EC is high (20,000-35,000 uS/cm) and freshwater inflows are low and salt water intrusion is of most concern, typically during the summer and early fall.

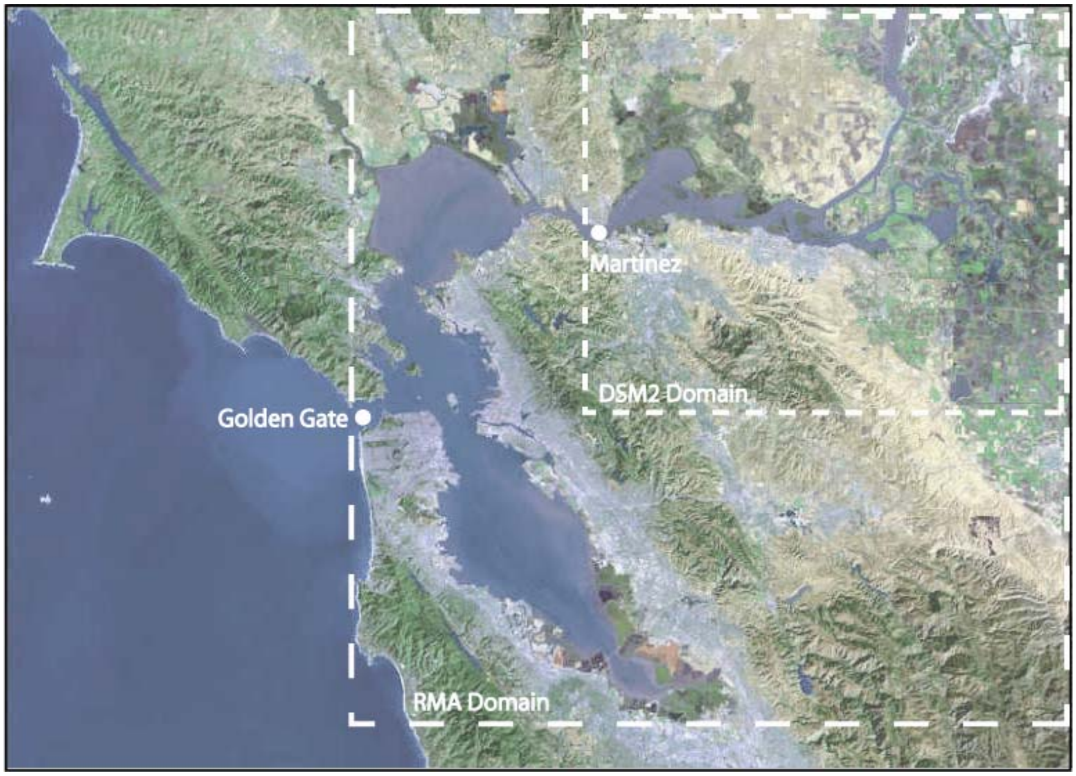


**Figure 5.12 Modeling Domains for RMA and DSM2**
Satellite image from USGS. (Anderson and Miller, 2005)

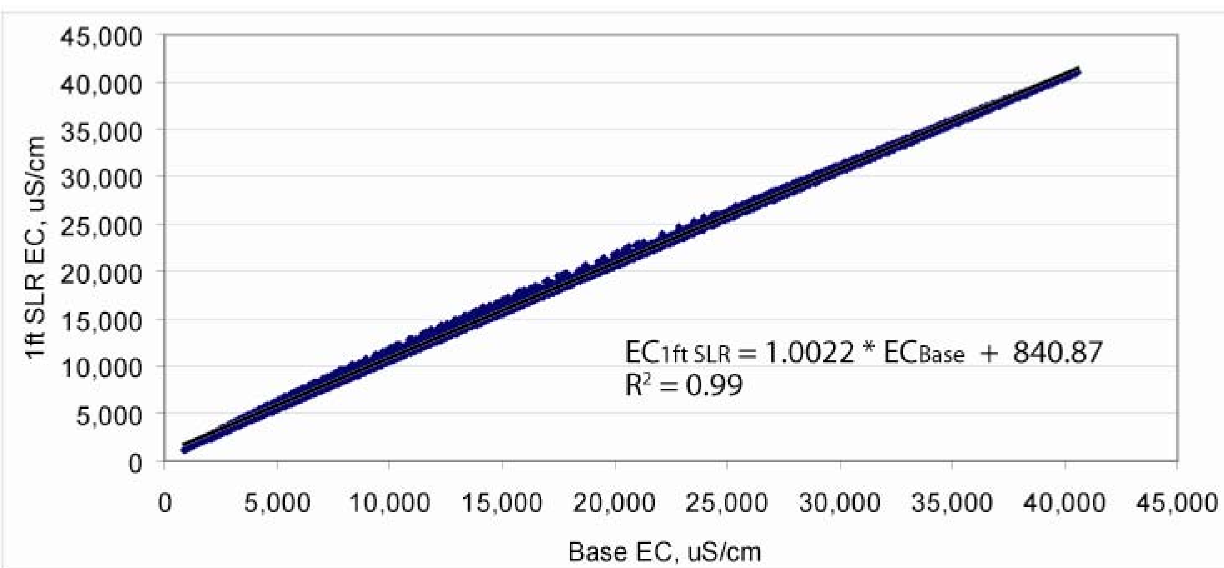


**Figure 5.13: Regression Relationship for EC at Martinez for a One-Foot Sea Level Rise.**
(Anderson and Miller, 2005)

The RMA modeling study from which the regression relationship in equation 5-4 was developed was a preliminary study that included the following assumptions:

- Historical tidal stage at Golden Gate was increased uniformly by one-foot,
- Ocean salinity is not affected by sea level rise [the same EC boundary condition of a constant ocean salinity was applied for both the base and 1ft SLR scenarios],
- Historical Delta inflows and exports were not modified to mitigate for salt water intrusion due to sea level rise [historical Delta inflows and exports were used for both the base and 1ft SLR scenarios],
- Agricultural return flows do not significantly affect EC at Martinez [Delta island diversions and return flows were not simulated],
- Temporary agricultural and fish barriers in the South Delta were not simulated, and
- Historical Delta inflows and exports for 1992 provide adequate ranges of flows and EC to develop an EC relationship at Martinez for one-foot sea level rise conditions that can be applied for any time period.

### 5.5.2 Sea Level Rise Effects on Delta Water Quality

Potential effects of a one-foot rise in sea level on Delta water quality were examined for DSM2 results using two different assumptions regarding Martinez EC (see section 5.5.1.1)

- Assume Martinez EC is the same as in the present sea level scenarios
- Assume that Martinez EC increases for a one-foot sea level rise

These results are a preliminary demonstration of the use of DSM2 to estimate a range of impacts given uncertainties in quantifying how much salt would be transported into the Delta under sea level rise with no modifications to system operations to try to reduce the salt water intrusion. Several assumptions that are involved in these studies are described in sections 5.2.3 and 5.5.1.1. Since available methodologies didn't allow consideration of changes to system operations for sea level rise scenarios, simulated constituent concentrations are compared with threshold values for selected water quality standards as a surrogate for evaluating the effects of sea level rise on water project operations to meet existing standards.

Daily average EC results from DSM2 for the 16-year simulation period were converted to daily average chloride concentrations using equations 5.1 and 5.2. Exceedance plots for daily average chloride concentrations at Rock Slough are shown in Figure 5.14. Percentiles and average chloride concentrations are shown in Table 5.20. Exceedance plots and percentile tables for other municipal and industrial intake locations are presented in the appendix in section 5.13. The sea level rise scenarios show an average increase in chloride concentrations of 15-20mg/l compared to the base case. Differences between the two sea level rise scenarios are typically 5-10mg/l. This indicates that raising the water levels at Martinez has more of an impact on chloride concentrations at Old River at Rock Slough than raising the Martinez salt concentrations. For the SWP and CVP, the average increase in chloride concentrations was about 10 mg/l (see section 5.13). Differences between the two sea level rise scenarios were less than 2mg/l.

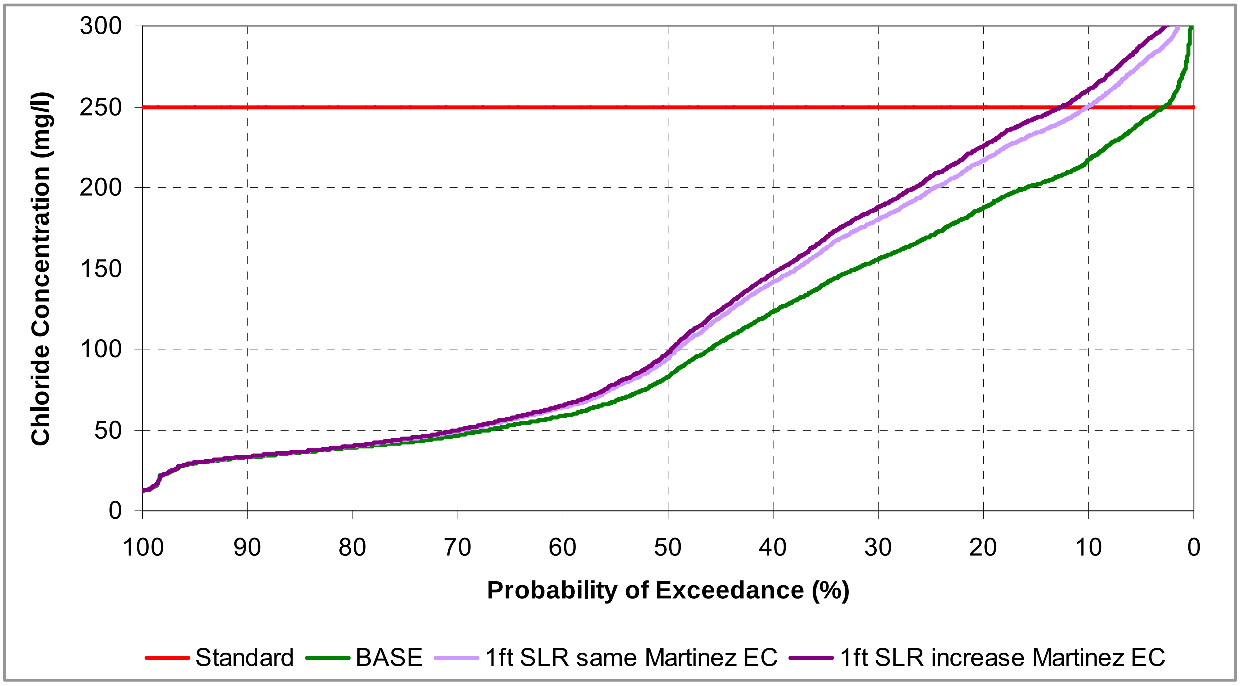


**Figure 5.14: Probability of Exceedance for Chlorides at Old R. at Rock Sl. for a One-Foot Sea Level Rise and no Changes in System Operations**

**Table 5.20: Chloride Concentration Percentiles (mg/l) for Old R. at Rock Sl. for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 30 | 33 | 42 | 83 | 170 | 217 | 240 | 109 |
| 1ft SLR same Martinez EC | 30 | 33 | 44 | 94 | 199 | 250 | 276 | 123 |
| 1ft SLR increase Martinez EC | 30 | 34 | 45 | 98 | 207 | 261 | 288 | 128 |

#### *5.5.2.1 250 mg/l Chloride Threshold for Sea Level Rise Scenarios*

Daily average chloride concentrations based on DSM2 simulation results for the two sea level rise scenarios without any changes in system operations were compared with the 250 mg/l maximum allowable daily average chloride concentration threshold (Table 5.9). The frequency that chloride concentrations were below the 250 mg/l threshold is presented in Table 5.21. Changes in the frequency that concentrations were below the threshold for sea level rise relative to the base case are shown in Table 5.22. For the base case, chloride concentrations are below the 250 mg/l chloride threshold at Old River at Rock Slough about 97 percent of the time. For the two sea level rise scenarios, chloride concentrations are below the threshold value at Old River at Rock Slough 88 percent to 90 percent of the time. For the scenario that assumes an increase in EC at Martinez the threshold value is exceeded about 2.5 percent more often than for the scenario that assumes that the EC at Martinez does not change. Chloride concentrations rarely exceeded 250mg/l at Old River at Highway 4 for both the base and the sea level rise scenarios. The 250 mg/l threshold was never exceeded at both the SWP and CVP for the base case and sea level rise scenarios.

**Table 5.21: Frequency that Chloride Concentrations were below the 250 mg/l Threshold for a One-Foot Sea Level Rise and no Changes in System Operations**

| Scenario/ Location | BASE | 1ft Sea Level Rise same Martinez EC | 1ft Sea Level Rise increase Martinez EC |
|---|---|---|---|
| CCWD-Old River at Rock Sl. | 97.2% | 89.9% | 87.5% |
| CCWD-Old River at Hwy 4 | 99.9% | 99.7% | 99.4% |
| SWP-Clifton Court | 100% | 100% | 100% |
| CVP-Tracy | 100% | 100% | 100% |

**Table 5.22: Change in Frequency that Chloride Concentrations were below the 250mg/l Threshold for a One-Foot Sea Level Rise and no Changes in System Operations Compared to the Base Case**

| Scenario/ Location | 1ft Sea Level Rise same Martinez EC | 1ft Sea Level Rise increase Martinez EC |
|---|---|---|
| CCWD-Old River at Rock Sl. | -7.3% | -9.8% |
| CCWD-Old River at Hwy 4 | -0.2% | -0.5% |
| SWP-Clifton Court | 0% | 0% |
| CVP-Tracy | 0% | 0% |

### *5.5.2.2 150 mg/l Chloride Threshold for Sea Level Rise Scenarios*

For the two sea level rise scenarios with no changes in system operations, daily average chloride concentrations were computed from DSM2 EC results using equation 5.1, and the results were compared to the 150 mg/l threshold (Table 5.9 and Table 5.10). There was complete compliance with the 150 mg/l standard in the base case (Table 5.23). For the sea level rise scenario that assumed no change in Martinez EC, the 150 mg/l threshold was exceeded in the critically dry years of 1976 and 1977. For the sea level rise scenario that assumed an increase in Martinez EC, the 150 mg/l threshold was exceeded in 1976, 1977, and 1989, a dry year. In most cases, existing operations lead to chloride concentrations below the 150 mg/l threshold, even under sea level rise conditions.

**Table 5.23: Comparison of Chloride Concentrations to the 150 mg/l Threshold at Old River at Rock Sl. for a One-Foot Sea Level Rise and no Changes in System Operations Number of days with chloride concentrations below 150 mg/l**

| Year | Yr. Type* | Min Days Cl≤150 mg/l | Base | 1ft SLR same Martinez EC | 1ft SLR increase Martinez EC |
|---|---|---|---|---|---|
| 1976 | C | 155 | 177 | **126** | **118** |
| 1977 | C | 155 | 161 | **102** | **94** |
| 1978 | AN | 190 | 247 | 240 | 237 |
| 1979 | BN | 175 | 259 | 226 | 223 |
| 1980 | AN | 190 | 269 | 263 | 261 |
| 1981 | D | 165 | 260 | 232 | 217 |
| 1982 | W | 240 | 365 | 365 | 365 |
| 1983 | W | 240 | 365 | 365 | 365 |
| 1984 | W | 240 | 295 | 289 | 288 |
| 1985 | D | 165 | 216 | 198 | 197 |
| 1986 | W | 240 | 287 | 265 | 257 |
| 1987 | D | 165 | 176 | 168 | 165 |
| 1988 | C | 155 | 230 | 209 | 206 |
| 1989 | D | 165 | 184 | 166 | **162** |
| 1990 | C | 155 | 222 | 181 | 176 |

*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical
Gray shading and bold text indicate values that exceeded the threshold.

### *5.5.2.3 Chloride Mass Loading for Sea Level Rise Scenarios*

Chloride mass loadings at municipal and industrial intakes were estimated based on chloride concentrations and export rates (equation 5.3). The mass loading estimates for CCWD are based on the combined diversion rate for CCWD's Old River diversions at Rock Slough and Highway 4 and the chloride concentrations at Rock Slough (see footnote 2 on page 5-1 for explanation of combined diversions). Since operations were not changed to try to lessen the effects of sea level rise, the export rates for each intake were the same for the base and sea level rise scenarios. Thus differences in mass loading rates are due only to differences in chloride concentrations.

For all intake locations, sea level rise increased the average chloride mass loadings by 13 percent-17 percent for Old River at Rock Slough, by 11 percent-14 percent for the SWP and by 7 percent-9 percent for the CVP. These ranges reflect the two sea level rise assumptions of no change in Martinez EC and increasing Martinez EC. The sea level rise scenarios increased the chloride mass loadings, and the climate change scenarios decreased them (see section 5.4.1.3). The combined affects of sea level rise and climate change are presented in section (5.5.3.3).

**Table 5.24: Chloride Mass Loading Percentiles (metric tons/day) for Old River at Rock Slough for a One-Foot Sea Level Rise with no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 0 | 9 | 19 | 45 | 80 | 115 | 146 | 54 |
| 1ft SLR same Martinez EC | 0 | 9 | 20 | 50 | 92 | 132 | 165 | 61 |
| 1 ft SLR increase Martinez EC | 0 | 9 | 20 | 51 | 96 | 138 | 172 | 63 |

**Table 5.25: Chloride Mass Loading Percentiles (metric tons/day) for State Water Project for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 48 | 80 | 264 | 460 | 1086 | 1763 | 2068 | 711 |
| 1ft SLR same Martinez EC | 49 | 84 | 267 | 514 | 1202 | 1925 | 2299 | 786 |
| 1 ft SLR increase Martinez EC | 50 | 86 | 270 | 527 | 1238 | 2014 | 2394 | 812 |

**Table 5.26: Chloride Mass Loading Percentiles (metric tons/day) for Central Valley Project for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 59 | 146 | 317 | 575 | 1037 | 1325 | 1540 | 686 |
| 1ft SLR same Martinez EC | 58 | 147 | 328 | 611 | 1140 | 1433 | 1648 | 734 |
| 1 ft SLR increase Martinez EC | 58 | 147 | 331 | 618 | 1163 | 1461 | 1696 | 749 |

### 5.5.3 Combined Climate Change and Sea Level Rise Effects on Delta Water Quality

Potential effects of a one-foot rise in sea level coupled with shifting precipitation and runoff patterns from climate change were examined. The results are preliminary and reflect several assumptions (see section 5.2.3) including:

- Martinez EC is the same as in the present sea level scenarios. Due to time constraints for this report, combined sea level rise and climate change scenarios were not run for the increased Martinez EC sea level rise scenario.
- System operations were only modified to reflect the changing precipitation and runoff patterns due to climate change. System operations were not modified to account for sea level rise.

For the combined sea level rise and climate change scenarios, daily average EC results from DSM2 for the 16-year simulation period were converted to daily average chloride concentrations using equations 5.1 and 5.2. Exceedance plots for daily average chloride concentrations at Rock Slough for the combined climate change and one-foot sea level rise scenarios with no changes to system operations for sea level rise are shown in Figure 5.15. Percentiles and average chloride concentrations are shown in Table 5.27. Exceedance plots and percentile tables for other municipal and industrial intake locations are presented in the appendix in section 5.14. For the combined climate change and sea level rise scenarios, average increases in chloride concentrations range from13-17mg/l compared to the base case. For the SWP and CVP, the average increase in chloride concentrations for the combined climate change and sea level rise scenarios was about 10 mg/l (see section 5.14).For all of these intakes, the increases in chloride concentrations are similar to increases due to sea level rise alone.

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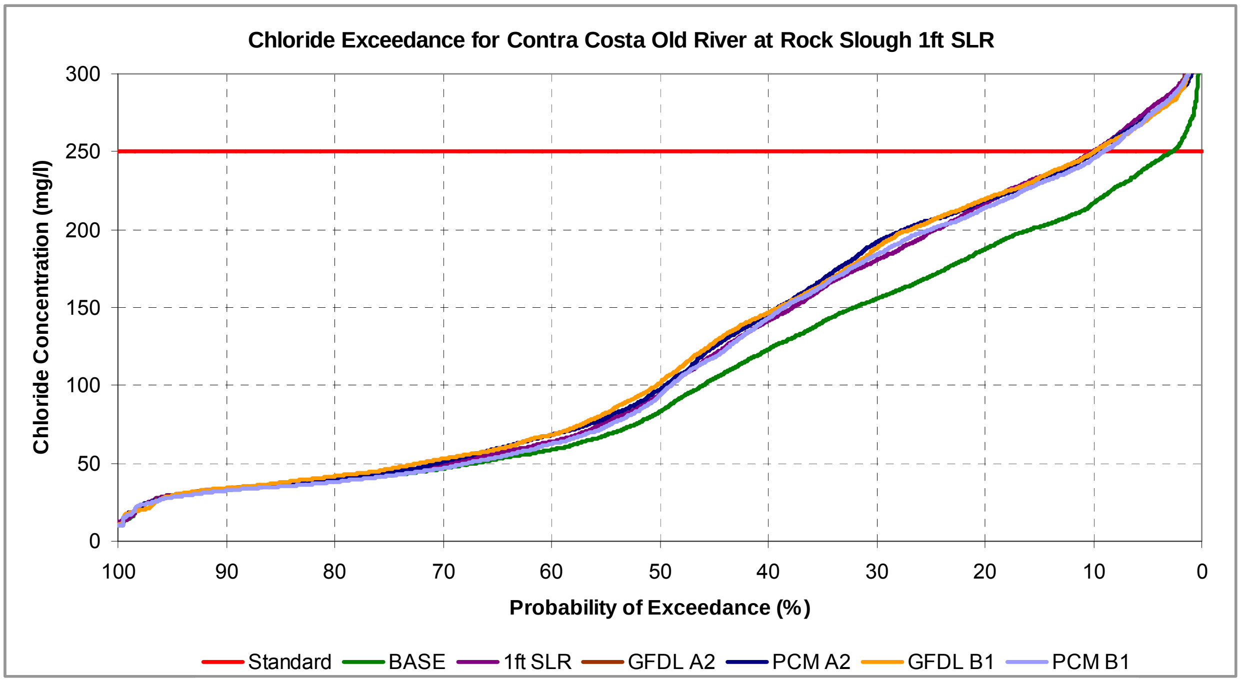


**Figure 5.15: Probability of Exceedance for Chlorides at Old River at Rock Slough for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR**

**Table 5.27: Chloride Concentration Percentiles (mg/l) for Old R. at Rock Sl. for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 30 | 33 | 42 | 83 | 170 | 217 | 240 | 109 |
| 1ft SLR same Mtz EC | 30 | 33 | 44 | 94 | 199 | 250 | 276 | 123 |
| GFDL A2 1ft SLR | 27 | 33 | 45 | 102 | 205 | 251 | 272 | 125 |
| PCM A2 1ft SLR | 29 | 34 | 44 | 97 | 206 | 249 | 273 | 125 |
| GFDL B1 1ft SLR | 29 | 34 | 46 | 102 | 205 | 250 | 271 | 126 |
| PCM B1 1ft SLR | 28 | 33 | 42 | 94 | 200 | 245 | 272 | 122 |

*All sea level rise scenarios in this table assume that Martinez EC is the same as in the present sea level scenarios.

### *5.5.3.1 250 mg/l Chloride Threshold for Combined Sea Level Rise and Climate Change Scenarios*

For the combined climate change and sea level rise scenarios with no additional changes to system operations for sea level rise, daily average chloride concentrations based on DSM2 simulation results were compared to the 250 mg/l daily average chloride concentration threshold

(Table 5.9). The frequency that chloride concentrations were below the 250 mg/l threshold is given in Table 5.28. Changes in the frequency that chloride concentrations were below the threshold relative to the base case are shown in Table 5.29. For the base case, the 250 mg/l chloride standard is met at Old River at Rock Slough about 97 percent of the time. For the combined climate change and one-foot sea level rise scenarios with no changes in system operations for sea level rise, chloride concentrations at Old River at Rock Slough were less than the threshold value about 90 percent of the time. This result is similar to the sea level rise only scenario (Table 5.21). Chloride concentrations rarely exceeded 250mg/l threshold at Old River at Highway 4 for all scenarios. Chloride concentrations never exceeded the 250 mg/l threshold at both the SWP and CVP for the base and combined climate change and sea level rise scenarios.

**Table 5.28: Frequency that Chloride Concentrations were below the 250 mg/l Threshold for Climate Change and a 1-ft Sea Level Rise with no Changes to Operations for SLR**

| Scenario/ Location | BASE | 1ft SLR | GFDL A2 1ft SLR | PCM A2 1ft SLR | GFDL B1 1ft SLR | PCM B1 1ft SLR |
|---|---|---|---|---|---|---|
| Contra Costa-Old R. at Rock Sl. | 97.2% | 89.9% | 89.6% | 90.3% | 90.1% | 90.9% |
| Contra Costa-Old R at Hwy 4 | 99.9% | 99.7% | 100.0% | 100.0% | 99.8% | 99.8% |
| SWP-Clifton Court | 100% | 100% | 100% | 100% | 100% | 100% |
| CVP-Tracy | 100% | 100% | 100% | 100% | 100% | 100% |

*Note that all sea level rise scenarios shown in this table assume that Martinez EC is the same as in the present sea level scenarios.

**Table 5.29: Change in Frequency that Chloride Concentrations were below the 250mg/l Threshold for Climate Change and a 1ft Sea Level Rise with no Changes to Operations for Sea Level Rise Compared to the Base Case**

| Scenario/ Location | 1ft SLR | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Contra Costa-Old River at Rock Sl. | -7.3% | -7.7% | -6.9% | -7.2% | -6.3% |
| Contra Costa-Old River at Hwy 4 | -0.2% | 0.1% | 0.1% | -0.1% | -0.1% |
| SWP-Clifton Court | 0% | 0% | 0% | 0% | 0% |
| CVP-Tracy | 0% | 0% | 0% | 0% | 0% |

*Note that all sea level rise scenarios shown in this table assume that Martinez EC is the same as in the present sea level scenarios.

### *5.5.3.2 150 mg/l Chloride Threshold for Combined Sea Level Rise and Climate Change Scenarios*

For the combined climate change and sea level rise scenarios with no additional changes in system operations for sea level rise, daily average chloride concentrations were computed from DSM2 EC results using equation 5.1, and the results were compared to the 150 mg/l chloride threshold (Table 5.9 and Table 5.10). The 150 mg/l threshold was never exceeded in the base case (Table 5.30). For the combined climate change and one-foot sea level rise scenarios with no changes in system operations for sea level rise, the threshold value was exceeded in the critically dry years of 1976 and 1977, and for some of the scenarios in 1989. In most cases, existing operations maintained compliance with the 150 mg/l chloride standard, even under combined climate change and sea level rise conditions.

**Table 5.30: Comparison of Chloride Concentrations to the 150 mg/l Threshold at Old R. at Rock Sl. for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR Number of Days that Chloride Concentrations were Below 150 mg/l**

| Year | Yr. Type* | Min Days Cl≤150 mg/l | Base | 1ft SLR | GFDL A2 1ft SLR | PCM A2 1ft SLR | GFDL B1 1ft SLR | PCM B1 1ft SLR |
|---|---|---|---|---|---|---|---|---|
| 1976 | C | 155 | 177 | **126** | **112** | **113** | **112** | **129** |
| 1977 | C | 155 | 161 | **102** | **107** | **105** | **113** | **107** |
| 1978 | AN | 190 | 247 | 240 | 248 | 245 | 238 | 245 |
| 1979 | BN | 175 | 259 | 226 | 231 | 233 | 230 | 240 |
| 1980 | AN | 190 | 269 | 263 | 258 | 256 | 255 | 255 |
| 1981 | D | 165 | 260 | 232 | 240 | 229 | 239 | 241 |
| 1982 | W | 240 | 365 | 365 | 343 | 365 | 341 | 365 |
| 1983 | W | 240 | 365 | 365 | 365 | 365 | 365 | 365 |
| 1984 | W | 240 | 295 | 289 | 299 | 301 | 301 | 291 |
| 1985 | D | 165 | 216 | 198 | 201 | 198 | 198 | 195 |
| 1986 | W | 240 | 287 | 265 | 242 | 250 | 242 | 246 |
| 1987 | D | 165 | 176 | 168 | 180 | 172 | 178 | 181 |
| 1988 | C | 155 | 230 | 209 | 211 | 207 | 209 | 224 |
| 1989 | D | 165 | 184 | 166 | **152** | 165 | **142** | **137** |
| 1990 | C | 155 | 222 | 181 | 182 | 162 | 183 | 162 |

*Sac 40-30-30 water year types: W=Wet, AN=Above Normal, BN=Below Normal, D=Dry, C=Critical
Gray shading and bold text indicate values that exceed the threshold.
All sea level rise scenarios assume that Martinez EC is the same as in the present sea level scenarios.

#### *5.5.3.3 Chloride Mass Loading for Combined Sea Level Rise and Climate Change Scenarios*

Chloride mass loadings at municipal and industrial intakes were estimated based on chloride concentrations and export rates (equation 5.3). The mass loading estimates for CCWD are based on the combined diversion rate for CCWD's Old River diversions at Rock Slough and Highway 4 and the chloride concentrations at Rock Slough (see footnote 2 on page 5-1 for explanation of combined diversions). Diversion rates for CCWD were identical for all scenarios. SWP and CVP operations were changed to reflect shifts in precipitation and runoff due to climate change, but they were not changed to try to lessen the effects of sea level rise.

For all intake locations, sea level rise increased the average chloride mass loadings by about 15 percent for Old River at Rock Slough, by 5 percent for the SWP and by 3 percent-7 percent for the CVP. For Old River at Rock Slough and for the Central Valley Project B1 scenarios, the mass loadings are similar to the sea level rise only scenario. For the SWP and for the CVP A2 scenarios, reduced exports for the climate change scenarios lead to lower mass loadings than in the sea level rise only scenario. This demonstrates that shifts in system operations due to changes in runoff patterns can lessen the effects of sea level rise at the intakes that are further away from the ocean.

**Table 5.31: Chloride Mass Loading Percentiles (metric tons/day) for Old River at Rock Sl. for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 0 | 9 | 19 | 45 | 80 | 115 | 146 | 54 |
| 1ft SLR same Martinez EC | 0 | 9 | 20 | 50 | 92 | 132 | 165 | 61 |
| GFDL A2 1ft SLR same Mtz EC | 0 | 7 | 21 | 53 | 92 | 137 | 163 | 62 |
| PCM A2 1ft SLR same Mtz EC | 0 | 9 | 22 | 53 | 90 | 129 | 163 | 62 |
| GFDL B1 1ft SLR same Mtz EC | 0 | 8 | 22 | 54 | 90 | 136 | 157 | 63 |
| PCM B1 1ft SLR same Mtz EC | 0 | 9 | 20 | 48 | 91 | 131 | 167 | 61 |

Note: Export rates were identical for all scenarios.

**Table 5.32: Chloride Mass Loading Percentiles (metric tons/day) for the State Water Project for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 48 | 80 | 264 | 460 | 1086 | 1763 | 2068 | 711 |
| 1ft SLR same Martinez EC | 49 | 84 | 267 | 514 | 1202 | 1925 | 2299 | 786 |
| GFDL A2 same Mtz EC | 51 | 74 | 245 | 530 | 1026 | 1536 | 1959 | 718 |
| PCM A2 same Mtz EC | 51 | 70 | 251 | 498 | 1075 | 1802 | 2188 | 740 |
| GFDL B1 same Mtz EC | 49 | 73 | 254 | 516 | 1091 | 1749 | 2118 | 744 |
| PCM B1 same Mtz EC | 48 | 76 | 262 | 521 | 1152 | 1922 | 2226 | 758 |

Note: Export rates were modified for climate change, but not for sea level rise.

**Table 5.33: Chloride Mass Loading Percentiles (metric tons/day) for the Central Valley Project for Climate Change and a One-Foot Sea Level Rise with no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| Base | 59 | 146 | 317 | 575 | 1037 | 1325 | 1540 | 686 |
| 1ft SLR same Martinez EC | 58 | 147 | 328 | 611 | 1140 | 1433 | 1648 | 734 |
| GFDL A2 same Mtz EC | 55 | 143 | 275 | 563 | 1099 | 1360 | 1576 | 695 |
| PCM A2 same Mtz EC | 53 | 141 | 320 | 569 | 1168 | 1408 | 1549 | 710 |
| GFDL B1 same Mtz EC | 65 | 175 | 346 | 586 | 1141 | 1394 | 1625 | 735 |
| PCM B1 same Mtz EC | 51 | 121 | 350 | 613 | 1160 | 1401 | 1635 | 736 |

Note: Export rates were modified for climate change, but not for sea level rise.

### 5.5.4 Sea Level Rise Effects on Potential to Overtop Delta Levees

This study examined potential effects of a one-foot increase in sea level on the potential to overtop levees on three islands in the western Delta, Sherman Island, Twitchell Island, and Jersey Island. These are the Delta islands closest to the ocean, and so they are most vulnerable to potential overtopping due to sea level rise. The lowest crest elevations on levees on those islands are shown in Figure 5.16. Simulated water levels for present sea level and one-foot sea level rise scenarios were compared to these low-crest elevations to determine potential overtopping (Table 5.34). For the purpose of this analysis, potential overtopping was defined as any time the daily maximum water level in the channel exceeded the minimum crest elevation on the levee. Actual levee overtopping and effects of wind-induced waves were not simulated. Results are preliminary and are presented for illustrative purposes only.

Results for the present sea level scenarios indicated that water levels were never high enough to potentially overtop the study levees, even when Delta inflows were modified by climate change. For all of the one-foot sea level rise scenarios, there were two potential levee overtoppings during the 16-year simulation when simulated water levels exceeded the minimum levee crest elevations. For both the base and climate change sea level rise scenarios, the potential overtoppings occurred at the same time and affected all five study locations. Actual overtopping events and their effects on water levels and water quality were not simulated.

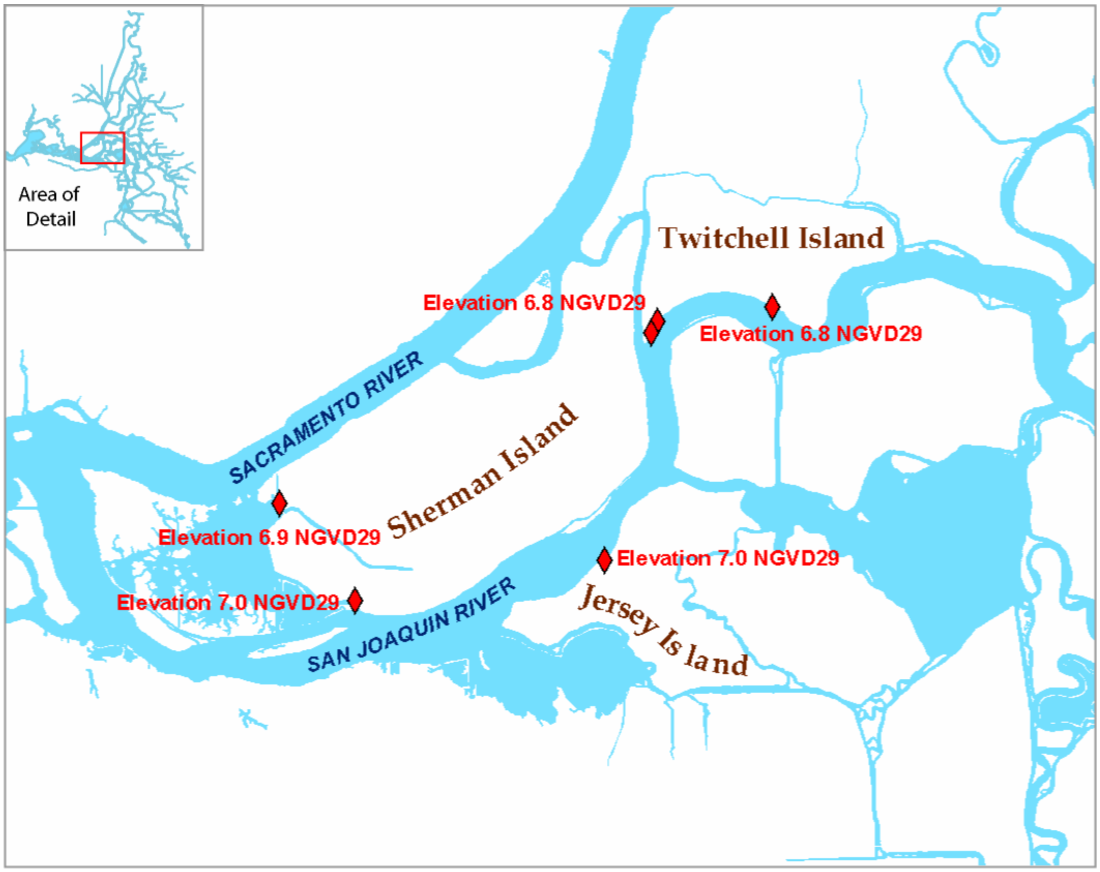


**Figure 5.16: Locations of Lowest Levee Elevation on Three Delta Islands**

**Table 5.34: Summary of Levee Overtopping Events for Sea Level Rise Scenarios**

| Location | Min Crest Elevation, ft | Number of Potential Overtopping Events in 16 yrs | | | |
|---|---|---|---|---|---|
| | | Base | 4 Climate Change Scenarios | 1 ft SLR | 4 Climate Change Scenarios 1ft SLR |
| NW Sherman Island | 6.9 | 0 | 0 | 2 | 2 |
| SW Sherman Island | 7.0 | 0 | 0 | 2 | 2 |
| SW Twitchell Island | 6.8 | 0 | 0 | 2 | 2 |
| SE Twitchell Island | 6.8 | 0 | 0 | 2 | 2 |
| W Jersey Island | 7.0 | 0 | 0 | 2 | 2 |

These results indicate that for the scenarios examined, sea level rise is more likely to increase the potential to overtop the study levees than changes in Delta inflows due to climate change. However, this analysis does not provide insight into potential changes in frequency of extreme events due to climate change. Since these climate change studies use perturbation ratios to modify historically-based reservoir inflows (see Chapter 4), the climate change scenarios preserve the historical hydrologic variability and do not reflect any potential changes in the frequency of extreme events. Thus for the combined sea level rise and climate change scenarios, the potential levee overtoppings occurred at the same time during periods as the sea level rise only scenario. All of the potential overtoppings corresponded to periods with historically high water levels. Levees in other parts of the Delta may be more vulnerable to overtopping due to shifts in reservoir release patterns. Future studies could examine potential effects of sea level rise on levees throughout the Delta.

## 5.6 Summary

### 5.6.1 Climate Change for Present Sea Level

The DSM2 model was used for preliminary assessment of potential climate change effects on the Delta for four scenarios. The four scenarios correspond to two greenhouse gas emissions scenarios represented by two global climate models. All four climate change scenarios represent warmer future conditions, and three scenarios reflect drier conditions. The fourth climate change scenario projects slightly wetter conditions.

Projected runoff for the climate change scenarios was used to drive an SWP and CVP operations model that provided Delta inflows and exports (see Chapter 4). These studies include the assumption that meeting Delta water quality standards is a top priority for the SWP and CVP operations. Thus the impacts assessment for the Delta already included some mitigation for climate change through modified system operations for maintaining Delta water quality standards. So Delta water quality effects for the four climate change scenarios were relatively minor. There were no significant changes in compliance with 250 mg/l chloride standard at the municipal and industrial intakes, and there was complete compliance with that standard at the SWP and CVP intakes for all of the scenarios. The only reduction in compliance with the 150mg/l chloride standard occurred for the two B1 climate change scenarios. Chloride mass loadings at the SWP for all climate change scenarios and CVP for the A2 scenarios were reduced for the climate change scenarios due to lower export rates. Overall, existing system flexibility was able to provide Delta water quality compliance for most of the climate change conditions examined.

For the water quality analysis, the choice of global climate model had more influence on the results than the choice of greenhouse gas emissions scenario. One way to address the uncertainties associated with climate models and emissions scenarios is to conduct analysis using multiple climate models representing multiple emissions scenarios.

### 5.6.2 Sea Level Rise

An analysis tool is not currently available to determine changes in system operations to maintain Delta water quality under sea level rise conditions. As a first step towards developing such a tool, preliminary studies were conducted for a one-foot sea level rise with present system operations. Simulated water quality constituent concentrations for sea level rise conditions with no changes in system operations were compared to threshold values as a surrogate for evaluating the effects of sea level rise on water project operations to meet existing standards.

Preliminary sea level rise studies examined changes in chloride concentrations at municipal and industrial intakes for a one-foot increase in sea level. Due to the uncertainties in how much salt would be transported into the Delta for sea level rise conditions, two scenarios were examined to provide a range of potential impacts. One scenario assumed that the EC at the DSM2 downstream boundary at Martinez did not change relative to present sea level conditions, and the second scenario assumed that Martinez EC increased based on results of a multi-dimensional modeling study.

Without adjusting system operations to try to lessen the effects of sea level rise, chloride concentrations at Old River at Rock Slough were below the 250 mg/l threshold about 90 percent of the time. In real time, operational adjustments will take place so these effects will translate into water supply impacts to the SWP and CVP. As stated above these impacts to water supply cannot be quantified at this time. Increased salt intrusion for the sea level rise scenarios lead to chloride concentrations that exceeded the 150 mg/l standard during some critical and dry years. Chloride mass loadings at all of the urban intakes increased due to higher chloride concentrations. Impacts were similar for the two salt intrusion assumptions.

### 5.6.3 Combined Climate Change and Sea Level Rise

Preliminary impacts assessments were also conducted for combined climate change and one-foot sea level rise scenarios. System operations were changed to reflect shifts in runoff patterns for climate change, but they were not changed to try to lessen the impacts of sea level rise. Comparisons of chloride concentrations with threshold values at municipal and industrial intakes and potential for overtopping Delta levees were examined. Comparisons of chloride concentrations with threshold values were similar to those for the sea level rise only scenarios. Chloride mass loadings for Old River at Rock Slough were similar for all of the combined climate change and sea level rise scenarios since the export rates were the same. For the SWP and CVP, chloride mass loadings for the combined climate change and sea level rise scenarios were lower than for the sea level rise only scenarios due to reduced export rates.

For the potential levee overtopping analysis, no potential overtoppings occurred for the present sea level conditions. A one-foot rise in sea level resulted in two potential overtoppings during the 16-year analysis. The overtopping potential was not changed when combined sea level rise and climate change conditions were examined. Effects of wind were not considered.

## 5.7 Future Directions

Future directions for Delta climate change studies may include extending existing analyses, improving analysis tools, investigating mitigation measures, and characterizing uncertainty.

A key area of interest is examining effects of sea level rise alone or combined with climate change on system operations. For the analysis approach presented in this report, an Artificial Neural Network (ANN) could be developed to represent sea level rise effects on Delta water quality. By incorporating a sea level rise ANN into the operations model CalSim-II, changes in system operations to reduce salt water intrusion into the Delta could be determined for sea level rise alone or combined with other climate change factors such as shifting runoff patterns. For more detailed studies of sea level rise effects on the Delta using DSM2, an improved characterization of potential salt intrusion into the Delta could be developed.

Additional topics related to sea level rise that could be examined included extending the potential levee overtopping analysis to other areas of the Delta. Existing simulation results could be used to estimate sea level rise effects on the stability of Delta levees. Potential effects for a range of increases in sea level could be examined.

Flexibility of the existing system to mitigate for climate change could be explored. Possible mitigation measures could include modifying reservoir releases, Delta exports, Delta Cross Channel operations, and temporary barrier operations. If present system flexibility isn't sufficient for mitigation, additional measures could be investigated such as modifying operating rules or considering new system components such as the proposed South Delta operable gates.

The main focus of future efforts will be to characterize uncertainty related to the climate change projections. For managers to make decisions, information is needed on both the magnitude of potential effects and the likelihood of those effects.

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## 5.9 References

Anderson and Miller. (2005). Chapter 5: Estimation of Electrical Conductivity at Martinez for Sea Level Rise Conditions. In: *Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh. 26th Annual Progress Report to the State Water Resources Control Board*. California Department of Water Resources. Sacramento, CA. October, 2005. http://modeling.water.ca.gov/delta/reports/annrpt/2005/2005Ch5.pdf

Ateljevich E. (2001a). Chapter 10: Planning Tide at the Martinez Boundary. In: *Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh. 22nd Annual Progress Report to the State Water Resources Control Board*. California Department of Water Resources. Sacramento, CA. http://modeling.water.ca.gov/delta/reports/annrpt/2001/2001Ch10.pdf

Ateljevich E. (2001b). Chapter 11: Improving Estimates of Salinity at the Martinez Boundary. In: *Methodology for Flow and Salinity Estimates in the Sacramento-San Joaquin Delta and Suisun Marsh. 22nd Annual Progress Report to the State Water Resources Control Board*. California Department of Water Resources. Sacramento, CA. http://modeling.water.ca.gov/delta/reports/annrpt/2001/2001Ch11.pdf

DWR (1995a). Sacramento San Joaquin Delta Atlas, California Department of Water Resources, Sacramento, CA, July 1995.

DWR (1995b). Estimation of Delta Island Diversions and Return Flows, California Department of Water Resources, Sacramento, CA, February 1995.

DWR (1995c). Representative Delta Island Return Flow Quality for DSM2, California Department of Water Resources, Sacramento, CA, May 1995.

DWR (2005). California Water Plan Update 2005, Volume 1-Stategic Plan, Chapter 4: Preparing for an Uncertain Future, California Department of Water Resources, Sacramento, CA, Public Review Draft. http://www.waterplan.water.ca.gov/cwpu2005/index.cfm

DWR (2006). http://www.publicaffairs.water.ca.gov/swp/delta.cfm accessed 1-19-06

Freeport (2003). Freeport Regional Water Project Draft EIR-EIS, Volume 3: Modeling Technical Appendix to the Draft Environmental Impact Report/Environmental Impact Statement, U.S. Department of the Interior, U.S. Bureau of Reclamation, the Freeport Regional Water Agency, Sacramento County Water Agency, and East Bay Municipal Water District, July 2003, http://www.freeportproject.org/deir/deir.html. Regression equations are on pg 4-34 of the following document http://www.freeportproject.org/deir/vol3/section04-3.pdf.

IPCC (2001). Intergovernmental Panel on Climate Change, Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the IPCC, J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.), Cambridge University Press, UK. pp 944. http://www.grida.no/climate/ipcc_tar/wg1/index.htm

Roos (2004). Maury Roos, California State Hydrologist, California Department of Water Resources, personal communication.

Suits, B. (2001). Relationships between EC, chloride and bromide at Delta export locations. Technical Memo, California Department of Water Resources, Sacramento, CA, May 29, 2001

SWRCB (1995). Water Quality Control Plan for the San Francisco Bay/Sacramento San Joaquin Delta Estuary, 95-1WR, State Water Resources Control Board, California Environmental Protection Agency, Sacramento, CA, May 1995.

USBR (2004). Chapter 6: Analytical Approach and Methods. In: *Long-Term Central Valley Project Operations Criteria and Plan.* United States Bureau of Reclamation. Sacramento, CA. June 2004.

USBR (2005). CALSIM II San Joaquin River Model (Draft), United States Bureau of Reclamation. Sacramento, CA. April, 2005. http://science.calwater.ca.gov/pdf/calsim/CALSIMSJR_DRAFT_072205.pdf

## 5.10 Abbreviations

ANN-Artificial Neural Network

CalSim-II -SWP and CVP operations model

CCWD-Contra Costa Water District

CVP- Central Valley Project

CVPIA-Central Valley Project Improvement Act

CWEMF-California Water and Environmental Modeling Forum

D1641-State Water Resources Control Board Decision 1641 on Delta water quality standards

DICU-Delta Island Consumptive Use

DSM2-Delta Simulation Model 2

DWR-California Department of Water Resources

EC-Electrical conductivity, a measure of salinity

EWA-Environmental Water Account

GCM-Global Climate Model

GFDL-Geophysical Fluid Dynamic Lab model

GHG-Greenhouse Gas

HWY-Highway

IPCC-Intergovernmental Panel on Climate Change

PCM-Parallel Climate Model

SAC-Sacramento River

SJR-San Joaquin River

SLR-Sea Level Rise

SWP-State Water Project

VIC-Variable Infiltration Capacity Model

WY-Water Year (October 1 to September 30)

## 5.11 Appendix A: DSM2 Inputs

This appendix provides tables of selected DSM2 input values.

**Delta Inflows**

- ❑ Sacramento River at I Street Bridge in Sacramento (Table 5.35)
- ❑ San Joaquin River at Vernalis (Table 5.36)

**Delta Exports and Diversions**

- ❑ State Water Project at Banks Pumping Plant (Table 5.37)
- ❑ Central Valley Project at Tracy Pumping Plant (Table 5.38)
- ❑ Contra Costa Water District (combined Old River diversions from Rock Slough and Highway 4) (Table 5.39)

**Table 5.35: DSM2 Input from CalSim-II: Sacramento River Flows (cfs) at Sacramento**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-75 | 17,863 | 12,673 | 15,573 | 12,573 | 18,478 |
| Nov-75 | 15,078 | 10,890 | 15,630 | 12,904 | 15,027 |
| Dec-75 | 15,560 | 12,797 | 10,636 | 12,305 | 12,111 |
| Jan-76 | 12,235 | 11,534 | 10,353 | 11,179 | 10,769 |
| Feb-76 | 13,354 | 11,566 | 11,863 | 11,525 | 12,199 |
| Mar-76 | 15,068 | 13,413 | 14,648 | 13,372 | 16,710 |
| Apr-76 | 9,702 | 9,426 | 9,545 | 9,416 | 9,575 |
| May-76 | 8,046 | 7,712 | 7,866 | 7,698 | 7,962 |
| Jun-76 | 12,821 | 12,959 | 13,584 | 13,365 | 12,460 |
| Jul-76 | 13,228 | 12,146 | 12,819 | 12,773 | 14,190 |
| Aug-76 | 10,993 | 9,908 | 10,486 | 10,253 | 9,844 |
| Sep-76 | 10,147 | 8,321 | 8,635 | 8,385 | 9,643 |
| Oct-76 | 7,811 | 7,763 | 7,771 | 7,765 | 7,796 |
| Nov-76 | 7,248 | 7,212 | 7,217 | 7,214 | 7,237 |
| Dec-76 | 9,348 | 6,752 | 6,757 | 6,753 | 6,959 |
| Jan-77 | 8,192 | 8,340 | 8,205 | 8,391 | 8,523 |
| Feb-77 | 9,469 | 7,897 | 7,842 | 7,662 | 7,767 |
| Mar-77 | 7,440 | 7,684 | 7,668 | 7,931 | 8,175 |
| Apr-77 | 8,567 | 8,571 | 8,571 | 8,647 | 8,568 |
| May-77 | 5,704 | 5,676 | 5,676 | 5,727 | 6,472 |
| Jun-77 | 9,537 | 9,491 | 9,488 | 9,584 | 11,312 |
| Jul-77 | 12,700 | 10,150 | 11,568 | 11,522 | 12,680 |
| Aug-77 | 8,588 | 7,802 | 8,600 | 8,577 | 8,462 |
| Sep-77 | 8,245 | 6,735 | 8,250 | 8,155 | 8,249 |
| Oct-77 | 7,735 | 7,075 | 6,849 | 7,453 | 7,737 |
| Nov-77 | 7,130 | 7,243 | 7,144 | 7,545 | 7,131 |
| Dec-77 | 15,471 | 15,716 | 15,260 | 15,648 | 15,269 |
| Jan-78 | 63,890 | 66,446 | 62,893 | 68,715 | 70,086 |
| Feb-78 | 52,536 | 61,753 | 49,313 | 58,126 | 58,664 |
| Mar-78 | 61,373 | 73,262 | 67,423 | 73,271 | 73,503 |
| Apr-78 | 36,433 | 32,776 | 34,568 | 32,730 | 43,377 |
| May-78 | 19,397 | 16,344 | 16,791 | 16,361 | 19,043 |
| Jun-78 | 14,823 | 18,805 | 15,368 | 18,962 | 14,920 |
| Jul-78 | 21,490 | 20,468 | 21,705 | 20,659 | 21,695 |
| Aug-78 | 17,756 | 16,396 | 18,032 | 16,428 | 18,322 |
| Sep-78 | 14,949 | 13,515 | 14,838 | 13,525 | 15,417 |
| Oct-78 | 10,305 | 10,412 | 10,261 | 10,496 | 10,554 |
| Nov-78 | 11,755 | 10,079 | 10,253 | 10,900 | 10,332 |
| Dec-78 | 8,667 | 11,206 | 8,289 | 13,404 | 8,383 |
| Jan-79 | 22,527 | 20,491 | 20,858 | 20,771 | 23,862 |
| Feb-79 | 37,221 | 31,858 | 33,244 | 31,778 | 34,859 |
| Mar-79 | 30,147 | 30,228 | 29,440 | 28,700 | 35,538 |
| Apr-79 | 17,240 | 16,918 | 17,122 | 16,936 | 18,364 |
| May-79 | 15,250 | 13,358 | 13,481 | 13,342 | 15,409 |
| Jun-79 | 21,138 | 17,435 | 20,789 | 17,316 | 21,275 |
| Jul-79 | 17,481 | 14,629 | 14,538 | 14,535 | 18,448 |
| Aug-79 | 15,445 | 14,908 | 15,200 | 14,721 | 16,023 |
| Sep-79 | 14,046 | 10,527 | 12,708 | 10,577 | 14,030 |

**Table 5.35: DSM2 Input from CalSim-II: Sacramento River Flows (cfs) at Sacramento (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-79 | 10,199 | 9,803 | 9,370 | 9,755 | 10,054 |
| Nov-79 | 13,383 | 12,681 | 12,956 | 13,059 | 13,480 |
| Dec-79 | 19,685 | 20,398 | 18,276 | 20,596 | 18,114 |
| Jan-80 | 74,269 | 74,316 | 73,465 | 74,559 | 75,159 |
| Feb-80 | 74,367 | 74,720 | 75,069 | 74,488 | 74,648 |
| Mar-80 | 44,213 | 49,229 | 46,649 | 49,392 | 56,602 |
| Apr-80 | 18,884 | 17,753 | 18,154 | 17,725 | 20,898 |
| May-80 | 15,671 | 13,984 | 14,392 | 13,918 | 15,258 |
| Jun-80 | 12,820 | 15,485 | 15,166 | 15,686 | 14,695 |
| Jul-80 | 18,699 | 16,812 | 19,812 | 17,870 | 20,024 |
| Aug-80 | 17,014 | 12,895 | 16,269 | 13,809 | 16,721 |
| Sep-80 | 14,012 | 11,504 | 11,831 | 11,526 | 14,227 |
| Oct-80 | 11,568 | 9,276 | 9,283 | 9,277 | 9,655 |
| Nov-80 | 8,853 | 8,603 | 8,892 | 9,311 | 9,412 |
| Dec-80 | 12,513 | 12,582 | 12,248 | 12,624 | 12,215 |
| Jan-81 | 21,469 | 22,017 | 21,090 | 22,187 | 22,650 |
| Feb-81 | 25,217 | 25,758 | 26,399 | 25,526 | 25,751 |
| Mar-81 | 29,580 | 26,680 | 23,329 | 28,722 | 36,183 |
| Apr-81 | 16,214 | 15,974 | 16,247 | 15,917 | 16,484 |
| May-81 | 10,949 | 10,411 | 10,592 | 10,410 | 10,949 |
| Jun-81 | 14,721 | 15,407 | 14,771 | 13,366 | 14,573 |
| Jul-81 | 17,771 | 15,035 | 15,594 | 15,589 | 17,623 |
| Aug-81 | 15,247 | 13,362 | 15,291 | 15,001 | 14,382 |
| Sep-81 | 13,857 | 11,589 | 11,746 | 11,625 | 13,609 |
| Oct-81 | 12,566 | 10,777 | 10,230 | 9,964 | 10,767 |
| Nov-81 | 31,571 | 26,160 | 29,202 | 29,009 | 36,384 |
| Dec-81 | 73,957 | 74,668 | 73,141 | 74,593 | 71,835 |
| Jan-82 | 68,660 | 72,623 | 65,754 | 73,359 | 73,558 |
| Feb-82 | 73,878 | 74,226 | 74,623 | 74,011 | 74,190 |
| Mar-82 | 71,357 | 73,606 | 73,039 | 73,639 | 74,034 |
| Apr-82 | 74,475 | 73,798 | 74,184 | 73,832 | 75,220 |
| May-82 | 39,827 | 25,178 | 29,784 | 25,134 | 37,372 |
| Jun-82 | 21,942 | 22,822 | 21,678 | 23,054 | 20,123 |
| Jul-82 | 18,866 | 20,072 | 19,778 | 20,071 | 19,391 |
| Aug-82 | 13,160 | 15,367 | 17,654 | 15,486 | 17,839 |
| Sep-82 | 17,174 | 14,366 | 15,851 | 14,366 | 17,032 |
| Oct-82 | 18,126 | 13,611 | 11,672 | 13,582 | 16,192 |
| Nov-82 | 37,037 | 23,328 | 30,128 | 26,130 | 31,073 |
| Dec-82 | 64,483 | 69,855 | 53,805 | 65,208 | 56,758 |
| Jan-83 | 71,244 | 73,187 | 69,680 | 73,465 | 73,568 |
| Feb-83 | 75,088 | 75,443 | 75,780 | 75,178 | 75,365 |
| Mar-83 | 77,464 | 78,354 | 77,903 | 78,435 | 79,055 |
| Apr-83 | 62,634 | 53,326 | 58,813 | 54,985 | 71,943 |
| May-83 | 56,061 | 36,111 | 40,874 | 36,041 | 54,021 |
| Jun-83 | 54,463 | 27,774 | 37,161 | 28,819 | 45,678 |
| Jul-83 | 23,061 | 17,810 | 17,761 | 17,220 | 20,917 |
| Aug-83 | 20,551 | 15,086 | 19,287 | 15,496 | 20,220 |
| Sep-83 | 26,629 | 20,383 | 25,821 | 23,725 | 26,584 |

**Table 5.35: DSM2 Input from CalSim-II: Sacramento River Flows (cfs) at Sacramento (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-83 | 19,560 | 18,926 | 17,794 | 18,379 | 20,092 |
| Nov-83 | 65,368 | 58,660 | 66,296 | 65,578 | 66,043 |
| Dec-83 | 75,185 | 76,378 | 74,491 | 76,092 | 74,203 |
| Jan-84 | 50,683 | 56,494 | 47,666 | 60,827 | 58,266 |
| Feb-84 | 34,027 | 38,624 | 39,952 | 34,452 | 36,023 |
| Mar-84 | 35,425 | 41,224 | 38,921 | 42,305 | 47,338 |
| Apr-84 | 18,696 | 15,098 | 16,030 | 17,764 | 16,792 |
| May-84 | 12,643 | 11,476 | 11,870 | 11,464 | 12,820 |
| Jun-84 | 19,109 | 17,812 | 19,570 | 17,638 | 18,568 |
| Jul-84 | 21,758 | 20,377 | 21,425 | 19,743 | 21,795 |
| Aug-84 | 14,080 | 13,763 | 14,187 | 13,266 | 14,183 |
| Sep-84 | 14,779 | 12,694 | 14,475 | 12,857 | 14,665 |
| Oct-84 | 11,554 | 8,854 | 9,588 | 8,693 | 11,936 |
| Nov-84 | 29,685 | 21,119 | 23,591 | 22,448 | 31,207 |
| Dec-84 | 21,806 | 24,234 | 20,176 | 23,951 | 19,602 |
| Jan-85 | 12,452 | 12,730 | 12,348 | 12,856 | 13,483 |
| Feb-85 | 16,394 | 16,905 | 17,631 | 16,676 | 16,981 |
| Mar-85 | 14,160 | 15,214 | 14,520 | 15,131 | 16,039 |
| Apr-85 | 12,790 | 13,613 | 11,785 | 13,992 | 13,247 |
| May-85 | 14,989 | 14,016 | 15,616 | 14,531 | 13,849 |
| Jun-85 | 14,037 | 14,331 | 14,008 | 14,228 | 14,252 |
| Jul-85 | 19,094 | 17,618 | 19,092 | 18,904 | 19,097 |
| Aug-85 | 17,293 | 15,333 | 16,993 | 16,981 | 16,591 |
| Sep-85 | 14,941 | 13,139 | 14,170 | 13,117 | 14,585 |
| Oct-85 | 12,015 | 9,803 | 9,836 | 9,866 | 13,121 |
| Nov-85 | 10,466 | 9,763 | 10,561 | 10,429 | 12,359 |
| Dec-85 | 15,952 | 17,338 | 15,763 | 16,933 | 15,634 |
| Jan-86 | 23,798 | 25,091 | 23,209 | 25,287 | 23,469 |
| Feb-86 | 78,551 | 79,043 | 79,619 | 78,795 | 79,214 |
| Mar-86 | 74,396 | 75,360 | 74,894 | 75,150 | 75,843 |
| Apr-86 | 19,689 | 18,055 | 18,799 | 17,987 | 21,630 |
| May-86 | 12,499 | 10,540 | 10,741 | 10,535 | 11,724 |
| Jun-86 | 11,145 | 14,936 | 14,934 | 15,649 | 14,786 |
| Jul-86 | 19,681 | 17,973 | 18,771 | 17,934 | 20,008 |
| Aug-86 | 17,254 | 13,466 | 14,070 | 13,628 | 16,407 |
| Sep-86 | 15,048 | 12,126 | 12,302 | 12,172 | 13,601 |
| Oct-86 | 11,832 | 9,715 | 9,758 | 9,594 | 10,523 |
| Nov-86 | 9,365 | 8,659 | 9,277 | 8,836 | 9,973 |
| Dec-86 | 8,963 | 9,138 | 8,880 | 9,095 | 8,821 |
| Jan-87 | 13,430 | 13,782 | 13,318 | 14,007 | 14,193 |
| Feb-87 | 20,787 | 21,380 | 21,964 | 21,151 | 21,399 |
| Mar-87 | 24,272 | 25,424 | 24,766 | 25,359 | 27,271 |
| Apr-87 | 14,647 | 11,084 | 11,220 | 11,123 | 13,941 |
| May-87 | 10,242 | 9,405 | 9,625 | 9,715 | 10,549 |
| Jun-87 | 11,241 | 10,612 | 11,017 | 10,924 | 12,352 |
| Jul-87 | 13,153 | 9,857 | 10,225 | 10,409 | 13,477 |
| Aug-87 | 12,465 | 9,952 | 10,892 | 9,818 | 13,397 |
| Sep-87 | 11,011 | 9,363 | 9,597 | 9,153 | 10,943 |

**Table 5.35: DSM2 Input from CalSim-II: Sacramento River Flows (cfs) at Sacramento (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-87 | 9,814 | 9,200 | 9,460 | 9,197 | 10,879 |
| Nov-87 | 8,896 | 8,497 | 8,500 | 8,494 | 8,944 |
| Dec-87 | 17,578 | 17,945 | 17,358 | 17,846 | 17,277 |
| Jan-88 | 28,123 | 28,131 | 27,735 | 28,818 | 28,374 |
| Feb-88 | 16,008 | 12,799 | 13,010 | 12,698 | 15,957 |
| Mar-88 | 8,685 | 8,883 | 8,847 | 9,280 | 9,580 |
| Apr-88 | 10,475 | 10,273 | 10,314 | 10,294 | 10,800 |
| May-88 | 9,754 | 9,819 | 9,810 | 9,811 | 9,667 |
| Jun-88 | 10,922 | 11,737 | 11,101 | 11,803 | 12,339 |
| Jul-88 | 9,130 | 8,938 | 8,823 | 9,194 | 9,980 |
| Aug-88 | 8,130 | 7,991 | 8,366 | 8,236 | 8,709 |
| Sep-88 | 6,195 | 6,589 | 6,279 | 6,407 | 5,882 |
| Oct-88 | 7,771 | 7,785 | 7,777 | 7,785 | 7,778 |
| Nov-88 | 9,993 | 9,718 | 10,072 | 9,933 | 10,092 |
| Dec-88 | 9,968 | 10,284 | 9,822 | 10,199 | 9,732 |
| Jan-89 | 12,814 | 12,943 | 12,666 | 13,035 | 13,125 |
| Feb-89 | 10,328 | 10,454 | 10,556 | 10,346 | 10,260 |
| Mar-89 | 47,840 | 60,757 | 51,571 | 58,410 | 67,796 |
| Apr-89 | 22,084 | 29,703 | 21,145 | 29,705 | 29,670 |
| May-89 | 15,373 | 21,237 | 15,441 | 21,241 | 21,200 |
| Jun-89 | 15,170 | 11,053 | 14,845 | 11,523 | 11,856 |
| Jul-89 | 18,046 | 16,272 | 14,002 | 17,339 | 18,780 |
| Aug-89 | 15,192 | 13,066 | 14,029 | 14,109 | 16,907 |
| Sep-89 | 15,211 | 13,196 | 13,563 | 13,237 | 15,276 |
| Oct-89 | 11,409 | 10,180 | 10,663 | 9,987 | 11,725 |
| Nov-89 | 9,196 | 8,561 | 8,707 | 8,656 | 11,200 |
| Dec-89 | 8,934 | 11,069 | 11,981 | 11,185 | 11,917 |
| Jan-90 | 18,954 | 19,488 | 18,981 | 19,807 | 19,642 |
| Feb-90 | 16,333 | 15,351 | 15,533 | 15,152 | 16,342 |
| Mar-90 | 12,359 | 13,148 | 12,784 | 13,440 | 13,128 |
| Apr-90 | 10,745 | 10,735 | 10,744 | 10,734 | 10,737 |
| May-90 | 9,169 | 8,763 | 9,022 | 8,760 | 9,371 |
| Jun-90 | 10,434 | 8,178 | 8,183 | 8,809 | 8,425 |
| Jul-90 | 9,577 | 10,091 | 9,776 | 10,097 | 9,454 |
| Aug-90 | 8,949 | 8,485 | 8,255 | 8,268 | 8,017 |
| Sep-90 | 8,293 | 8,275 | 8,246 | 8,290 | 8,296 |
| Oct-90 | 7,745 | 7,737 | 7,745 | 7,736 | 7,746 |
| Nov-90 | 7,223 | 7,216 | 7,223 | 7,216 | 7,223 |
| Dec-90 | 6,721 | 6,715 | 6,721 | 6,715 | 7,010 |
| Jan-91 | 6,576 | 6,577 | 6,539 | 6,808 | 6,820 |
| Feb-91 | 8,350 | 8,366 | 8,605 | 8,439 | 8,472 |
| Mar-91 | 31,783 | 32,148 | 32,136 | 32,314 | 33,002 |
| Apr-91 | 13,266 | 12,800 | 13,143 | 13,105 | 14,314 |
| May-91 | 8,786 | 7,652 | 8,089 | 7,999 | 8,964 |
| Jun-91 | 8,093 | 7,229 | 7,304 | 7,044 | 10,171 |
| Jul-91 | 10,700 | 11,045 | 11,079 | 11,296 | 11,223 |
| Aug-91 | 8,100 | 6,830 | 7,907 | 7,336 | 8,264 |
| Sep-91 | 8,471 | 6,190 | 7,793 | 8,392 | 8,355 |

**Table 5.36: DSM2 Input from CalSim-II: San Joaquin River Flows (cfs) at Vernalis**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-75 | 2,946 | 2,063 | 2,421 | 2,019 | 2,652 |
| Nov-75 | 1,805 | 1,753 | 1,918 | 1,732 | 1,856 |
| Dec-75 | 1,910 | 1,858 | 1,885 | 1,837 | 1,904 |
| Jan-76 | 1,721 | 1,669 | 1,693 | 1,648 | 1,715 |
| Feb-76 | 1,933 | 1,879 | 2,039 | 1,858 | 2,021 |
| Mar-76 | 1,775 | 1,662 | 1,690 | 1,661 | 1,734 |
| Apr-76 | 2,450 | 2,442 | 2,447 | 2,445 | 2,450 |
| May-76 | 2,262 | 2,249 | 2,256 | 2,254 | 2,261 |
| Jun-76 | 1,486 | 1,449 | 1,470 | 1,463 | 1,483 |
| Jul-76 | 1,427 | 1,152 | 1,407 | 1,108 | 1,423 |
| Aug-76 | 1,347 | 857 | 911 | 858 | 1,139 |
| Sep-76 | 1,178 | 1,160 | 1,171 | 1,162 | 1,179 |
| Oct-76 | 3,209 | 3,101 | 3,131 | 2,915 | 3,171 |
| Nov-76 | 2,100 | 2,050 | 2,078 | 2,050 | 2,090 |
| Dec-76 | 1,693 | 1,642 | 1,670 | 1,643 | 1,682 |
| Jan-77 | 1,306 | 1,189 | 1,220 | 1,191 | 1,264 |
| Feb-77 | 1,383 | 1,260 | 1,294 | 1,265 | 1,340 |
| Mar-77 | 1,275 | 1,268 | 1,272 | 1,256 | 1,275 |
| Apr-77 | 1,702 | 1,698 | 1,700 | 1,624 | 1,702 |
| May-77 | 1,581 | 1,574 | 1,577 | 1,480 | 1,581 |
| Jun-77 | 1,236 | 1,216 | 1,223 | 1,209 | 1,236 |
| Jul-77 | 798 | 684 | 788 | 685 | 788 |
| Aug-77 | 680 | 646 | 673 | 647 | 680 |
| Sep-77 | 982 | 956 | 975 | 958 | 981 |
| Oct-77 | 1,454 | 1,442 | 1,626 | 1,200 | 1,454 |
| Nov-77 | 1,351 | 1,270 | 1,350 | 1,262 | 1,351 |
| Dec-77 | 1,524 | 1,518 | 1,522 | 1,535 | 1,524 |
| Jan-78 | 3,727 | 3,247 | 3,248 | 3,248 | 3,251 |
| Feb-78 | 7,843 | 8,901 | 8,385 | 6,816 | 7,735 |
| Mar-78 | 9,089 | 10,909 | 10,055 | 9,268 | 9,773 |
| Apr-78 | 12,921 | 14,729 | 13,976 | 12,726 | 14,273 |
| May-78 | 11,897 | 12,235 | 12,588 | 9,647 | 13,952 |
| Jun-78 | 11,295 | 3,840 | 7,262 | 3,687 | 7,372 |
| Jul-78 | 2,470 | 2,263 | 2,263 | 2,263 | 2,263 |
| Aug-78 | 1,908 | 1,908 | 1,908 | 1,908 | 1,908 |
| Sep-78 | 2,194 | 1,614 | 1,614 | 1,614 | 1,725 |
| Oct-78 | 4,206 | 2,408 | 3,694 | 2,621 | 4,202 |
| Nov-78 | 1,648 | 1,606 | 1,681 | 1,604 | 1,650 |
| Dec-78 | 1,829 | 1,787 | 1,823 | 1,898 | 1,831 |
| Jan-79 | 3,851 | 4,284 | 3,770 | 4,278 | 4,363 |
| Feb-79 | 9,064 | 5,809 | 6,625 | 4,816 | 10,257 |
| Mar-79 | 8,638 | 6,609 | 9,480 | 5,839 | 10,407 |
| Apr-79 | 6,349 | 6,369 | 6,482 | 5,729 | 6,790 |
| May-79 | 5,904 | 5,597 | 5,868 | 5,008 | 6,114 |
| Jun-79 | 2,190 | 2,093 | 2,116 | 2,094 | 2,334 |
| Jul-79 | 1,849 | 1,803 | 1,818 | 1,805 | 1,849 |
| Aug-79 | 1,764 | 1,694 | 1,705 | 1,695 | 1,764 |
| Sep-79 | 1,870 | 1,820 | 1,837 | 1,797 | 1,883 |

**Table 5.36: DSM2 Input from CalSim-II: San Joaquin River Flows (cfs) at Vernalis (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-79 | 2,255 | 2,200 | 2,236 | 2,081 | 2,281 |
| Nov-79 | 1,808 | 1,732 | 1,788 | 1,618 | 1,821 |
| Dec-79 | 1,945 | 1,866 | 1,923 | 1,752 | 1,958 |
| Jan-80 | 11,058 | 10,135 | 7,211 | 7,463 | 11,747 |
| Feb-80 | 21,061 | 24,227 | 27,335 | 12,986 | 26,166 |
| Mar-80 | 13,100 | 17,772 | 15,092 | 14,019 | 16,080 |
| Apr-80 | 7,544 | 9,844 | 9,434 | 8,528 | 9,136 |
| May-80 | 6,767 | 6,218 | 6,527 | 5,690 | 7,183 |
| Jun-80 | 5,214 | 2,445 | 2,766 | 2,405 | 2,891 |
| Jul-80 | 3,864 | 1,952 | 2,135 | 1,920 | 2,262 |
| Aug-80 | 2,014 | 1,788 | 1,916 | 1,766 | 2,006 |
| Sep-80 | 2,611 | 1,708 | 1,770 | 1,689 | 2,211 |
| Oct-80 | 4,278 | 1,988 | 2,940 | 1,979 | 3,763 |
| Nov-80 | 1,742 | 1,688 | 1,718 | 1,634 | 1,740 |
| Dec-80 | 1,885 | 1,829 | 1,859 | 1,776 | 1,883 |
| Jan-81 | 2,106 | 2,023 | 2,057 | 2,019 | 2,085 |
| Feb-81 | 2,547 | 2,280 | 2,523 | 2,280 | 2,604 |
| Mar-81 | 3,483 | 2,240 | 3,957 | 2,220 | 4,303 |
| Apr-81 | 4,327 | 3,907 | 4,340 | 3,906 | 4,588 |
| May-81 | 3,461 | 2,767 | 3,806 | 2,710 | 3,750 |
| Jun-81 | 1,710 | 1,671 | 1,702 | 1,676 | 1,683 |
| Jul-81 | 1,678 | 1,631 | 1,668 | 1,637 | 1,645 |
| Aug-81 | 1,625 | 1,589 | 1,617 | 1,486 | 1,600 |
| Sep-81 | 1,567 | 1,311 | 1,561 | 1,310 | 1,549 |
| Oct-81 | 2,104 | 2,042 | 2,100 | 2,027 | 2,100 |
| Nov-81 | 1,708 | 1,661 | 1,689 | 1,657 | 1,703 |
| Dec-81 | 1,760 | 1,711 | 1,741 | 1,707 | 1,754 |
| Jan-82 | 6,242 | 6,697 | 4,673 | 5,878 | 5,941 |
| Feb-82 | 13,580 | 16,895 | 17,143 | 10,856 | 17,456 |
| Mar-82 | 14,865 | 19,929 | 16,487 | 15,515 | 18,363 |
| Apr-82 | 24,622 | 30,388 | 29,743 | 27,701 | 29,908 |
| May-82 | 16,058 | 14,288 | 15,150 | 12,939 | 16,504 |
| Jun-82 | 9,692 | 3,738 | 4,247 | 3,738 | 5,012 |
| Jul-82 | 3,715 | 2,511 | 2,804 | 2,511 | 3,191 |
| Aug-82 | 2,199 | 2,199 | 2,199 | 2,199 | 2,199 |
| Sep-82 | 3,563 | 1,837 | 3,331 | 1,837 | 3,382 |
| Oct-82 | 12,098 | 3,340 | 8,876 | 3,369 | 10,131 |
| Nov-82 | 7,981 | 5,876 | 9,890 | 9,739 | 9,744 |
| Dec-82 | 18,184 | 21,017 | 13,073 | 17,211 | 13,383 |
| Jan-83 | 23,332 | 28,727 | 23,427 | 29,754 | 26,805 |
| Feb-83 | 31,051 | 35,096 | 38,220 | 26,681 | 34,742 |
| Mar-83 | 37,383 | 47,697 | 41,589 | 39,407 | 44,295 |
| Apr-83 | 19,986 | 23,136 | 22,652 | 21,521 | 22,363 |
| May-83 | 20,416 | 19,270 | 19,789 | 17,881 | 20,879 |
| Jun-83 | 34,195 | 10,326 | 20,598 | 9,633 | 22,664 |
| Jul-83 | 17,655 | 3,333 | 9,375 | 3,997 | 13,234 |
| Aug-83 | 2,082 | 2,082 | 2,082 | 2,082 | 2,082 |
| Sep-83 | 5,958 | 3,069 | 4,827 | 3,339 | 5,236 |

**Table 5.36: DSM2 Input from CalSim-II: San Joaquin River Flows (cfs) at Vernalis (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-83 | 11,980 | 5,880 | 11,773 | 5,759 | 11,820 |
| Nov-83 | 12,960 | 8,708 | 15,882 | 15,330 | 15,748 |
| Dec-83 | 20,682 | 28,501 | 16,607 | 23,593 | 15,626 |
| Jan-84 | 14,354 | 18,070 | 14,455 | 18,775 | 16,712 |
| Feb-84 | 9,683 | 10,593 | 12,064 | 7,987 | 10,999 |
| Mar-84 | 6,092 | 8,591 | 6,980 | 6,525 | 8,034 |
| Apr-84 | 5,530 | 5,551 | 5,552 | 5,433 | 5,680 |
| May-84 | 5,064 | 4,948 | 5,015 | 4,908 | 5,065 |
| Jun-84 | 2,627 | 2,428 | 2,540 | 2,356 | 2,629 |
| Jul-84 | 2,243 | 2,184 | 2,235 | 2,188 | 2,243 |
| Aug-84 | 2,137 | 2,099 | 2,135 | 2,101 | 2,139 |
| Sep-84 | 1,969 | 1,938 | 1,959 | 1,932 | 1,969 |
| Oct-84 | 2,343 | 2,301 | 2,327 | 2,288 | 2,343 |
| Nov-84 | 1,922 | 1,900 | 1,914 | 1,894 | 1,922 |
| Dec-84 | 1,971 | 1,948 | 1,963 | 1,942 | 1,971 |
| Jan-85 | 1,791 | 1,764 | 1,782 | 1,758 | 1,791 |
| Feb-85 | 2,211 | 2,174 | 2,201 | 2,169 | 2,211 |
| Mar-85 | 2,191 | 2,098 | 2,172 | 2,081 | 2,188 |
| Apr-85 | 3,241 | 2,573 | 3,241 | 2,574 | 3,241 |
| May-85 | 3,491 | 2,376 | 3,086 | 2,383 | 3,419 |
| Jun-85 | 1,744 | 1,731 | 1,745 | 1,752 | 1,746 |
| Jul-85 | 1,651 | 1,635 | 1,652 | 1,660 | 1,653 |
| Aug-85 | 1,580 | 1,133 | 1,581 | 1,018 | 1,582 |
| Sep-85 | 1,577 | 1,346 | 1,339 | 1,352 | 1,527 |
| Oct-85 | 2,119 | 2,012 | 2,086 | 2,001 | 2,114 |
| Nov-85 | 1,698 | 1,740 | 1,674 | 1,738 | 1,695 |
| Dec-85 | 1,776 | 1,818 | 1,753 | 1,817 | 1,774 |
| Jan-86 | 2,182 | 1,674 | 1,751 | 1,662 | 1,765 |
| Feb-86 | 13,469 | 16,280 | 19,260 | 7,964 | 18,396 |
| Mar-86 | 23,294 | 33,269 | 28,189 | 20,725 | 30,362 |
| Apr-86 | 12,075 | 14,596 | 14,225 | 13,234 | 13,765 |
| May-86 | 8,356 | 7,526 | 7,894 | 6,515 | 8,604 |
| Jun-86 | 6,517 | 2,130 | 2,801 | 2,130 | 2,752 |
| Jul-86 | 2,389 | 2,370 | 2,378 | 2,129 | 2,387 |
| Aug-86 | 2,169 | 2,154 | 2,161 | 2,070 | 2,168 |
| Sep-86 | 2,169 | 2,153 | 2,160 | 2,062 | 2,167 |
| Oct-86 | 2,566 | 2,105 | 2,112 | 2,104 | 2,127 |
| Nov-86 | 1,748 | 1,742 | 1,745 | 1,696 | 1,748 |
| Dec-86 | 1,794 | 1,787 | 1,790 | 1,741 | 1,794 |
| Jan-87 | 1,675 | 1,663 | 1,669 | 1,618 | 1,674 |
| Feb-87 | 2,041 | 2,019 | 2,029 | 1,974 | 2,039 |
| Mar-87 | 1,961 | 1,855 | 1,870 | 1,855 | 1,934 |
| Apr-87 | 2,475 | 2,464 | 2,467 | 2,467 | 2,483 |
| May-87 | 2,287 | 2,268 | 2,274 | 2,273 | 2,299 |
| Jun-87 | 1,531 | 1,476 | 1,491 | 1,491 | 1,566 |
| Jul-87 | 1,514 | 1,205 | 1,466 | 1,196 | 1,555 |
| Aug-87 | 1,252 | 825 | 833 | 826 | 1,064 |
| Sep-87 | 1,197 | 1,171 | 1,182 | 1,173 | 1,208 |

**Table 5.36: DSM2 Input from CalSim-II: San Joaquin River Flows (cfs) at Vernalis (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-87 | 1,676 | 1,588 | 1,593 | 1,590 | 1,658 |
| Nov-87 | 1,330 | 1,279 | 1,301 | 1,282 | 1,327 |
| Dec-87 | 1,288 | 1,236 | 1,258 | 1,238 | 1,286 |
| Jan-88 | 1,280 | 1,169 | 1,185 | 1,173 | 1,261 |
| Feb-88 | 1,326 | 1,206 | 1,224 | 1,212 | 1,313 |
| Mar-88 | 1,254 | 1,250 | 1,250 | 1,250 | 1,252 |
| Apr-88 | 1,719 | 1,713 | 1,714 | 1,713 | 1,716 |
| May-88 | 1,586 | 1,578 | 1,578 | 1,577 | 1,582 |
| Jun-88 | 1,262 | 1,239 | 1,240 | 1,238 | 1,251 |
| Jul-88 | 969 | 993 | 1,020 | 979 | 1,003 |
| Aug-88 | 688 | 670 | 677 | 666 | 685 |
| Sep-88 | 1,033 | 1,014 | 1,022 | 1,010 | 1,029 |
| Oct-88 | 1,554 | 1,345 | 1,522 | 1,309 | 1,552 |
| Nov-88 | 1,279 | 1,201 | 1,273 | 1,227 | 1,278 |
| Dec-88 | 1,391 | 1,358 | 1,384 | 1,358 | 1,389 |
| Jan-89 | 1,183 | 1,175 | 1,178 | 1,176 | 1,180 |
| Feb-89 | 1,360 | 1,349 | 1,351 | 1,349 | 1,355 |
| Mar-89 | 1,596 | 1,592 | 1,595 | 1,590 | 1,596 |
| Apr-89 | 1,727 | 1,695 | 1,714 | 1,696 | 1,737 |
| May-89 | 1,439 | 1,403 | 1,418 | 1,407 | 1,453 |
| Jun-89 | 1,292 | 1,255 | 1,256 | 1,277 | 1,322 |
| Jul-89 | 1,292 | 1,200 | 1,286 | 1,116 | 1,281 |
| Aug-89 | 803 | 789 | 793 | 784 | 811 |
| Sep-89 | 1,164 | 1,150 | 1,154 | 1,149 | 1,173 |
| Oct-89 | 1,370 | 1,321 | 1,322 | 1,308 | 1,579 |
| Nov-89 | 1,324 | 1,225 | 1,236 | 1,314 | 1,328 |
| Dec-89 | 1,254 | 1,154 | 1,161 | 1,157 | 1,258 |
| Jan-90 | 1,194 | 1,183 | 1,186 | 1,188 | 1,201 |
| Feb-90 | 1,380 | 1,363 | 1,365 | 1,372 | 1,392 |
| Mar-90 | 1,315 | 1,314 | 1,314 | 1,313 | 1,315 |
| Apr-90 | 1,570 | 1,566 | 1,568 | 1,564 | 1,571 |
| May-90 | 1,307 | 1,304 | 1,305 | 1,301 | 1,308 |
| Jun-90 | 1,164 | 1,162 | 1,163 | 1,161 | 1,164 |
| Jul-90 | 1,062 | 935 | 1,013 | 907 | 1,065 |
| Aug-90 | 728 | 721 | 724 | 716 | 730 |
| Sep-90 | 1,085 | 1,080 | 1,082 | 1,007 | 1,086 |
| Oct-90 | 1,212 | 1,051 | 1,052 | 1,016 | 1,257 |
| Nov-90 | 1,173 | 1,173 | 1,173 | 1,133 | 1,173 |
| Dec-90 | 1,130 | 1,130 | 1,130 | 1,130 | 1,130 |
| Jan-91 | 1,006 | 1,004 | 1,033 | 1,003 | 1,033 |
| Feb-91 | 1,128 | 1,133 | 1,149 | 1,106 | 1,149 |
| Mar-91 | 2,387 | 2,383 | 2,385 | 2,383 | 2,387 |
| Apr-91 | 2,245 | 2,230 | 2,237 | 2,228 | 2,246 |
| May-91 | 1,690 | 1,672 | 1,681 | 1,670 | 1,692 |
| Jun-91 | 1,106 | 1,074 | 1,092 | 1,088 | 1,118 |
| Jul-91 | 1,073 | 1,035 | 1,056 | 1,006 | 1,087 |
| Aug-91 | 777 | 757 | 767 | 755 | 780 |
| Sep-91 | 1,026 | 1,008 | 1,017 | 1,008 | 1,029 |

**Table 5.37: DSM2 Input from CalSim-II: State Water Project Exports (cfs)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-75 | 6,680 | 5,334 | 6,680 | 5,136 | 6,680 |
| Nov-75 | 6,680 | 2,328 | 6,680 | 2,673 | 6,680 |
| Dec-75 | 7,013 | 1,380 | 300 | 1,343 | 4,367 |
| Jan-76 | 3,972 | 4,234 | 3,115 | 3,903 | 3,365 |
| Feb-76 | 3,987 | 2,609 | 2,467 | 2,564 | 2,921 |
| Mar-76 | 3,416 | 2,757 | 3,199 | 3,197 | 4,403 |
| Apr-76 | 1,721 | 1,557 | 1,638 | 1,551 | 1,677 |
| May-76 | 1,517 | 1,357 | 1,436 | 1,352 | 1,479 |
| Jun-76 | 3,152 | 2,884 | 3,430 | 2,989 | 2,909 |
| Jul-76 | 2,424 | 3,386 | 4,162 | 3,629 | 2,996 |
| Aug-76 | 4,808 | 2,775 | 3,553 | 2,984 | 3,632 |
| Sep-76 | 3,672 | 1,828 | 2,119 | 1,906 | 3,174 |
| Oct-76 | 2,792 | 2,063 | 1,780 | 1,987 | 2,391 |
| Nov-76 | 2,945 | 1,177 | 1,780 | 1,582 | 2,558 |
| Dec-76 | 3,049 | 1,888 | 1,925 | 1,715 | 2,558 |
| Jan-77 | 2,764 | 2,096 | 2,013 | 2,232 | 2,493 |
| Feb-77 | 919 | 1,077 | 1,034 | 855 | 858 |
| Mar-77 | 497 | 1,219 | 1,200 | 1,455 | 1,706 |
| Apr-77 | 300 | 300 | 300 | 300 | 300 |
| May-77 | 413 | 300 | 300 | 300 | 1,105 |
| Jun-77 | 300 | 300 | 300 | 300 | 300 |
| Jul-77 | 461 | 300 | 352 | 329 | 461 |
| Aug-77 | 306 | 300 | 300 | 300 | 342 |
| Sep-77 | 1,703 | 2,079 | 1,609 | 1,564 | 1,701 |
| Oct-77 | 763 | 2,347 | 2,634 | 2,869 | 542 |
| Nov-77 | 1,386 | 1,245 | 1,623 | 1,527 | 1,477 |
| Dec-77 | 5,717 | 4,210 | 5,565 | 6,102 | 5,635 |
| Jan-78 | 7,455 | 6,934 | 6,589 | 5,577 | 6,930 |
| Feb-78 | 4,092 | 4,233 | 3,679 | 4,380 | 4,316 |
| Mar-78 | 5,115 | 5,337 | 4,977 | 5,280 | 5,440 |
| Apr-78 | 5,516 | 5,490 | 5,546 | 5,464 | 5,452 |
| May-78 | 4,844 | 4,532 | 4,899 | 1,620 | 4,758 |
| Jun-78 | 4,713 | 4,046 | 3,490 | 4,047 | 3,374 |
| Jul-78 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Aug-78 | 6,680 | 5,991 | 6,526 | 6,001 | 6,680 |
| Sep-78 | 6,680 | 5,362 | 6,227 | 5,368 | 6,680 |
| Oct-78 | 4,174 | 3,199 | 3,828 | 3,427 | 4,421 |
| Nov-78 | 3,417 | 2,198 | 3,262 | 2,847 | 2,991 |
| Dec-78 | 1,695 | 3,108 | 1,504 | 4,863 | 1,312 |
| Jan-79 | 7,964 | 8,108 | 7,937 | 8,106 | 8,134 |
| Feb-79 | 8,500 | 8,500 | 8,500 | 8,285 | 8,500 |
| Mar-79 | 7,561 | 7,561 | 7,561 | 7,561 | 7,561 |
| Apr-79 | 4,020 | 3,844 | 4,317 | 3,626 | 4,429 |
| May-79 | 3,718 | 3,780 | 3,657 | 3,018 | 3,795 |
| Jun-79 | 3,948 | 3,494 | 3,868 | 2,918 | 4,188 |
| Jul-79 | 4,454 | 4,744 | 4,676 | 4,245 | 4,830 |
| Aug-79 | 5,754 | 5,608 | 5,731 | 5,436 | 5,970 |
| Sep-79 | 6,005 | 3,021 | 5,188 | 3,030 | 6,006 |

**Table 5.37: DSM2 Input from CalSim-II: State Water Project Exports (cfs) (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-79 | 3,597 | 3,693 | 2,835 | 3,676 | 3,743 |
| Nov-79 | 4,239 | 3,534 | 4,844 | 3,851 | 4,279 |
| Dec-79 | 7,019 | 7,008 | 7,015 | 7,000 | 7,021 |
| Jan-80 | 8,500 | 8,500 | 8,500 | 8,500 | 8,500 |
| Feb-80 | 8,437 | 8,347 | 8,069 | 8,267 | 7,726 |
| Mar-80 | 5,072 | 4,241 | 4,471 | 4,264 | 4,656 |
| Apr-80 | 4,535 | 3,940 | 4,204 | 3,967 | 4,403 |
| May-80 | 4,163 | 4,375 | 4,417 | 3,682 | 4,365 |
| Jun-80 | 2,250 | 3,405 | 3,407 | 3,433 | 3,181 |
| Jul-80 | 6,680 | 6,296 | 6,680 | 6,494 | 6,680 |
| Aug-80 | 6,680 | 5,053 | 6,680 | 5,478 | 6,680 |
| Sep-80 | 6,680 | 4,577 | 4,834 | 4,578 | 6,680 |
| Oct-80 | 5,889 | 2,631 | 2,791 | 2,665 | 3,713 |
| Nov-80 | 1,759 | 1,288 | 1,704 | 1,299 | 1,989 |
| Dec-80 | 3,629 | 4,282 | 3,639 | 4,403 | 2,941 |
| Jan-81 | 7,382 | 7,354 | 7,366 | 7,353 | 7,375 |
| Feb-81 | 5,654 | 5,499 | 5,808 | 5,418 | 5,610 |
| Mar-81 | 7,074 | 5,293 | 5,231 | 5,134 | 6,529 |
| Apr-81 | 2,707 | 2,564 | 2,801 | 2,544 | 2,890 |
| May-81 | 2,127 | 1,935 | 2,126 | 1,915 | 2,152 |
| Jun-81 | 2,909 | 2,957 | 1,605 | 300 | 3,015 |
| Jul-81 | 5,219 | 3,016 | 3,038 | 3,425 | 5,038 |
| Aug-81 | 5,079 | 4,970 | 5,913 | 5,837 | 4,900 |
| Sep-81 | 5,546 | 3,940 | 4,198 | 3,978 | 5,665 |
| Oct-81 | 3,896 | 3,225 | 3,244 | 3,092 | 3,602 |
| Nov-81 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Dec-81 | 7,002 | 6,993 | 6,998 | 6,992 | 7,001 |
| Jan-82 | 8,500 | 8,500 | 8,238 | 8,500 | 8,500 |
| Feb-82 | 8,500 | 8,500 | 8,500 | 8,500 | 8,500 |
| Mar-82 | 7,561 | 7,535 | 7,561 | 7,352 | 7,561 |
| Apr-82 | 6,125 | 6,125 | 6,125 | 6,125 | 6,125 |
| May-82 | 6,177 | 6,177 | 6,177 | 6,177 | 6,177 |
| Jun-82 | 6,680 | 4,984 | 4,873 | 5,025 | 4,869 |
| Jul-82 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Aug-82 | 3,304 | 6,077 | 6,680 | 6,115 | 6,680 |
| Sep-82 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Oct-82 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Nov-82 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Dec-82 | 7,678 | 7,678 | 6,761 | 7,678 | 6,755 |
| Jan-83 | 3,472 | 3,477 | 3,476 | 3,477 | 3,474 |
| Feb-83 | 3,548 | 3,548 | 3,548 | 3,548 | 3,548 |
| Mar-83 | 3,555 | 3,555 | 3,555 | 3,555 | 3,555 |
| Apr-83 | 3,749 | 3,749 | 3,749 | 3,749 | 3,749 |
| May-83 | 3,171 | 3,171 | 3,171 | 3,171 | 3,171 |
| Jun-83 | 3,877 | 3,877 | 3,877 | 3,877 | 3,877 |
| Jul-83 | 6,638 | 6,119 | 6,638 | 6,194 | 6,638 |
| Aug-83 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Sep-83 | 5,039 | 5,573 | 5,039 | 5,496 | 5,039 |

**Table 5.37: DSM2 Input from CalSim-II: State Water Project Exports (cfs) (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-83 | 3,682 | 3,682 | 3,682 | 3,682 | 3,682 |
| Nov-83 | 3,144 | 3,144 | 3,144 | 3,144 | 3,144 |
| Dec-83 | 3,723 | 3,723 | 3,723 | 3,723 | 3,723 |
| Jan-84 | 5,640 | 5,640 | 5,640 | 5,640 | 5,640 |
| Feb-84 | 6,531 | 6,509 | 6,531 | 6,506 | 6,531 |
| Mar-84 | 6,635 | 6,564 | 6,619 | 6,564 | 6,635 |
| Apr-84 | 3,499 | 1,880 | 1,914 | 3,413 | 3,356 |
| May-84 | 2,899 | 2,781 | 2,825 | 2,776 | 2,916 |
| Jun-84 | 3,974 | 3,875 | 4,039 | 3,425 | 3,880 |
| Jul-84 | 5,093 | 4,771 | 5,062 | 4,269 | 5,198 |
| Aug-84 | 4,981 | 4,630 | 5,090 | 4,132 | 5,086 |
| Sep-84 | 6,680 | 5,772 | 6,680 | 5,850 | 6,606 |
| Oct-84 | 5,541 | 3,916 | 4,371 | 3,928 | 5,726 |
| Nov-84 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Dec-84 | 7,040 | 7,036 | 7,039 | 7,035 | 7,040 |
| Jan-85 | 4,443 | 4,703 | 4,340 | 4,822 | 5,478 |
| Feb-85 | 4,167 | 4,490 | 4,719 | 4,438 | 4,432 |
| Mar-85 | 2,560 | 3,215 | 2,356 | 2,791 | 2,362 |
| Apr-85 | 2,356 | 2,230 | 2,221 | 2,249 | 2,393 |
| May-85 | 2,497 | 2,183 | 2,424 | 2,219 | 2,387 |
| Jun-85 | 2,795 | 2,843 | 2,790 | 2,829 | 2,833 |
| Jul-85 | 6,680 | 6,680 | 6,680 | 6,680 | 6,680 |
| Aug-85 | 6,680 | 6,647 | 6,680 | 6,601 | 6,680 |
| Sep-85 | 6,680 | 5,123 | 5,685 | 5,003 | 6,680 |
| Oct-85 | 5,411 | 3,610 | 3,525 | 3,524 | 5,886 |
| Nov-85 | 3,894 | 3,880 | 3,899 | 3,804 | 4,363 |
| Dec-85 | 6,900 | 6,825 | 6,480 | 6,995 | 6,687 |
| Jan-86 | 7,407 | 7,238 | 7,264 | 7,234 | 7,268 |
| Feb-86 | 8,500 | 8,500 | 8,500 | 8,500 | 8,500 |
| Mar-86 | 5,388 | 5,384 | 5,460 | 5,002 | 6,084 |
| Apr-86 | 4,901 | 4,149 | 4,423 | 4,276 | 4,806 |
| May-86 | 4,988 | 3,857 | 4,063 | 2,623 | 4,857 |
| Jun-86 | 2,020 | 3,206 | 3,323 | 3,329 | 3,288 |
| Jul-86 | 6,680 | 5,564 | 6,680 | 5,711 | 6,680 |
| Aug-86 | 6,680 | 5,297 | 5,562 | 5,319 | 6,680 |
| Sep-86 | 6,680 | 5,134 | 5,253 | 5,098 | 6,102 |
| Oct-86 | 4,471 | 3,129 | 2,563 | 3,236 | 3,110 |
| Nov-86 | 1,302 | 1,147 | 1,445 | 1,251 | 1,445 |
| Dec-86 | 2,356 | 3,245 | 2,325 | 2,916 | 2,166 |
| Jan-87 | 6,572 | 4,826 | 4,640 | 4,970 | 5,308 |
| Feb-87 | 7,360 | 6,872 | 7,356 | 7,210 | 7,360 |
| Mar-87 | 5,086 | 4,197 | 4,435 | 4,156 | 4,764 |
| Apr-87 | 2,141 | 300 | 300 | 300 | 2,064 |
| May-87 | 300 | 300 | 300 | 300 | 300 |
| Jun-87 | 300 | 300 | 300 | 300 | 526 |
| Jul-87 | 3,445 | 810 | 1,071 | 985 | 2,692 |
| Aug-87 | 5,279 | 3,225 | 4,076 | 2,304 | 5,073 |
| Sep-87 | 3,863 | 2,927 | 3,056 | 2,910 | 3,498 |

**Table 5.37: DSM2 Input from CalSim-II: State Water Project Exports (cfs) (cont.)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-87 | 2,809 | 2,360 | 2,481 | 2,263 | 2,860 |
| Nov-87 | 2,071 | 1,875 | 2,146 | 1,985 | 2,175 |
| Dec-87 | 6,629 | 6,341 | 6,220 | 6,375 | 3,961 |
| Jan-88 | 7,107 | 7,070 | 7,075 | 7,071 | 7,100 |
| Feb-88 | 1,428 | 1,588 | 1,612 | 1,322 | 1,368 |
| Mar-88 | 511 | 702 | 664 | 1,102 | 1,424 |
| Apr-88 | 1,482 | 1,448 | 1,464 | 1,450 | 1,507 |
| May-88 | 1,407 | 1,412 | 1,411 | 1,411 | 1,399 |
| Jun-88 | 300 | 1,043 | 300 | 892 | 803 |
| Jul-88 | 482 | 300 | 300 | 300 | 382 |
| Aug-88 | 300 | 300 | 300 | 300 | 300 |
| Sep-88 | 942 | 1,005 | 950 | 966 | 876 |
| Oct-88 | 1,138 | 910 | 1,049 | 772 | 820 |
| Nov-88 | 2,515 | 2,167 | 2,742 | 2,573 | 2,810 |
| Dec-88 | 2,780 | 3,420 | 2,456 | 3,057 | 2,273 |
| Jan-89 | 3,282 | 3,395 | 3,246 | 3,554 | 3,660 |
| Feb-89 | 1,212 | 1,308 | 1,377 | 1,222 | 1,156 |
| Mar-89 | 6,937 | 6,937 | 6,937 | 6,936 | 6,937 |
| Apr-89 | 2,551 | 300 | 2,468 | 300 | 300 |
| May-89 | 1,975 | 2,489 | 1,974 | 2,488 | 2,504 |
| Jun-89 | 3,345 | 2,589 | 4,465 | 2,569 | 2,370 |
| Jul-89 | 6,670 | 6,680 | 4,086 | 6,680 | 6,680 |
| Aug-89 | 6,275 | 5,862 | 6,680 | 6,191 | 6,680 |
| Sep-89 | 6,328 | 4,834 | 5,076 | 4,860 | 6,680 |
| Oct-89 | 4,778 | 3,580 | 3,983 | 3,617 | 5,591 |
| Nov-89 | 2,198 | 2,299 | 2,836 | 2,259 | 2,158 |
| Dec-89 | 300 | 4,944 | 5,144 | 5,049 | 5,641 |
| Jan-90 | 7,078 | 7,074 | 7,075 | 7,076 | 7,080 |
| Feb-90 | 2,385 | 2,546 | 2,686 | 2,391 | 2,410 |
| Mar-90 | 2,530 | 2,667 | 2,604 | 2,718 | 3,041 |
| Apr-90 | 300 | 300 | 300 | 300 | 300 |
| May-90 | 1,358 | 1,320 | 1,344 | 1,318 | 1,377 |
| Jun-90 | 2,074 | 300 | 300 | 300 | 300 |
| Jul-90 | 300 | 300 | 300 | 300 | 300 |
| Aug-90 | 1,430 | 300 | 300 | 300 | 300 |
| Sep-90 | 1,794 | 1,777 | 1,744 | 1,719 | 1,793 |
| Oct-90 | 1,023 | 862 | 1,117 | 671 | 1,169 |
| Nov-90 | 1,361 | 300 | 609 | 300 | 888 |
| Dec-90 | 1,306 | 300 | 1,324 | 300 | 1,351 |
| Jan-91 | 921 | 1,591 | 1,277 | 1,888 | 1,710 |
| Feb-91 | 1,254 | 1,178 | 1,173 | 976 | 1,048 |
| Mar-91 | 7,065 | 7,064 | 7,065 | 7,064 | 7,065 |
| Apr-91 | 1,801 | 1,270 | 1,389 | 1,419 | 2,084 |
| May-91 | 1,478 | 1,370 | 1,412 | 1,400 | 1,495 |
| Jun-91 | 300 | 300 | 300 | 300 | 2,022 |
| Jul-91 | 555 | 300 | 446 | 423 | 655 |
| Aug-91 | 300 | 382 | 300 | 300 | 300 |
| Sep-91 | 983 | 2,475 | 1,609 | 967 | 890 |

**Table 5.38: DSM2 Input from CalSim-II: Central Valley Project Exports (cfs)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-75 | 4,600 | 4,449 | 4,600 | 4,554 | 4,600 |
| Nov-75 | 4,600 | 3,497 | 4,600 | 4,600 | 4,600 |
| Dec-75 | 4,600 | 800 | 1,200 | 800 | 4,342 |
| Jan-76 | 4,229 | 4,600 | 4,600 | 4,600 | 4,183 |
| Feb-76 | 3,174 | 3,723 | 4,071 | 3,740 | 3,417 |
| Mar-76 | 2,717 | 2,757 | 2,758 | 2,303 | 2,291 |
| Apr-76 | 1,721 | 1,557 | 1,638 | 1,551 | 1,677 |
| May-76 | 1,517 | 1,357 | 1,436 | 1,352 | 1,479 |
| Jun-76 | 1,436 | 1,753 | 1,853 | 2,031 | 1,480 |
| Jul-76 | 1,315 | 1,602 | 1,752 | 1,940 | 1,357 |
| Aug-76 | 2,518 | 1,756 | 1,830 | 2,001 | 2,345 |
| Sep-76 | 3,242 | 3,271 | 3,302 | 3,257 | 3,247 |
| Oct-76 | 2,448 | 3,625 | 3,637 | 3,565 | 3,024 |
| Nov-76 | 1,767 | 2,780 | 2,481 | 2,172 | 1,842 |
| Dec-76 | 1,689 | 1,841 | 1,590 | 2,197 | 950 |
| Jan-77 | 2,489 | 2,387 | 2,623 | 2,134 | 2,504 |
| Feb-77 | 2,616 | 800 | 800 | 800 | 955 |
| Mar-77 | 800 | 800 | 800 | 800 | 800 |
| Apr-77 | 800 | 800 | 800 | 800 | 800 |
| May-77 | 800 | 800 | 800 | 800 | 1,105 |
| Jun-77 | 1,026 | 800 | 800 | 800 | 2,643 |
| Jul-77 | 2,509 | 600 | 1,927 | 1,813 | 2,272 |
| Aug-77 | 2,979 | 1,789 | 2,732 | 2,679 | 2,979 |
| Sep-77 | 3,078 | 1,889 | 3,169 | 3,101 | 3,083 |
| Oct-77 | 3,050 | 1,013 | 600 | 600 | 3,051 |
| Nov-77 | 1,489 | 1,758 | 1,420 | 1,444 | 1,691 |
| Dec-77 | 4,600 | 3,795 | 4,209 | 4,427 | 4,257 |
| Jan-78 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-78 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Mar-78 | 1,894 | 4,262 | 4,091 | 3,681 | 2,206 |
| Apr-78 | 2,692 | 2,538 | 2,692 | 2,692 | 2,692 |
| May-78 | 3,896 | 3,896 | 3,896 | 3,896 | 3,896 |
| Jun-78 | 4,600 | 4,046 | 4,600 | 4,047 | 4,600 |
| Jul-78 | 4,600 | 3,354 | 4,600 | 3,546 | 4,600 |
| Aug-78 | 4,600 | 4,232 | 4,488 | 4,323 | 4,600 |
| Sep-78 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Oct-78 | 4,600 | 3,885 | 4,390 | 3,954 | 4,600 |
| Nov-78 | 3,964 | 2,907 | 2,872 | 2,906 | 3,325 |
| Dec-78 | 3,010 | 4,377 | 2,914 | 4,377 | 2,993 |
| Jan-79 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-79 | 4,548 | 4,600 | 4,600 | 4,600 | 4,600 |
| Mar-79 | 2,589 | 4,600 | 4,600 | 4,600 | 4,281 |
| Apr-79 | 3,646 | 3,844 | 3,284 | 3,626 | 3,647 |
| May-79 | 3,718 | 2,948 | 3,334 | 3,018 | 3,795 |
| Jun-79 | 4,161 | 800 | 3,811 | 1,247 | 4,211 |
| Jul-79 | 3,999 | 800 | 800 | 1,191 | 4,596 |
| Aug-79 | 4,549 | 3,838 | 4,008 | 4,048 | 3,822 |
| Sep-79 | 4,478 | 4,389 | 4,401 | 4,397 | 4,478 |

**Table 5.38: DSM2 Input from CalSim-II: Central Valley Project Exports (cfs)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-79 | 3,620 | 3,220 | 3,071 | 3,074 | 3,495 |
| Nov-79 | 4,013 | 3,913 | 3,844 | 3,644 | 4,146 |
| Dec-79 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jan-80 | 4,600 | 4,015 | 4,600 | 4,600 | 4,600 |
| Feb-80 | 4,600 | 943 | 1,655 | 1,419 | 4,273 |
| Mar-80 | 2,591 | 1,335 | 1,537 | 1,401 | 1,944 |
| Apr-80 | 2,699 | 1,951 | 2,252 | 2,155 | 2,699 |
| May-80 | 3,884 | 2,819 | 3,239 | 3,102 | 3,884 |
| Jun-80 | 4,600 | 3,405 | 3,407 | 3,433 | 3,512 |
| Jul-80 | 4,600 | 1,186 | 3,720 | 2,010 | 4,310 |
| Aug-80 | 4,600 | 2,563 | 3,727 | 3,105 | 4,578 |
| Sep-80 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Oct-80 | 4,600 | 3,289 | 4,083 | 3,246 | 4,351 |
| Nov-80 | 3,231 | 2,900 | 2,895 | 3,212 | 3,659 |
| Dec-80 | 4,227 | 4,159 | 4,223 | 4,222 | 4,227 |
| Jan-81 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-81 | 4,349 | 4,600 | 4,600 | 4,600 | 4,600 |
| Mar-81 | 2,892 | 4,600 | 2,394 | 4,600 | 4,600 |
| Apr-81 | 2,707 | 2,564 | 2,801 | 2,544 | 2,890 |
| May-81 | 2,127 | 1,935 | 2,126 | 1,915 | 2,152 |
| Jun-81 | 2,897 | 3,073 | 4,214 | 3,833 | 2,729 |
| Jul-81 | 4,600 | 4,023 | 4,600 | 4,175 | 4,600 |
| Aug-81 | 4,600 | 3,407 | 3,893 | 3,521 | 4,080 |
| Sep-81 | 4,600 | 4,228 | 4,400 | 4,247 | 4,309 |
| Oct-81 | 4,129 | 2,581 | 2,729 | 2,771 | 2,912 |
| Nov-81 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Dec-81 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jan-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Mar-82 | 4,600 | 3,542 | 4,600 | 4,600 | 4,229 |
| Apr-82 | 3,954 | 2,690 | 2,897 | 2,973 | 2,690 |
| May-82 | 3,895 | 3,895 | 3,895 | 3,895 | 3,895 |
| Jun-82 | 4,600 | 4,571 | 4,571 | 4,571 | 4,600 |
| Jul-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Aug-82 | 4,600 | 3,302 | 4,578 | 3,416 | 4,600 |
| Sep-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Oct-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Nov-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Dec-82 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jan-83 | 3,741 | 4,600 | 3,995 | 4,600 | 3,970 |
| Feb-83 | 2,251 | 4,298 | 2,251 | 4,173 | 2,251 |
| Mar-83 | 1,955 | 1,955 | 1,955 | 1,955 | 1,955 |
| Apr-83 | 2,687 | 2,687 | 2,687 | 2,687 | 2,687 |
| May-83 | 3,892 | 3,892 | 3,892 | 3,892 | 3,892 |
| Jun-83 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jul-83 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Aug-83 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Sep-83 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |

**Table 5.38: DSM2 Input from CalSim-II: Central Valley Project Exports (cfs)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-83 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Nov-83 | 3,310 | 4,093 | 4,093 | 4,093 | 4,006 |
| Dec-83 | 1,445 | 1,445 | 1,445 | 1,445 | 1,445 |
| Jan-84 | 1,919 | 1,919 | 1,919 | 1,919 | 1,919 |
| Feb-84 | 2,869 | 2,173 | 2,173 | 2,872 | 2,692 |
| Mar-84 | 3,032 | 2,154 | 2,898 | 2,741 | 3,026 |
| Apr-84 | 3,499 | 2,743 | 3,188 | 3,413 | 3,356 |
| May-84 | 2,899 | 2,781 | 2,825 | 2,776 | 2,916 |
| Jun-84 | 3,974 | 3,274 | 4,039 | 3,381 | 3,880 |
| Jul-84 | 4,600 | 3,591 | 4,483 | 3,717 | 4,590 |
| Aug-84 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Sep-84 | 4,600 | 4,128 | 4,394 | 4,151 | 4,600 |
| Oct-84 | 4,468 | 3,589 | 3,888 | 3,403 | 4,533 |
| Nov-84 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Dec-84 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jan-85 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-85 | 4,600 | 4,490 | 4,600 | 4,438 | 4,600 |
| Mar-85 | 3,523 | 3,204 | 3,846 | 3,593 | 4,378 |
| Apr-85 | 2,356 | 2,230 | 2,221 | 2,249 | 2,393 |
| May-85 | 2,497 | 1,912 | 2,469 | 2,219 | 2,387 |
| Jun-85 | 2,795 | 2,843 | 2,790 | 2,829 | 2,833 |
| Jul-85 | 4,600 | 3,103 | 4,600 | 4,416 | 4,600 |
| Aug-85 | 4,600 | 2,669 | 4,386 | 3,712 | 4,073 |
| Sep-85 | 4,191 | 4,423 | 4,529 | 4,532 | 3,927 |
| Oct-85 | 3,006 | 2,036 | 2,867 | 2,588 | 3,049 |
| Nov-85 | 2,765 | 2,842 | 2,671 | 2,820 | 4,129 |
| Dec-85 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Jan-86 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-86 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Mar-86 | 4,600 | 4,600 | 4,573 | 4,600 | 3,828 |
| Apr-86 | 2,254 | 1,725 | 1,808 | 1,865 | 2,049 |
| May-86 | 3,016 | 2,318 | 2,627 | 2,340 | 2,962 |
| Jun-86 | 4,600 | 2,785 | 3,323 | 3,329 | 3,288 |
| Jul-86 | 3,097 | 800 | 800 | 800 | 1,651 |
| Aug-86 | 4,525 | 3,383 | 3,345 | 3,161 | 4,522 |
| Sep-86 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Oct-86 | 4,600 | 3,377 | 3,988 | 3,145 | 4,217 |
| Nov-86 | 4,424 | 3,683 | 3,896 | 3,681 | 4,569 |
| Dec-86 | 2,622 | 2,084 | 2,822 | 2,316 | 2,789 |
| Jan-87 | 2,590 | 4,221 | 4,223 | 4,221 | 4,393 |
| Feb-87 | 2,336 | 3,676 | 3,287 | 3,570 | 2,926 |
| Mar-87 | 1,901 | 1,526 | 1,677 | 1,533 | 1,885 |
| Apr-87 | 2,141 | 800 | 800 | 800 | 2,064 |
| May-87 | 1,507 | 956 | 1,182 | 1,194 | 1,730 |
| Jun-87 | 2,001 | 1,072 | 1,438 | 1,458 | 2,949 |
| Jul-87 | 2,015 | 879 | 1,315 | 1,339 | 3,138 |
| Aug-87 | 1,895 | 800 | 1,117 | 1,436 | 2,740 |
| Sep-87 | 3,440 | 2,715 | 2,830 | 2,526 | 3,751 |

**Table 5.38: DSM2 Input from CalSim-II: Central Valley Project Exports (cfs)**

| Date | BASE | GFDL A2 | PCM A2 | GFDL B1 | PCM B1 |
|---|---|---|---|---|---|
| Oct-87 | 2,102 | 2,778 | 2,603 | 2,960 | 2,904 |
| Nov-87 | 3,080 | 2,841 | 2,593 | 2,634 | 3,024 |
| Dec-87 | 4,600 | 4,600 | 4,600 | 4,600 | 1,241 |
| Jan-88 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-88 | 4,600 | 1,106 | 1,314 | 1,279 | 4,600 |
| Mar-88 | 800 | 800 | 800 | 800 | 800 |
| Apr-88 | 1,482 | 1,448 | 1,464 | 1,450 | 1,507 |
| May-88 | 1,407 | 1,412 | 1,411 | 1,411 | 1,399 |
| Jun-88 | 1,093 | 1,132 | 1,245 | 1,348 | 1,990 |
| Jul-88 | 878 | 883 | 800 | 1,125 | 1,857 |
| Aug-88 | 1,125 | 916 | 1,511 | 1,280 | 1,995 |
| Sep-88 | 2,814 | 2,849 | 2,820 | 2,830 | 2,785 |
| Oct-88 | 3,097 | 3,034 | 3,089 | 3,022 | 3,099 |
| Nov-88 | 2,434 | 2,577 | 2,321 | 2,463 | 2,470 |
| Dec-88 | 3,557 | 2,995 | 3,723 | 3,226 | 3,696 |
| Jan-89 | 4,213 | 4,211 | 4,211 | 4,211 | 4,212 |
| Feb-89 | 2,720 | 2,746 | 2,769 | 2,721 | 2,704 |
| Mar-89 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Apr-89 | 2,551 | 2,670 | 2,468 | 2,668 | 2,684 |
| May-89 | 1,975 | 2,489 | 1,974 | 2,488 | 2,504 |
| Jun-89 | 2,544 | 1,273 | 1,298 | 1,778 | 2,370 |
| Jul-89 | 2,658 | 800 | 1,201 | 1,781 | 3,380 |
| Aug-89 | 2,390 | 1,009 | 1,198 | 1,418 | 2,914 |
| Sep-89 | 4,426 | 4,600 | 4,600 | 4,600 | 4,121 |
| Oct-89 | 2,719 | 2,325 | 2,333 | 2,337 | 2,625 |
| Nov-89 | 1,959 | 2,019 | 1,872 | 1,728 | 3,475 |
| Dec-89 | 800 | 1,189 | 1,367 | 1,610 | 2,128 |
| Jan-90 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Feb-90 | 4,600 | 3,451 | 3,488 | 3,413 | 4,600 |
| Mar-90 | 2,530 | 2,667 | 2,604 | 2,718 | 2,287 |
| Apr-90 | 800 | 800 | 800 | 800 | 800 |
| May-90 | 1,358 | 1,320 | 1,344 | 1,318 | 1,377 |
| Jun-90 | 1,278 | 800 | 800 | 1,430 | 1,042 |
| Jul-90 | 1,039 | 800 | 800 | 800 | 800 |
| Aug-90 | 1,339 | 2,223 | 1,675 | 1,887 | 1,099 |
| Sep-90 | 2,821 | 2,821 | 2,821 | 2,821 | 2,826 |
| Oct-90 | 2,697 | 2,952 | 2,955 | 2,941 | 3,022 |
| Nov-90 | 1,485 | 2,140 | 1,459 | 2,397 | 1,510 |
| Dec-90 | 2,019 | 1,631 | 998 | 1,327 | 800 |
| Jan-91 | 1,668 | 1,515 | 1,821 | 1,449 | 1,669 |
| Feb-91 | 1,262 | 822 | 1,082 | 1,056 | 1,167 |
| Mar-91 | 4,600 | 4,600 | 4,600 | 4,600 | 4,600 |
| Apr-91 | 1,491 | 1,576 | 1,793 | 1,760 | 2,084 |
| May-91 | 1,478 | 1,370 | 1,412 | 1,400 | 1,495 |
| Jun-91 | 1,656 | 600 | 861 | 600 | 2,022 |
| Jul-91 | 800 | 600 | 600 | 600 | 1,508 |
| Aug-91 | 2,034 | 600 | 2,270 | 1,498 | 1,946 |
| Sep-91 | 3,520 | 1,017 | 2,362 | 3,450 | 3,498 |

**Table 5.39: DSM2 Input from CalSim-II: Contra Costa Water District Diversions (cfs)**

| Water Yr | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1976 | 220 | 187 | 148 | 120 | 99 | 197 | 0 | 145 | 249 | 164 | 168 | 279 |
| 1977 | 241 | 66 | 49 | 115 | 162 | 197 | 180 | 241 | 249 | 324 | 273 | 279 |
| 1978 | 241 | 193 | 177 | 143 | 162 | 99 | 111 | 220 | 281 | 511 | 538 | 464 |
| 1979 | 413 | 183 | 172 | 120 | 103 | 200 | 0 | 220 | 474 | 329 | 356 | 264 |
| 1980 | 236 | 183 | 146 | 120 | 61 | 99 | 0 | 220 | 418 | 327 | 355 | 264 |
| 1981 | 236 | 188 | 146 | 120 | 103 | 99 | 0 | 220 | 430 | 332 | 356 | 264 |
| 1982 | 236 | 185 | 145 | 120 | 103 | 34 | 0 | 220 | 479 | 327 | 355 | 264 |
| 1983 | 233 | 185 | 145 | 120 | 103 | 99 | 0 | 220 | 410 | 329 | 356 | 279 |
| 1984 | 223 | 143 | 181 | 122 | 101 | 99 | 0 | 220 | 435 | 329 | 356 | 281 |
| 1985 | 224 | 183 | 145 | 120 | 103 | 99 | 0 | 220 | 434 | 330 | 356 | 264 |
| 1986 | 237 | 150 | 145 | 120 | 56 | 150 | 0 | 220 | 420 | 327 | 355 | 264 |
| 1987 | 234 | 183 | 145 | 120 | 103 | 99 | 0 | 220 | 437 | 329 | 338 | 264 |
| 1988 | 96 | 71 | 99 | 120 | 99 | 99 | 0 | 220 | 281 | 153 | 231 | 103 |
| 1989 | 213 | 183 | 145 | 120 | 103 | 99 | 111 | 220 | 481 | 511 | 538 | 264 |
| 1990 | 213 | 183 | 145 | 120 | 103 | 197 | 0 | 241 | 249 | 250 | 233 | 166 |
| 1991 | 184 | 193 | 177 | 143 | 162 | 197 | 180 | 241 | 249 | 324 | 273 | 279 |

Note: Values represent combined Old River at Rock Slough and Old River at Highway 4 diversions. CCWD diversions were identical for the base case and all climate change scenarios.

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## 5.12 Appendix B: Additional Chloride Exceedance Plots and Percentile Tables for Present Sea Level Scenarios

This appendix provides chloride exceedance plots and percentile tables computed from daily average DSM2 results at selected municipal and industrial intake locations.

- CCWD at Old River diversion at Highway 4 (Figure 5.17 and Table 5.40)
- SWP at Clifton Court Forebay (Figure 5.18 and Table 5.41)
- CVP at Tracy (Figure 5.19 and Table 5.42)

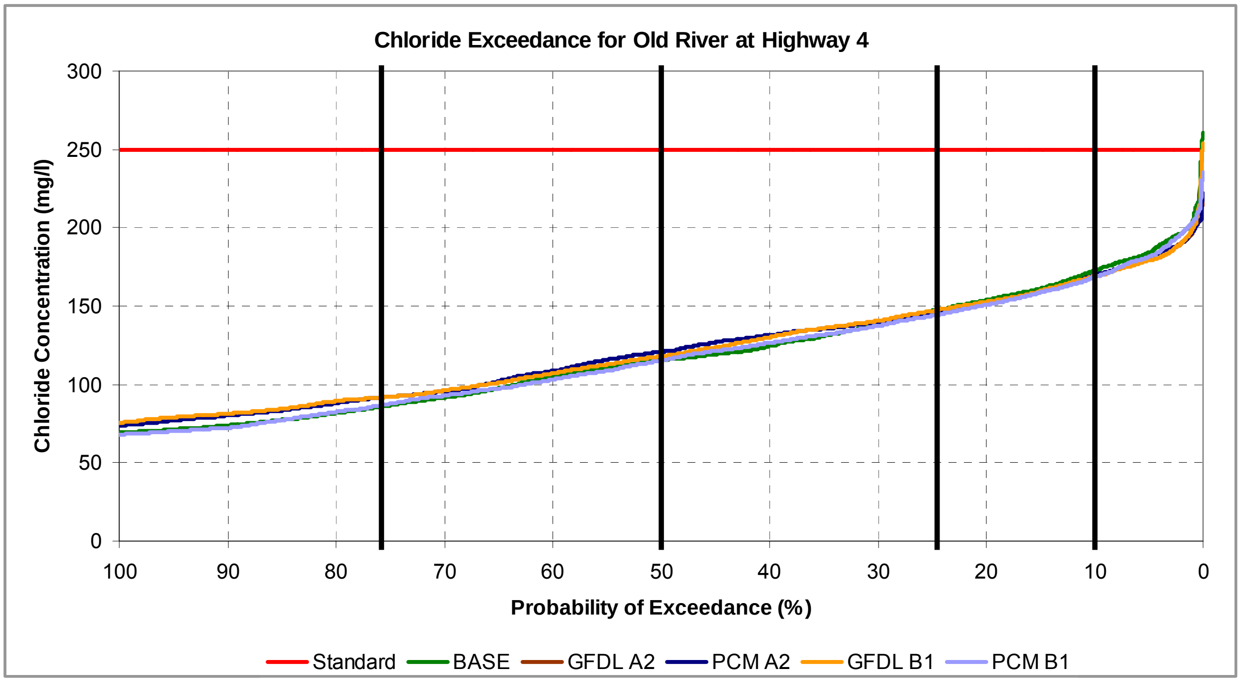



**Figure 5.17: Probability of Exceedance for Chlorides at Old River at Highway 4**

**Table 5.40: Chloride Concentration Percentiles (mg/l) for Old River at Highway 4**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 11 | 21 | 33 | 69 | 133 | 170 | 183 | 85 |
| GFDL A2 | 10 | 21 | 33 | 76 | 136 | 166 | 179 | 86 |
| PCM A2 | 10 | 20 | 32 | 74 | 137 | 167 | 180 | 86 |
| GFDL B1 | 14 | 22 | 35 | 75 | 137 | 167 | 179 | 87 |
| PCM B1 | 10 | 20 | 31 | 68 | 133 | 166 | 181 | 83 |

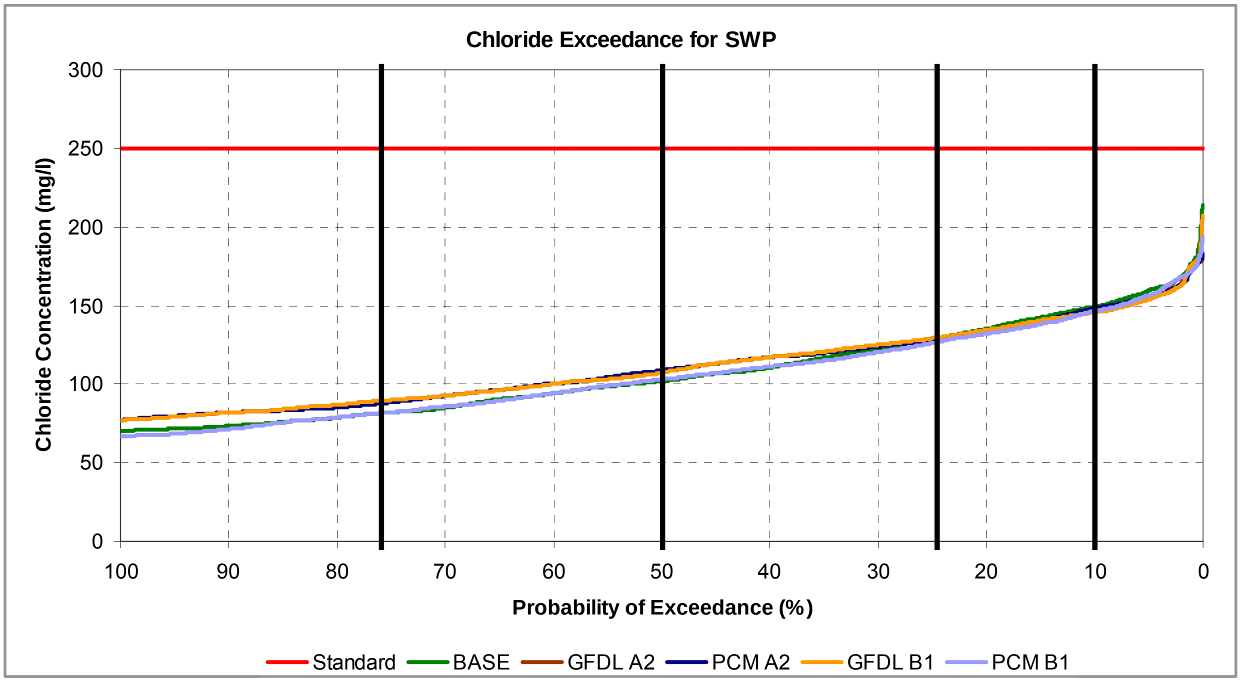



**Figure 5.18: Probability of Exceedance for Chlorides at the State Water Project**

**Table 5.41: Chloride Concentration Percentiles (mg/l) for the State Water Project**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 22 | 34 | 70 | 119 | 148 | 158 | 78 |
| GFDL A2 | 10 | 21 | 37 | 77 | 121 | 146 | 154 | 80 |
| PCM A2 | 10 | 20 | 35 | 77 | 121 | 146 | 154 | 80 |
| GFDL B1 | 10 | 25 | 39 | 77 | 122 | 145 | 153 | 81 |
| PCM B1 | 10 | 19 | 33 | 67 | 116 | 145 | 156 | 76 |

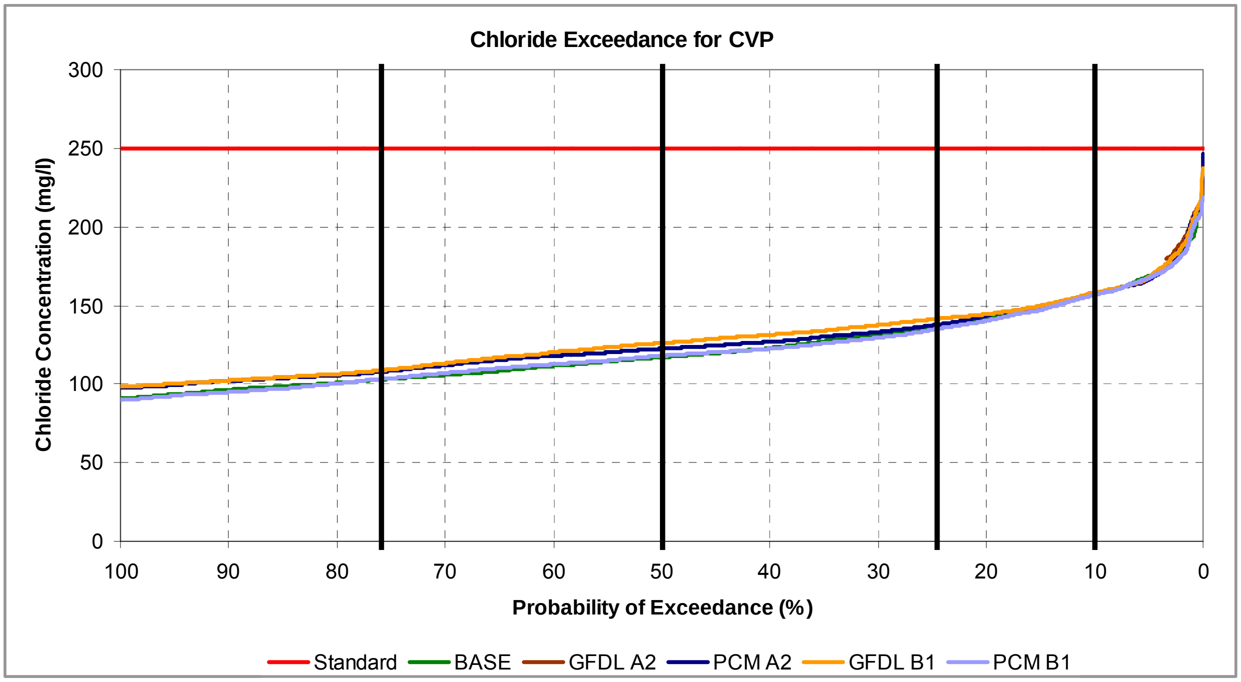



**Figure 5.19: Probability of Exceedance for Chlorides at the Central Valley Project**

**Table 5.42: Chloride Concentration Percentiles (mg/l) for the Central Valley Project**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 16 | 53 | 91 | 129 | 155 | 168 | 91 |
| GFDL A2 | 10 | 18 | 60 | 100 | 134 | 156 | 169 | 96 |
| PCM A2 | 10 | 15 | 56 | 97 | 131 | 156 | 166 | 94 |
| GFDL B1 | 11 | 26 | 60 | 99 | 135 | 156 | 167 | 97 |
| PCM B1 | 10 | 15 | 54 | 90 | 127 | 155 | 167 | 90 |

## 5.13 Appendix D: Additional Chloride Exceedance Plots and Percentile Tables for One-Foot Sea Level Scenarios

This appendix provides chloride exceedance plots and percentile tables computed from daily average DSM2 results for one-foot sea level rise scenarios at selected municipal and industrial intake locations. No operations changes were made to try to reduce the effects of sea level rise.

- CCWD at Old River diversion at Highway 4 (Figure 5.20 and Table 5.43)
- SWP at Clifton Court Forebay (Figure 5.21 and Table 5.44)
- CVP at Tracy (Figure 5.22 and Table 5.45)

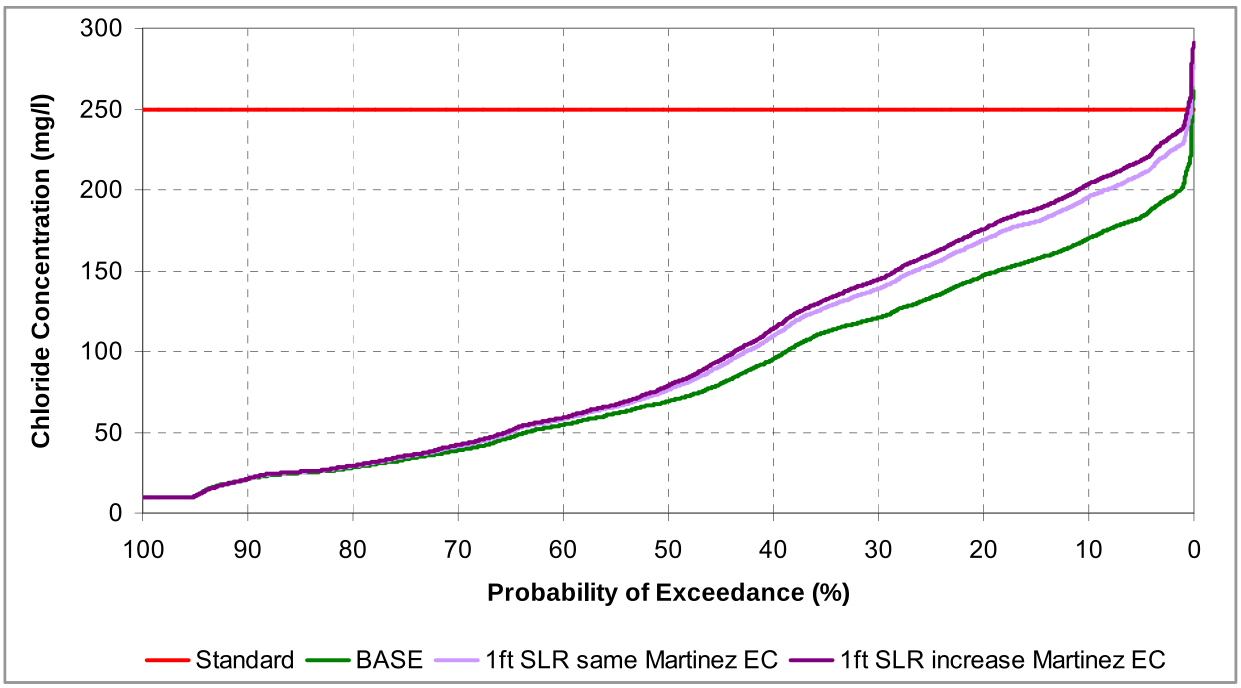



**Figure 5.20: Probability of Exceedance for Chlorides at Old R. at Hwy 4 for a One-Foot Sea Level Rise and no Changes in System Operations**

**Table 5.43: Chloride Concentration Percentiles (mg/l) for Old R. at Hwy 4 for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 11 | 21 | 33 | 69 | 133 | 170 | 183 | 85 |
| 1ft SLR same Martinez EC | 11 | 21 | 35 | 76 | 154 | 196 | 210 | 96 |
| 1ft SLR increase Martinez EC | 11 | 21 | 35 | 79 | 160 | 204 | 218 | 99 |

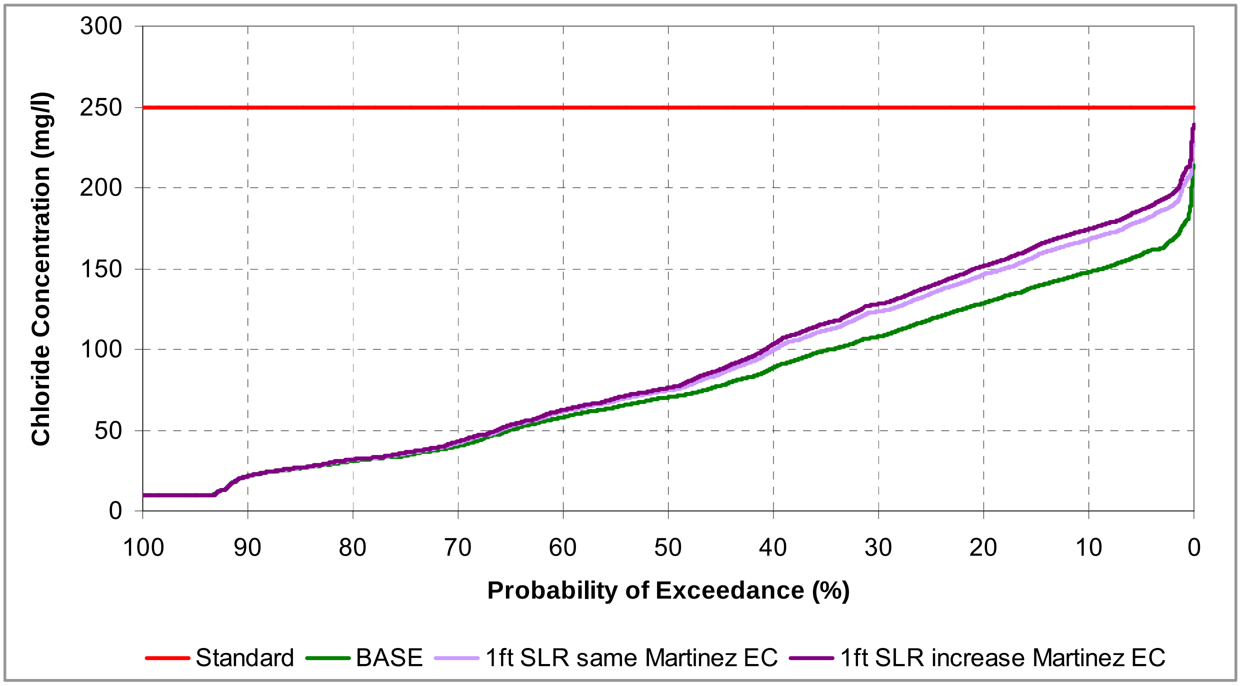



**Figure 5.21: Probability of Exceedance for Chlorides at the State Water Project for a One-Foot Sea Level Rise and no Changes in System Operations**

**Table 5.44: Chloride Concentration Percentiles (mg/l) for the State Water Project for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 22 | 34 | 70 | 119 | 148 | 158 | 78 |
| 1ft SLR same Martinez EC | 10 | 21 | 36 | 75 | 135 | 168 | 180 | 87 |
| 1ft SLR increase Martinez EC | 10 | 22 | 36 | 76 | 139 | 174 | 186 | 89 |

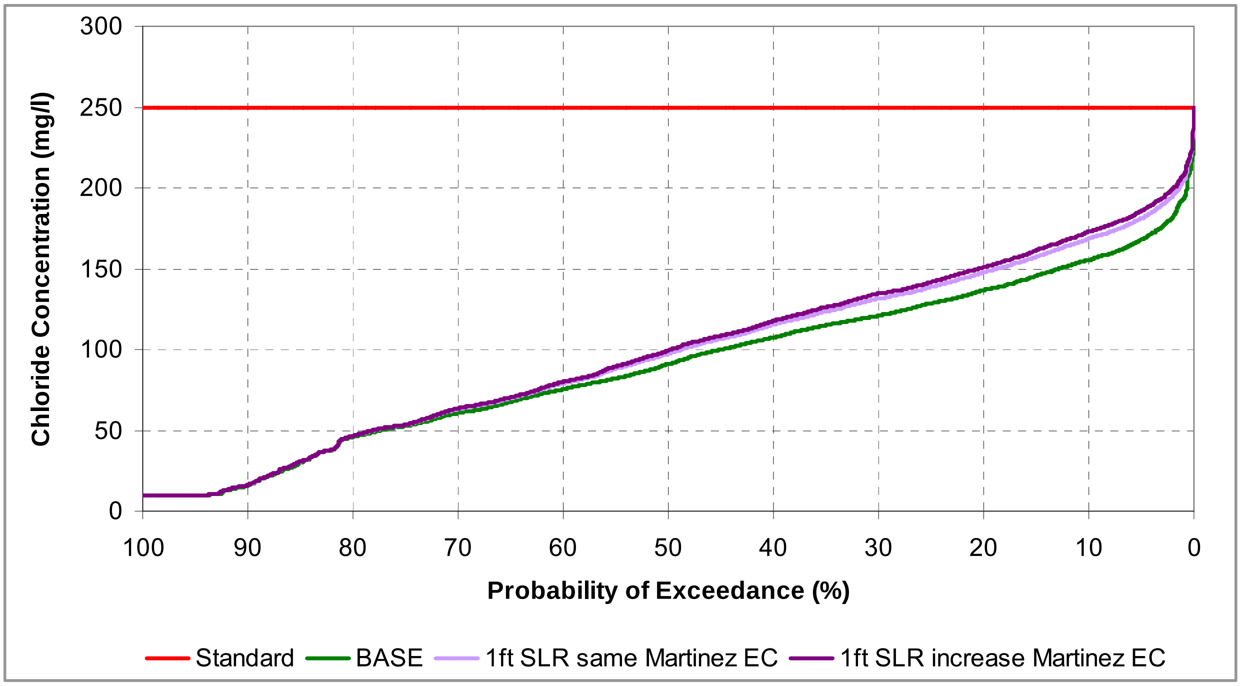



**Figure 5.22: Probability of Exceedance for Chlorides at the Central Valley Project for a One-Foot Sea Level Rise and no Changes in System Operations**

**Table 5.45: Chloride Concentration Percentiles (mg/l) for the Central Valley Project for a One-Foot Sea Level Rise and no Changes in System Operations**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 16 | 53 | 91 | 129 | 155 | 168 | 91 |
| 1ft SLR same Martinez EC | 10 | 16 | 53 | 97 | 139 | 169 | 181 | 97 |
| 1ft SLR increase Martinez EC | 10 | 16 | 53 | 99 | 142 | 173 | 186 | 98 |

## 5.14 Appendix E: Additional Chloride Exceedance Plots and Percentile Tables for Combined Climate Change and One-Foot Sea Level Scenarios

This appendix provides chloride exceedance plots and percentile tables computed from daily average DSM2 results for combined climate change and one-foot sea level rise scenarios at selected municipal and industrial intake locations. No changes in operations were made to account for sea level rise (SLR).

- CCWD at Old River diversion at Highway 4 (Figure 5.23 and Table 5.46)
- SWP at Clifton Court Forebay (Figure 5.24 and Table 5.47)
- CVP at Tracy (Figure 5.25 and Table 5.48)

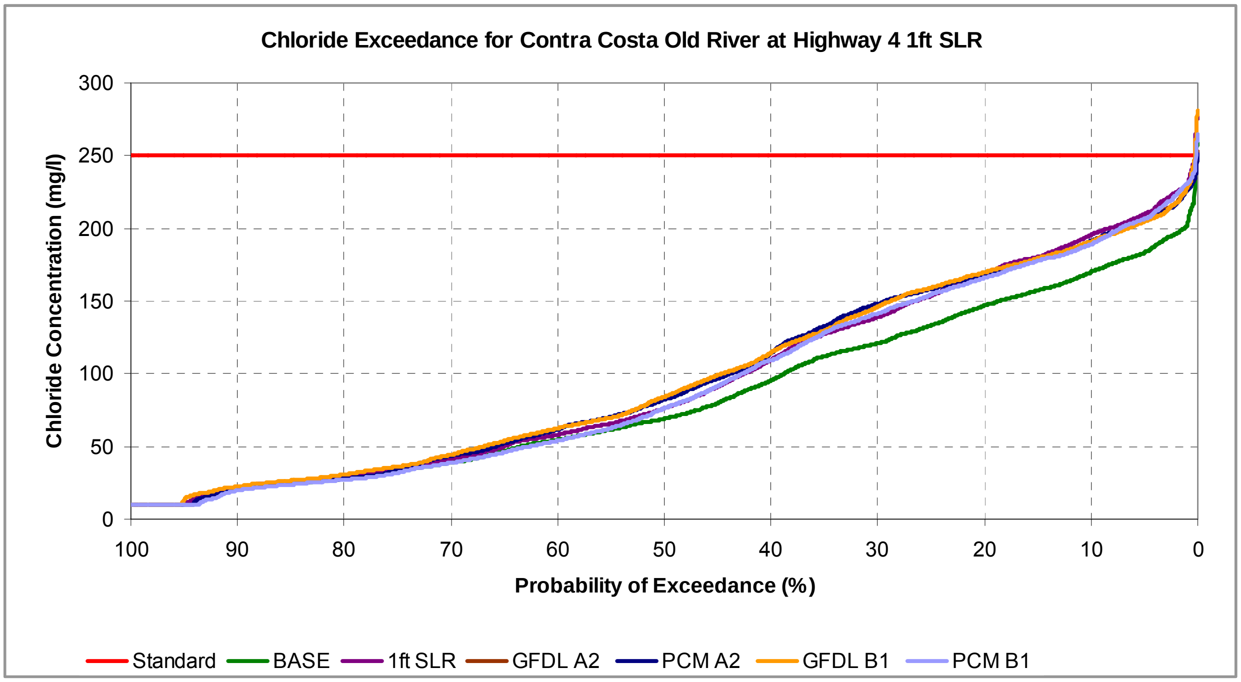



**Figure 5.23: Probability of Exceedance for Chlorides at Old River at Highway 4 for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

**Table 5.46: Chloride Concentration Percentiles (mg/l) for Old R. at Highway 4 for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 11 | 21 | 33 | 69 | 133 | 170 | 183 | 85 |
| 1ft SLR same Mtz EC | 11 | 21 | 35 | 76 | 154 | 196 | 210 | 96 |
| GFDL A2 1ft SLR | 10 | 21 | 35 | 85 | 158 | 191 | 205 | 97 |
| PCM A2 1ft SLR | 10 | 21 | 35 | 82 | 158 | 191 | 206 | 97 |
| GFDL B1 1ft SLR | 13 | 22 | 36 | 84 | 159 | 191 | 205 | 98 |
| PCM B1 1ft SLR | 10 | 20 | 32 | 76 | 154 | 189 | 207 | 94 |

*All sea level rise scenarios in this table assume that Martinez EC is the same as in the present sea level scenarios.

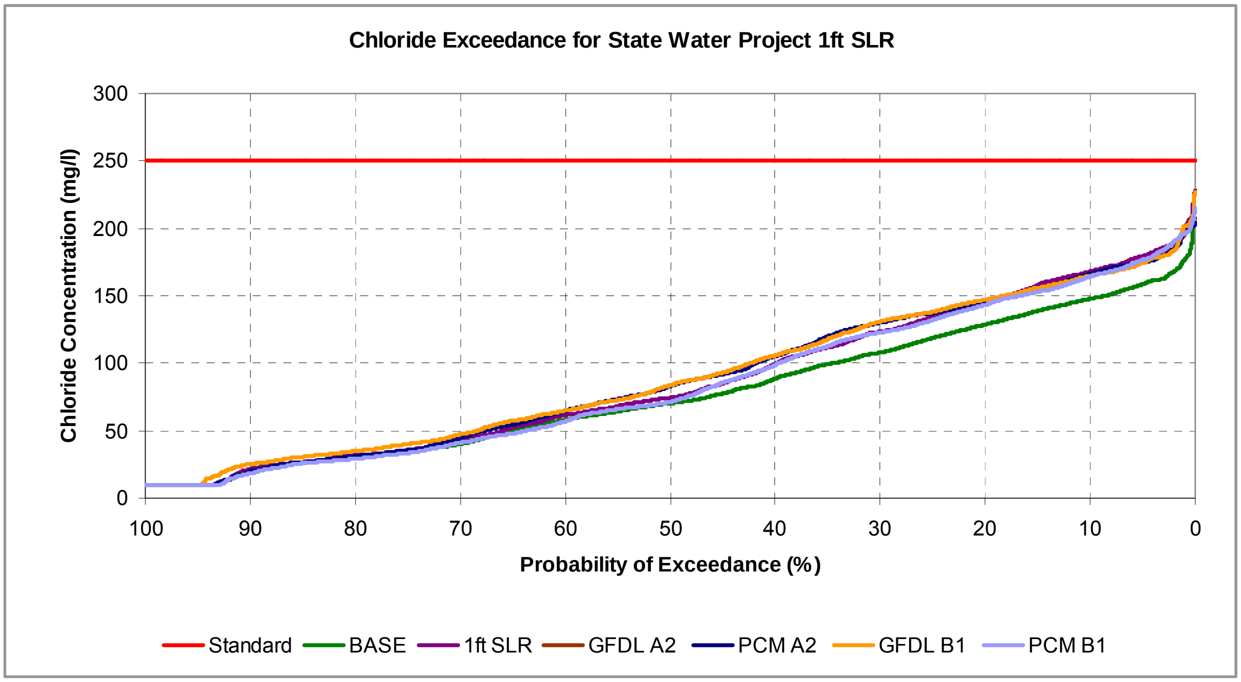



**Figure 5.24: Probability of Exceedance for Chlorides at the State Water Project for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

**Table 5.47: Chloride Concentration Percentiles (mg/l) for the State Water Project for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 22 | 34 | 70 | 119 | 148 | 158 | 78 |
| 1ft SLR same Mtz EC | 10 | 21 | 36 | 75 | 135 | 168 | 180 | 87 |
| GFDL A2 1ft SLR | 10 | 22 | 38 | 83 | 138 | 166 | 175 | 89 |
| PCM A2 1ft SLR | 10 | 20 | 35 | 83 | 137 | 166 | 175 | 89 |
| GFDL B1 1ft SLR | 10 | 25 | 40 | 84 | 138 | 165 | 174 | 90 |
| PCM B1 1ft SLR | 10 | 18 | 33 | 71 | 132 | 164 | 177 | 85 |

*All sea level rise scenarios in this table assume that Martinez EC is the same as in the present sea level scenarios.

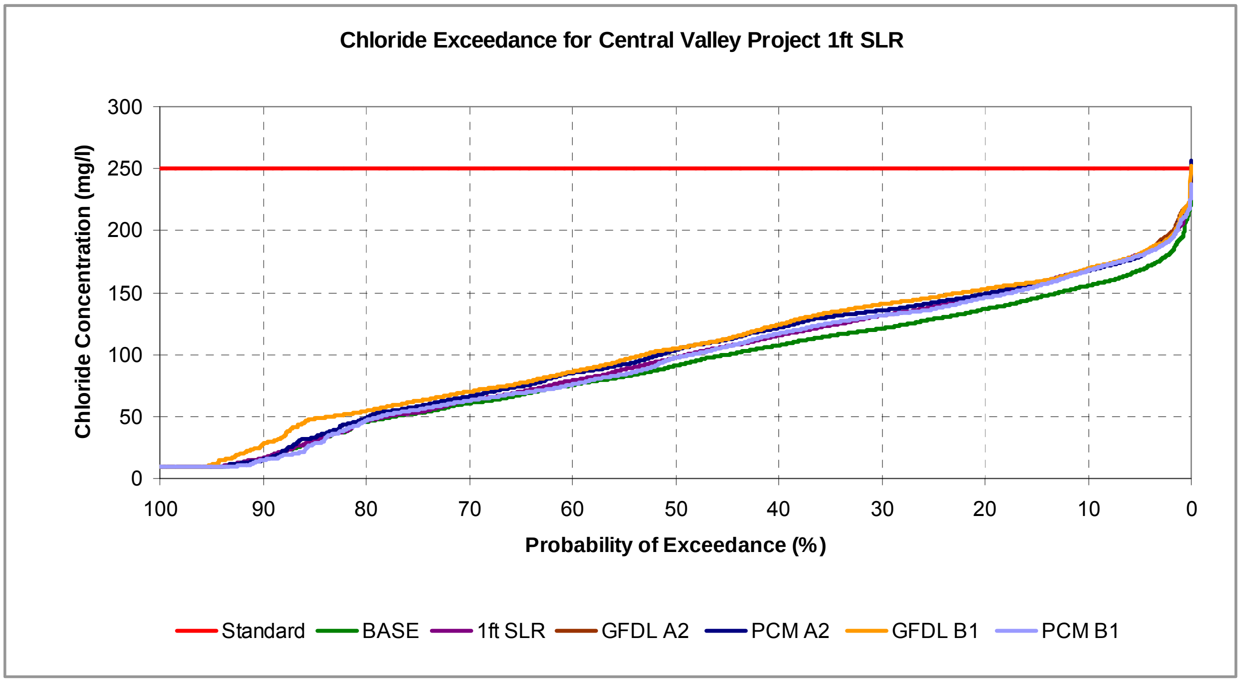



**Figure 5.25: Probability of Exceedance for Chlorides at the Central Valley Project for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

**Table 5.48: Chloride Concentration Percentiles (mg/l) for the Central Valley Project for Climate Change and a One-Foot Sea Level Rise and no Changes in Operations for SLR**

| | 5% | 10% | 25% | 50% | 75% | 90% | 95% | Avg |
|---|---|---|---|---|---|---|---|---|
| BASE | 10 | 16 | 53 | 91 | 129 | 155 | 168 | 91 |
| 1ft SLR same Mtz EC | 10 | 16 | 53 | 97 | 139 | 169 | 181 | 97 |
| GFDL A2 1ft SLR | 10 | 18 | 63 | 105 | 145 | 170 | 182 | 103 |
| PCM A2 1ft SLR | 10 | 15 | 58 | 104 | 142 | 168 | 179 | 100 |
| GFDL B1 1ft SLR | 11 | 28 | 63 | 105 | 146 | 169 | 181 | 103 |
| PCM B1 1ft SLR | 10 | 15 | 55 | 97 | 137 | 167 | 180 | 96 |

*All sea level rise scenarios in this table assume that Martinez EC is the same as in the present sea level scenarios.

# Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
**July 2006**

# Chapter 6:
# Climate Change Impacts on Flood Management

**Author:**

Michael Anderson, PhD, PE
California Department of Water Resources, Division of Flood Management, Hydrology Branch, Sacramento

**Contributors:**

[illegible]

[illegible]
California Department of Water Resources, Division of Flood Management, Hydrology Branch, Sacramento

**Peer Reviewers:**

[illegible]

[illegible]

# 6 Climate Change Impacts on Flood Management

## 6.1 Introduction

Changing climate can have a significant impact on the timing and magnitude of precipitation and runoff in California. Climate is the time-averaged state of temperature, winds, precipitation and runoff. Flooding, however, results from individual weather events which can be considered random phenomena on the time scale of climate (e.g. 30 to 50 years). From year to year, there is a large amount of variability in winter rainfall and associated runoff patterns. This large variability creates uncertainty when evaluating changes in weather events due to climate change.

One way to address this uncertainty is to look at long-term precipitation, temperature, and runoff records in California and identify any trends that may have occurred over the past century. Future change can then be inferred from trends identified in the past record. However, a straight extrapolation of historical trends into the future may not be accurate.

Climate modeling tries to simulate these nonlinear components and their evolution with changing greenhouse gas levels in the atmosphere. Results from these global-scale simulations have been downscaled to provide information on potential changes over California. However, the model results provided relate to climate properties, not weather properties. Because of this, the results cannot be used directly to evaluate changes in specific rainfall and runoff patterns leading to floods or to changes in frequency of floods or droughts.

The climate model simulation data can be used to compare simulated future trends in precipitation, temperature, and runoff to historical trends. The model-derived trends also can be used to guide extrapolation of historical trends. Based on these efforts and using some assumptions, changes in runoff to a given rainfall pattern can be estimated using watershed models.

Such analyses are just the start of work that needs to be completed to evaluate climate change impacts on precipitation and the associated water supply or flood runoff in California. This chapter presents the initial work that has been done and outlines future work and data needed to complete such work. The topics covered in this chapter are illustrated in Figure 6-1. This chapter starts with a literature review of work on climate change and runoff in California. The chapter then examines the historical record for existing trends and investigates the information that can be obtained from the climate change scenarios selected for study by the state's Climate Action Team. After discussing the elements of the climate change scenario data that are not suitable for flood analysis, the chapter concludes with a description of climate change scenario data that would be suitable for analyzing climate change impacts on flood frequency and outlines future work directions.  It is important to note that the work presented here is an analysis of past and potential future changes to California hydrology.  It is not a recommendation for making changes to existing flood risk, flood frequency, or water supply practices and analyses.

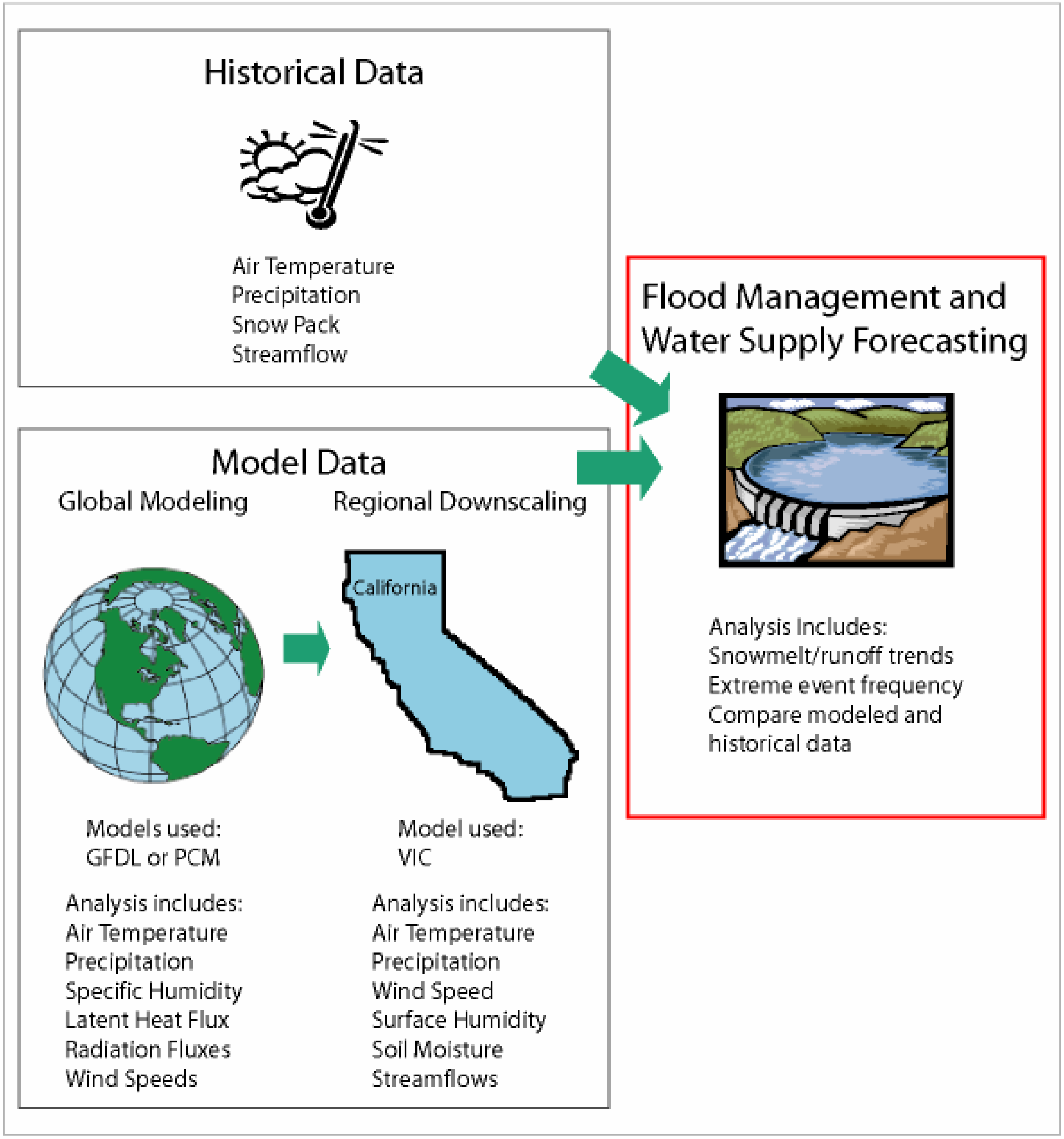



**Figure 6-1 Relation of climate change scenario simulations to flood analysis**

## 6.2 Literature Review of Flood Analysis and Climate Change

In 1988, the United Nations Environmental Programme and the World Meteorological Organization established the Intergovernmental Panel on Climate Change (IPCC). It released the First Assessment Report in 1990, the Second Assessment Report in 1995, and the Third Assessment Report in 2001 (IPCC FAR 1990, SAR 1995, TAR 2001). Beginning in 2000, the U.S. Global Climate Change Research Program (USGCRP) has released a series of regional and sectorial assessment reports. The IPCC TAR and USGCRP Report of the Water Sector (USGCRP Water 2001) provide up-to-date summaries of the potential consequences of global warming.

The IPCC reports that climate model projections with a transient 1 percent annual increase in greenhouse gas emissions show an increase in the global mean near-surface air temperature of 1.4 to 5.8 $^{o}$C, with a 95 percent probability interval of 1.7 to 4.9 $^{o}$C by 2100 (Wigley and Roper 2001). Both reports indicate that likely changes during the 21$^{st}$ century include: higher maximum and minimum temperatures with a decreasing diurnal range over U.S. land areas, more intense precipitation events, increased summer continental drying, and increased risk of drought. Climate model projections of precipitation amounts remains uncertain, however, the rain to snow ratio, at least in the Sierra Nevada appears to be increasing under the climate change scenarios discussed in the USGCRP Water Sector Report (USGCRP Water 2001).

Further research has been done to investigate the potential impacts of climate change on California hydrology using climate model projections and land surface-hydrology models. Table 6-1 lists the references grouped by the type of study conducted. As can be seen from Table 6-1, there are three main types of studies that have been conducted: regression studies, computer model simulation of watersheds using GCM data directly, and computer model simulation of watersheds using climate change data that has been downscaled. Downscaling means inferring finer detail data from the GCM results. This process is based on statistical properties of a region or through the use of a finer-grid scale dynamic model of the atmosphere and land surface.

**Table 6-1Climate Change Studies and Runoff in California**

| STUDY TYPE | REFERENCES |
|---|---|
| Regression | Revelle and Waggoner (1983)<br>Stewart et al. (2004) |
| GCM | Gleick (1987)<br>Lettenmaier and Gan (1990)<br>Dettinger et al. (2004) |
| GCM with Downscaling | Miller et al. (1999)<br>Knowles and Cayan (2001)<br>Wilby and Dettinger (2000)<br>Miller (2003)<br>Wood et al. (2004)<br>Van Rheenen et al. (2004)<br>Christensen et al. (2004)<br>Kim (2005)<br>Maurer and Duffy (2005) |
| Other | Jeton et al. (1996)<br>Bardini et al. (2001)<br>Knowles and Cayan (2004) |

Also noted in Table 6-1 are studies that do not fit into the above three categories. These studies include watershed studies with set incremental changes to temperature and precipitation (Jeton et al., 1996), an analysis of the changes to the Sacramento and San Joaquin River Delta associated with runoff changes in the upper watersheds (Knowles and Cayan, 2004), and an assessment of climate change data and known impacts to date combined with an assessment of mitigation measures for DWR (Bardini et al., 2001).

The consensus of the above-cited studies is that climate change will impact the timing and magnitude of runoff and flooding patterns in California. Expected impacts include more precipitation falling as rain rather than snow and an earlier melt to the winter snowpack. The uncertainty lies in the magnitude of these changes and any changes associated with the frequency and magnitude of future floods and droughts. The following sections investigate historical changes to precipitation, temperature, and runoff as well as potential changes identified by the latest climate change simulations and their associated consequences.

## 6.3 Historical Precipitation, Temperature, and Runoff Trends

Former state climatologist James Goodridge compiled an extensive collection of long-term precipitation and temperature data across the state. These data sets have been used to identify precipitation and temperature trends that have occurred in the last 100 years. Long-term runoff records in selected watersheds were also examined for trends. Results are presented below. In order to determine if the identified trends were statistically significant, a t-test with an alpha value of 0.05 was used.

### 6.3.1 Precipitation

Figure 6-2 shows the statewide average of annual precipitation from 102 stations across California from 1890 to 2002. The average annual precipitation for California of 23.8 inches has not changed significantly over the past century. In an effort to determine if there has been a change in precipitation distribution over the state, the precipitation records were sorted by latitude placed into three categories: south, central, and north. The division between south and central is 35 degrees north latitude and the division between central and north is 39 degrees north latitude.

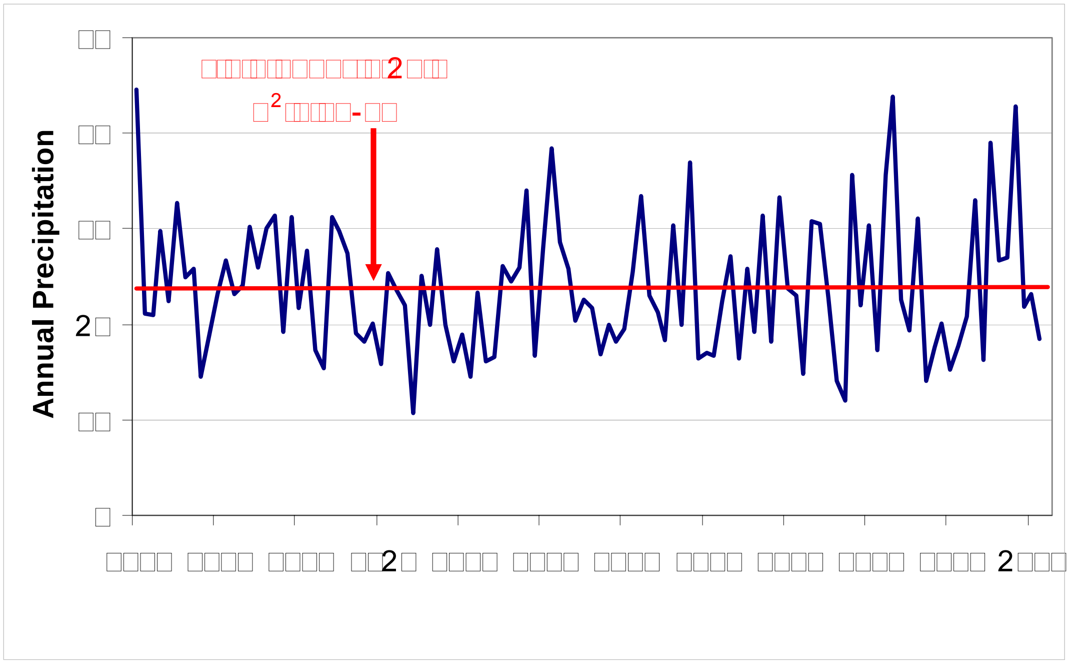


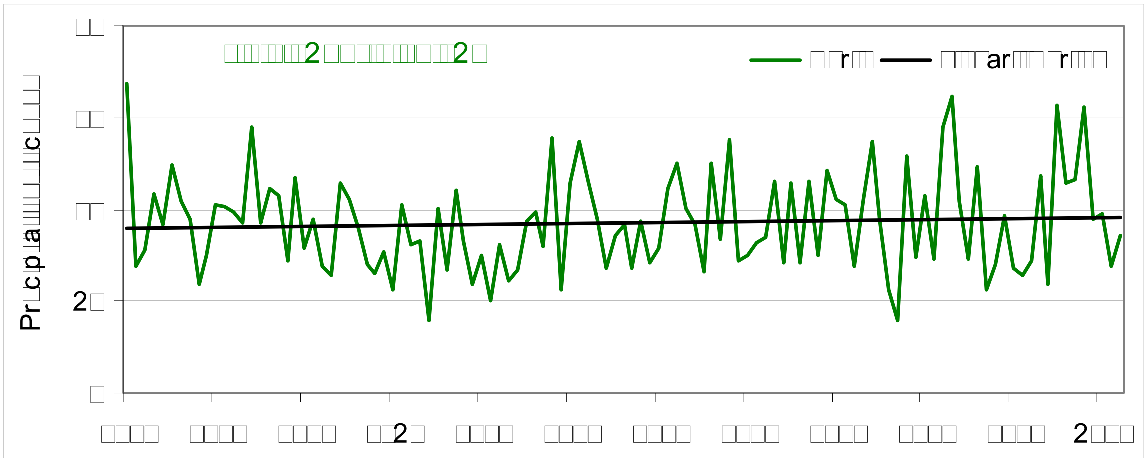

**Figure 6-2 Average annual precipitation for California 1890-2002 with trend line.**

Average annual precipitation is plotted with trend lines in Figure 6-3 for the south, central, and north regions for 1890-2002. The south and central regions both show a minor decreasing trend in precipitation while the north part of the state shows a minor increase. The trends do not yield a significant change in the average precipitation over the course of the century. But if focus is shifted to the last 30 years, an increasing trend can be found for all three regions as is shown in Figure 6-4. This may be an artifact of the big El Nino seasons of 1983 and 1998. Using the t-test, only the trends for central and northern California were determined to be statistically significant.

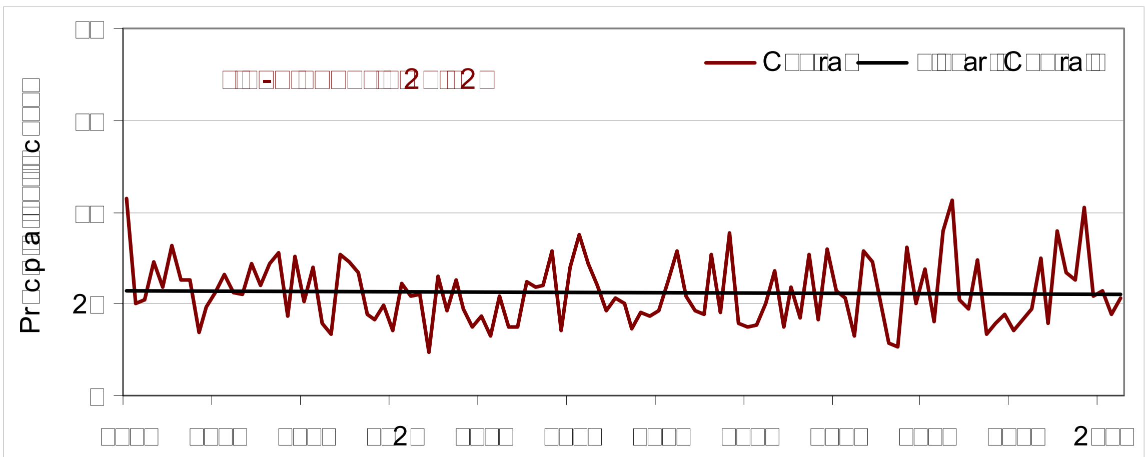
Figure 6-4 depicts annual precipitation for the three regions and a fit linear trend for the past 30 years. This increasing trend over the past 30 years is consistent with the research presented in Chapter 2 which points to increasing precipitation over the state. But it does contradict data presented in Bardini and others (2001). Their data pointed to potential decreasing precipitation. The differences can likely be related to the difference in the period selected to identify the trend. Extremes at the beginning or end of the time series can significantly impact the magnitude of the identified trend.

While the average precipitation has little or no trend over the past century, the variability has a distinct and statistically significant increase, which can be seen in Figure 6-5. Figure 6-5 depicts the coefficient of variation (standard deviation divided by the mean) based on a 10-year moving average of mean and standard deviation values of the annual precipitation time series. There is a distinct upward trend in the variability over the past century with end of period values about 75 percent larger than beginning- of-period values. This increase in variability is much larger than any of the linear trends identified in the average values of the data. There is some evidence from scattered precipitation measurements from 1850 to 1900 that the $19^{th}$ century was more variable than the $20^{th}$.

a) Northern Region: California-Oregon border to 39° latitude



b) Central Region: 35 ° - 39° latitude



c) Southern Region: 35 ° latitude to California-Mexico border

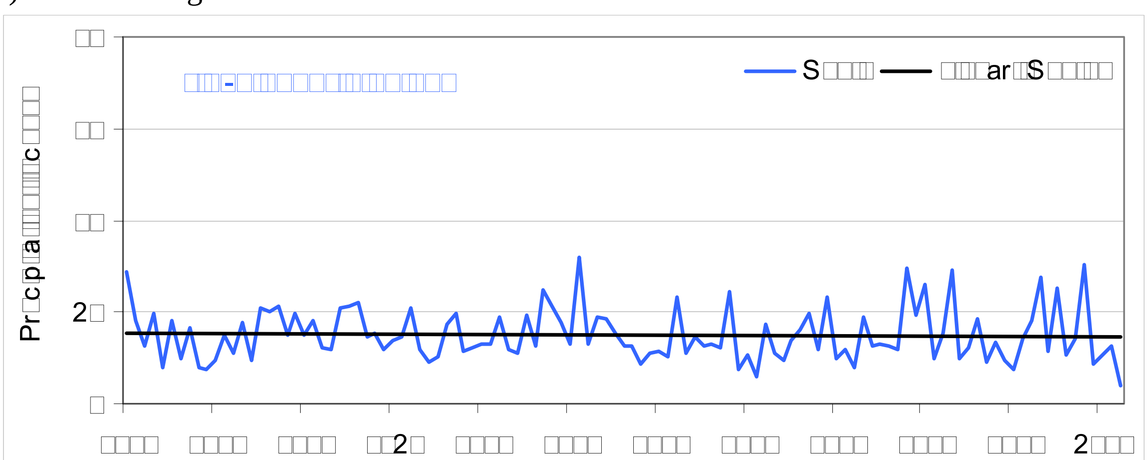


**Figure 6-3 Annual average precipitation with trends by region**

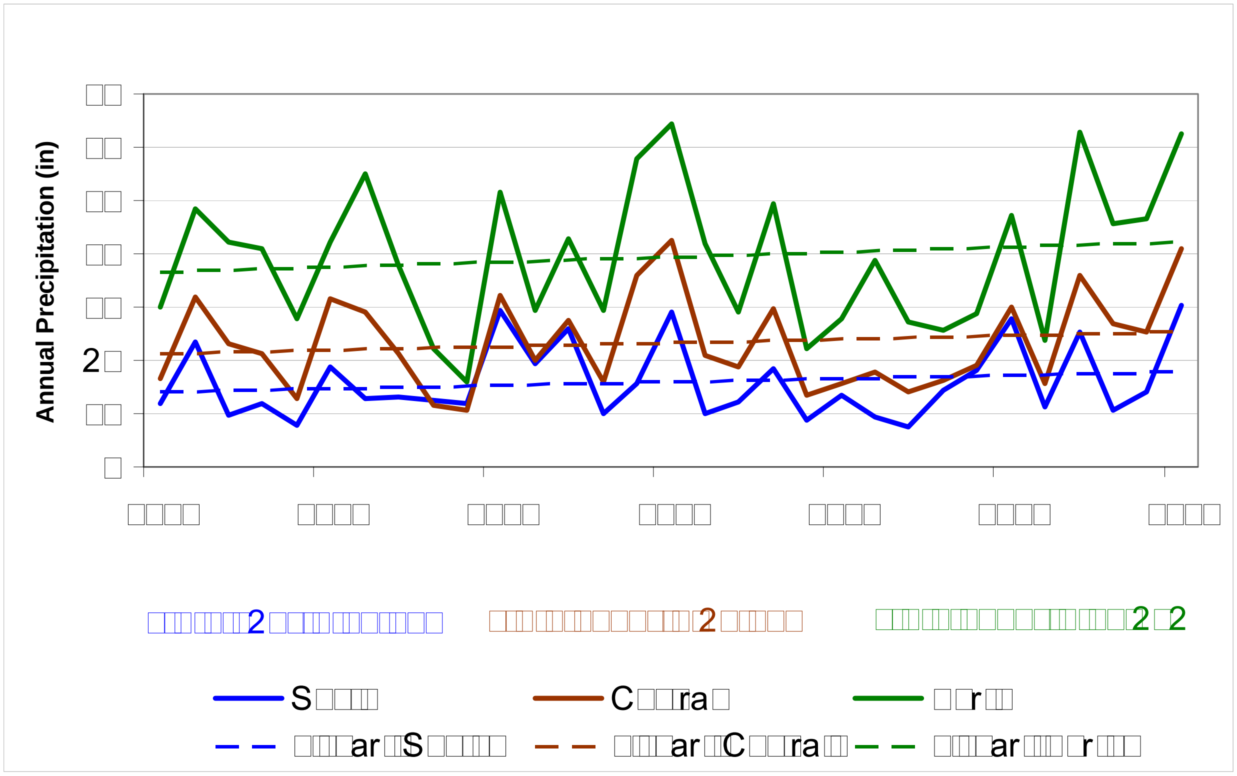



**Figure 6-4 Linear trends of annual precipitation for the past 30 years**

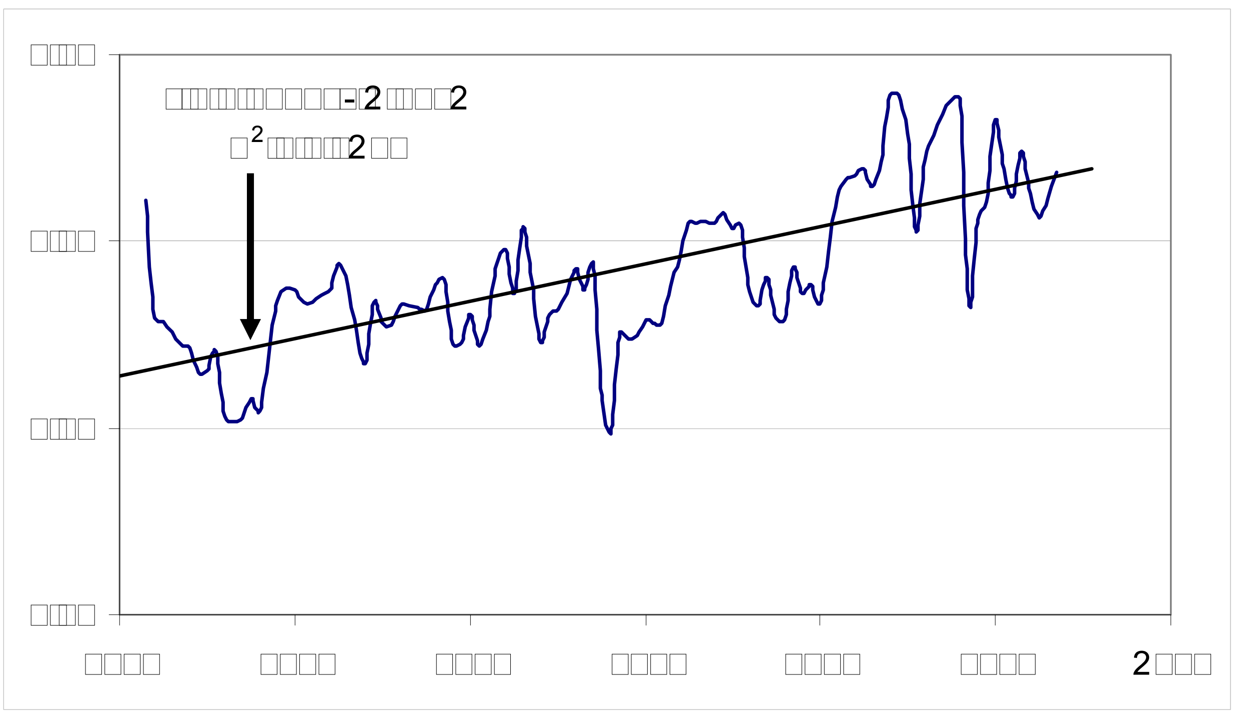


**Figure 6-5 Coefficient of variation for statewide average precipitation with trend line**

### 6.3.2 Temperature

In California, increases in atmospheric temperature have already been observed over the past 100 years. Using 226 temperature stations with data record lengths on the order of 100 years, the following trends were identified. The annual maximum, average, and minimum temperatures for California are shown in Figure 6-6. All three time series show a statistically significant increasing trend of about 2 degrees Fahrenheit per century. The minimum temperatures show the largest trend while the maximum temperatures show the smallest.

In terms of variability, Figure 6-7 depicts the trends in the variability of annual maximum, average, and minimum temperatures averaged over the state. For the maximum and average temperatures, there is not a statistically significant trend. For the minimum temperatures, there is a statistically significant decreasing trend in the variability. This, along with the identified trend in state average minimum temperatures indicate that the lower bound of temperature in the state is moving upward and that this upward trend is damping out the variability of the minimum temperature. As a consequence, on average, there may be fewer cold extreme temperature days in the future as a result of global warming. This result is coincident with other studies (see for example Easterling et al, 2000.)

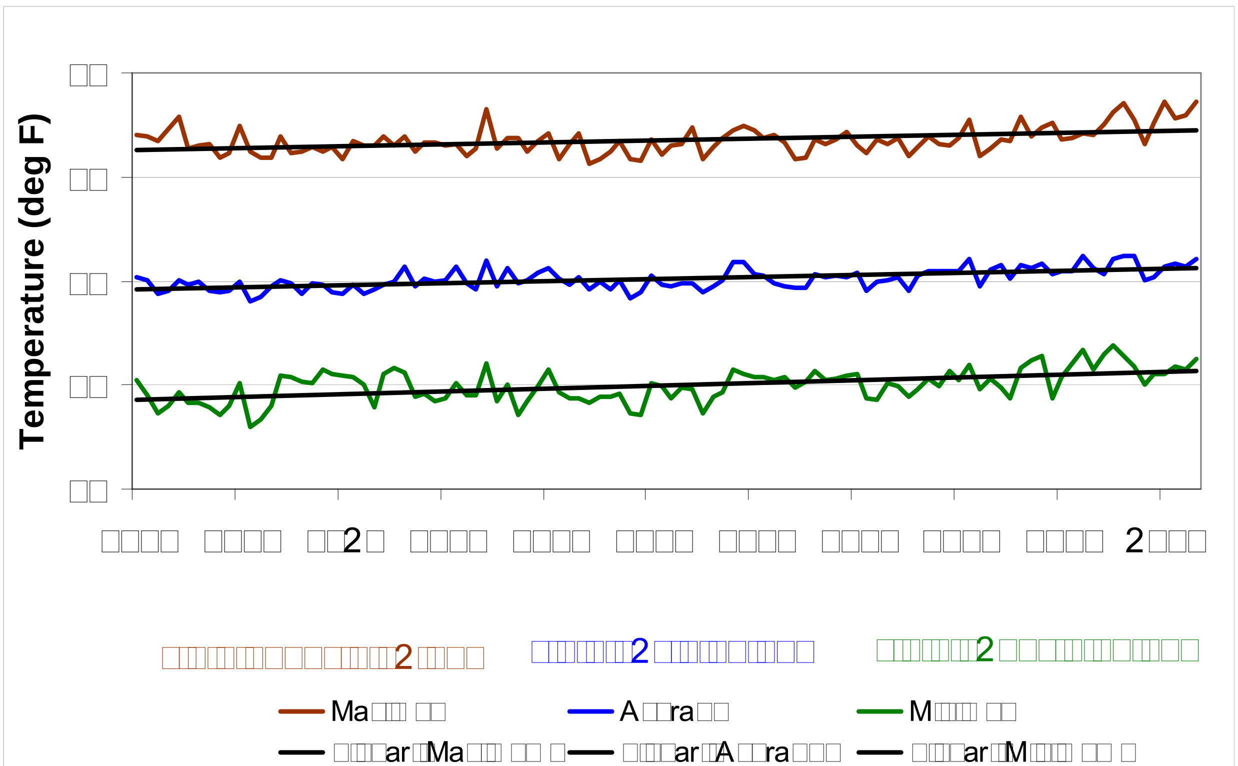
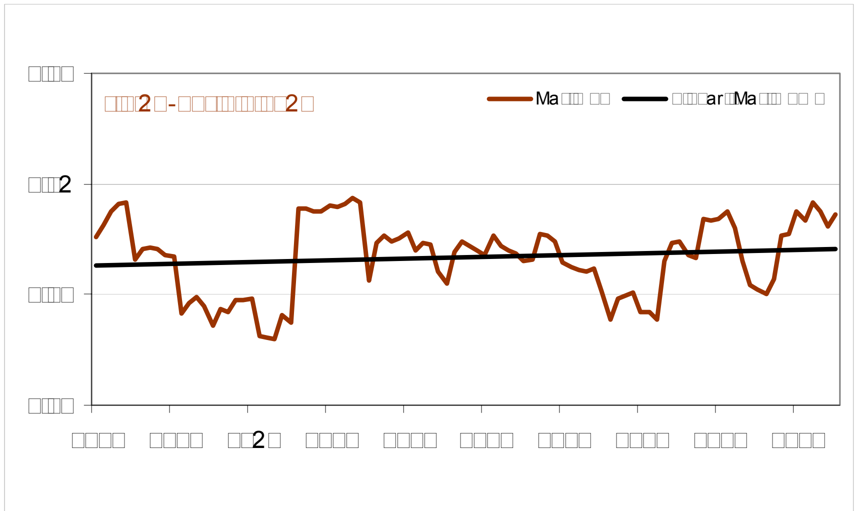
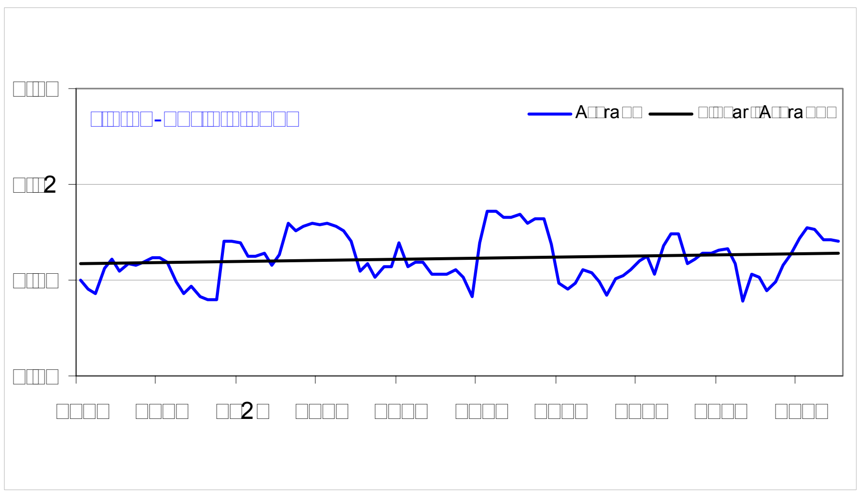



**Figure 6-6 State average maximum, average, and minimum temperature time series**

a) Coefficient of Variation over time for maximum temperature



b) Coefficient of Variation over time for average temperature



c) Coefficient of Variation over time for minimum temperature

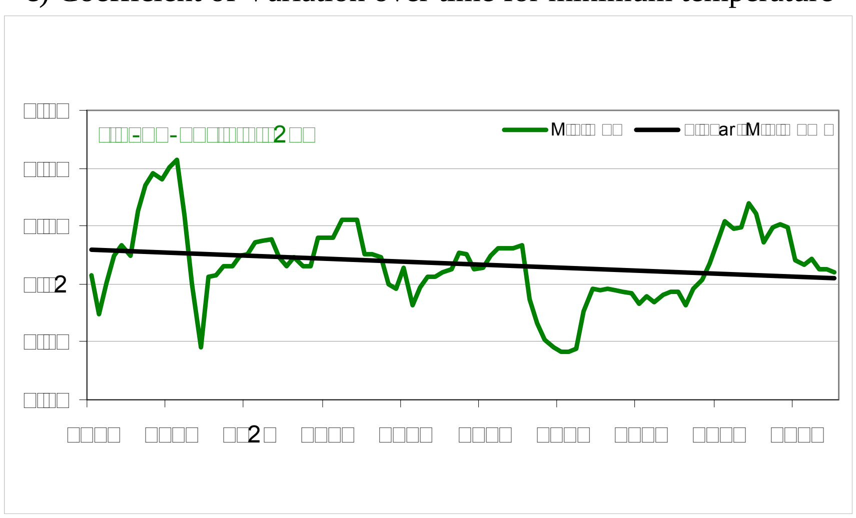


**Figure 6-7 Variability of annual maximum, average and minimum temperature**

Other state temperature trends can be identified. Figure 6-8 shows the change in trend of average temperature identified over the past 100 years versus latitude in 2.5 degree increments. The magnitude of the temperature trend decreases with latitude from over 3 degrees Fahrenheit per century in the south part of the state to less than a degree Fahrenheit in the northernmost part of the state.

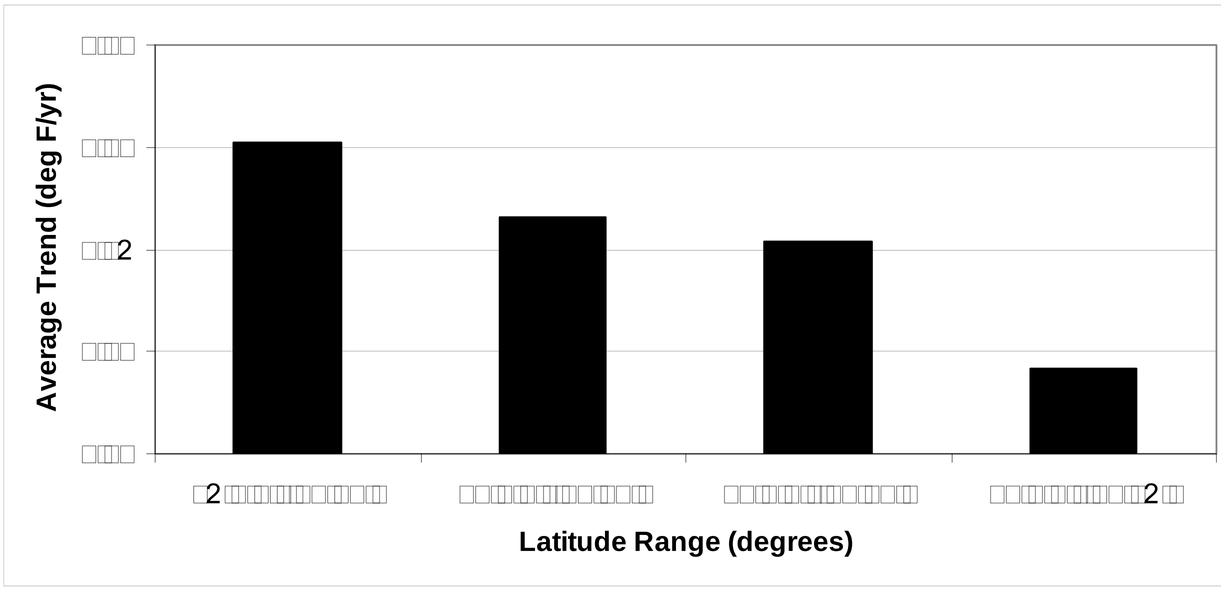



**Figure 6-8 Temperature trend variation with latitude**

Former state climatologist James Goodridge found a difference in temperature trend with population as seen in Figure 6-9. The lowest trend line is associated with a rural county with a population of less than 100,000 people while the topmost trend line is associated with a highly urbanized county with a population greater than 1 million. As noted in the figure, these trends are based on 65 stations sorted by county population.  Note that all three lines show an increasing trend in temperature indicating that temperatures have been increasing even in rural areas.  In addition, in urban areas, temperature increases are accentuated indicating that future temperature increases will be even greater in urban areas.

Peterson (2003) of the National Climatic Data Center offers a different point of view.  He conducted a study that rigorously removed elevation, equipment, and location variations from temperature records at urban and rural sites.  His work indicates that there is no urban heating effect.  This is an area of ongoing research and debate among scientists.

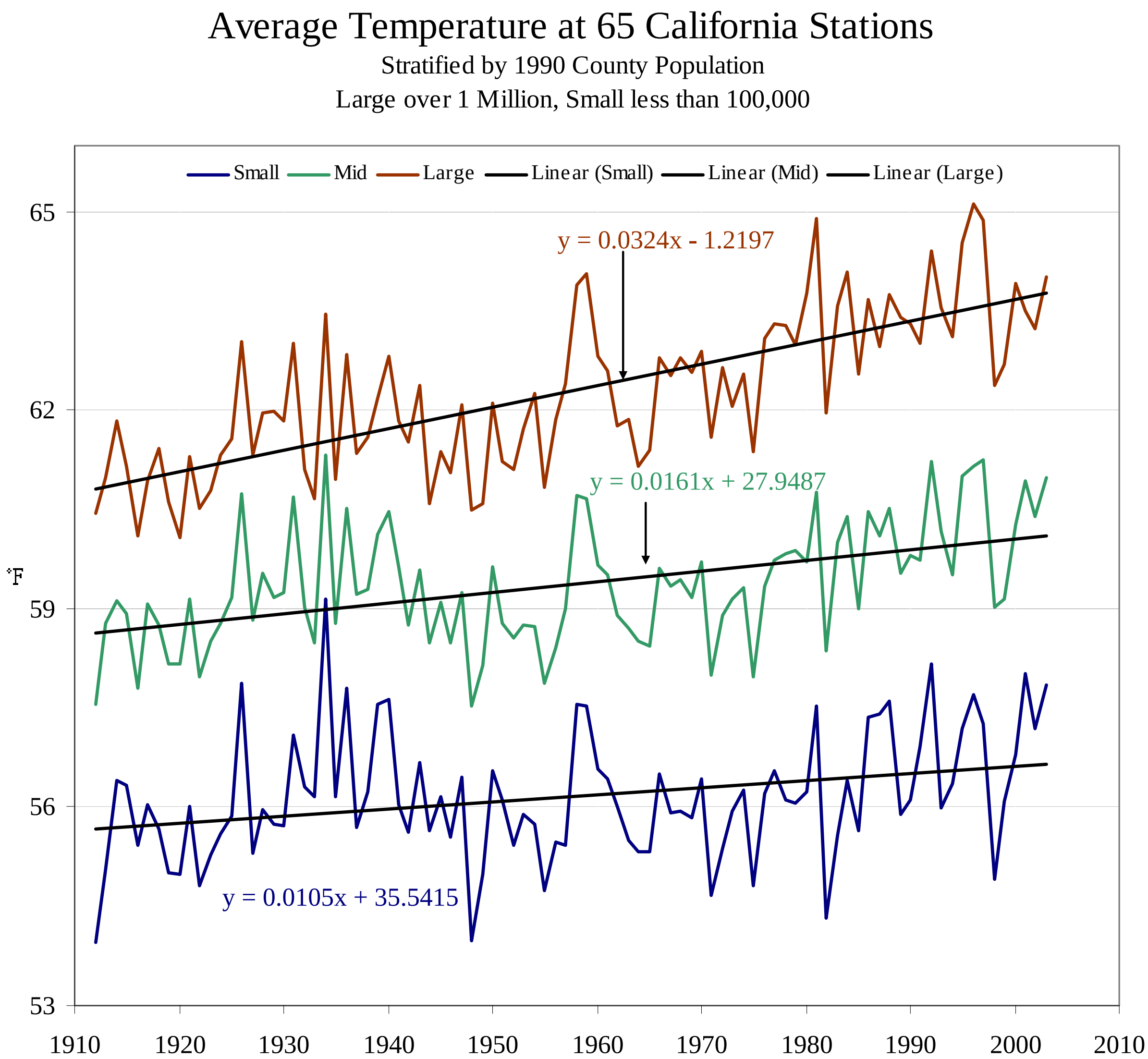



**Figure 6-9 Temperature trends by county population in California.**

### 6.3.3 Runoff

Runoff trends can be divided into two categories. The first is trends in annual-water-year-runoff volumes. The second is trends associated with peak runoff for different return periods. Both trends are investigated here.

#### *6.3.3.1 Annual Runoff*

Annual water year (October 1 to September 30) unimpaired runoff time series were computed for 24 rivers across the state whose locations are shown in Figure 6-10. The time frame for most basins runs from 1905 to 2005. Total period and split period statistics were generated for each basin. The dividing year for the split period statistics is 1955 which is approximately halfway through the observed record.

Table 6-2 lists the total period, pre-1955 period and post-1955 period average annual runoff in thousand acre-feet for the 25 basins. Table 6-2 also includes the percent change from pre-1955 to post 1955. The sum of all 25 basins shows a 9 percent increase in average annual runoff from 1905-1955 to 1956-2005. In general, the northern rivers show a larger increase in average annual runoff than the southern rivers.

**Table 6-2 Average Annual Water Year Runoff for Selected California Watersheds**

| Station | Total Period (taf) | Pre 1955 (taf) | Post 1955 (taf) | % Change |
|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
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**Figure 6-10 Map of Runoff Forecast Points**

In addition to the individual basin runoff, runoff of four major rivers is used to compute the Sacramento and San Joaquin River Indices. The index values not only look at current year runoff, but incorporate a term for last year's conditions as well. Figure 6-11 shows the time series plot and linear trend fit for the Sacramento River Index and Figure 6-12 shows the time series plot and linear trend fit for the San Joaquin River Index. From these figures it can be seen that there is a slight decreasing trend in the San Joaquin Index and a slight increasing trend in the Sacramento River Index. These results are consistent with the precipitation trend results over the past century described earlier.  However, neither trend was identified as being statistically significant.

In terms of runoff variability, the coefficient of variation is plotted for the Sacramento and San Joaquin River Indices in Figure 6-13. Both time series show an increase with the linear trend fit, but only the Sacramento trend is statistically significant. In fact, the variability increases markedly in both series from the 1970s through the mid-1990s. Since 1995, both series' variability has dropped back to values consistent with the beginning of the period.

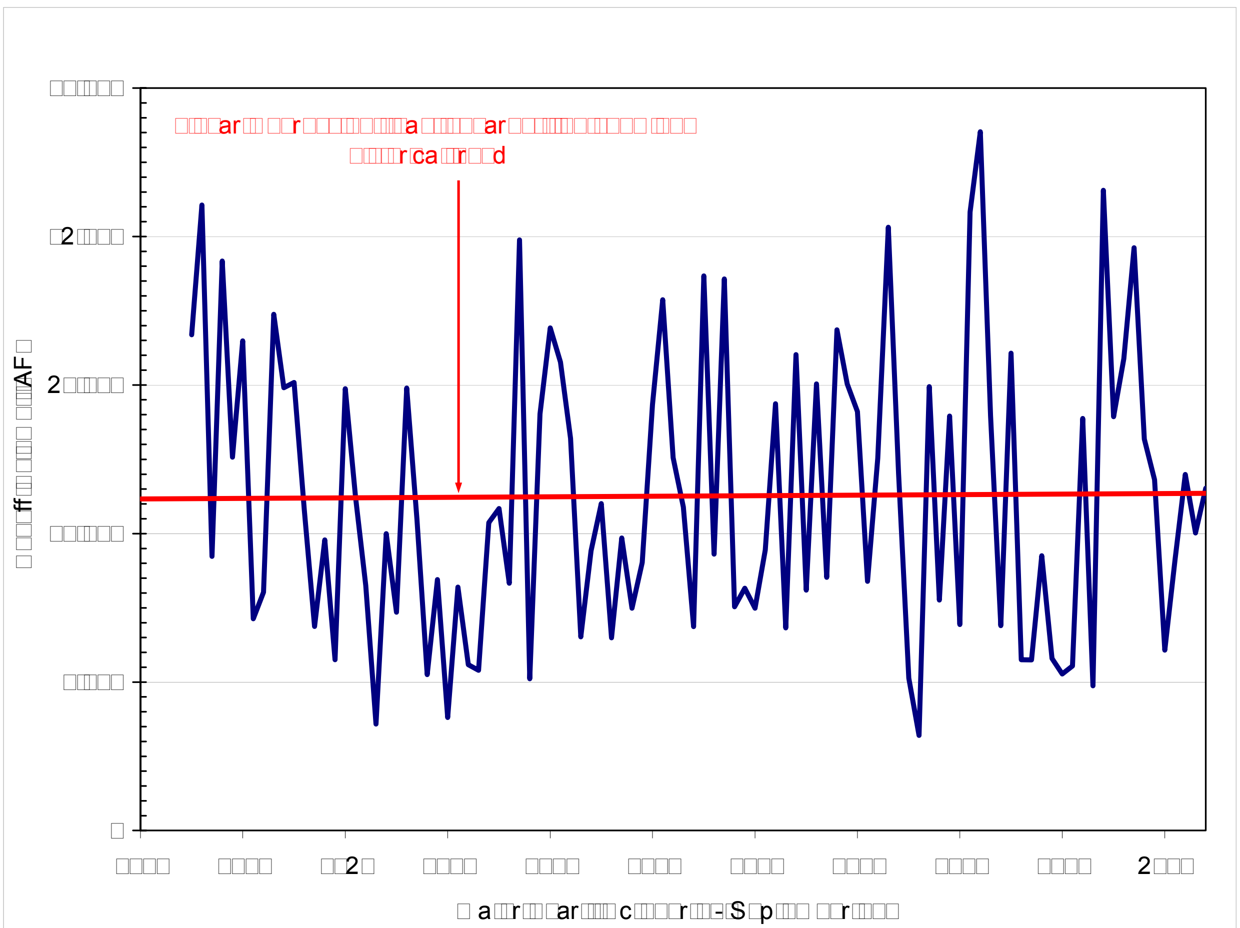

**Figure 6-11 Time series of Sacramento River Index water year runoff with fit linear trend**

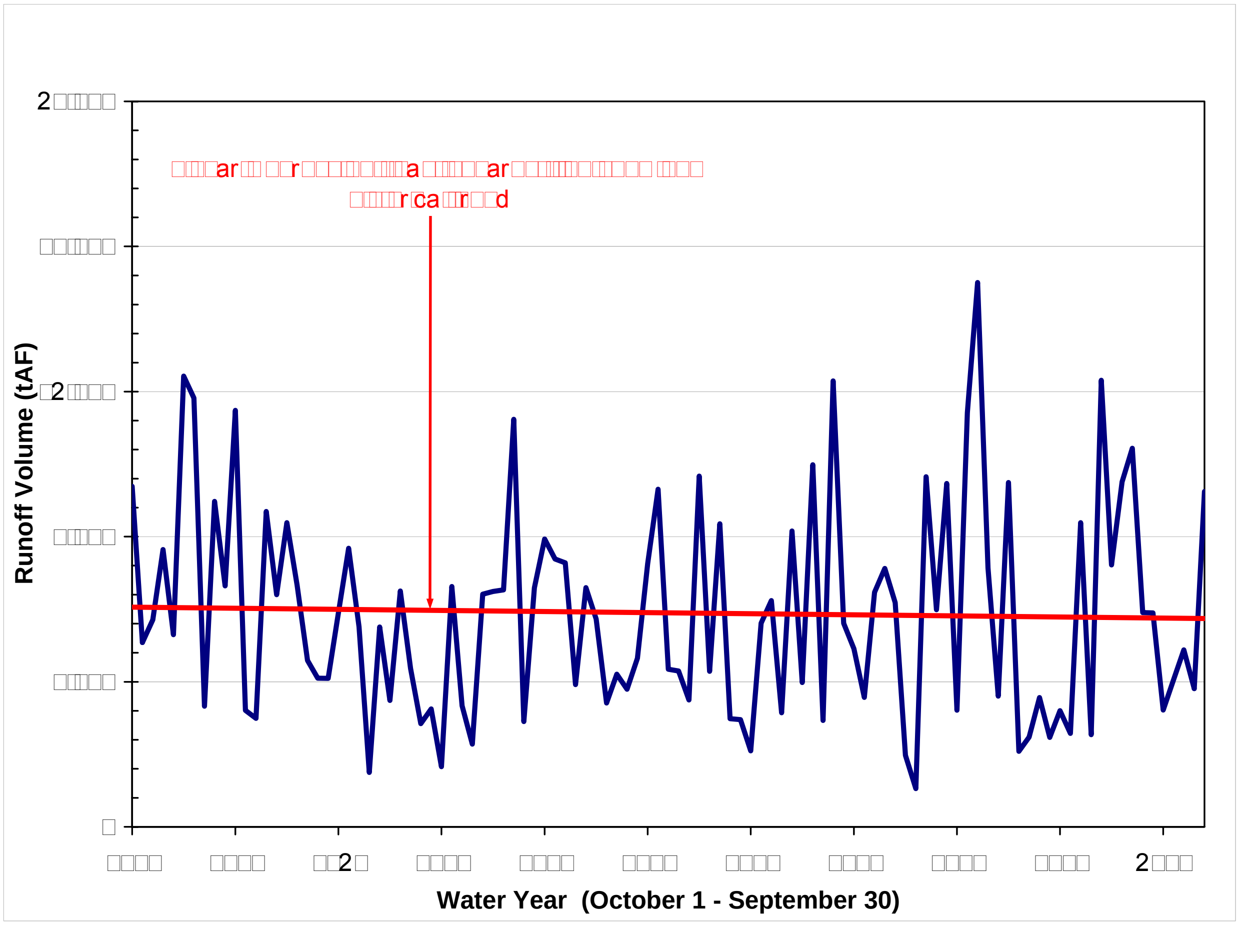


**Figure 6-12 Time series of San Joaquin River Index water year runoff with fit linear trend**

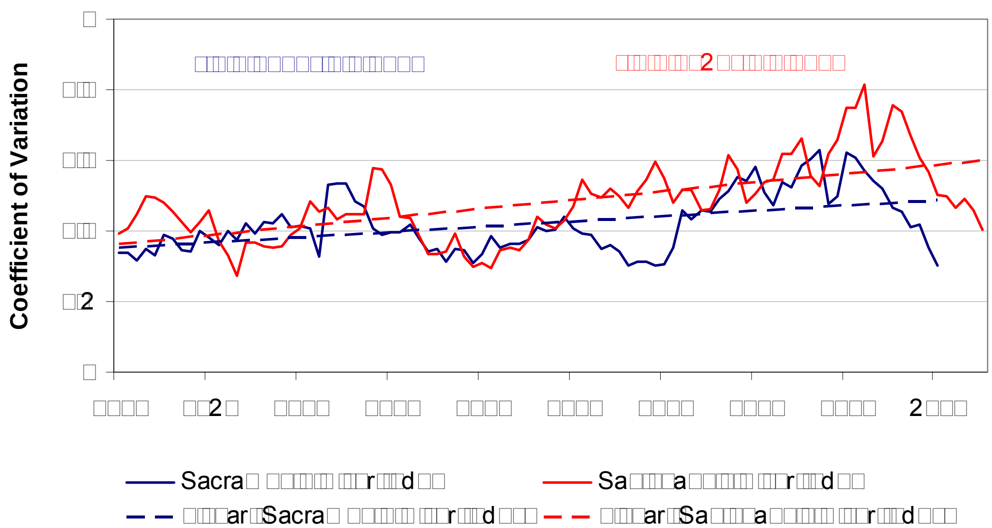


**Figure 6-13 Variability of Sacramento and San Joaquin River Index through time**

Another element to annual runoff is the timing of that runoff. Winter storms deliver snow to higher elevations that historically has melted in April – July. This spring runoff serves as a significant portion of the water supply for dry summers and falls. The April – July runoff over time is shown in Figure 6-14 for the Sacramento River system and in Figure 6-15 for the San Joaquin River system. Both indices show a decrease in the fraction of annual runoff made up from April – July runoff over the past 100 years. This indicates that a greater percentage of the annual runoff is occurring earlier in the year when flood control needs supersede water storage in reservoirs with flood control and water supply purposes. However, in terms of the t-test for statistical significance, neither trend was identified as statistically significant.

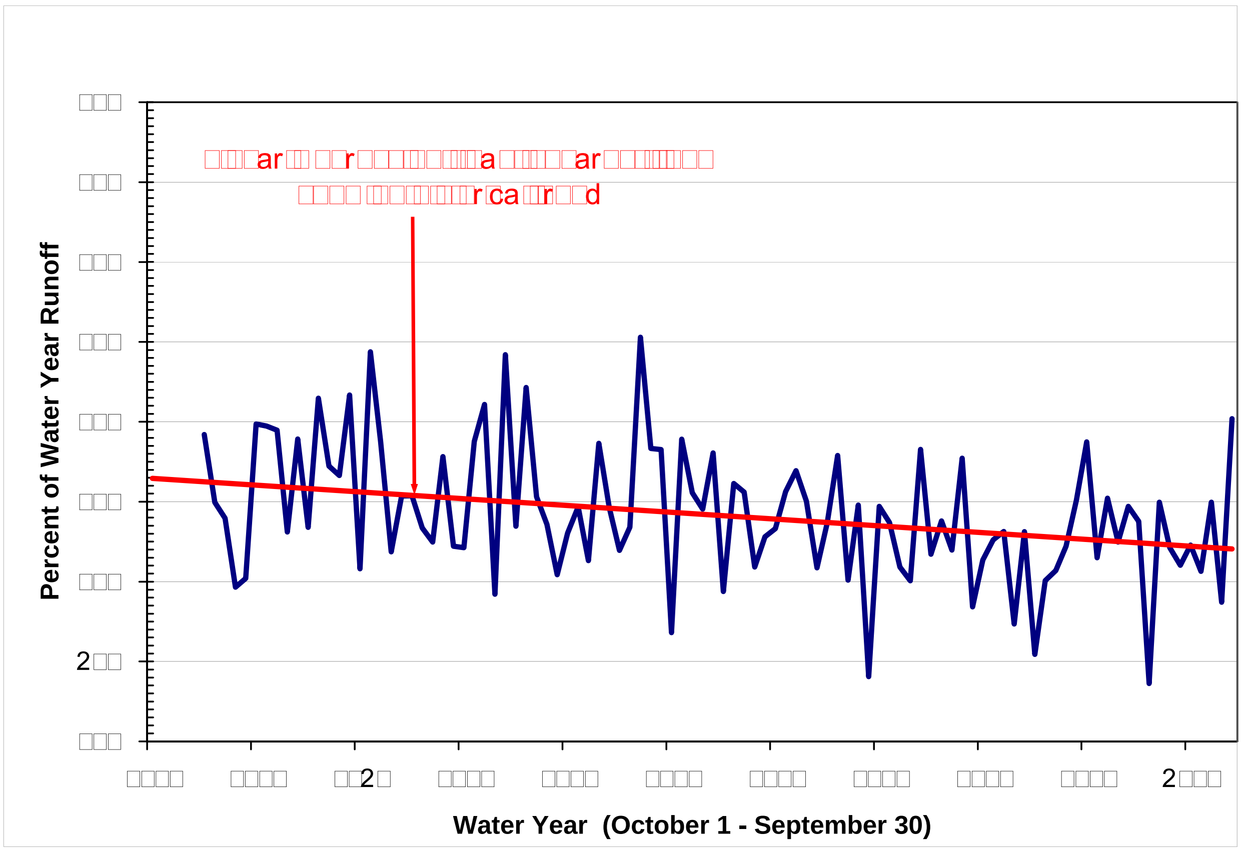


**Figure 6-14 April-July Runoff as a percent of water year runoff for the Sacramento River System**

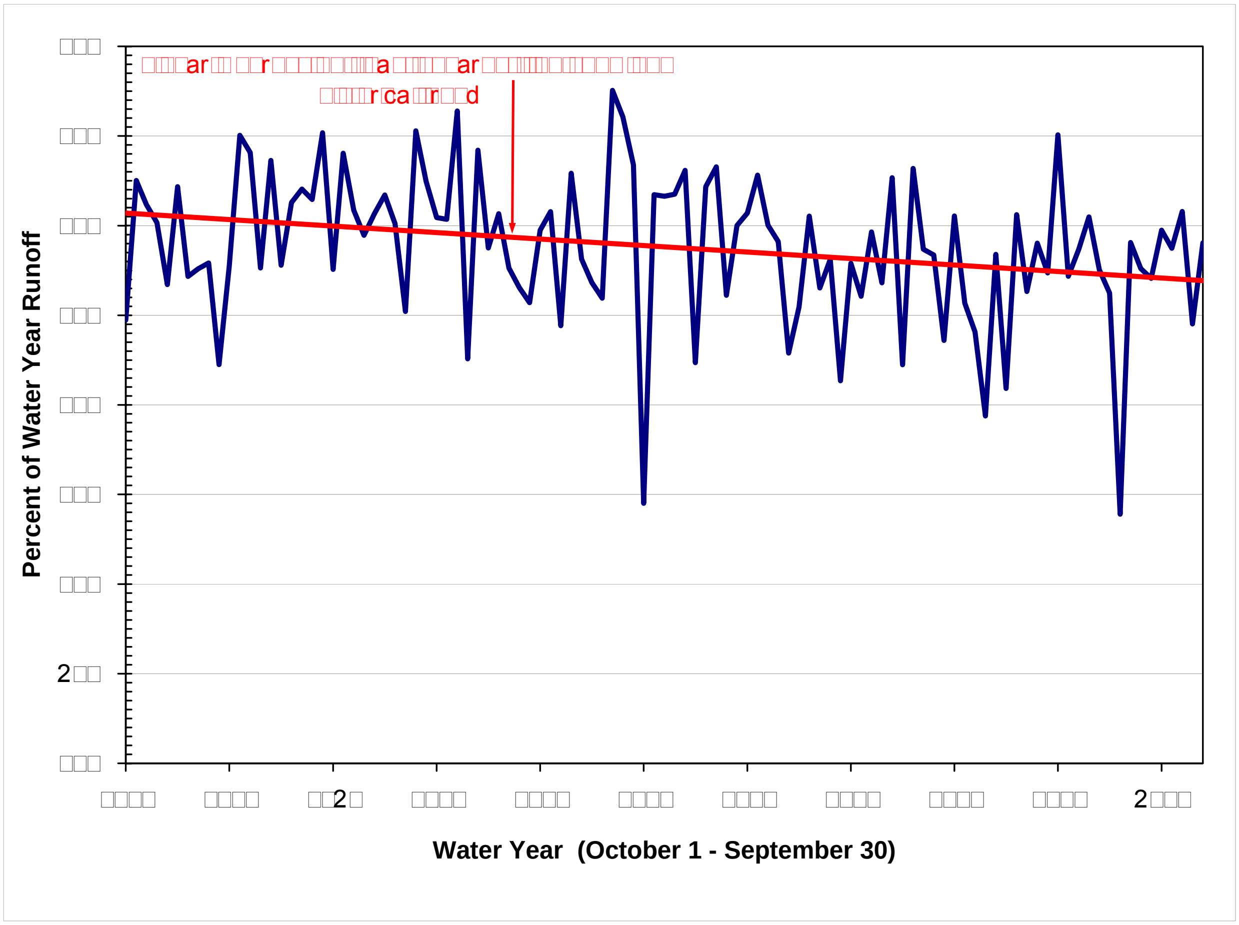


**Figure 6-15 April-July Runoff as a percent of water year runoff for the San Joaquin River System**

Another indication that spring runoff is occurring earlier in the year can be seen in Figure 6-16. It depicts the flow centroid day at the Michigan Bar stream gage on the Cosumnes River computed from historical flow data. A flow centroid day is the number of days after October 1 for 50 percent of the annual volume to pass. For watersheds with snowmelt, this day is usually in April or May (Julian day 182-243). The Cosumnes River is a lower-elevation watershed with a maximum elevation of slightly less than 8,000 feet. It has a modest snowpack in the upper reaches of the basin. There is also a 40,000 acre-foot reservoir on a tributary to the North Fork (Jenkinson Reservoir) that diverts water from the basin. In the absence of a major runoff event (seen as the sharp downward spikes in the time series such as 1986 and 1997) in the basin, the snowmelt makes up a significant portion of the annual runoff in the watershed and drives the location of the flow centroid day. As can be seen from the above figure, the movement over time of the flow centroid day to earlier in the year indicates that, on average, the snowmelt in the basin is occurring earlier (from mid March in 1908 to the beginning of March in 1998). Based on the linear trend line fit to the data, this change in timing is about 10 days over 90 years. However, based on the t-test, the trend was not identified as statistically significant.

With more of the annual runoff including some snow melt occurring earlier in the year, runoff historically used for water supply starts to overlap the time period when reservoir space is reserved for flood control. This overlap may lead to the need to carefully review early spring reservoir operation.

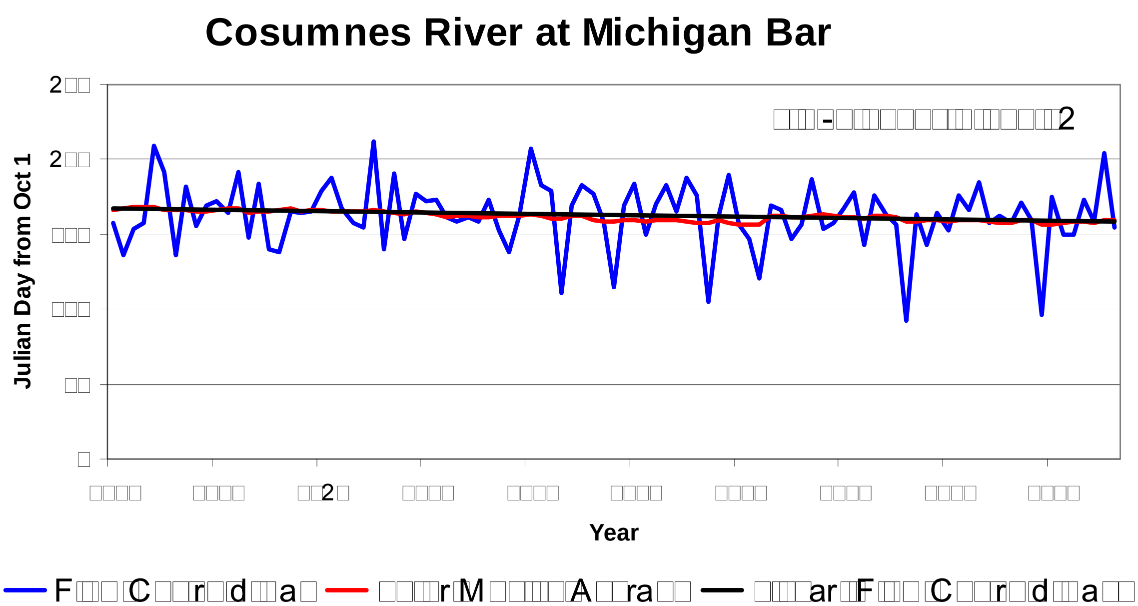


**Figure 6-16 Flow centroid day versus time for the Cosumnes River at Michigan Bar**

### *6.3.3.2 Annual Maximum Flood from Three Day Average Flows*

For peak runoff analysis, six rivers were chosen with long peak flow records. The peak flows evaluated here are three-day average peak flows. The six rivers chosen include three in the Central Valley: Feather, American, and Tuolumne; and three coastal rivers: the Eel River in the north, the Arroyo Seco in central California, and the Santa Margarita River in the south. Their locations are shown in Figure 6-17.

For the analysis, total period mean, standard deviation, and skew statistics are computed for each river. In addition, the records were divided into two time periods with 1955 as the boundary. The year 1955 was chosen as the boundary because it divides the data sets in half. Mean, standard deviation and skew statistics were computed for the two time periods as well. These values are shown in Table 6-3. As can be seen from Table 6-3, the means and standard deviations all increased from the pre 1955 time period to the post 1955 time period with the exception of the Arroyo Seco mean which remained constant. The skew statistics increased except for the Arroyo Seco which remained constant and the Santa Margarita, which decreased.


**Figure 6-17 Map of station location for peak flow analysis**

Using these statistics, Bulletin 17-B (Water Resources Council, 1982) procedures were used to compute the 10-year, 50-year, and 100-year return period flows for the six rivers for the total period, pre-1955 period, and post-1955 period. The Bulletin 17-B procedures fit the data to a log-Pearson type III distribution. The flow values for the different return periods are shown in Table 6-4. Percent differences from Pre-1955 conditions to Post-1955 conditions are shown in Table 6-5.

**Table 6-3 Comparison of discharge statistics by basin and time period (values in 1000 cfs)**

| River Basin | American | Feather | Tuolumne | Eel | Arroyo Seco | Santa Margarita |
|---|---|---|---|---|---|---|
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**Table 6-4Comparison of different return period flows by basin and time period**

| River Basin (Values in 1000 cfs) | American (1905-2004) | Feather (1904-2004) | Tuolumne (1897-2000) | Eel (1917-2004) | Arroyo Seco (1902-2004) | Santa Margarita (1931-2004) |
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**Table 6-5 Percent increase in return period discharges from pre-1955 to post-1955 by basin**

| River Basin | American | Feather | Tuolumne | Eel | Arroyo Seco | Santa Margarita |
|---|---|---|---|---|---|---|
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As can be seen from Table 6-5, the 100-year three-day peak flows have more than doubled for the American, Tuolumne, and Eel rivers. The only river with little change in its return period flows is the Arroyo Seco. Examination of the data shows that there was only one major event (defined as a value greater than the mean plus two standard deviations) for the Feather, American, and Tuolumne Rivers in the pre-1955 period. In the post 1955 period, the number of major events jumps to four. For the coastal rivers a similar pattern emerges. From this information it can be seen that the annual peak three-day mean discharges are becoming more variable and larger for many sites in California.

Climate model studies such as Miller and others (2003) and Dettinger and others (2004) indicate that this trend will continue in response to global warming. Stedinger and Crainiceanu (2001) examine frequency analysis issues when the underlying statistical moments are not stationary as has been assumed in this section. They find that the stationary model works just as well at identifying flood risk as more complex models that try to incorporate trends in historical data.

### 6.3.4 Historical Trend Summary

Over the past 100 years the following trends have been identified and were described in preceding sections:

Precipitation

- No significant trend exists in statewide average precipitation from 1890-2000
- A small increasing trend in statewide precipitation is found from 1970-2000
- A slight increasing trend in precipitation appears in the north part of the state
- A slight decreasing trend in precipitation appears in the south part of the state
- Precipitation variability increased during the 20th century

Temperature

- A slight increasing temperature trend is observed in statewide average of maximum, average and minimum temperatures
- Larger temperature trends are associated with urban areas
- Variability in minimum temperature is slightly decreasing
- Variability in maximum and average temperature is slightly increasing

Runoff – Annual

- Annual runoff shows increasing trend in Sacramento River System
- Annual runoff shows slight decreasing trend in San Joaquin River System
- April-July runoff as percentage of annual runoff is decreasing in both Sacramento and San Joaquin River Systems
- Variability in annual runoff is increasing

Runoff – Peak Flow

- Increase in 10, 50 and 100 year return period peak flows are observed for six basins studied
- Variability in annual peak flows is increasing in six basins studied
- Change between the first and last half of the record are large except for Arroyo Seco

## 6.4 Climate Change Scenario Simulation Data

### 6.4.1 GCM Simulation Results

The studies presented in this report focus on the four climate change scenarios selected by the Climate Action Team appointed in response to the governor's Executive Order S-3-05 on climate change. The four climate change scenarios consist to two greenhouse gas (GHG) emissions scenarios developed by the Intergovernmental Panel on Climate Change (IPCC), known as A2 and B1, each represented by two different Global Climate Models (GCMs), the Geophysical Fluid Dynamic Lab model (GFDL) and the Parallel Climate Model (PCM).

The A2 emissions scenario assumes high population growth, regional based economic growth, and slow technological changes which results in significantly higher GHG emissions. The B1 scenario represents low population growth, global based economic growth and sustainable development which results in the lowest increase of GHG emissions of the IPCC scenarios. For more information on the GCMs and scenarios used in this report, refer to Chapter 3. For the following sections examining impacts based on climate change simulation results, the four climate change scenarios are referred to as:

- GFDL A2
- PCM A2
- GFDL B1
- PCM B1

Precipitation and temperature time series for southern and northern California were created using the GCM simulation results. Precipitation results are shown in Figure 6-18 for Northern California and Figure 6-19 for Southern California. Note that scenario simulations for a given GCM do not differ until after year 2000. For both Northern and Southern California, neither model accurately reproduces historical precipitation variability. Because of this, future variability represented by the model can not be considered reliable.

In terms of average precipitation, for Northern California, the GFDL model predicts a 20 percent decrease in precipitation after 2050 for the A2 scenario and a 10 percent decrease for the B1 scenario. The PCM model predicts no change for either scenario. For Southern California, the GFDL model predicts a 10 percent decrease in precipitation after 2050 for both scenarios while the PCM model predicts a 1 percent decrease in precipitation for both scenarios. By 2100 however, the PCM model predicts a 10 percent increase in precipitation for both scenarios.

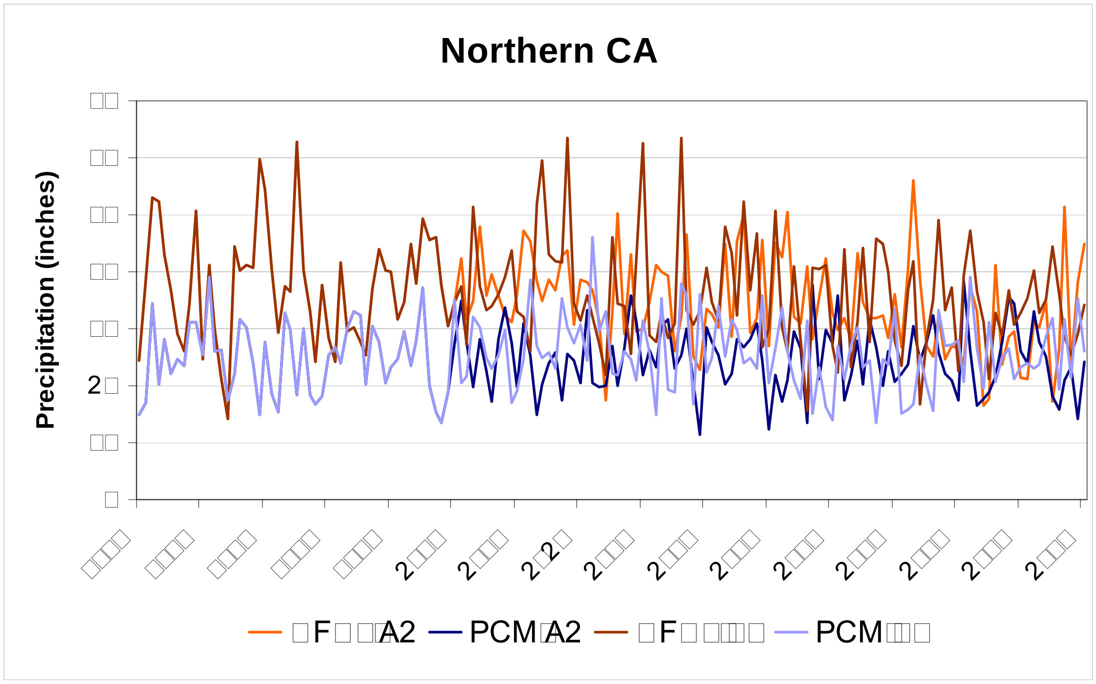



**Figure 6-18 GCM precipitation results for Northern California**

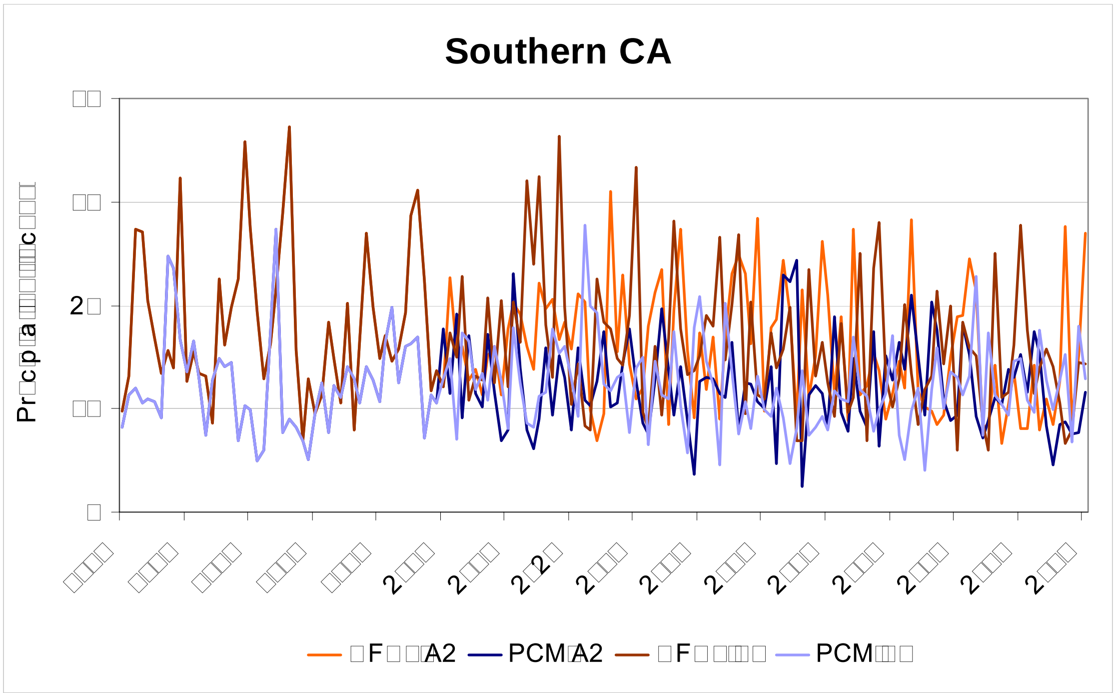



**Figure 6-19 GCM precipitation results for Southern California**

Temperature results for both models are shown in Figure 6-20 for Northern California and in Figure 6-21 for Southern California. For Northern California, the GFDL model predicts a larger temperature increase than the PCM model. By 2050, the PCM model predicts a one degree Celsius increase in temperature for both scenarios while the GFDL model predicts a 2.25-degree increase for both scenarios. Increases up to 5 degrees C occur by 2100 in the GFDL model.

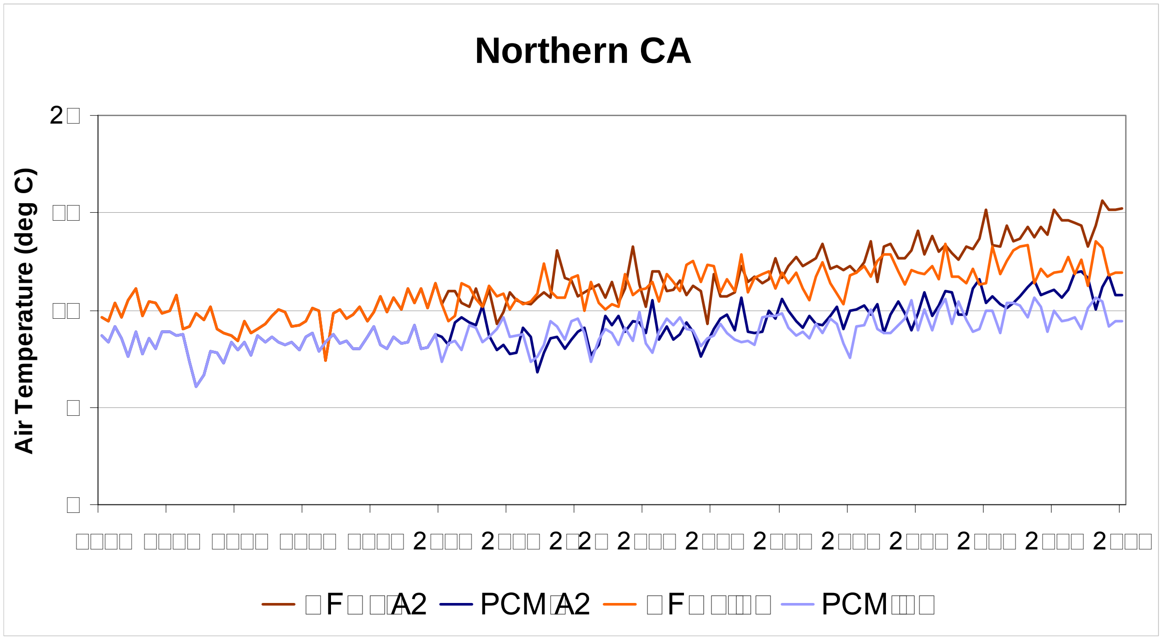



**Figure 6-20 GCM temperature results for Northern California**

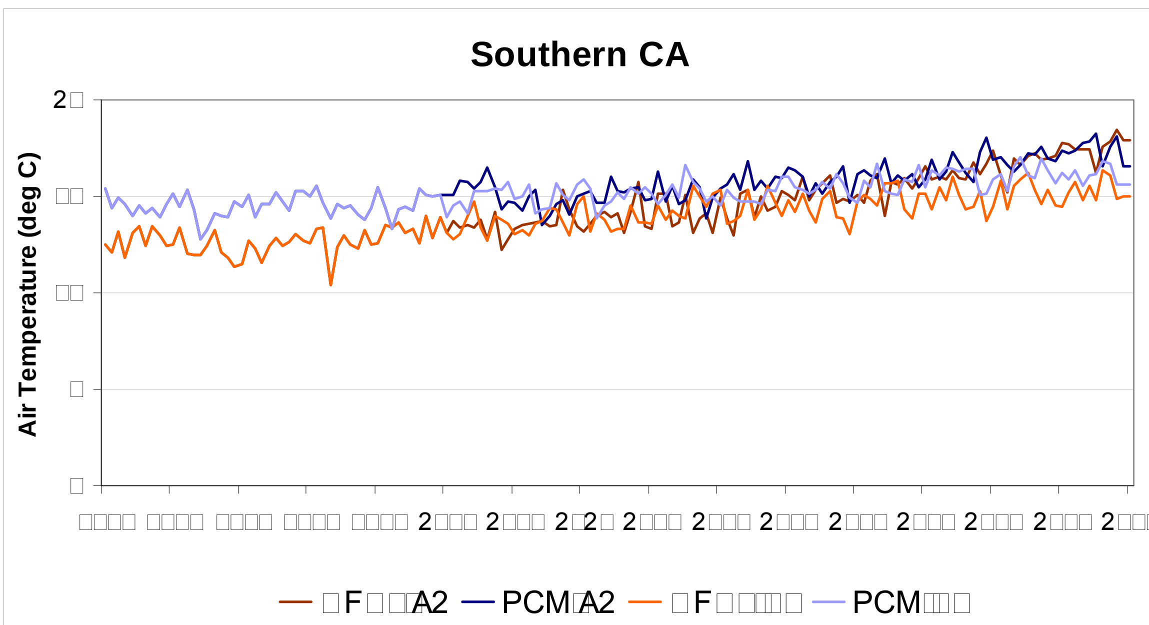



**Figure 6-21 GCM temperature results for Southern California**

The GCM results presented here are at a scale of about 100-200 km horizontal resolution. California's topography is highly varied which leads to a more complex temperature and precipitation patterns than can be expected from a GCM simulation at this resolution. Because of this, downscaling procedures were carried out on the GCM scale results to create finer resolution (10-20 km) data suitable for analysis over California.

### 6.4.2 Downscaled Results

Professor Ed Maurer of Santa Clara University statistically downscaled monthly data from each of the GCM simulations to California and then used the data to drive a land surface model known as the VIC (Variable Infiltration Capacity) model. Details of the downscaling and VIC model can be found in Maurer (2005). Data from these simulations were provided to Department of Water Resources staff for analysis. VIC model results for 12 sites across the state were averaged to obtain the precipitation and temperature time-series plots shown in Figure 6-22 and Figure 6-23 respectively. Runoff results from the VIC model were sampled from seven Central Valley watersheds. Annual, October through March, and April through July runoff volumes were analyzed and compared to historical records.

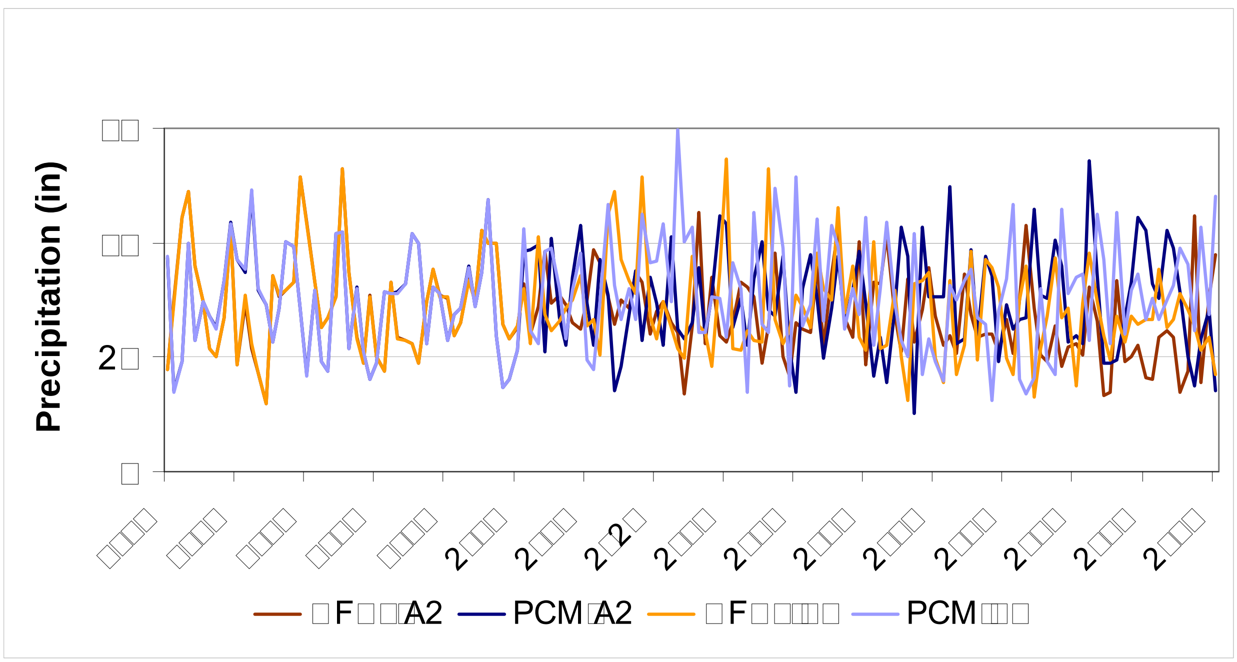
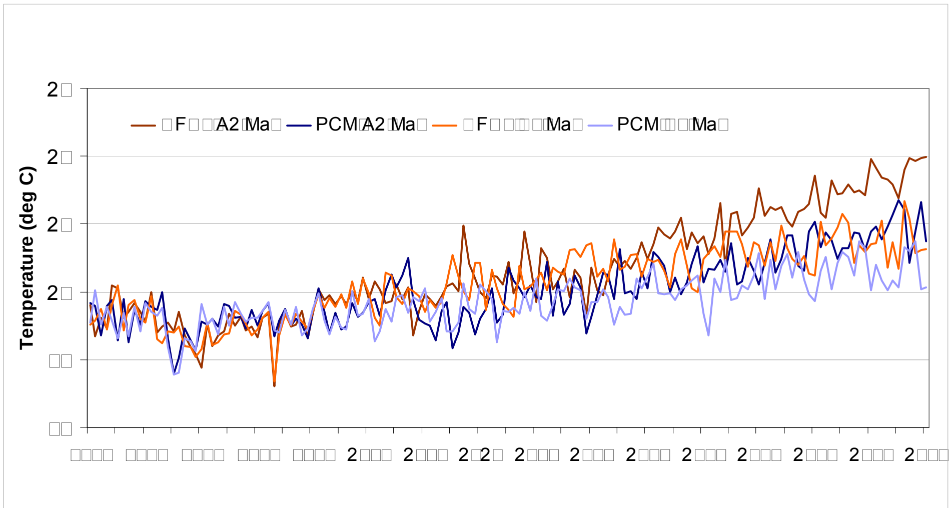
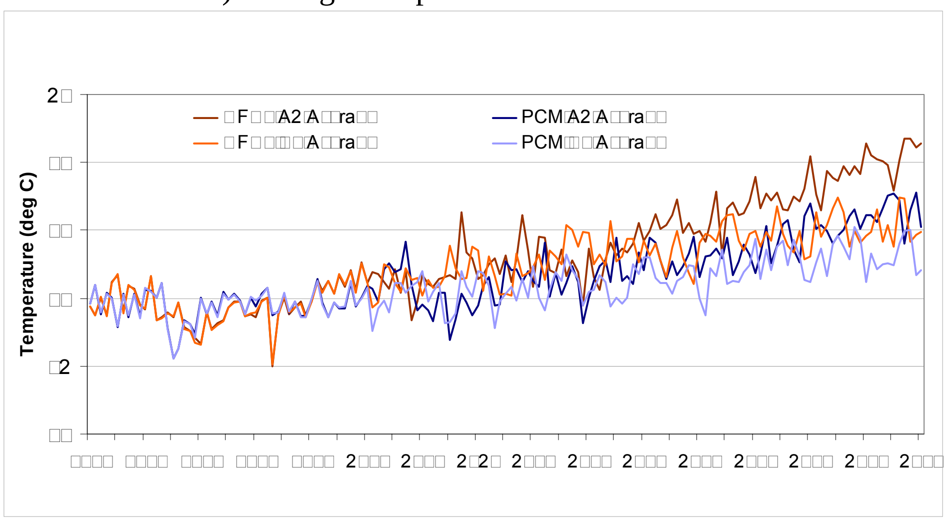



**Figure 6-22 Downscaled precipitation time series from VIC model**

a) Maximum air temperature from VIC model




b) Average Temperature from VIC model




c) Minimum temperature from VIC model

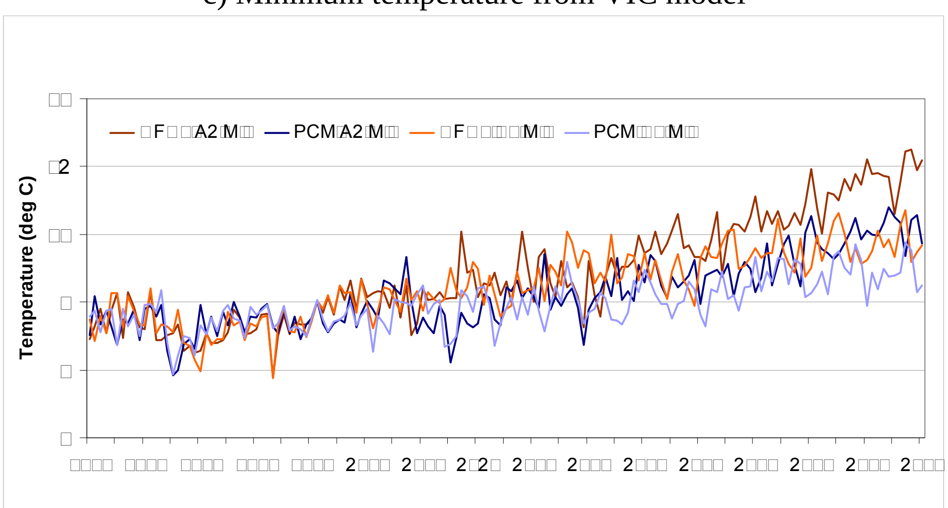



**Figure 6-23 Downscaled average maximum, and minimum temperature time series**

### 6.4.2.1 Precipitation

The scenario simulation results shown in Figure 6-22 depict little change in precipitation by 2050. Comparison of 30-year averages for the end of the $20^{th}$ century and middle $21^{st}$ century show a 5 percent decrease in precipitation for the GFDL model for both scenarios. The PCM model on the other hand shows no change for the A2 scenario and a 5 percent increase for the B1 scenario.

### 6.4.2.2 Temperature

For temperature there is a distinct increasing trend in average, maximum, and minimum temperature for both models and both scenarios. By 2050, the PCM model shows an average 1 degree C increase in average, maximum, and minimum temperature, while the GFDL shows an average 2 degree C increase. As in the GCM results, increases up to 5 degrees C exist by 2100 in the GFDL model results.

### 6.4.2.3 Runoff

In order to verify the ability of the scenario simulation data to represent water supply elements in California, the October-March, April-July, and annual runoff volume averages and standard deviations for the years 1951-2000 were compared for seven basins. The percent differences, computed as (modeled – observed)/observed, from observed average values for October-March are shown in Table 6-6, for April-July in Table 6-7, and annual values in Table 6-8. The percent differences from observed values for the standard deviations are shown in Table 6-9 for October-March, Table 6-10 for April-July, and Table 6-11 for annual values. In general, the simulated runoff values were closer to the observed values during the October-March period. Only the American and Kings basins have errors greater than 10 percent. However, in April-July, which is the important time period for water supply, the simulated data does not match up as well. Two basins, the Feather and Merced watersheds match up within 7 percent or less. The Sacramento and Tuolumne errors are between 10 percent and 20 percent, while the others are all greater than 30 percent.

The standard deviation represents the year-to-year variability in the system. As can be seen from Table 6-9, Table 6-10, and Table 6-11 with a few exceptions, both models had difficulty representing the historical year-to-year variability for the October through March, April through July, and annual periods. Both the GFDL and PCM models show less variability than has been observed. This inability to capture the historical year-to-year variability means that any prolonged dry or wet periods during the future portion of the simulations are suspect and cannot be interpreted as prolonged flood or drought cycles.

**Table 6-6 Modeled vs Observed Percent Differences in Oct-Mar Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 6-7 Modeled vs Observed Percent Differences in Apr-July Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 6-8 Modeled vs Observed Percent Differences in Annual Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 6-9 Modeled vs Observed Percent Differences in Oct-Mar Runoff Standard Deviation**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |

**Table 6-10 Modeled vs Observed Percent Differences in Apr-Jul Runoff Standard Deviation**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| Sacra□ □□□□ | S□a□a□ | □□ □ | □□□ □ | 2□□ □ | 2□□ □ |
| F□a□□r□ | □r□□□□ | □□□ □ | □□□ □ | □□□ □ | 2□□ □ |
| A□ □r□ca□□ | F□□□□ □ | □□□ □ | □□□ □ | 2□□ □ | 2□□ □ |
| S□a□□a□□□ | □□□ M□□□□□□ | □□□ □ | □□□ □ | 2□□ □ | 2□□ □ |
| M□rc□d□ | □a□□McC□r□□ | □□□ □ | □□ □ | □□ □ | □□ □ |
| □□□□□ □□□ | □□□ P□dr□□ | □□ □ | □□ □ | □□ □ | □□ □ |
| □□□□□ | P□□□F□a□ | □□□ □ | □□□ □ | □□□ □ | □□□ □ |

**Table 6-11 Modeled vs Observed Percent Differences in Annual Runoff Standard Deviation**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| Sacra□ □□□□ | S□a□a□ | 2□□ □ | 2□□ □ | □□□ □ | 2□□ □ |
| F□a□□r□ | □r□□□□ | -□□□ □ | -□□□ □ | -□□□ □ | -□□□ □ |
| A□ □r□ca□□ | F□□□□ □ | -□□□ □ | -□□□ □ | -□□□ □ | -□□□ □ |
| S□a□□a□□□ | □□□ M□□□□□□ | -2□□ □ | -2□□ □ | -□□□ □ | -□□□ □ |
| M□rc□d□ | □a□□McC□r□□ | □□ □ | 2□ □ | □□□ □ | □□□ □ |
| □□□□□ □□□ | □□□ P□dr□□ | -□□ □ | -□□ □ | □□ □ | □□ □ |
| □□□□□ | P□□□F□a□ | 2□□ □ | 2□□ □ | □□□ □ | □□□ □ |

With the understanding that the simulated runoff does not match historically observed statistics very well, the following tables show the percent change from historical conditions that occurs for the 2035-2064 period relative to the 1961-1990 period. Table 6-12 shows the percent changes in the mean for October through March. The April-July percent changes in the mean are shown in Table 6-13 and the annual changes in the mean are shown in Table 6-14**.**

While the magnitude of the changes may be suspect due to the large errors in representing the historical conditions, some general trends can be noted. With the exception of the PCM-A2 simulation for inflows to Shasta reservoir, all October through March runoff values are larger in the 30 years centered on 2050 (future) than the 30 years centered on 1975 (present). For the April through July runoff all future values are less than present with the exception of inflows to Shasta and Oroville for the PCM-B1 scenario. On an annual basis, the PCM model predicts changes less than 10 percent for all basins for both scenarios. However, the changes are positive (increase in annual runoff) for the B1 scenario and negative (decrease in annual runoff) for the A2 scenario. The GFDL model predicts less than 20 percent changes all basins for both scenarios. The GFDL predicts decreases in annual runoff with the exception of Shasta and Oroville inflows for the B1 scenario.

**Table 6-12 Percent Differences in Future to Present Oct-Mar Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| Sacra□ □□□□ | S□a□a□ | □□ □ | □□ □ | □□ □ | □□ □ |
| F□a□□r□ | □r□□□□ | □□□ □ | □□□ □ | □□□ □ | □□□ □ |
| A□ □r□ca□□ | F□□□□ □ | □□□ □ | □□□ □ | □□ □ | □□ □ |
| S□a□□a□□□ | □□□ M□□□□□□ | □□□ □ | □2□ □ | □□ □ | □□□ □ |
| M□rc□d□ | □a□□McC□r□□ | 22□ □ | □□□ □ | 2□ □ | □□□ □ |
| □□□□□ □□□ | □□□P□dr□□ | □□□ □ | □□ □ | □□ □ | □□□ □ |
| □□□□□ | P□□□F□a□□ | □□□ □ | □□□ □ | □□ □ | □□□ □ |

**Table 6-13  Percent Differences in Future to Present Apr-Jul Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| Sacra□ □□□□ | S□a□a□ | -□□ □ | □□ □ | -2□□ □ | -22□ □ |
| F□a□□r□ | □r□□□□ | -□□□ □ | -□□ □ | -2□□ □ | -□□□ □ |
| A□ □r□ca□□ | F□□□□ □ | -2□□ □ | -□□□ □ | -□□□ □ | -□□□ □ |
| S□a□□a□□□ | □□□ M□□□□□□ | -□□□ □ | -□□ □ | -□□□ □ | -□□□ □ |
| M□rc□d□ | □□McC□r□□ | -□□□ □ | -□□□ □ | -2□□ □ | -2□□ □ |
| □□□□□ □□□ | □□□P□dr□□ | -□□ □ | -□□ □ | -2□□ □ | -2□□ □ |
| □□□□□ | P□□□F□a□□ | -□□ □ | -□2□ □ | -2□□ □ | -2□□ □ |

**Table 6-14 Percent Differences in Future to Present Annual Runoff Average**

| Watershed | Inflow Location | PCM-B1 | PCM-A2 | GFDL-B1 | GFDL-A2 |
|---|---|---|---|---|---|
| Sacra□ □□□□ | S□a□a□ | 2□ □ | □□ □ | -2□ □ | -□□ □ |
| F□a□□r□ | □r□□□□ | □□ □ | □□ □ | -□□ □ | -□□ □ |
| A□ □r□ca□□ | F□□□□ □ | -2□ □ | □□ □ | -□□□ □ | -□□□ □ |
| S□a□□a□□□ | □□□ M□□□□□□ | □□ □ | □□ □ | -□□□ □ | -□□□ □ |
| M□rc□d□ | □□McC□r□□ | 2□ □ | -□□ □ | -□□□ □ | -□□□ □ |
| □□□□□ □□□ | □□□P□dr□□ | □□ □ | -□□ □ | -□□□ □ | -□□□ □ |
| □□□□□ | P□□□F□a□□ | 2□ □ | -2□ □ | -□□□ □ | -□□□ □ |

### *6.4.2.4  Peak Flow Runoff*

Data provided from the GCM simulations is at a monthly time scale. Such data are not suitable to investigate peak flow runoff changes associated with climate change. Peak flows are associated with given weather events that are a fundamentally different scale from climate. In order to generate data appropriate for peak flow runoff analyses, the GCM simulations would have to be able to correctly simulate the magnitude, location, and variability of the atmospheric circulations associated with extreme rainfall and runoff. For future climate scenarios, a large sample of GCM realizations would enable a probabilistic approach to assess changes in extreme precipitation and runoff frequency. At this time, this analysis is left for future work.

### 6.4.3 Summary of GCM Model Results

There is great uncertainty in the magnitude, timing, and location of precipitation and runoff changes associated with climate change. Historical trends depend on the time frame chosen, although most changes are small. The magnitude of model-derived changes is less than the magnitude of the differences between observed and modeled statistics for the historical period. One way to avoid this problem is to use multiple simulations and compute averages of the multiple simulations. These ensemble averages are then used to analyze expected changes associated with climate change.

It should be noted that maximum, minimum and average temperatures have risen in the past and are expected to continue to rise across the state based on model simulations. There is some range (1 to 5 degrees C) in the amount of warming expected depending on the model and scenario. While changes in flood frequency can not be quantified from the simulation results, some elements of climate change based runoff changes can be quantified. These are explored in the next section.

## 6.5 Potential Impacts

Changes in runoff associated with climate change can be related to the changes in watershed response due to the modification of the seasonal snowpack. Increasing temperatures will likely push the snow level in watersheds to higher elevations leaving more of the watershed available to contribute to direct winter runoff processes. In addition, higher elevation snow levels decrease the available watershed area for snowpack to develop. Both of these issues are explored in this section. For other studies, see a special issue of Climatic Change (Vol. 62, 2004) which included a number of studies on climate change impacts on California water resources.

A simple hydrologic model of the Feather River watershed, HED71 (Buer, 1988), is used to illustrate the effects of greater contributing area on direct runoff. It is a simple forecasting model and is not a physically based model of the watershed. However, the HED71 model has the ability to specify the elevation where the snowpack starts. Elevations below this are used to generate direct runoff from an input precipitation event. As such the HED71 model can be used to evaluate the relative changes in runoff associated with different contributing areas.

A winter storm pattern of rainfall was chosen which dropped a total of 10 inches of rain in a 72 hour period. This corresponds to a 10-15 year return period event. The timing of the rainfall is shown in Figure 6-24. The HED71 model was run with a base case snow elevation of 4500 feet. Three scenario simulations were run with snow elevations at 5000, 6000, and 7000 feet which are associated with a respective 1, 3, and 5 degree Celsius rise in mean atmospheric temperature. These values are based on the assumption of a 500 foot increase in snow elevation for each 1 degree Celsius increase in mean atmospheric temperature. The percent increases in contributing area over the base case for these three temperature changes are 57 percent, 184 percent, and 250 percent respectively. Note that for the 5 degree increase in temperature, only 2 percent of the watershed is covered with snow and is assumed not to contribute to direct runoff.

Based on these simulations, the peak runoff from this storm increased 23 percent, 83 percent and 131 percent respectively. The runoff hydrographs scaled by the peak flow of the base case are shown in Figure 6-25. As can be seen from Figure 6-25, there is a significant increase in direct runoff volume associated with higher elevations for snowpack due to the increased contributing area of the watershed. The more than doubling of the peak runoff associated with a 5 degree Celsius increase in mean atmospheric temperature would cause significant changes in the return period of peak runoff associated with a specified rainfall event.

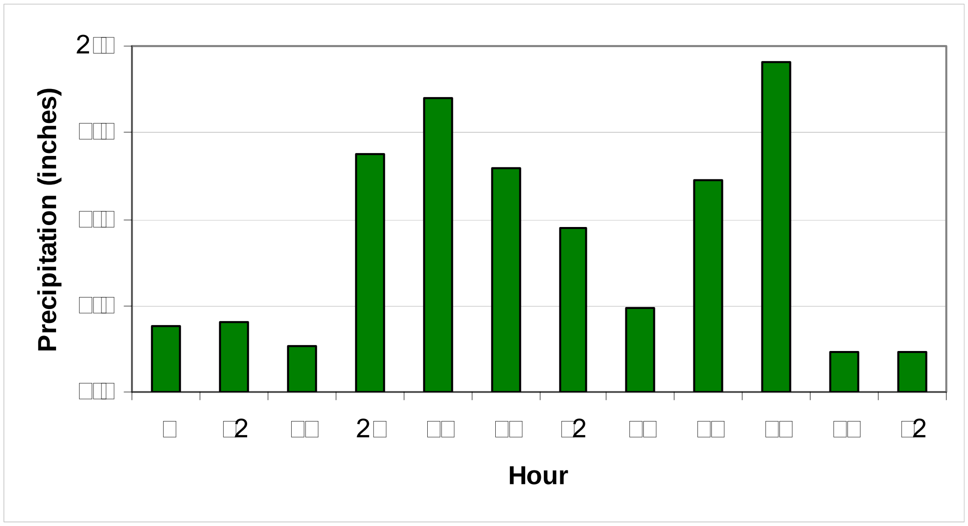



**Figure 6-24 Input hyetograph to HED71 model.**

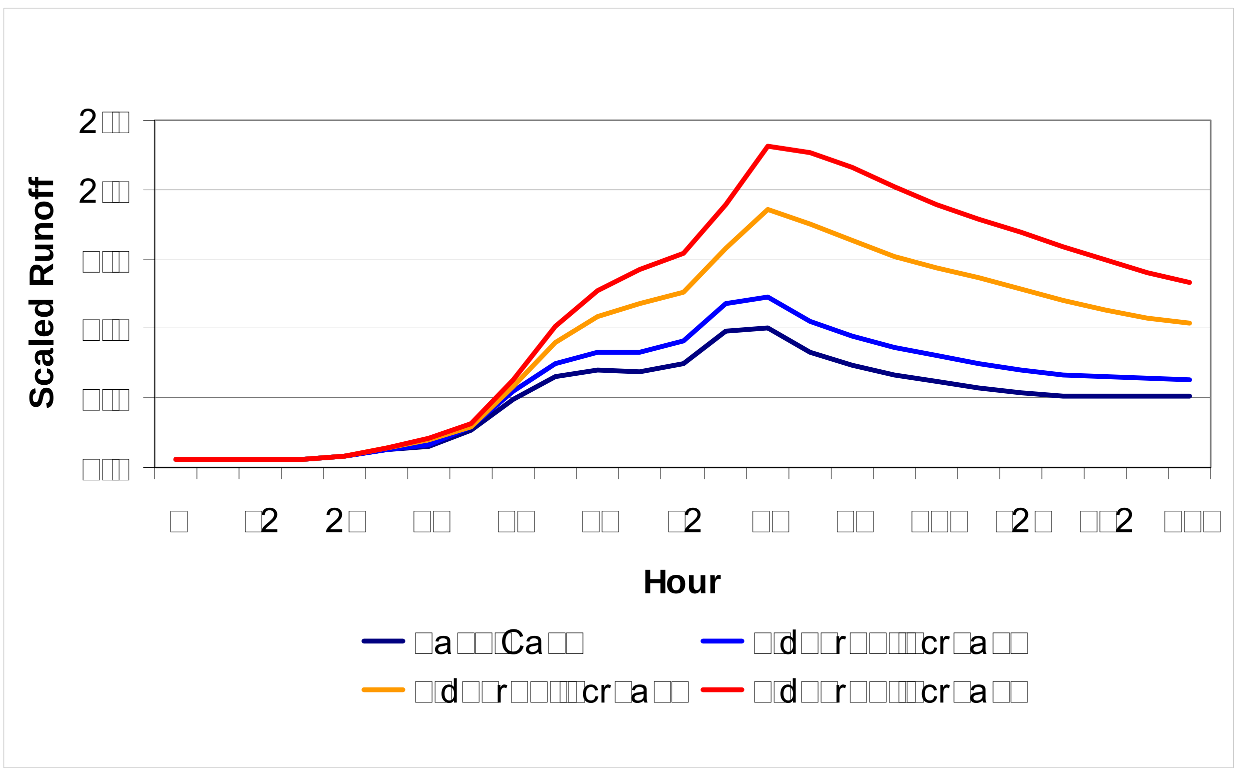



**Figure 6-25 Direct runoff changes due to increasing contributing area of watershed**

As pointed out earlier, higher snow elevations not only mean more area to contribute to direct runoff for a given winter storm, but there is less area for snowpack to develop at higher elevations. The impact of higher snow elevations due to higher atmospheric temperatures is estimated using area-elevation curves for watersheds. Computations assumed a 500 foot increase in elevation of snowpack for each degree Celsius of atmospheric temperature warming. Table 6-15 lists the percentage of watershed area covered with snow for 25 basins given mean atmospheric temperature increases from 1 to 5 degrees Celsius.

**Table 6-15 Snow Covered Area Changes with Temperature for Selected Watersheds**

| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
|---|---|---|---|---|---|---|---|---|---|
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible]2[illegible] | 2[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible]2[illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | 2[illegible] | [illegible] | [illegible]2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | [illegible]2[illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | [illegible]2[illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | 2[illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] | [illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 22[illegible] |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] |
| [illegible] | [illegible]2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] |
| [illegible] | [illegible] | [illegible]2[illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | 2[illegible] | [illegible] |

As can be seen from Table 6-15, the northern watersheds lose the majority of their area for snowpack development once the temperature increases reach or exceed 2 degrees Celsius. Lower elevation basins such as the Cosumnes, may lose their snowpack entirely in drier years. Higher elevation basins tributary to the San Joaquin River are less impacted than the northern basins. However, these basins produce less annual runoff than the basins in the north. Increasing peak flows due to winter storms and smaller snowpacks in terms of the percentage of the watershed covered can have significant impacts on the operation of flood control and water supply structures in California.

Knowles and Cayan (2004) and Mote and others (2005) discuss how snow responds to climate change based on latitude and elevation. Knowles and Cayan (2004) note that the greatest changes to snowpack due to climate change are in the 4000 to 9000 foot elevation range for the Sacramento River Basin. Mote and others (2005) show that the trends in spring snowpack in the western United States are largely due to long-term warming trends. Year-to-year variability due to changes in the Pacific Ocean like El Nino at most only account for one third of the magnitude of the trend. They also note that future warming will likely change most seasonal snowpack sites to sites that will accumulate and melt several times each year.

## 6.6 Discussion

Over the past century there have been observed changes to the average, maximum, and minimum temperatures and their variability, changes to the annual precipitation variability, and changes to the three-day peak discharge statistics. Over the past 30 years there has been a small increase in observed statewide average annual precipitation as well.

For this report, four climate-change simulations (two models x two scenarios) were evaluated for information on potential impacts to runoff patterns in California. Increasing temperatures are likely to lead to increased elevations for snowpack formation which leads to a greater contributing area available for winter storm runoff. In a sample calculation, the peak runoff for a given event is shown to double under a 5 degree Celsius warming. The percent decrease in watershed area available for snowpack was also shown for 1 to 5 degree Celsius warming. In addition to these changes, warmer temperatures may lead to early melting of the snowpack. Analysis of observed data indicates that a two-week shift has already occurred for lower elevations. The combination of earlier melt times, greater variability and greater potential for direct storm runoff may challenge the current system of flood protection and water supply in the state. Because of this, future work is needed in the following areas.

In order to better understand the risks associated with global climate change on California's runoff patterns, it is important to be able to quantify the uncertainty in projected changes to flood and drought frequencies and to the quantity and timing of water supply runoff. Future efforts to address these issues include:

- Continue historical data trend and variability evaluation
- Periodically update frequency-based data for design computations
- Evaluate new climate change model-derived data sets
- Develop new water supply forecasting technologies that can adapt to the changing distribution of the state's annual water supply
- Incorporate methodologies to quantify the uncertainty in potential climate change based impacts into the water supply planning process

For flood frequency analysis, future synthetic daily flow datasets may eventually be produced from climate change model output that will be suitable for flood frequency analyses. As these future datasets become available, they must be evaluated for their ability to represent current magnitude and variability as well as predicted changes due to climate change. At this time there is no dataset that would provide meaningful results.

Another area that may produce useful flood forecasting information examines historical data in order to identify critical atmospheric circulation parameters and their threshold values associated with extreme flooding events. As the circulation patterns in the GCMs improve and are shown to represent current conditions (location, frequency, variability) correctly, circulation patterns under increased greenhouse gas concentrations can be examined for the flood producing patterns or critical threshold characteristics. Improved forecasting technologies will help the implementation of adaptive strategies to mitigate the atmospheric and hydrologic changes that may increase flood risk.

For water supply analyses, it is important to identify potential changes to the land covered by snowpack and to identify changes to the magnitude and timing of snowpack growth and decay. Earlier melt patterns may necessitate new forecast bulletin products such as a March to May runoff forecast being created to complement existing April-July water supply forecasts. The inclusion of March in the forecast process introduces a large element of variability. Uncertainties related to this variability would have to be quantified as part of the water supply forecast product. Improved understanding of the potential future changes to the magnitude and timing of water supply runoff will enable better forecast products which can improve adaptive strategies for water supply operations in the state.

## 6.7 References

Bardini, G., S. Guillen, B. Pierotti, H. Rooks, S. Sou. 2001. *Climate Change in Califonria: Potential Consequences and strategies to cope and adapt*. California Department of Water Resources Report. 91 pp.

Barnett, T., R. Malone, W. Pennell, D. Stammer, B. Semtner and W. Washington. 2004. "The Effects of Climate Change on Water Resources in the West: Introduction and Overview", *Climatic Change*, 62, 1-11.

Buer, S. 1988. Program Manual: HED71 for Headwater Runoff Forecasting. California Department of Water Resources Division of Flood Management.

Christensen, N.S., A.W. Wood, N. Voisin, D. P. Lettenmaier and R. N. Palmer. 2004. "The effects of climate change on the hydrology and water resources of the Colorado River Basin", *Climatic Change*, 62, 337-363.

Dettinger, M., D. Cayan, M. Meyer, and A. Jeton, 2004. "Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American Rivers, Sierra Nevada, 1900-2099", *Climatic Change*, 62, 283-317.

Easterling, (2000). *Observed Variability and Trends in Extreme Climate Events: A Brief Review.* [D.R. Easterling, J.L. Evans, P. Ya. Groisman, T.R. Karl1, K.E. Kunkel, P. Ambenje] Bulletin of the American Meteorological Society, **81**, March 2000, 417-425. http://www.ncdc.noaa.gov/oa/pub/data/special/extr-bams2.pdf

Gleick, P.H., 1987. "The development and testing of a water balance model for climate impact assessment: Modeling the Sacramento basin", *Water Resources Research*, 23, 1049-1061.

Intergovernmental Panel on Climate Change, 1990. *Climate Change: The IPCC Scientific Assessment*, J.T. Houghton, G.J. Jenkins, and J.J. Ephraums (eds.) Cambridge University Press. Cambridge, UK, 365 pp.

Intergovernmental Panel on Climate Change, 1995. *Climate Change 1995: The Science of Climate Change*, J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.) Cambridge University Press. Cambridge, UK, 572 pp.

Intergovernmental Panel on Climate Change, 2001. *Climate Change 2001: The Scientific Basis*. Cambridge Univ. Press. 881 pp.

Jeton, A.E., M.D. Dettinger, and J.L.. Smith, 1996. "Potential effects of climate change on streamflow: Eastern and western slopes of the Sierra Nevada, California and Nevada". *U.S. Geological Survey, Water Resources Investigations Rep*. 95-4260, 44pp.

Kim, J. 2005. "A projection of the effects of climate change induced by increased CO2 on extreme hydrologic events in the western U.S.", *Climatic Change*, 68, 153-168.

Knowles, N. and D.R. Cayan, 2001. *Global climate change: Potential effects on the Sacramento-San Joaquin watershed and the San Francisco Estuary*.

http://meteora.ucsd.edu/~knowles/papers/Globaland California.pdf

Knowles, N. And D.R. Cayan. 2004. "Elevational dependence of projected hydrologic changes in the san francisco estuary and watershed", *Climatic Change*, 62, 319-336.

Lettenmaier, D.P. and T.Y. Gan, 1990. "Hydrologic sensitivities of the Sacramento-San Joaquin River Basin, California, to global warming". *Water Resources Res*, 26, 69-86.

Maurer, E.P. 2005. "Uncertainty in hydrologic impacts of climate change in the Sierra Nevada Mountains, California under two emissions scenarios", *Climatic Change*, (submitted 29 April 2005).

Maurer, E.P. and P. B. Duffy. 2005. "Uncertainty in projections of streamflow changes due to climate change in California", *Geophysical Research Letters*, 32, L03704.

Miller, N.L., J. Kim, R.K. Hartman, and J. Farrara, 1999. "Downscaled climate and streamflow study of the Southwestern United States", *J. American Water Resources Association*, 35, 1525-1537.

Miller, N.L., K.E. Bashford, and E. Strem, 2003. "Potential impacts of climate change of California hydrology". *J. Amer. Water Resourc. Assoc*, 39, 771-784.

Mote, PW, AF Hamlet, MP Clark, and DP Lettenmaier, 2005. Declining mountain snowpack in western North America, Bulletin of the American Meteorological Society, 86:39-49.

Peterson, T., 2003. "Assessment of Urban Versus Rural In Situ Surface Temperatures in the Contiguous United States: No Difference Found", *Journal of Climate*, 16: 2941–2959.

Revelle, R.R. and P.E. Waggoner,1983. "Effects of a carbon dioxide induced climatic change on water supplies in the Western United States". In *Changing Climate*, National Academy of Sciences Press, Washington, D.C.

Stedinger, J.R, and C. M. Crainiceanu, "Climate Variability and Flood-Risk Management, Risk-Based Decision Making", in *Water Resources IX, Proceedings of the Ninth Conference, United Engineering Foundation , Santa Barbara, CA, Oct. 15-20, 2000*, pp. 77-86, Amer. Society of Civil Engineers, Reston, VA, 2001.

Stewart, I.T., D.R. Cayan and M. D. Dettinger, 2004. "Changes in snowmelt runoff timing in western North America under a `business as usual' climate change scenario", *Climatic Change*, 62, 217-232.

USGRCP Water, 2000. *Water: The potential consequences of climate variabbility and change*. A report of the National Assessment Group for the USGCRP. 151 pp.

VanRheenen, N.T. A.W. Wood, R.N. Palmer and D.P. Lettenmaier. 2004. "Potential implications of pcm climate change scenarios for sacramento–san joaquin river basin hydrology and water resources", *Climatic Change*, 62, 257-281.

Water Resources Council, 1982. Guidelines for determining flood flow frequency, Bulletin 17B, United States Geological Survey Office of Water Data Coordination.

Wigley, T.M.L. and S.C.B. Roper, 2001. "Interpretation of high projections for global-mean warming". *Science*, 293, 451-454.

Wilby, R.L. and M.D. Dettinger, 2000. "Streamflow changes in the Sierra Nevada, California, simulated using statistically downscaled general circulation model output". In *Linking Climate Change to Land Surface Change*, Ed. S. McLaren and D. Kniven, Kluwer Academic Pub., 99-121.

Wood, A.W., L. R. Leung, V. Sridhar and D. P. Lettenmaier. 2004. "Hydrologic implications of dynamical and statistical approaches to downscaling climate model outputs" *Climatic Change*, 62, 189-216.

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# Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
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# Chapter 7:
# Climate Change Impacts on Evapotranspiration

**Authors:**

Roy M. Peterson, Jr. Ph.D.
California Department of Water Resources, Division Environmental Services, Sacramento.

Richard L. Snyder Ph.D.
Biometeorology Specialist, Department of Land, Air and Water Resources, University of California, Davis.

Morteza N. Orang Ph.D.
California Department of Water Resources, Division Planning and Local Assistance, Sacramento.

Hongbing Yin P.E.
California Department of Water Resources, Bay Delta Office, Sacramento.

**Peer Reviewers:**

Richard G. Allen, Ph.D., University of Idaho, Kimberly

Hugo G. Hidalgo, Ph.D., Scripps Institute of Oceanography

Theodore C. Hsiao, Ph.D. University of California, Davis

# 7 Climate Change Impacts on Evapotranspiration

## 7.1 Introduction

Possible increases in crop water demand and reduced water resource availability due to climate change are a growing concern among scientists and policy makers. We discuss the potential response of evapotranspiration (ET) to global climate change. Evapotranspiration is the vaporization or release of water vapor to the atmosphere from the terrestrial landscape. There are two parts to ET. First is evaporation, which includes vaporization of water from the soil and wet plant surfaces. Second is transpiration, which is vaporization that occurs within the leaves with the water vapor diffusing through pores in the leaves to the atmosphere. Water for transpiration comes from the soil through the plants and to the atmosphere. So the transpiration rate depends on the integration of soil, plant, and atmospheric factors. The evaporation rate depends on soil factors and frequency and amount of precipitation and irrigation, which determine water availability for vaporization.

In this chapter, we provide the current ET demand in California together with possible future ET demand under climate change. Population growth and likely crop pattern shifts are considered as factors that affect climate change ET estimates. An energy budget analysis to examine the net energy flux involved with ET and the physiological processes that influence ET are provided to explain the ET mechanisms affected by climate change. We describe a promising water management simulation model, SIMulation ET of Applied Water (SIMETAW). It is described in relation to climate prediction to estimate future net irrigation needs for crops.

## 7.2 Evaporative Demand for Applied Water in California

### 7.2.1 Current settings

California has produced the highest agricultural value in the country for the past 50 years. In 1997, 10.8 million acres of the state were devoted to harvested crops with another 14.4 million acres devoted to pasture and rangeland. Half of the fruits, nuts and vegetables in the country are produced in California. It is the only state producing commercial quantities of almonds, artichokes, clingstone peaches, figs, raisins, walnuts, pistachios, nectarines, olives, dates, and prunes. California also leads the nation in dairy production. In 2003, the latest available information for California agriculture production, California earned $29.4 billion in agriculture income (USDA, 2003).

This land of milk and honey results from a geography of fertile valleys, coastal plains, and gently rolling foothills and sharp tall mountains. The tall mountains in the north and on the eastern side of the state accumulate snow in winter for a water reserve during the next growing season. A semiarid Mediterranean climate provides a long frost-free growing season in most of the state. And there is abundant sunshine, a key to a plentiful agriculture and lush native vegetation.

The native vegetation of the state has a net primary productivity (NPP) that reflects the natural carrying capacity with respect to water and other natural resources. The native NPP is less than that of the state's crop production mainly because of the supplemental irrigation water applied. Figure 7-1 provides a regional map of California with the state's 10 hydrologic regions and Figure 7-2 is a map of 18 reference evapotranspiration ($ET_o$) zones California. The hydrological zones have traditionally been used for water resources planning and the ETo zone map has further refined ET estimation in California. Reference evapotranspiration is the ET from a vegetated surface with an approximate height of 0.12 m that is similar to clipped, cool-season grass (ASCE-EWRI, 2005). DWR's California Irrigation Management Information System (CIMIS) network (Snyder and Pruitt, 1992) was the main source of data used to develop the $ET_o$ map. The Pruitt and Doorenbos (1977) hourly $ET_o$ equation rather than the hourly ASCE-EWRI Penman-Monteith equation is used in CIMIS. The results, however, are similar for both equations (Ventura et al., 1999). The monthly and annual total $ET_o$ for each of the eighteen zones is listed in Table 7.1 to illustrate the variability through the year and between zones. The ETo rates listed for the zones show the spatial patterns and relative variation of average annual ETo with extremes from 32.9 to 71.6 inches per year.

Rainfall and irrigation water are the principal sources of water for agricultural production. Irrigation water includes groundwater pumped from aquifers and surface water delivered through natural and man-made and watercourses. The surface water generally originates in the mountains as snowmelt and surface runoff from precipitation. It is temporarily stored in reservoirs for later distribution during the peak-demand season. Excluding water used to meet instream flow requirements, Delta water quality, and other environmental uses, 80 percent of the developed water supply supports agriculture while 20 percent serves urban uses.

Most of the agricultural water contributes to crop ET. But water is also used for cultural practices, such as leaching salts and for frost protection. It is also used for groundwater recharge. The term consumptive use is used and it refers to the water vaporized to produce a crop or ET. Evapotranspiration of applied water ($ET_{aw}$) is equal to ET minus effective precipitation, the amount of rainfall available for use by a crop. Therefore, $ET_{aw}$ is the amount of irrigation water that is consumed by the crop. Additional irrigation water is applied to account for non-uniform distribution of the irrigation water and to control salinity. Most of the applied irrigation water contributes to $ET_{aw}$, so it is essential information for water resources planning and management. Projections for the actual demand for irrigation water are predicted using estimates of irrigation application efficiency. These estimates depend on the irrigation system and management, water requirements for leaching and other cultural practices, and $ET_{aw}$ or applied irrigation water is transpired by crops and evaporated from soil and plant surfaces.

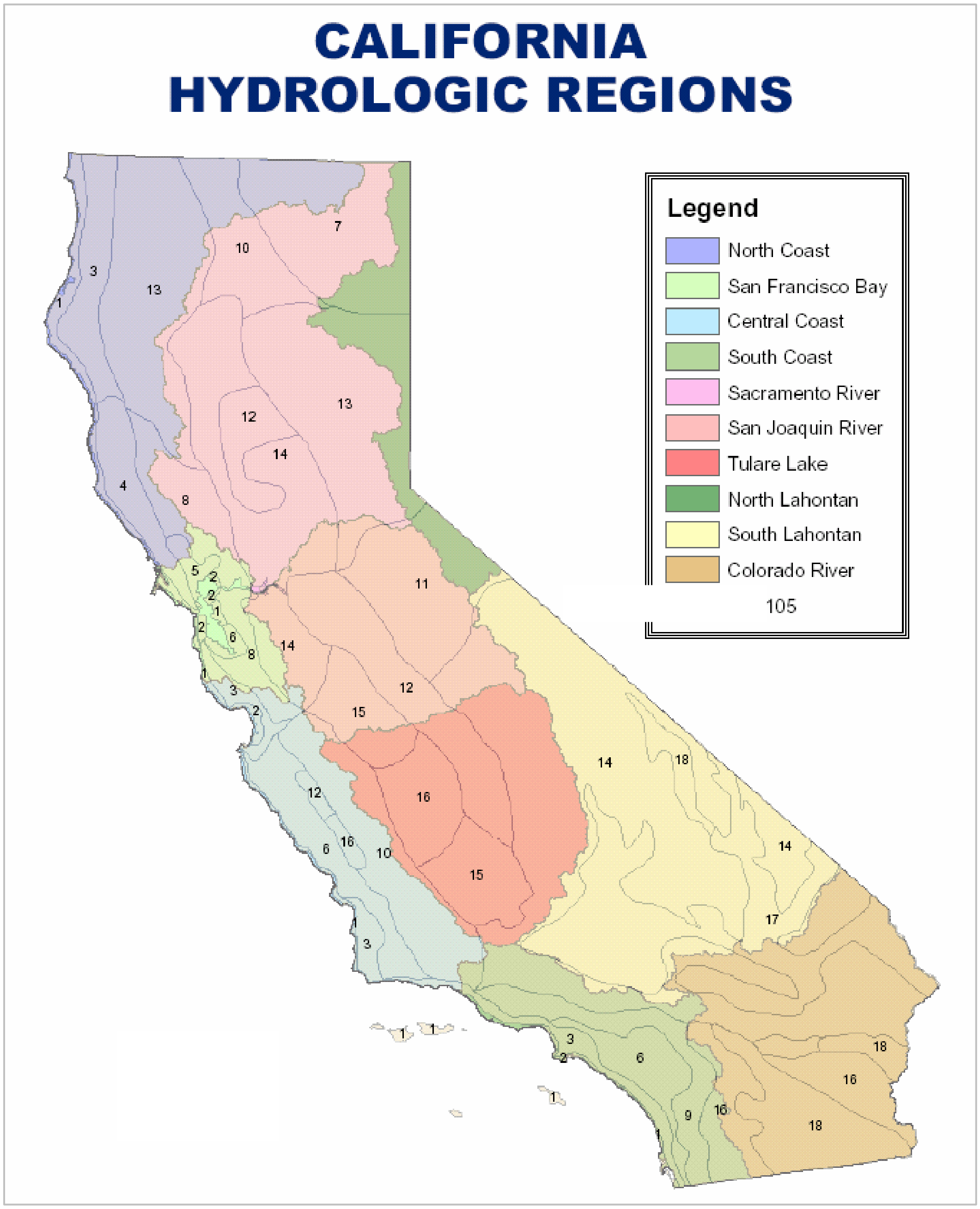


**Figure 7-1 Hydrological regions coded by color**
(Numbers are the ET zones listed in the legend and coded by color in Figure 7-2)

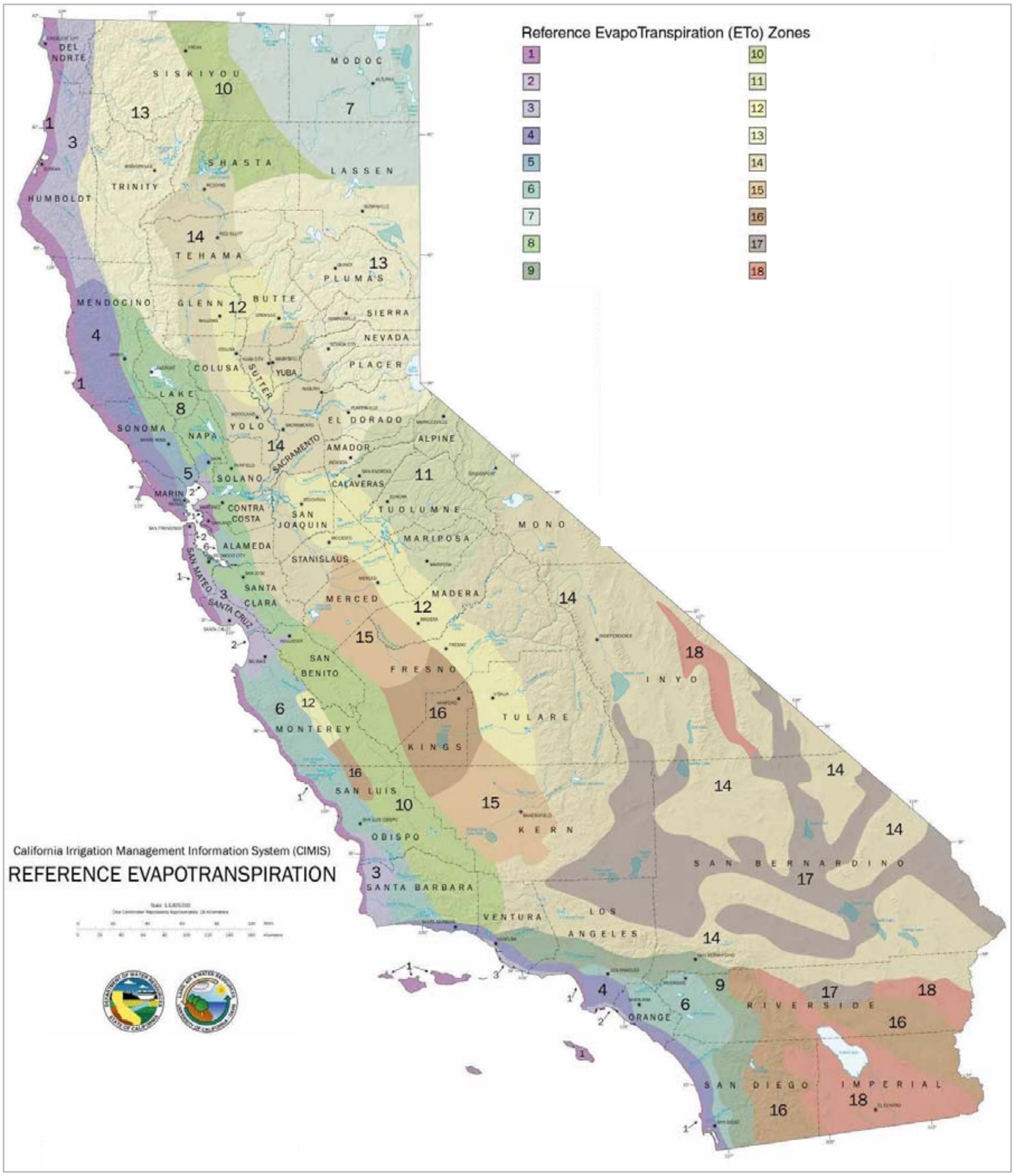


**Figure 7-2. Reference evapotranspiration zones**

**Table 7.1. Monthly and total reference evapotranspiration (ETo) by ETo zone for the California ETo zone map in inches per month.**

| Zone | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.9 | 1.4 | 2.5 | 3.3 | 4.0 | 4.5 | 4.7 | 4.0 | 3.3 | 2.5 | 1.2 | 0.6 | 32.9 |
| 2 | 1.2 | 1.7 | 3.1 | 3.9 | 4.7 | 5.1 | 5.0 | 4.7 | 3.9 | 2.8 | 1.8 | 1.2 | 39.0 |
| 3 | 1.9 | 2.2 | 3.7 | 4.8 | 5.3 | 5.7 | 5.6 | 5.3 | 4.2 | 3.4 | 2.4 | 1.9 | 46.3 |
| 4 | 1.9 | 2.2 | 3.4 | 4.5 | 5.3 | 5.7 | 5.9 | 5.6 | 4.5 | 3.4 | 2.4 | 1.9 | 46.6 |
| 5 | 0.9 | 1.7 | 2.8 | 4.2 | 5.6 | 6.3 | 6.5 | 5.9 | 4.5 | 3.1 | 1.5 | 0.9 | 43.9 |
| 6 | 1.9 | 2.2 | 3.4 | 4.8 | 5.6 | 6.3 | 6.5 | 6.2 | 4.8 | 3.7 | 2.4 | 1.9 | 49.7 |
| 7 | 0.6 | 1.4 | 2.5 | 3.9 | 5.3 | 6.3 | 7.4 | 6.5 | 4.8 | 2.8 | 1.2 | 0.6 | 43.3 |
| 8 | 1.2 | 1.7 | 3.4 | 4.8 | 6.2 | 6.9 | 7.4 | 6.5 | 5.1 | 3.4 | 1.8 | 0.9 | 49.4 |
| 9 | 2.2 | 2.8 | 4.0 | 5.1 | 5.9 | 6.6 | 7.4 | 6.8 | 5.7 | 4.0 | 2.7 | 1.9 | 55.1 |
| 10 | 0.9 | 1.7 | 3.1 | 4.5 | 5.9 | 7.2 | 8.1 | 7.1 | 5.1 | 3.1 | 1.5 | 0.9 | 49.1 |
| 11 | 1.6 | 2.2 | 3.1 | 4.5 | 5.9 | 7.2 | 8.1 | 7.4 | 5.7 | 3.7 | 2.1 | 1.6 | 53.1 |
| 12 | 1.2 | 2.0 | 3.4 | 5.1 | 6.8 | 7.8 | 8.1 | 7.1 | 5.4 | 3.7 | 1.8 | 0.9 | 53.4 |
| 13 | 1.2 | 2.0 | 3.1 | 4.8 | 6.5 | 7.8 | 9.0 | 7.8 | 5.7 | 3.7 | 1.8 | 0.9 | 54.3 |
| 14 | 1.6 | 2.2 | 3.7 | 5.1 | 6.8 | 7.8 | 8.7 | 7.8 | 5.7 | 4.0 | 2.1 | 1.6 | 57.0 |
| 15 | 1.2 | 2.2 | 3.7 | 5.7 | 7.4 | 8.1 | 8.7 | 7.8 | 5.7 | 4.0 | 2.1 | 1.2 | 57.9 |
| 16 | 1.6 | 2.5 | 4.0 | 5.7 | 7.8 | 8.7 | 9.3 | 8.4 | 6.3 | 4.3 | 2.4 | 1.6 | 62.5 |
| 17 | 1.9 | 2.8 | 4.7 | 6.0 | 8.1 | 9.0 | 9.9 | 8.7 | 6.6 | 4.3 | 2.7 | 1.9 | 66.5 |
| 18 | 2.5 | 3.4 | 5.3 | 6.9 | 8.7 | 9.6 | 9.6 | 8.7 | 6.9 | 5.0 | 3.0 | 2.2 | 71.6 |

The average annual $ET_{aw}$ in the state's ten hydrologic regions, during the most recently recorded normal water year 2000 (DWR-DPLA, 2005), ranged from 13.56 acre-inch per acre per year to 44.52 acre-inch per acre per year (Table 7.2). These $ET_{aw}$ values are weighted by the acreages of crops grown in each region. They also reflect the variability in planting and harvest dates, ETo, and effective precipitation for each crop in each hydrologic region. Crop coefficients used to calculate crop $ET_{aw}$ from $ET_o$ came from a variety of sources including DWR Bulletin 113-3, April 1975, Bulletin 113-4, April 1986 and Food and Agriculture Organization of the United Nations Irrigation and Drainage Paper 56 Crop Evapotranspiration, 1998. Soil available water estimates were based on data in soil survey publications from the USDA National Resources Conservation Service. Records of daily precipitation from weather stations located near agricultural areas are used in a model along with ETo data and soil information to estimate the amount of precipitation available for crop consumption. The $ET_{aw}$ values extend from October 1, 1999 through September 30, 2000. $ET_{aw}$ values vary from year-to-year with changes in the proportions of irrigated acreage planted to each crop category, change in cultivars planted, the quantity and distribution (spatial and temporal) of precipitation, water applied for cultural practices, irrigation water management, variation in ETo and other factors.

The statewide average annual $ET_{aw}$ for 20 important agricultural crop categories are listed in Table 7.3. These average ETaw values reflect the distribution of crops across the ETo zones in California. They are based upon the same data from Water Year 2000 used to estimate the average $ET_{aw}$ for each hydrologic region. Safflower used the least water, averaging 9.48 acre-inch per acre while alfalfa used the most, averaging 42.72 acre-inch per acre.

**Table 7.2 Estimated Annual ET of applied water by hydrologic region during the 2000 water year in acre feet per acre, from DWR-DPLA 2005**

| Region | Name | ETaw (acre-inch/acre) |
|---|---|---|
| 01 | North Coast | 20.28 |
| 02 | San Francisco Bay | 14.16 |
| 03 | Central Coast | 13.56 |
| 04 | South Coast | 27.60 |
| 05 | Sacramento River | 28.92 |
| 06 | San Joaquin River | 26.04 |
| 07 | Tulare Lake | 26.76 |
| 08 | North Lahontan | 28.92 |
| 09 | South Lahontan | 44.52 |
| 10 | Colorado River | 42.96 |

**Table 7.3 ET of applied water in acre inch per acre for some of the main commodities grown in California.**

| Commodity | ETaw (acre-in/acre) |
|---|---|
| Grains | 12.72 |
| Rice | 37.44 |
| Cotton | 28.44 |
| Sugar Beet | 30.72 |
| Corn | 22.20 |
| Dry Bean | 18.36 |
| Safflower | 9.48 |
| Other Field Crops | 22.44 |
| Alfalfa | 42.72 |
| Pasture | 34.68 |
| Processing Tomatoes | 24.36 |
| Fresh Market Tomatoes | 20.40 |
| Cucurbits | 18.72 |
| Onions Garlic | 29.16 |
| Potatoes | 20.04 |
| Other Truck Crops | 15.84 |
| Almonds Pistachios | 33.12 |
| Other Deciduous Orchards | 32.16 |
| Subtropical Crops | 30.36 |
| Vineyards | 17.3 |

### 7.2.2 Projected ET changes for the California landscape impacted by climate change

Hidalgo et al. (2005) investigated the impacts of climate change on irrigation water demand with respect to reference ET ($ET_o$) in California and found that the highest interseasonal variability of $ET_o$ daily anomalies occurs during the spring, mainly in response to variations in cloudiness. Daily $ET_o$ values were closely associated with net radiation ($R_n$), relative humidity, and cloud cover, and are less related to average daily temperature. In the next section about energy budget the relationships between climatic factors are discussed along with relative influences they exert. Although Hidalgo et al (2005) concluded that to maintain $ET_o$ in the current condition requires a decrease in $R_n$ of about 6 percent to compensate for a temperature increase of 3ºC, they did not account for increased stomatal resistance that is likely to result from higher $CO_2$ concentration, which is discussed in detail later in this chapter. Hidalgo et al. were clearly correct in that the effects of climate change on $ET_o$ are difficult to forecast because of the uncertainty of cloud cover and relative humidity. Allen et al. (1991) concluded that a $CO_2$ induced climate change resulted in an increased $ET_o$ which then translated to an increased $ET_{aw}$.

### 7.2.3 Landscape influences on ET that complicate climate change effects

Climate influences biophysical features in the landscape, but the physical landscape also influences climate and affects the interaction between climate and landscape. For example, crop irrigation reduces the air temperature and urban surfaces commonly increase temperature.

Future urban growth affects the statewide ET demand by decreasing irrigated agriculture land. In population studies, Landis and Reilly (2004) reported that the greatest urban expansion is likely to happen on flat land of valley floors. They listed the greatest risk to important farmland as land in the Inland Empire and in the Central Valley.

Increasing urbanization can increase the heat-island effect (a localized elevation in temperature over the ambient air temperature) and could lead to small increases in advection of additional heat to nearby crops. Advection is the horizontal transfer of heat or scalars, such as water vapor or $CO_2$, that results when wind blows air reflecting characteristics of one surface over another surface with different characteristics. Energy fluxes over irrigated crops are usually vertical, but there can be edge effects when local advection occurs. When there is warm air advection, the horizontal transfer of energy can increase ET on crop edges. This can lead to moderate stress, which reduces plant size, or severe stress that reduces ET and photosynthesis. This is quite noticeable where irrigated fields are surrounded by bare, dry soil. Affected crops are often shorter and appear more stressed on the edges than in the middle of the field. There is also regional warm air advection, which occurs when heat is horizontally transferred over cropped areas. This often happens in the Central Valley where warm air from the drier foothills moves over irrigated land in the middle of the valley. For regional advection, however, the heat transfer is mostly vertical. This means there is more available energy for evaporation than is supplied by net radiation and soil heat flux. The result is a reduced $ET_{c/}ET_{pot}$ ratio because $Et_{pot}$ increases due to advection. Urbanization could lead to some additional warming and it might increased advection. Although small in its reach, increased advection could result from urban expansion into irrigated crops in an increasing dentate edge.

Other effects on ET from growing urbanization next to agricultural land include physiological impacts from air toxicants, most notably ozone, and regional atmospheric dimming from particulates and pollutants above and around urban centers and held in place by inversion due to high atmospheric pressure during the summer growing season.

### 7.2.4 Changes in cropping and irrigation methods that interact with climate change

Throughout the 150 years of California agriculture, many changes in crop types and shifts in cropping patterns have occurred. In addition to land loss to urbanization, land use conversions for agriculture are driven by irrigation water availability, changes in multiple cropping, and changes in the crops due to economics. Biophysical changes that result from climate change could contribute to these factors. For example, with warming temperatures, citrus production could move farther north in the Central Valley and deciduous orchard crops that have large chill requirements might have reduced production or be forced out of the area. Shifts in cropping patterns are likely to continue with increased water cost and possibly with changes in regional climates. There are, however, no comprehensive studies of projected changes in California agriculture resulting from climate change (Hayhoe et al., 2004). Water resources availability will likely be the main environmental variable determining shifts in crop distribution (Field et al., 1999).

Based on surveys conducted jointly by the University of California and California Department of Water Resources, a definite trend towards growing more perennial crops and using low-volume, pressurized irrigation systems has occurred during the past 30 years (CDWR Bulletin 160-05). While this has improved the economic benefits resulting from irrigation and has likely improved on-farm irrigation efficiency during years with adequate water supplies, growers have reduced ability to adapt during dry periods. For example they don't have annual field or row crops that could be fallowed during droughts. With adequate water supplies, this trend is good, but it is financially dangerous in terms of drought response and mitigation.

The value integration network simulation model (CALVIN) and the statewide water and agricultural production simulation model (SWAP) were developed at the University of California, Davis, and they were coupled to investigate climate change in California by modifying crop yields and amount of irrigated water used (Tanaka et al., 2005). They concluded that by the end of the century there will be a 24 percent decrease in the amount of water devoted to agriculture and only a 6 percent decrease in agricultural income. The differences in water use and income were attributed to growing higher value crops and increased irrigation application efficiency. Higher application efficiencies mean higher ratios of water consumption by evapotranspiration to water applied. This can reduce both diversions for irrigation and reduced return flow. In some instances, this may reduce supplies to downstream projects depending on whether the reduction in diversions or return flow is larger. Generally, if outflows from basins are near minimum values, only reductions in ET upstream will free up water for transfer from irrigated agriculture.

## 7.3 Energy Budget

An energy budget can account for all input and output energy fluxes to a terrestrial landscape. Among these fluxes is the mass balance of water phase change of liquid water to gaseous water vapor. This accounting is a useful analytic tool to investigate the affect of climate change on evapotranspiration. The Penman-Monteith equation, which is described in Appendix 1, is a partly empirical algorithm that was derived from energy budget considerations. It was modified by the ASCE-EWRI (2005) to derive a reference evapotranspiration (ETo) rate from meteorological measurements of minimum and maximum temperature, humidity, solar radiation and wind speed. There is, however, a difficulty in estimating crop evapotranspiration (ETc) or ETo for a climate-changed environment because of a lack of knowledge about canopy resistance to water vapor loss in an elevated $CO_2$ environment. Nonetheless, using FACE measurements of stomatal resistance (Long et al., 2004) for elevated $CO_2$ and the same approach used by Allen et al. (1989) to estimate canopy from stomatal resistance for use in estimating ETo, an increase in $CO_2$ concentration to 550 ppm is expected to increase the daily mean canopy resistance from 70 to 87 s $m^{-1}$.

It is important that the ASCE-EWRI (2005) has fixed the $ET_o$ canopy resistance at 70 s $m^{-1}$ for daily calculations and it is unlikely to be changed in the near future. The equation, however, should be updated if the canopy resistance changes. This is necessary because crop coefficient values were mostly developed by calculating the ratio $K_c = ET_c/ET_o$, where $ET_o$ was the ET of the reference grass surface and $ET_c$ was the crop ET. Consequently, the standardized reference ET equation should provide a good estimate of the ET of a 0.12 m tall, cool-season grass surface or the $K_c$ values will surely be incorrect. It is possible that $K_c$ values could change because of differences in stomatal responses to climate change, but changing the $ET_o$ equation and assuming that the $K_c$ ratio will be conserved is more plausible than maintaining a standardized equation that gives an incorrect estimate of the $K_c$ ratio denominator. To investigate possible ET changes in response to climate change, the daily (24-hour) ASCE-EWRI (2005) $ET_o$ equation is used and the temperatures and canopy resistance are changed to investigate how the ET of a 0.12 m tall, cool-season grass might change. It is assumed that other crops will respond similarly to the grass and the $K_c$ values will not change.

The Consumptive Use Program (CUP) was developed by DWR and the University of California, Davis to estimate crop evapotranspiration for planning purposes. CUP was written, using MS Excel software, as a tool to help California growers and water purveyors obtain accurate estimates of crop water requirement information from monthly mean data. The program takes input weather data and estimates monthly reference evapotranspiration (ETo) using the Penman-Montieth equation. Then the program uses a curve fitting technique to derive one year of daily weather and ETo data from the monthly data. A feature to vary the canopy resistance as well as the temperature allows users to investigate the effects of increasing canopy resistance on $ET_o$. Current monthly mean climate data from Davis, CA and a canopy resistance of 70 s $m^{-1}$ were input into CUP to calculate $ET_o$ rates using the Penman-Monteith equation. The process was repeated using an elevated $3^oC$ minimum and maximum temperature, holding all other variables constant. The process was repeated a third time with an increase in the minimum and maximum temperature and the dew point temperature by $3^oC$ while holding other variables constant. Finally, the combination of the air and dew point temperature increase by $3^oC$ and a canopy resistance increase to 87 s $m^{-1}$ was computed. Figure 7-3 shows a comparison of the smoothed curves of calculated $ET_o$ for the four scenarios. Increasing only air temperature, resulted in a 18.7 percent increase in $ET_o$. Increasing the air and dew point temperatures led to a 8.5 percent increase in $ET_o$. Increasing the temperatures and the canopy resistance to 87 s/m led to a 3.2 percent increase in $ET_o$ over current conditions. While the percentage increase is small when the canopy resistance is included, the volume of water relative to California is considerable. Other factors like changes in solar radiation due to changes in cloudiness or air pollution and changes in wind speed were not considered.

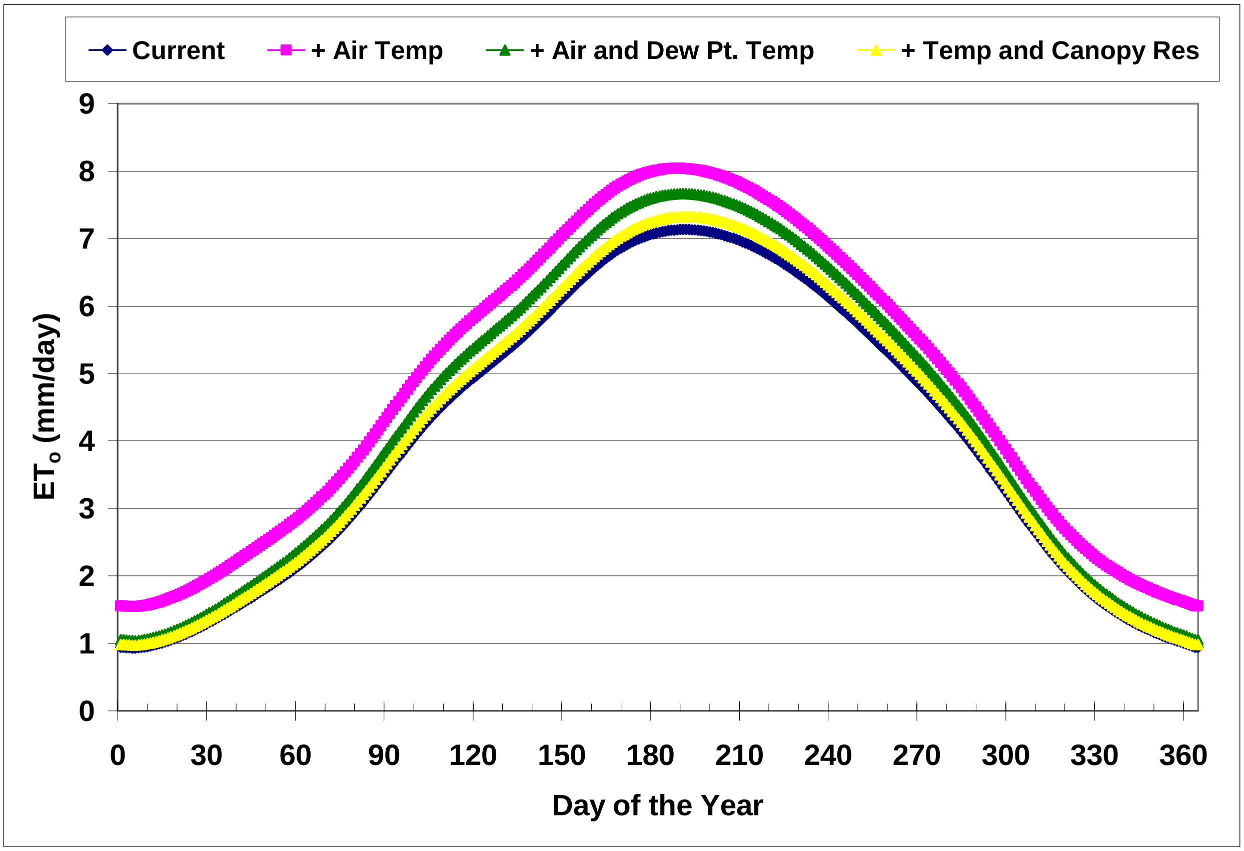


**Figure 7-3 ET$_o$ comparison for current and climate change conditions**
ETo comparison for current conditions (navy), for minimum and maximum temperature elevated 3°C (pink), for minimum and maximum and dew point temperature elevated by 3°C(green), and for temperature elevated 3°C and canopy resistance increased to 87 s/m (yellow).

## 7.4 Plant Physiology and Climate Change

### 7.4.1 Plant physiological and morphological adaptation

Plants adapt to a changed physical environment through physiologically and morphologically modification. For changes in temperature and $CO_2$, the two main plant adaptations are to control the water continuum between soil and atmosphere and to adjust photosynthetic carbon fixation.

In transpiration, water vaporizes inside leaves and diffuses through stomata (i.e., pores in the leaf surface) to the ambient air. Simultaneously, $CO_2$ is diffusing from the atmosphere into the leaves through the same stomata. When stomata partially close, $CO_2$ flow into the leaves and $H_2O$ flow from the leaves are both affected at the same time. However, since mesophyl resistance (i.e., resistance of the cell walls to passage of the $CO_2$) is typically much higher than stomatal resistance, stomatal closure has less effect on $CO_2$ uptake than it does on transpiration, which is restricted by the smaller stomatal aperture. In experiments carried out in enriched $CO_2$ environments, which are described later, typical agronomic plants exhibited a 20 percent reduction in stomatal conductance and a 20 percent increase in photosynthesis (Long et al., 2004).

In addition to being influenced by the environment, plants also influence their environment. Evaporation from the soil is directly affected by the plant canopy shading. The canopy size and density (i.e., coverage) and the rate of development all influence crop ET. The plant coverage is often quantified with the leaf area index (LAI), which is determined as the ratio of the canopy leaf area per unit ground area under the canopy. Theoretically, there is an optimal LAI that reduces soil evaporation on one hand, which increases water for transpiration and other plant processes, and that minimizes self shading of leaves that decreases growth and reproduction. The rate of canopy growth and closure is often quantified using the relative growth rate (RGR) or the growth per unit of biomass. The RGR optimization depends on below ground and above ground assimilate allocation that influence depth of rooting for water and nutrient attainment as well as canopy development, photosynthesis, and ground shading. To varying degrees, depending on the specific crop or even cultivars, there is a possibility for adaptation during plant growth and development (phenotypic plasticity) or for genetically fixed trait expression regardless of the environment.

What is most important for the ET, is not the total amount of leaf area produced but the rate of canopy development and closure (Hsiao and Xu, 2005), which can take up to two months in herbaceous crops. That is, the LAI is less important than the rate at which the canopy foliage develops and shades the ground. The rate of canopy closure is important for determining the relative contributions of evaporation and transpiration to ET. At planting, soil evaporation comprises 100 percent of the $ET_c$, but the contribution from the soil decreases until it is small relative to transpiration once a canopy reaches about 75 percent ground cover for field and row crops, and about 70 percent for tree and vine crops. This change occurs because the crop canopy intercepts most of the radiation before it reaches the ground once 75 percent ground cover is attained.

### 7.4.2 Transpiration and photosynthesis

Several plant physiology processes are often simultaneously influenced by environment factors. Figure 7-4 shows the relation of photosynthesis and transpiration together with the climatological factors influencing the two processes. Nitrogen assimilation, which occurs through the plant roots, can be affected by transpiration rate. It is included because of its importance as a control node in the photosynthetic process. Nitrogen is particularly important as part of the of Rubisco assimilation pathway. Rubisco is said to be the most abundant protein, and is an enzyme with a low efficiency that is pivotal as the initial and limiting step in the fixation of carbon in photosynthesis of most agronomic crops. Appendix 2, detailing the photosynthesis response curve to $CO_{2,}$ provides a fuller description of Rubisco and photosynthesis).

There are several photosynthetic pathways found in different plant species. In the $C_3$ pathway, which is the most widespread and is the photosynthetic system of most agriculture plant species, $CO_2$ is initially fixed by Rubisco during the day (i.e. in the presence of light) and then converted to a three-carbon intermediate. In the $C_4$ pathway $CO_2$ is initially fixed by PEP carboxylase during the day to form four-carbon acids. The $C_3$ and $C_4$ plants also differ anatomically, with $C_4$ plants maintaining a higher $c_i$ (intercellular $CO_2$ concentration) and a lower stomatal conductance for the same $CO_2$ assimilation rate.

Both light and dark respiration are included Figure 7-4 because respiration accounts for about 25 percent of plant energy expenditure. Respiration is an intercellular process in which molecules, particularly pyruviate in the citric acid cycle, are oxidized with the release of energy. It involves the complete breakdown of sugar or other organic compounds to $CO_2$ and $H_2O$. In addition to respiration relating photosynthesis, transpiration and nitrogen metabolism in an energy currency, optimization respiration is also important in the differential responses of plant biomass production to changes in atmospheric $CO_2$, which in turn is related to nitrogen form involved in intermediate metabolism. This concept is developed further in the physiological response section.

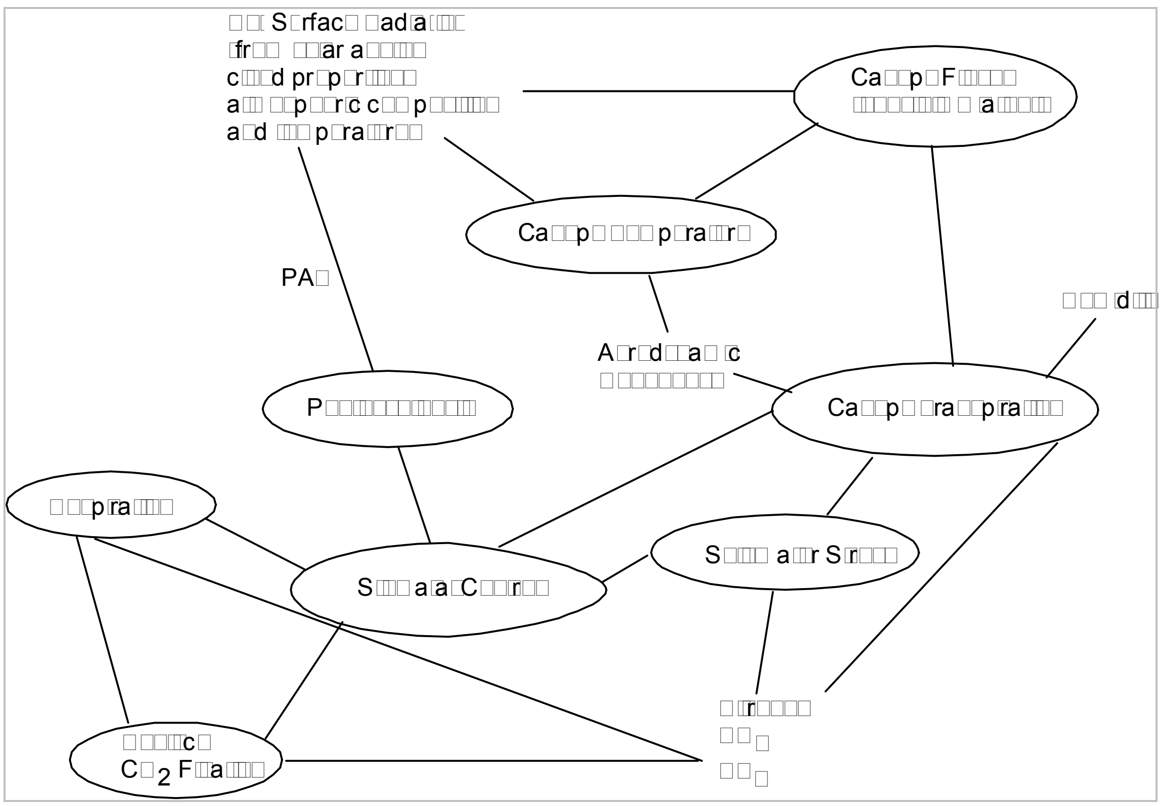

**Figure 7-4 Relation of transpiration, photosynthesis and nitrogen.**
Photsynthetically available radiation (PAR) indicates the total energy available for photosynthesis

In summary, the relation of the three physiology processes diagramed in Figure 1 are not necessarily direct but rather optimizations which can be either passive or active. Therefore, care is needed in extrapolating relations such as the total leaf area and stomatal density where feedback loops involving Rubisco density and its long term adaptations influence the relation of stomata function in $CO_2$ enriched environments. This concept will be discussed in a later section. The water use efficiency (WUE) quantitatively relates assimilation to transpiration. Assimilation is used here as the incorporation of an inorganic resource such as $CO_2$ or $NH_4$ into organic compounds; it is often synonymous with net photosynthesis. WUE = A/T, where A is assimilation and T is transpiration. Transpiration efficiency has been used to describe the ratio of carbon gained to water transpired at the whole plant level, that is assimilation per transpiration (Condon and Hall, 1977). In agronomy, WUE is typically regarded as the ratio of carbon fixed per unit water use; so at a crop level it is the amount of dry matter production per unit of total water transpired (T).

### 7.4.3 Effect of increased $CO_2$ on plant physiology and morphology

In an atmosphere with increased $CO_2$, the balance between photosynthesis and transpiration appears to change (Long et al., 2004). Plants adjust their stomatal opening to maintain the $CO_2$ concentration within the plant leaf intercellular space ($c_i$) so that it does not limit photosynthesis. Less stomatal opening is required at high atmospheric $CO_2$ concentration ($c_a$). Many researchers report that stomatal conductance decreases with rising atmospheric $CO_2$ concentration to maintain a constant ($c_i/c_a$) (Long et al, 2004; Hsiao and Jackson, 1999). Because the stomata partially close to maintain the concentration gradient between the air and stomatal cavities under elevated $CO_2$ concentration and the water vapor gradient is unchanged, the photosynthesis rate is little affected and the transpiration rate declines because of the stomatal closure, resulting in a small increase in WUE though an increase in photosynthetic demand (see Appendix 2 The photosynthesis Response Curve to $CO_2$).

With increased $CO_2$ for fixing carbon in photosynthesis, the diffusion of $CO_2$ into the plant leaf and water vaporization out through the same stomata is influenced by the availability of activation sites for fixing $CO_2$, which in turn is influenced by the availability of nitrogen to make the sites (i.e. enzymes, which for most crops is Rubisco). New findings suggest respiration could prove important to nitrogen assimilation at elevated $CO_2$ (Rachmilevitch et al., 2004). The forms of nitrogen used by a plant and elevated $CO_2$ can influence respiration (Rachmilevitch et al., 2004). The form of nitrogen used in plant intermediate metabolism, whether $NO_3$ or $NH_{4,}$ varies between species and even at different growth stages for the same plant. Plants that use $NO_3$ as their primary nitrogen source are unable to sustain rapid growth under elevated $CO_2$ because of interferences with respiration.

Figure 7-5 provides response relationships to increased atmospheric $CO_2$ for processes shown in Figure 7-4. The initial finding for this summarization of responses to $CO_2$ increase comes from growth chamber studies performed usually on individual leaves or individual plants. More recently, a good body of evidence for plant physiological responses to elevated $CO_2$ (about 570 $\mu$mole mol$^{-1}$) has been reported from FACE field studies on small plots.

Long et al. (2004) summarized the findings from these FACE sites in a meta analysis, which allows statistical analysis of the studies as a whole to understand elevated $CO_2$ influences. They found that biomass assimilation increased by about 20 percent while seed production increased about 24 percent. However, nitrogen in the leaves of longer-term plants decreased 17 percent and Rubisco decreased 15 percent. The LAI increased but not significantly.

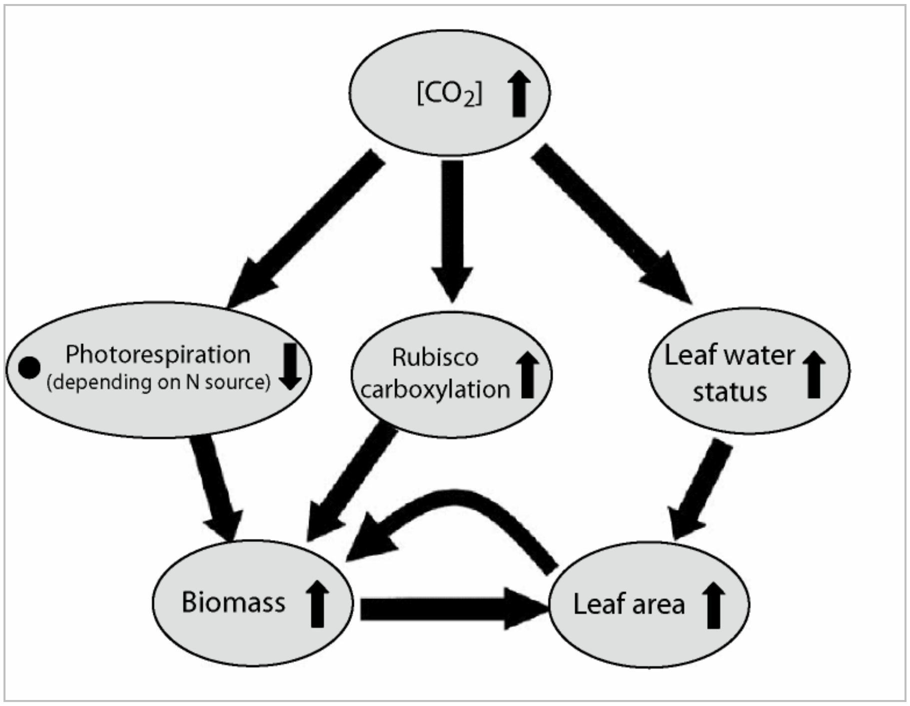


**Figure 7-5. $CO_2$ effects and interactions on $C_3$ plant production.**
CO2 effects and interactions on C3 plant production. The small arrows inside ovals indicate influence of CO2 on process (modified from Long et al, 2004)

Influences of elevated temperature and $CO_2$ on crop growth and phenology are topics of importance in determining ET for a future California landscape. For both herbaceous plant life and woody perennials, the influence of climate change on leaf senescence needs further study. Physiological changes like the apparent earlier or faster leaf aging in deciduous tress at elevated $CO_2$ can reduce seasonal ET. Evaporation from the soil is mainly affected by wetness of the soil surface, hydraulic properties of the soil, energy availability, and wind speed beneath the canopy so that advances in regional climate scale models are needed to understand influences of radiation and wind speed trends. Wind speed in particular is difficult to model and projects and accurate modeling of wind speed is unlikely to occur in the near future. Physiological changes like the apparent earlier or faster leaf aging in deciduous tress at elevated $CO_2$ can reduce seasonal ET and can be estimated.

It is widely held that increased $CO_2$ concentration could improve WUE, and needs more analysis at least on a whole plant level, if not the plant community level. When using whole plant examination of climate change impact that considers WUE by scaling up from relations such as LAI and stomata conductance there is a need to consider the influence of carbon assimilation from increased carbon fixation efficiency. Groups are using a variety of methods to investigate WUE. The isotope discrimination methodology for WUE is a direct measure that is easily obtained from any tissue in a plant. Seed companies are using this technique to develop plants with increased assimilation relative to transpiration to achieve a better WUE at elevated $CO_2$ or temperature. There is, however, a likely maximum theoretical upper bound to the gains in plant

WUE that are obtainable (Cowan and Farquhar, 1977). The likely upper bound to WUE brings into focus the need to look at a systems level for both understanding and for possible water use reductions per unit production. A system vision needs to considers the $CO_2$ and temperature environmental influence on plants, the plants influence on the local ET environment and the on farm water delivery to plants.

## 7.5 A Simulation Model for Estimating ET of Applied Water (SIMETAW)

### 7.5.1 SIMEATAW model description

SIMETAW (Simulation of Evapotranspiration of Applied Water) is a computer application program that can simulate several decades of daily weather data from climate records. It is useful for studying the effect of climate change on Crop evapotranspiration ($ET_c$) and evapotranspiration of applied water ($ET_{aw}$). SIMETAW was written mainly for use in water demand planning. SIMETAW can use either observed daily climate records or it can simulate daily weather data from monthly means for a specified period of years. The observed or simulated daily data are then used to estimate reference evapotranspiration ($ET_o$). Crop evapotranspiration is calculated for each day in the period of record using the product of the daily $ET_o$ values and a crop coefficient ($K_c$) factor. The seasonal change in Kc factors is determined using a slightly modified procedure that was originally presented by Doorenbos and Pruitt (1977). This method enables the representation of day-to-day variations in evaporative demand.

Monthly climate data include solar radiation ($R_s$), maximum ($T_x$) and minimum ($T_n$) air temperature, wind speed at 2 m height ($U_2$), dew point temperature ($T_d$), number of rainy days per month (NRD), and monthly total rainfall (Pcp). SIMETAW computes $ET_o$ using the daily (24-hour) Penman-Monteith equation (ASCE-EWRI, 2005). Daily $ET_c$ rates are estimated by multiplying $ET_o$ by a crop coefficient ($K_c$) factor. In addition, observed or simulated daily rainfall, soil water holding characteristics, effective rooting depths, maximum soil depths, and $ET_c$ are used to determine effective rainfall and to generate hypothetical irrigation schedules to estimate the seasonal and annual $ET_{aw}$. All of the water balance calculations are done on a daily rather than monthly basis, which improves the estimation of effective rainfall and, hence, $ET_{aw}$. A two-stage soil evaporation model is used to estimate bare soil evaporation as a function of mean $ET_o$ and wetting frequency in days. The bare soil evaporation rates are used to determine the off-season evapotranspiration and as a base-line for in-season $K_c$ calculations. Since $ET_c$ is unlikely to fall below the evaporation from an unirrigated bare soil, the crop Kc factors are not allowed to fall below the bare soil $K_c$ value on any given date. In addition, SIMETAW accounts for the influence of orchard cover crops on $K_c$ values, and it adjusts for tree and vine crop immaturity.

Combining atmospheric general circulation models (GCMs) with regional landscape models for downscaled model climatic results can provide estimates of future monthly climate variables, which can be used as simulation input for SIMETAW. Daily means of $R_s$, $T_x$, $T_n$, $U_2$, and $T_d$ by month are used to simulate daily weather data for several decades and the Penman-Monteith equation is then used to estimate daily $ET_o$ for the period of record. Increasing or decreasing one or more of the weather variables in the monthly climate prediction will influence the daily weather simulation and hence $ET_o$ calculation. For example, changing the rainfall pattern to have more precipitation in the fall and spring with less in the winter can be used to study the impact on the $ET_{aw}$. The ability to change the canopy resistance in response to higher $CO_2$ concentration was included in SIMETAW to more accurately estimate the effect of climate change on $ET_o$ by accounting for both canopy resistance and temperature changes.

### 7.5.2 Input data requirement

Either observed or simulated daily climate data are used in SIMETAW to determine $ET_o$. When monthly data are input, the daily data are simulated. Data from CIMIS or from a non-CIMIS data source can be input as long as data are in the correct format. For the water balance calculations, soil and crop information are input to calculate $ET_c$ and $ET_{aw}$.

A main feature of SIMETAW is that it simulates daily weather data from monthly climate data and estimates reference $ET_o$. Because of this feature, SIMETAW can be used to examine a range of climate scenarios for California's agricultural water demand using GCM scenarios and regional downsizing models. Using four climate change scenarios and a downsizing model to determine a running mean of monthly climate data centered around 2020 and 2050, SIMETAW can simulate daily weather data, and determine $ET_o$, $ET_c$, and $ET_{aw}$ for some major crops grown in California. Possible values for canopy resistance can be input into the program to determine the effect of canopy resistance on $ET_o$.

SIMETAW was developed for water demand planning and it can help to plan for the effects of climate change as well as for current climate conditions. At this time, the limitation is the downscaling of GCMs to a regional scale. When regional long range predictions of $R_s$, $T_x$, $T_n$, $T_d$, $U_2$, and precipitation resulting from climate change are available, predicted daily means of the data by month can be input into SIMETAW to provide estimates of agricultural water demand.

### 7.5.3 Output files

Files created by SIMETAW are listed as following:

- Several years of raw or simulated daily weather data including calculated $ET_o$ from raw or simulated data by weather station
- Several years of daily calculated crop coefficients, crop evapotranspiration and water balance calculations by crop within a study area
- One year mean of simulated or non-simulated daily and monthly $ET_c$ and $ET_{aw}$ data averaged over the data set
- Several years of simulated or non-simulated seasonal and annual total of $ET_c$ and $ET_{aw}$ by crop within a study area
- Simulated or non-simulated seasonal and annual total of $ET_c$ and $ET_{aw}$ averaged over the years of record

### 7.5.4 Weather simulation

Weather simulation models are often used in conjunction with other models to evaluate possible crop responses to environmental conditions. In SIMETAW, daily climate data are used to estimate $ET_o$ and $K_c$ values are used with the $ET_o$ to estimate $ET_c$. Rainfall data are then used with estimates of $ET_c$ to determine $ET_{aw}$. Either daily climate records or simulated daily data can be used for the calculations.

#### *7.5.4.1 Rainfall*

Characteristics and patterns of rainfall are highly seasonal and localized, and it is difficult to create a general, seasonal model that is applicable to all locations. Recognizing the fact that rainfall patterns are usually skewed to the right toward extreme heavy amount and that rain status of the previous day tends to affect the present day condition, a gamma distribution and Markov chain modeling approach was applied to described rainfall patterns for periods within which rainfall patterns are relatively uniform. This approach consists of two models: two-state, first order Markov chain and a gamma distribution function. These models require long-term daily rainfall data to estimate model parameters. SIMETAW, however, uses monthly averages of total rainfall amount and number of rain days to obtain all parameters for the Gamma and Markov Chain models.

#### *7.5.4.2 Wind speed*

The simulation of wind speed is a simpler procedure, requiring only the gamma distribution function as described for rainfall. Although using a gamma distribution provides good estimates of extreme values of wind speed, there is a tendency to have some unrealistically high wind speed values generated for use in $ET_o$ calculations. Because wind speed depends on atmospheric pressure gradients, no correlation between wind speed and the other weather parameters used to estimate $ET_o$ exists. Therefore, the random matching of high wind speeds with conditions favorable to high evaporation rates leads to unrealistically high $ET_o$ estimates on some days. To eliminate this problem, an upper limit for simulated wind speed was set at twice the mean wind speed. This is believed to be a reasonable upper limit for a weather generator used to estimate $ET_o$ because extreme wind speed values are generally associated with severe storms and $ET_o$ is generally not important during such conditions.

#### *7.5.4.3 Temperature, solar radiation, and humidity*

Temperature, solar radiation, and humidity data usually follow a Fourier series distribution. Therefore, the model of these variables may be expressed as:

Xki = mki (1 + dki Cki) (1)

where k = 1, 2 and 3 (k=1 represents maximum temperature; k = 2 represents minimum temperature; and
k =3 represents solar radiation), mki is the estimated daily mean, and Cki is the estimated daily coefficient of variation of the ith day, i = 1, 2, … , 365 and for the kth variable.

SIMETAW simplifies the parameter estimation procedure of Richardson and Wright (1984), requiring only monthly means as inputs. From a study of 34 locations within the United States, the coefficient of variability (CV) values appear to be inversely related to the means. The same approach is used to calculate the daily CV values. In addition, a series of functional relationships were developed between the parameters of the mean curves and the parameters of the coefficient of variation curves, which made it possible to calculate Cki coefficients from mki curves without additional input data requirement.

### 7.5.5 Validation of daily simulated weather data of SIMETAW

Validity of the SIMETAW model was tested by comparing simulated with observed daily weather data. In this section, nine years of daily measured weather data from the CIMIS station in Davis were compared with 30 years of simulated daily weather data. Figure 7-6, Figure 7-7, and Figure 7-8 show that $R_s$, $T_x$, and P values from the simulation were well correlated with values from CIMIS. Similar results were observed for $T_n$, $u_2$, and $T_d$ data. Although comparisons are only shown for Davis, similar results were found in other climatic regions of the state.

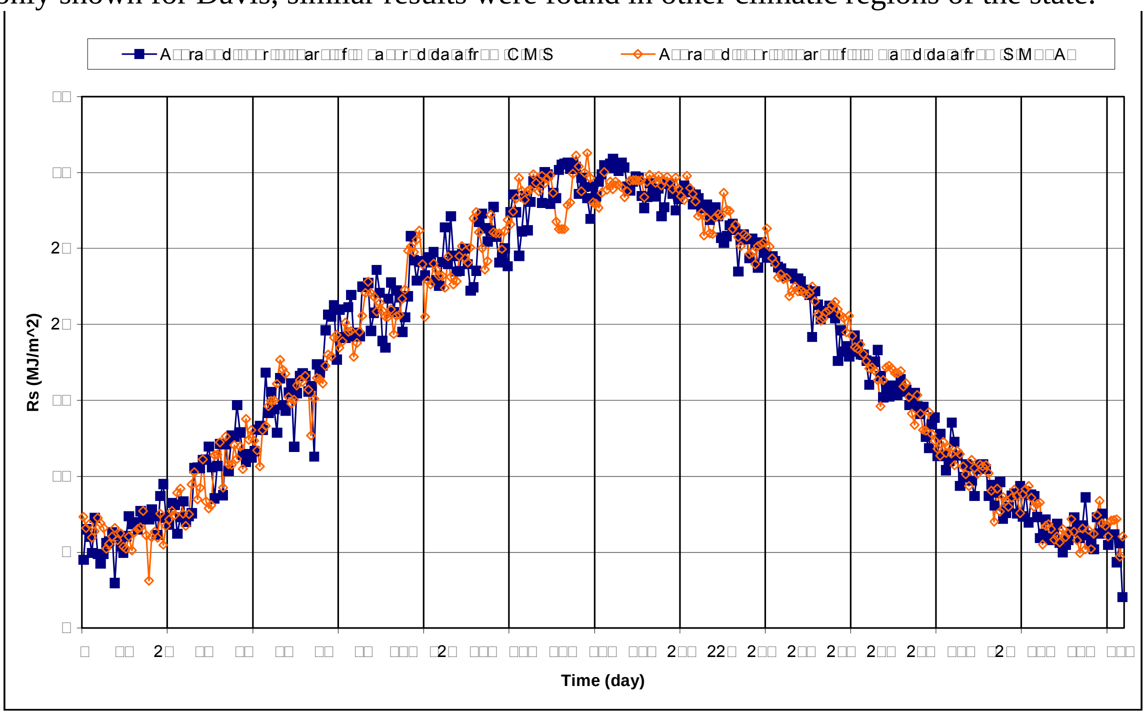


**Figure 7-6. Comparison of measured and simulated daily solar radiation at Davis**

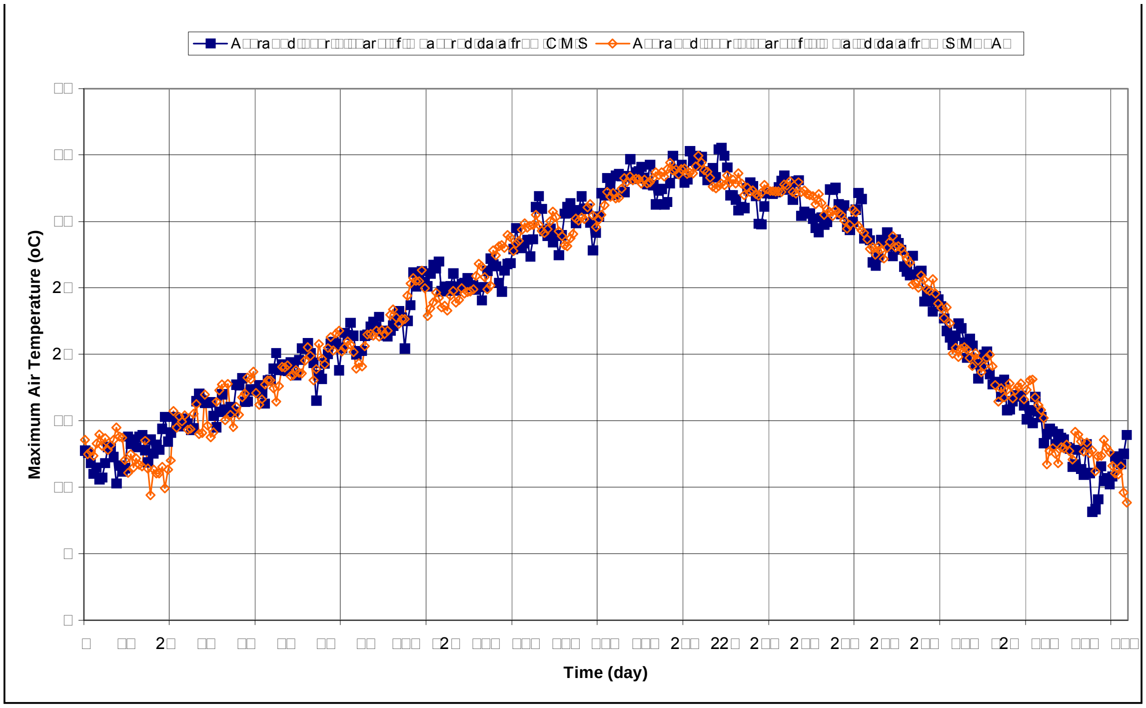


**Figure 7-7. Comparison of measured and simulated air temperature at Davis**

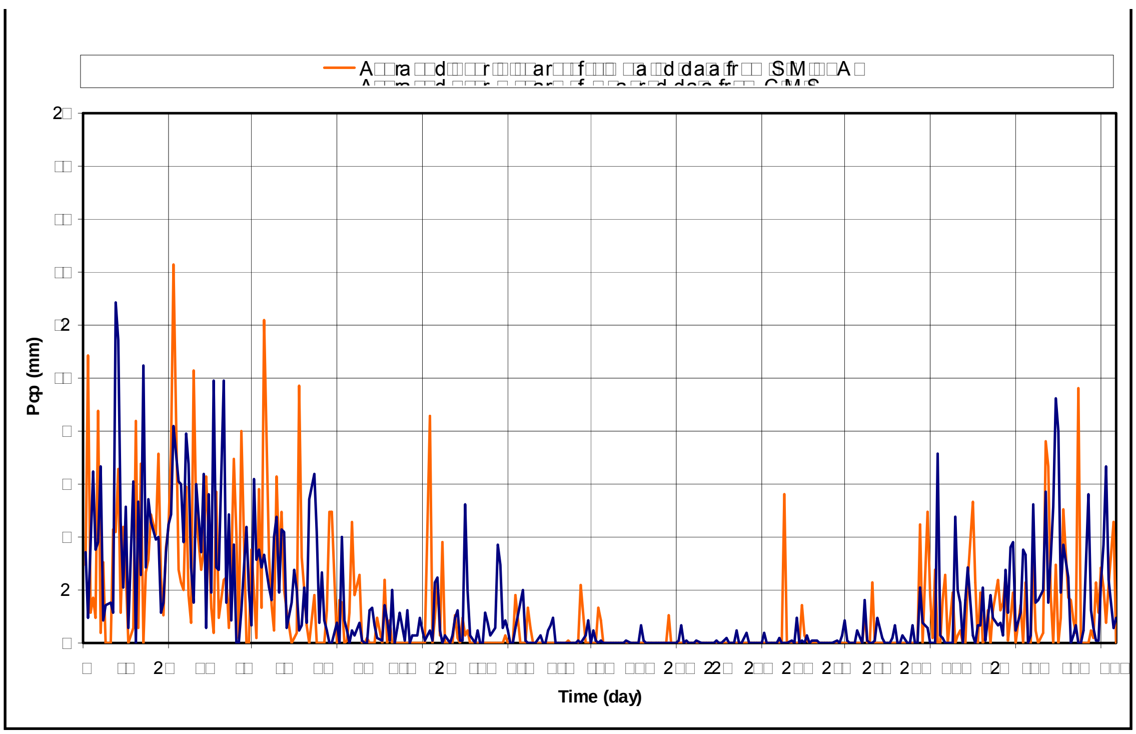


**Figure 7-8. Comparison of measured and simulated precipitation at Davis**

Using weather data from CIMIS stations near Davis, Oceanside, and Bishop, comparisons were made between $ET_o$ from CIMIS and $ET_o$ simulated from SIMETAW and averaged over the period of record (Figure 7-9, Figure 7-10, and Figure 7-11). CIMIS-based estimates of $ET_o$ closely matched those from the SIMETAW program.

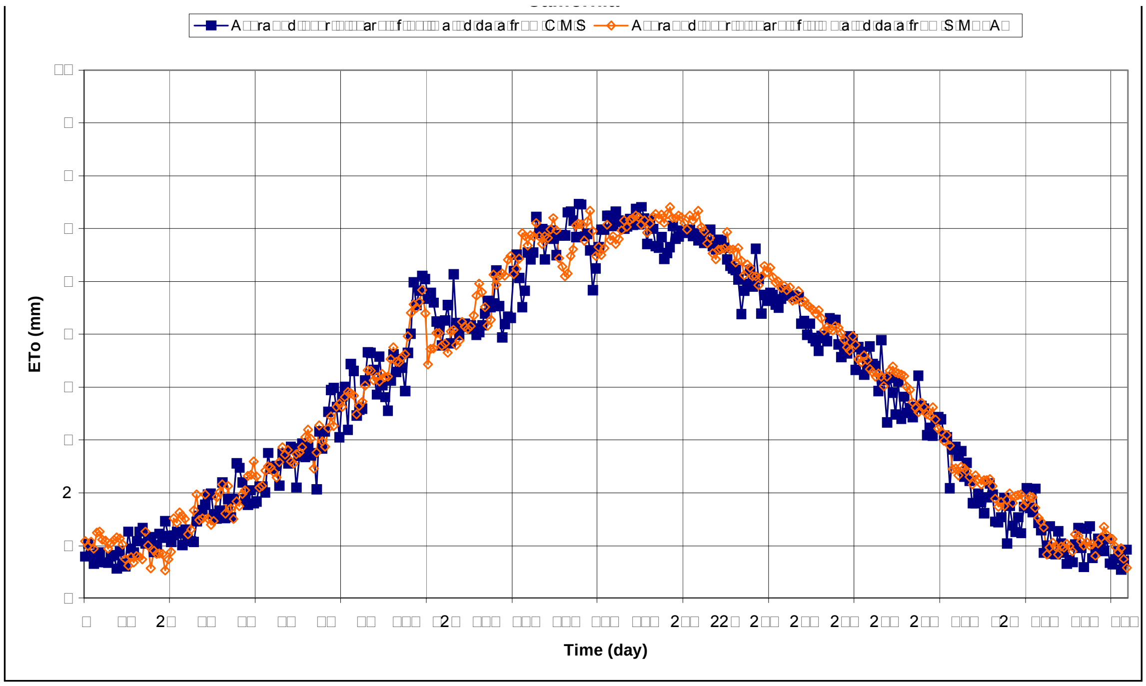


**Figure 7-9. Comparison of estimated and simulated reference ET at Davis**

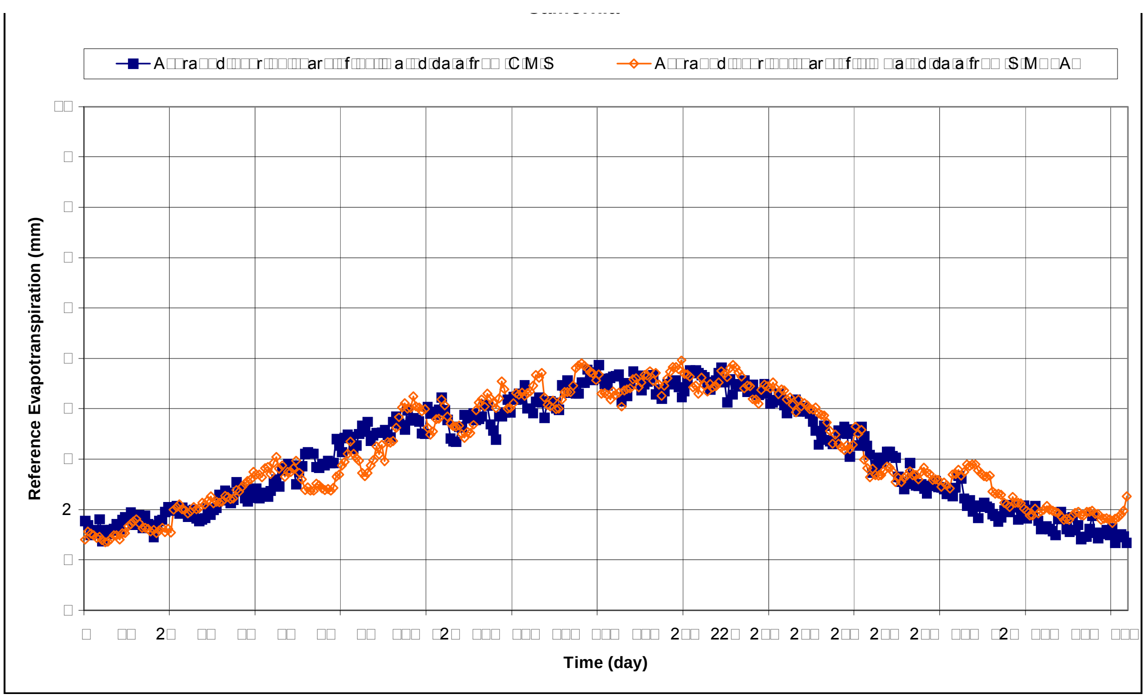


**Figure 7-10. Comparison of estimated and simulated reference ET at Oceanside**

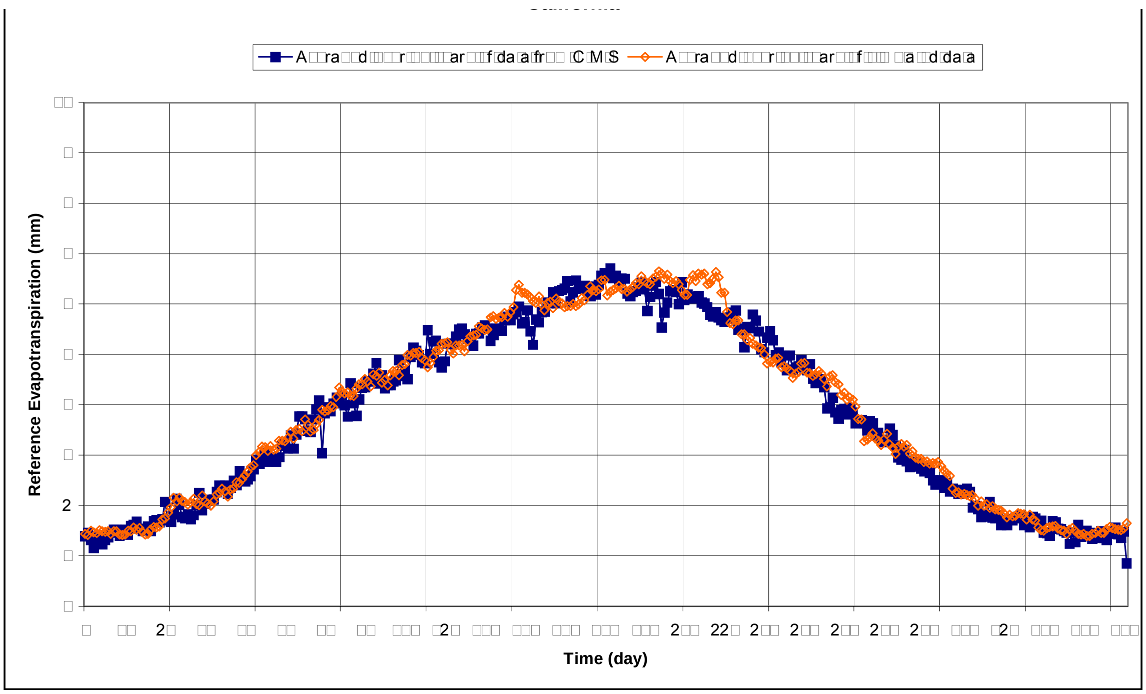


**Figure 7-11. Comparison of estimated and simulated reference ET at Bishop**

### 7.5.6 Canopy resistance sensitivity test for SIMETAW calculation of ET

To determine the influence of canopy resistance on $ET_o$ rates, three values of canopy resistance (70, 85, and 100 s $m^{-1}$) with the current monthly climate data from Davis were used with SIMETAW to simulate 30 years of daily $ET_o$ data. As canopy resistance value increased to 85 and 100 s $m^{-1}$, the $ET_o$ rate decreased by 4.7 percent and 9.0 percent, respectively (Figure 7-12). The $ET_o$ increase due to a $3^oC$ temperature increase, however, will more than offset the decrease due canopy resistance. The effect of $CO_2$ concentration on canopy resistance and $ET_o$ rates was roughly estimated and more intensive research on canopy resistance under higher temperature and $CO_2$ concentrations is needed to confirm the estimates.

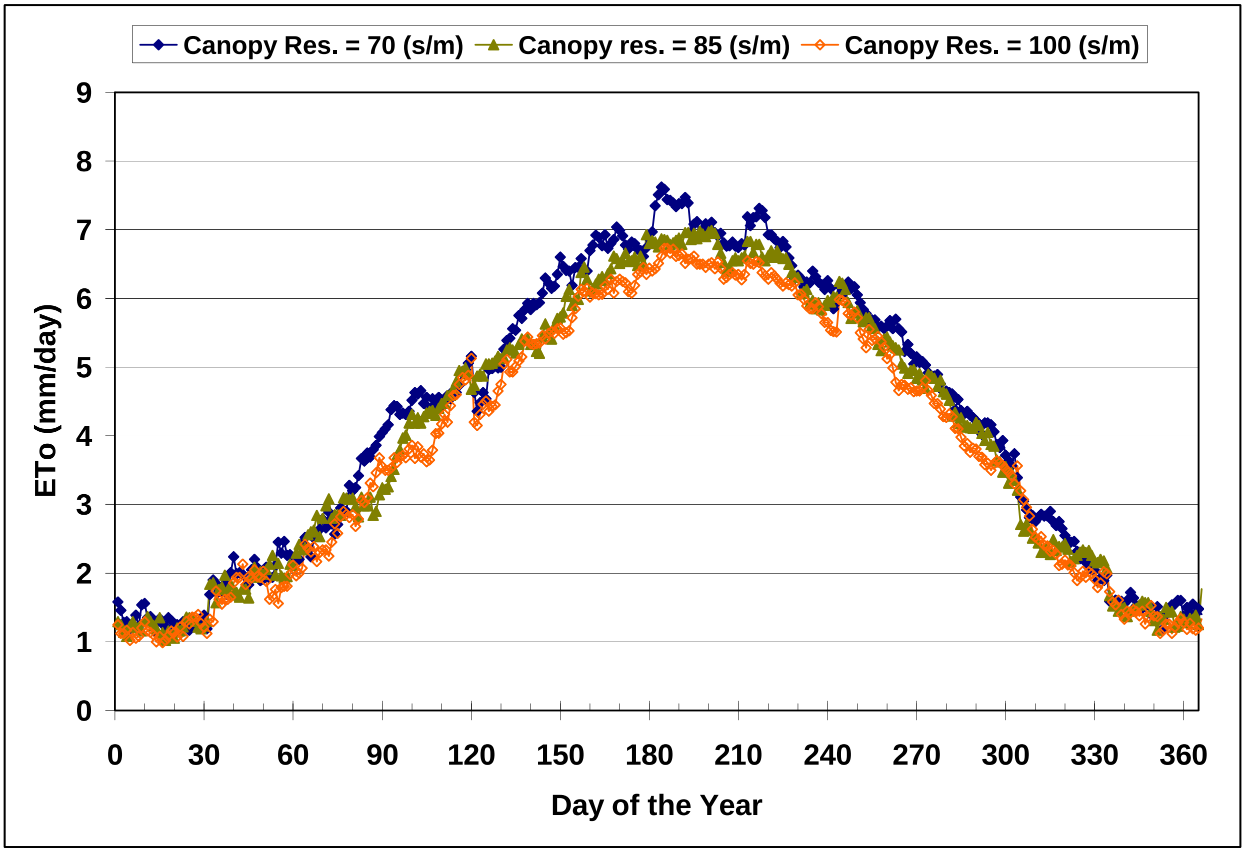


**Figure 7-12. Comparison of simulated daily $ET_o$ using the canopy resistance values 70, 85, and 100 s/m and current climate data from Davis**

## 7.6 Using SIMETAW as a DWR Modeling Tool for Climate Change Planning

The preceding sections on using SIMETAW to calculate $ET_o$, $ET_c$ and $ET_{aw}$ demonstrate the potential to use SIMETAW, with downscaled GCM simulation data as input, for calculation of $ET_o$, $ET_c$, and $ET_{aw.}$ SIMETAW has potential as both a stand alone model for evaluating hypothetical climate change impact on $ET_c$ and $ET_{aw}$ or by coupling with downscaled GCM models to provide predictions of future agricultural water needs (Figure 7-13). The $ET_c$ and $ET_{aw}$ output from SIMETAW can serve as input to the DWR Consumptive Use Model to calculate crop water requirement for given planning areas. This possible integration is discussed in Chapter 8 of this report.

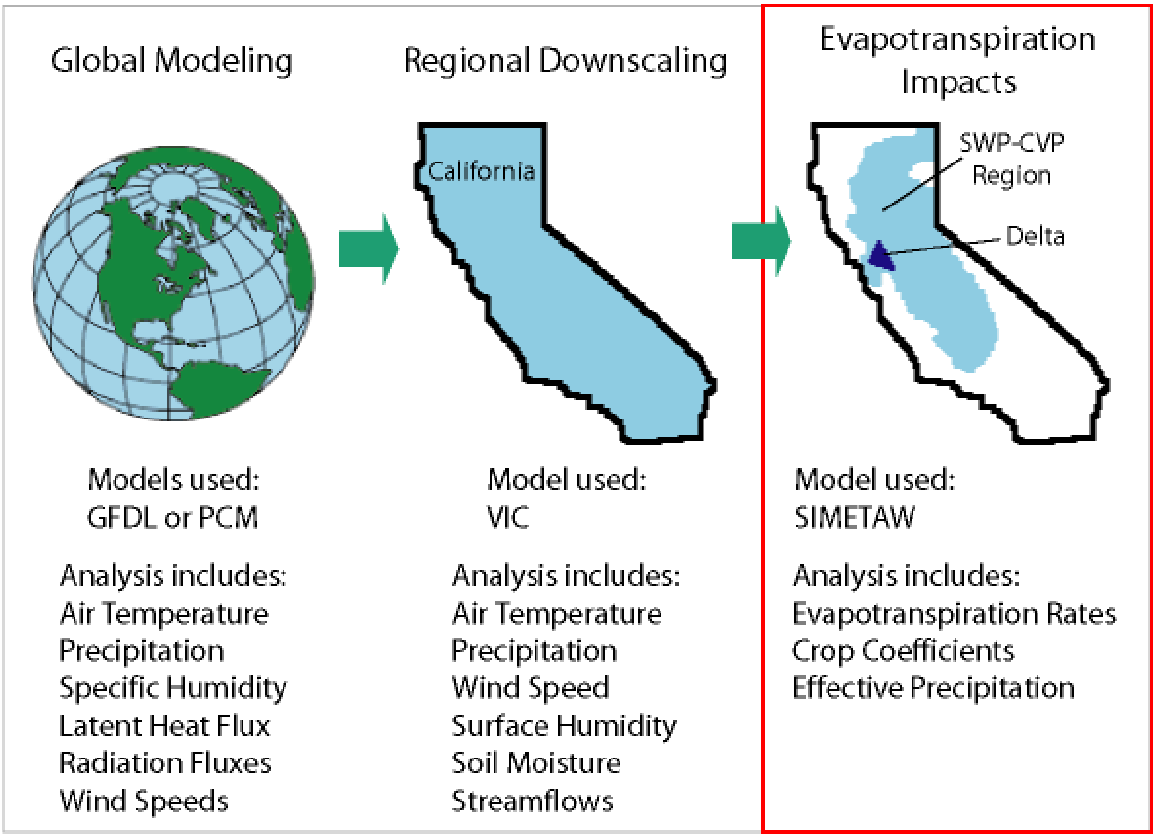


**Figure 7-13. Use of SIMETAW for climate change impacts on water resource planning**

## 7.7 Conclusions

It is difficult to accurately estimate the direct effect of global temperature on ET. As long as the minimum temperature and the dew point temperature continue to increase faster than the maximum temperature, the aerodynamic term of the Penman-Monteith $ET_o$ equation is unlikely to increase substantially. This has been the pattern during the past five decades of global temperature rise. Increasing air temperature causes the weighting factor of the radiation-term of the Penman-Monteith equation to increase, but, because of the effect on stomatal closure, increasing $CO_2$ concentration causes it to decline. Based on limited information, the two effects seem to partially offset one another with the temperature rise resulting in a slightly greater influence on ET than $CO_2$ in our analysis. Though the net rise in ET we derived is small the influence in water demand for California as a whole is notable. Since natural environments of elevated temperature and $CO_2$ do not exist on a scale large enough to provide natural boundary layer conditions, it is difficult to study the effects of climate change on ET. More research is needed on the influence of elevated $CO_2$ and air temperature on canopy resistance.

The SIMETAW model is a promising analytic tool for water management planning that can use input from regional downscaled climate change models. Although it seems that little increase in ET is expected, the net statewide water demand from even a small ET increase is important for water management. The effect of global change on regional precipitation, wind speed, and cropping pattern shifts are unknown at this time. Climate change could affect California agriculture and water resources, and wise planning is required to avoid serious problems.

## 7.8 Acknowledgments

We thank Jeff Amthor, Peter Curtis and Arnold Bloom for their thoughtful suggestions. Ed Morris, Jean Woods and Harry Spanglet read and made comments on an earlier version of this chapter for which we are grateful.

## 7.9 References

Allen, R.G., Jensen, M.E., Wright, J.L., and Burman, R.D. 1989. Operational estimates of reference evapotranspiration. Agron. J. 81: 650-662.

Allen, R.G., F.N. Gichuki and C. Rosenzweig. 1991. $CO_2$-induced Climatic Changes and Irrig. Water Requirements. J. Wat. Resour. Plan.& Man. ASCE 117(2):157-178.

Allen, R.G., Pereira, L.S., Raes, D., and Smith, M. (1998) "Crop Evapotranspiration: Guidelines for computing crop water requirement." Irrig. And Drain. Paper 56, Food and Agriculture Organization of the United Nations, Rome, 300 pp.

Amthor JS (1999). Increasing atmospheric CO2 concentration, water use, and water stress: scaling up from the plant to the landscape. In: Y Luo, HA Mooney (eds) Carbon Dioxide and Environmental Stress. Academic Press, San Diego, 33-59.

ASCE-EWRI. (2005). The ASCE Standardized Reference Evapotranspiration Equation. Technical Committee report to the Environmental and Water Resources Institute of the American Society of Civil Engineers from the Task Committee on Standardization of Reference Evapotranspiration. 173 p.

California Department of Water Resources, Division of Planning and Local Assistance (2005). Bulletin 160–05: Draft California Water Plan (California Department of Water Resources, Sacramento).

California Department of Water Resources, Division of Planning and Local Assistance (2005).

Condon, A.G. and Hall, A.E. (1997) Adaptation to diverse environments: variation in water-use efficiency within crop species. In L.E. Jackson (ed) Ecology in Agriculture. Academic Press, San Diego, 79-116.

Cowan, I.R. and Farquhar, C.D. (1977). Stomatal diffusion in relation to leaf metabolism and environment. Symp. Soc. Exp. Biol. 31, 471-505.

Field, C. B., Daily, G. C., Davis, F. W., Gaines, S., Matson, P. A., Melack, J. and Miller, N. L. (1999). Confronting Climate Change in California: Ecological Impacts on the Golden State (Union of Concerned Scientists, Cambridge, MA, and Ecological Society of America, Washington, DC).

Gilgen, H., Wild, M. and Ohmura, A. (1998). Means and trends of short wave irradiance at the surface estimated from Global Energy Balance Archive Data. J. of Clim. 11: 2042-2061.

Hayhoe, K., D. Cayan, C.B. Field, P.C. Frumhoff, E.P. Maurer, N.L. Miller, S.C. Moser, S.H. Schneider, K.N. Cahill, E.E. Cleland, L. Dale, R. Drapek, R.M. Hanemann, L.S. Kalkstein, J. Lenihan, C.K. Lunch, R.P. Neilson, S.C. Sheridan, and J.H. Verville. (2004). Emissions pathways, climate change, and impacts on California. Proceedings of the National Academy of Sciences of the United States of America 101:12422-12427.

Hidalgo, H.G., Cayan, D.R., Dettinger, M.D. (2005). Sources of variability of evapotranspiration in California. J. Hydrometerology. 6, 3-19.

Hsiao, T.C. and Jackson, R.B. (1999). Interactive effects of water stress and elevated $CO_2$ on growth, photosynthesis, and water use efficiency. In: Y Luo, HA Mooney (eds) Carbon Dioxide and Environmental Stress. Academic Press, San Diego, 3-31.

Hsiao, T.C. and Xu, L. (2005). Evapotranspiration and relative contribution by the soil and the plant. In California Department of Water Resources. 2005. Bulletin 160-05 Vol. 4 Reference Guide.

Landis, J.D. and Reilly, M (2004). How We Will Grow: Baseline Projections of the Growth of California's Urban Footprint through the Year 2100 Institute of Urban and Regional Development, University of California, Berkeley.

Long, S.P., Ainsworth, E.A., Rogers, A. and Ort, D.R. (2004). Rising atmospheric carbon dioxide: plants FACE the future. Ann. Rev. Plant Biol. 55, 591-628.

Monteith, J. L.(1965) Evaporation and environment. In: The state and movement of water in living organisms, XIXth symposium, Soc. for Exp. Biol. Swansea, Cambridge University Press, p 205-234.

Penman, H. L. (1948) Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, A193: 120-145.

Pruitt, W. O. and Doorenbos, J. (1977) Empirical calibration, a requisite for evaporation formulae based on daily or longer mean climatic data? ICID conference on Evapotranspiration, Budapest, Hungary, May 26-28, 1977. International Commission on Irrigation and Drainage.

Rachmilevitch, S., Cousins, A.B., Bloom, A.J. (2004). Nitrate assimilation in plant shoots depends on photorespiration. Proceedings of the National Academy of Sciences of the United States of America 101:11506-11510.

Roderick and Farquhar (2002). The cause of decreased pan evaporation over the past 50 years. Science 298: 1410-1411.

Snyder, R. L. and Pruitt, W.O. (1992) Evapotranspiration data management in California. Proceedings/Water Forum '92, August 2-6, 1992, Baltimore, MD.

Stanhill, J. and Cohen, S. (2001). Global dimming: a review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. Agric. and For. Meteorol. 107: 255-278.

Tanaka, S.K., Zhu, T, Lund, J.R., Howitt, R.E., Jenkins, M.W., Pulido, M.A., Tauber, M., Ritzema, R.S., Ferreira, I.C. (2005). Climate Warming and Water Management Adaptation for California. Climatic Change, (in press).

U.S. Department of Agriculture (2003) California Agricultural Statistics 2003.

Ventura, F., D. Spano, P. Duce and R.L. Snyder. 1999. An evaluation of common evapotranspiration equations. Irrig. Sci. 18:163-170.

## 7.10 Appendix 1 Energy Budget Analysis for Climate Change

### 7.10.1 Physical bases for temperature, sensible heat and water vapor transfer

Any moving object has kinetic energy that is proportional to the product of half of the mass and the square of its velocity. Although air molecules have small mass, they move fast (1,600-2,000 km $h^{-1}$) and there are many ($2.65 \times 10^{25}$) molecules per cubic meter. Therefore, there are many collisions between air molecules and objects within the air volume. When the air molecules strike an object such as a thermometer some kinetic energy is transferred to the object. In the case of a glass thermometer, the energy resulting from air molecule impacts increases movement of molecules in the glass and transfers by conduction into the instrument where it transfers to the liquid temperature indicator. As energy is absorbed, liquid in the thermometer expands and moves up the thermometer tube. When molecules strike the outside of the thermometer at a faster velocity, and more frequently more heat is transferred and the measured temperature rises. If molecules strike the thermometer at lower velocity and at lower frequency the liquid contracts and the measured temperature drops. The kinetic energy contained in air is commonly called "sensible heat" because it is heat (energy) that one can sense. Generally, small volumes of air have uniform heat content, but big differences can occur between the large air parcels due to energy transfers by radiation, conduction and latent heat exchanges. Wind and turbulence cause air parcels with different sensible heat content to move and mix with other air parcels and to transfer sensible heat between objects.

Evaporation of liquid water requires energy to break hydrogen bonds between water molecules. It is widely believed that evaporation increases with air temperature. Strictly speaking, it is actually the water temperature at the surface that determines the evaporation rate. Air temperature can affect the evaporation rate if sensible heat is transferred from the air to the water surface. The rate of heat transfer, however, depends on turbulence as well as the temperature difference between the air and water. Sensible heat transfer to a wet surface depends on atmospheric stability, wind speed, and surface roughness. For transpiration from plants, the rate of water vapor transfer is further complicated by plant morphology that affects energy absorption and turbulence and by plant physiology (i.e., stomatal opening and closing) in response to environmental factors including water availability and $CO_2$ concentration.

Vaporization of water occurs when energy (sensible heat or radiant energy) is used to break hydrogen bonds between the water molecules. Therefore, the rate of energy consumed in the vaporization process provides a measure of the evaporation rate. Evapotranspiration rates are commonly estimated using energy balance by considering the net radiation ($R_n$), heat conduction into and out of the soil and plants (G), atmospheric sensible heat flux density (H), and atmospheric latent heat flux density (LE). Net radiation is the amount of short- and long-wave radiation absorbed by a surface, and it is the main source of energy for vaporization. Net radiation ($R_n$) is commonly partitioned into soil heat flux density (*G*), sensible heat flux density, and latent heat flux density (*LE*) and the energy consumed in the evaporation process is therefore expressed as:

$$LE = R_n - G - H \qquad (\mathrm{W\ m^{-2}}) \qquad (1)$$

where L is the latent heat of vaporization ($L \approx 2454$ J g$^{-1}$ at 20$^{o}$C) and *E* is the water vapor flux density (g m$^{-2}$ s$^{-1}$). In equation 1, $R_n$ is positive when the energy flux is towards the surface and LE, G and H are positive for fluxes away from the surface.

Using Equation 1, one could measure $R_n$, G, and H to estimate LE. Then the rate of evaporation is calculated by dividing LE by L to determine the mass flux density of water vapor. There are methods available to measure the components in Equation 1, but they are not widely used because it is somewhat difficult and expensive to measure the variables, especially H, accurately. Efforts to obtain a simple and inexpensive technique continue, but there is still no perfect method. Other methods to estimate ET using more readily available variables are available.

## 7.10.2 Penman-Monteith equation

Penman (1948) presented a method to estimate *LE* for short, uniform vegetation using readily available weather variables measured at one level assuming the surface was wet with a canopy resistance $r_c = 0$. Monteith (1966) refined Penman's equation to adjust LE for canopy resistances greater than zero. The so-called Penman-Monteith equation is expressed as:

$$LE = \left(\frac{\Delta}{\Delta + \gamma *}\right)(R_n - G) + \left(\frac{\rho C_p}{\Delta + \gamma *}\right)\left(\frac{e_s - e}{r_a}\right) \qquad (\mathrm{W\ m^{-2}}) \qquad (2)$$

In Equation 2, $\Delta$ is the slope of the saturation vapor pressure curve at the air temperature, $\gamma \approx 0.066$ kPa $K^{-1}$ is the psychrometric constant, $r_c$ is the canopy resistance, $r_a$ is the aerodynamic resistance, $\rho$ is the air density (g $m^{-3}$), $C_p$ is the specific heat at constant pressure (J $g^{-1}K^{-1}$), $e_s$ is the saturation vapor pressure, and *e* is the actual atmospheric vapor pressure. For more information on the variables in Equation 2, see ASCE-EWRI (2005). The parameter $\gamma^* = \gamma\left(1+\frac{r_c}{r_a}\right)$ in Equation 2 is a modified psychrometric constant, which was introduced by Monteith to account for the effects of canopy resistance on *ET*. The left-hand term of Equation 2 is often called the radiation or available energy term and the right-hand term is called the aerodynamic term because it accounts for the contribution of aerodynamic transfer of sensible heat to *ET*.

Aerodynamic resistance ($r_a$) is equal to the reciprocal of the aerodynamic conductance ($g_a$), which is defined as the rate that 1 m of a particular scalar will transfer through 1 $m^2$ horizontal plane. Therefore, $g_a$ and $r_a$ have the units m $s^{-1}$ and s $m^{-1}$, respectively. When $r_a$ increases, then $g_a$ decreases, the vertical transfer of sensible and latent heat decreases, and the LE rate falls. Like $r_a$, the canopy resistance ($r_c$) equals the reciprocal of the canopy conductance ($g_c$) and the canopy conductance is the rate at which 1 $m^3$ of air will pass through 1 $m^2$ of horizontal plane. When $r_c$ increases, $g_c$ decreases and LE is reduced. The $r_c$ is the resistance to water vapor transfer from the canopy elements and soil to a level near the top of a canopy and $r_a$ is the resistance to vapor transfer from that level to the ambient air above the canopy. The $r_a$ and $r_c$ resistances are in series, so the higher of the two resistances limits the LE rate. As plant stomata close, $r_c$ increases, $\gamma^*$ increases, and LE decreases (Equation 2). When the surface is wet, then $r_c = 0$, $\gamma^*=\gamma$ and the Penman-Monteith equation reduces to the Penman (1948) form.

### 7.10.3 Aerodynamic term response to temperature rise

The Penman-Monteith equation is useful to investigate the effect of possible climate change on evapotranspiration. Roderick and Farquar (2002) noted that the global mean maximum and minimum temperatures have increased by approximately 0.1 and 0.2 $^oC$ per decade during the last 50 years and there has been no observable change in the vapor pressure deficit ($e_s$ – e) during the same time period. The minimum temperature is highly correlated with the dew point temperature, which is directly related to the actual vapor pressure of the atmosphere. The fact that the minimum has risen faster than the maximum temperature supports the idea that the dew point temperature and hence the actual vapor pressure (e) have risen and compensated for the temperature induced rise in saturation vapor pressure ($e_s$).

The temperature weighting function term $\left(\frac{\rho C_p}{\Delta+\gamma *}\right)$ in Equation 2 decreases with rising temperature and with increasing $r_c$ (Figure 7-14). Since $e_s$ - e has not changed in recent decades and the weighting function decreases with increasing temperature, it is likely that the aerodynamic term of Equation 2 has not changed or slightly decreased with global temperature rise during the past 50 years. Unless the $e_s$ term begins to increase more rapidly than e, the aerodynamic term is unlikely to be greatly affected by global temperature increase.

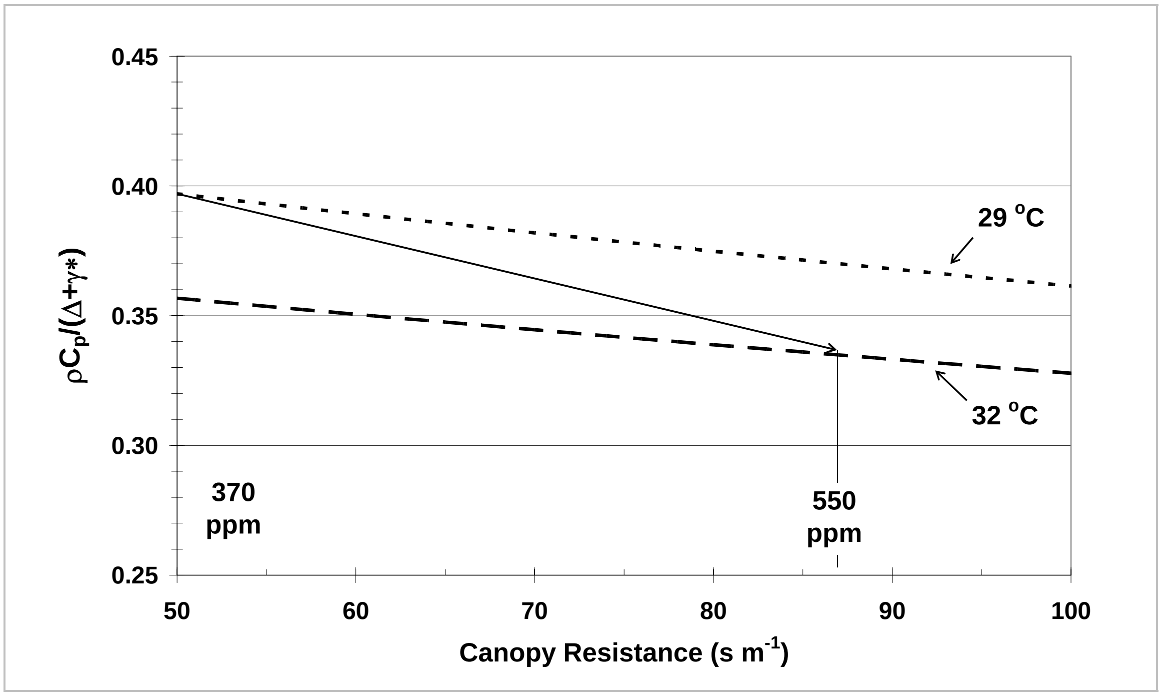


**Figure 7-14. A plot of $(\rho C_p)/(\Delta + \gamma *)$ versus canopy resistance for a 3 °C temperature increase as a function of canopy resistance**

### 7.10.4 Radiation term response to temperature rise

A 3 °C temperature rise will increase the $\left(\frac{\Delta}{\Delta + \gamma *}\right)$ radiation-term weighting function by about 4.5 percent so the effect is to increase the contribution of the radiation term to LE, causing a higher ET rate. There is, however, some evidence that increased turbidity of the atmosphere has globally decreased the amount of solar (short-wave) radiation reaching the surface (Roderick and Farquar, 2002), and the radiation-term weighting function increase with temperature is partially offset by decreasing solar radiation received at the surface.

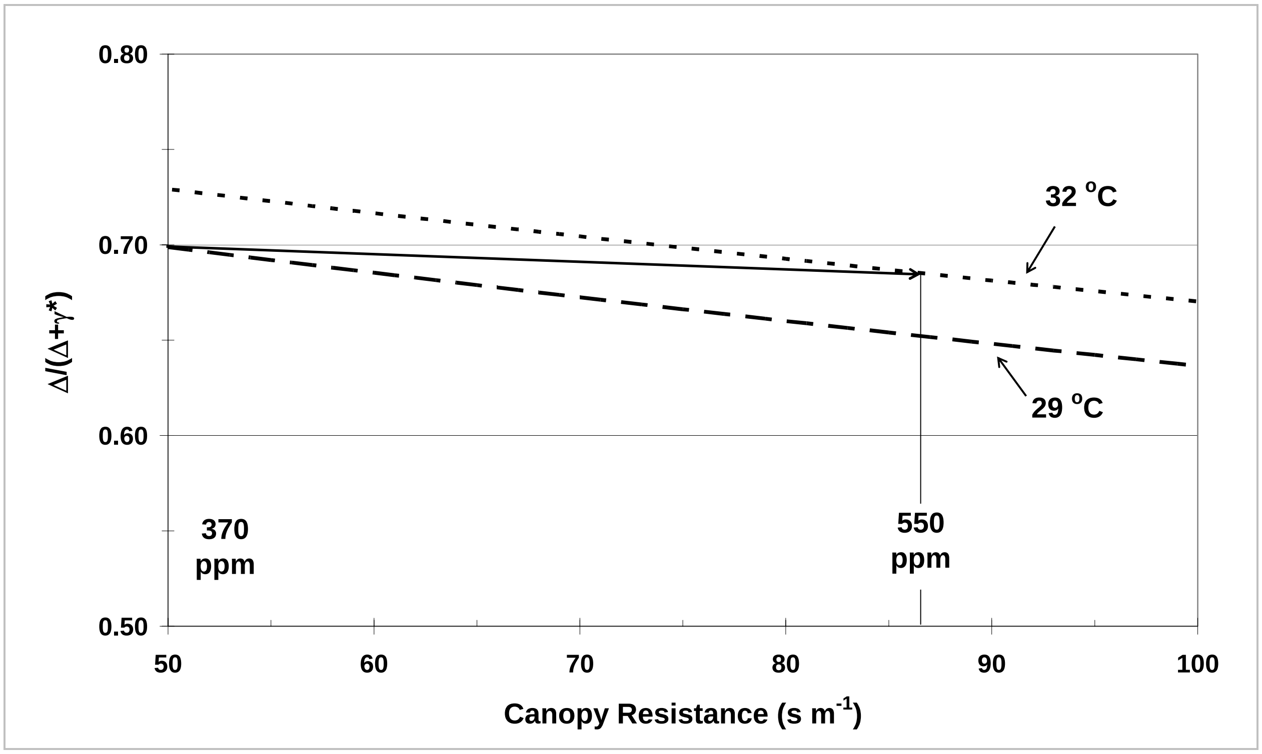


**Figure 7-15. A plot of $\Delta/(\Delta+\gamma^*)$ versus canopy resistance for a 3 °C temperature increase as a function of canopy resistance.**

Another factor that is often neglected in predictions of temperature effects on ET is the influence of increased $CO_2$ on stomatal closure and hence canopy resistance. Stomata exhibit partial closure with increasing $CO_2$ content, but, there is little information on the effect of $CO_2$ concentration on canopy resistance. The typical enhanced $CO_2$ concentrations reported in the FACE projects was about 550 ppm, and Long et al. (2004) indicated that the leaf stomatal conductance decreased about 20 percent for $C_3$ species plants under those conditions. Then using the same procedure to estimate canopy resistance for reference evapotranspiration (Allen et al., 1989) with today's $CO_2$ concentration, the midday canopy resistance is predicted to increase from about 50 to 87 s $m^{-1}$ as shown in Fig. 7.3. Therefore, if the canopy resistance does increase to 87 s $m^{-1}$, the increase in the radiation-term weighting factor due to a 3 °C increase in temperature is nearly offset by the higher canopy resistance. For comparison, the midday canopy resistances of tall alfalfa (50 cm) and tall grass (12 cm) are approximately 30 s $m^{-1}$ and 50 s $m^{-1}$, respectively (ASCE-EWRI, 2005). The $r_c$ is high at night (≥ 200 s $m^{-1}$) when the stomata are closed. There is a decrease in rc after sunrise to the minimum value and then an increase in the late afternoon as the sun descends toward the horizon. The mean 24-hour $r_c$ is about 70 s $m^{-1}$ for the grass and about 45 s $m^{-1}$ for the alfalfa (ASCE-EWRI, 2005). Again, there is a paucity of research on the effect of $CO_2$ concentration on canopy resistance, but it clearly will increase and the reduction in the radiation-term weighting function will at least partially offset the increase due to temperature. The magnitude of the change depends on how much the temperature and $CO_2$ concentration increase. Clearly, more research is needed to determine the influence of temperature and $CO_2$ concentration on canopy resistance before a truly accurate assessment is possible.

Evaporation from ponds, lakes, rivers, and other bodies of water can also be impacted by climate change. Recently, several groups have reported decreasing evaporation rates from standard pans, and they used this as evidence that the climate is cooling rather than warming. However, the surface resistance of water is zero and the aerodynamic resistance is high, so $\gamma^* = \gamma$ in Equation 2 and the equation simplifies to the Penman (1948) equation. Again, $e_s - e$ has not changed in recent decades, so the change in the aerodynamic term is unlikely to influence evaporation from bodies of water. Increasing temperature does increase the weighting function of the radiation term and there is no stomatal influence, so canopy resistance will not counteract the temperature effect on the radiation term of the $ET_o$ equation. There is some evidence for the reduction in solar radiation due to pollution effects on atmospheric turbidity or perhaps reflectivity of clouds and other factors (Stanhill and Cohen, 2001; Gilgen et al., 1998), and this might be the cause for reduced pan evaporation reported in some regions of the world.

Assuming a little or no increase in the radiation-term weighting function in response to rising temperature, the increasing $CO_2$ concentration effect on canopy resistance, and a decrease in short-wave radiation at the surface, little or no increase in the radiation term contribution to ET is expected with climate change. Since the aerodynamic term also shows little response to climate change, it is anticipated that the effect of climate change on *ET* will be minimal. Other environmental responses to climate change such as precipitation and wind patterns and changes in cropping and irrigation methods, however, could greatly affect water resource availability and hence irrigation water requirements.

## 7.11 Appendix 2 The photosynthesis Response Curve to $CO_2$

The assimilation of $CO_2$ as a function of intercellular $CO_2$ is provided in Figure 7-16.
The rate of carbon assimilation is determined by supply and demand for $CO_2$. The supply of $CO_2$ is determined by diffusion in the gas and liquid phases. It can be limited by essential constraints in the pathway from the atmosphere to the leaf sites of carbon fixation (carboxylation) most notably at the canopy boundary and at the stomata, which are related to the plants energy budget. The demand for $CO_2$ is determined by the rate of processing $CO_2$ in the chloroplast, which is determined most importantly by biochemistry, in particular Rubisco, the first enzyme in the metabolic pathway for assimilation of $CO_2$. It can also be limited by environmental factors such as irradiance. The electron transport plot relative to $CO_2$ concentration is included in Figure 7-16 for comparison to the carbon assimilation. The assimilation of $CO_2$ plot in Figure 7-16 has two principal regions, the first occurs at lower $CO_2$ concentrations and is referred to as the $CO_2$ limited region. The second at the higher $CO_2$ concentrations is the place where available limits to precursors of Rubisco are limiting. Two horizontal lines of Figure 7-16 indicate the intercellular $CO_2$ concentration at the atmospheric $CO_2$ concentration given the supply function indicated by the line from the atmospheric concentration to the response curve. The slope of the supply function is the leaf conductance measured. The possible long-term adjustment of plants to elevated $CO_2$ by sifting the supply curve downward is referred to as downregulation. Long et al (2004) concluded that there is a substantial reduction in Rubisco at elevated $CO_2$, suggesting acclimation to elevate $CO_2$, but that there was not downregulation.

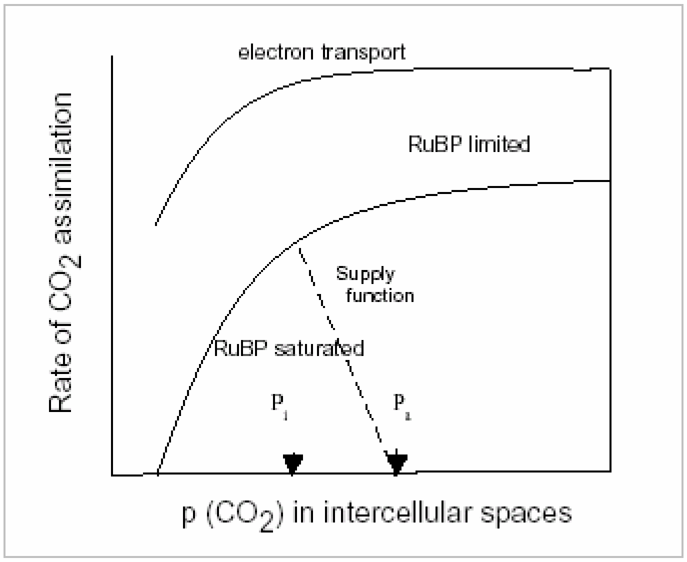


**Figure 7-16. Photosynthesis Response Curve to $CO_2$**
(After Lambers et al, 1998)

## 7.12 Appendix 3 The Penman-Monteith equation for reference evapotranspiration ($ET_o$) used in SIMETAW

Reference evapotranspiration ($ET_o$) is estimated from daily weather data using a modified version of the Penman-Monteith equation (Allen et al., 1998; ASCE-EWRI, 2005). The equation is:

$$ET_o = \frac{0.408 \, \Delta \, (R_n - G) + \gamma \, \frac{900}{T + 273} \, u_2 \, (e_s - e_a)}{\Delta + \gamma \, (1 + 0.34 \, u_2)} \qquad (3)$$

where Δ is the slope of the saturation vapor pressure at mean air temperature curve (kPa $^oC^{-1}$), $R_n$ and G are the net radiation and soil heat flux density in MJ $m^{-2}d^{-1}$, γ is the psychrometric constant (kPa $^oC^{-1}$), T is the daily mean temperature ($^oC$), $u_2$ is the mean wind speed in m $s^{-1}$, $e_s$ is the saturation vapor pressure (kPa) determined as the mean saturation vapor pressure calculated from the daily maximum and minimum air temperature ($^oC$), and $e_a$ is the actual vapor pressure (kPa) calculated from the mean dew point temperature ($^oC$) for the day. The coefficient 0.408 converts the $R_n$ – G term from MJ $m^{-2}d^{-1}$ to mm $d^{-1}$, and the coefficient 900 combines several constants and converts units of the aerodynamic component to mm $d^{-1}$. The product 0.34 $u_2$ in the denominator is an estimated ratio of the 0.12-m tall canopy surface resistance ($r_c$=70 s $m^{-1}$) to the aerodynamic resistance ($r_a$=205/$u^2$ s $m^{-1}$). It is assumed that the temperature, humidity, and wind speed are measured between 1.5 m (5 ft) and 2.0 m (6.6 ft) above a grass-covered soil surface. For a complete explanation of the equation, see (ASCE-EWRI, 2005).

## 7.13 List of Abbreviations

ASCE-American Society of Civil Engineers
CALVIN-The California value integration network model
CIMIS-California Irrigation Management Information System
CUP-Consumptive use program
ET-Evapotranspiration
ETo-Reference Evapotranspiration
ETAW-Evapotranspiration of applied water
EWRI- Environmental and Water Resources Institute
FACE-Free-Air Carbon dioxide enrichment
GCM-General Circulation Model
LAI-Leaf Area Index
NPP-Net primary production
PAR-Photosynthetically Available Radiation
RGR-Relative Growth Rate
SIMETAW-SIMulation ET of Applied Water
SWAP-statewide water and agricultural production model (WUE-Water use efficiency
WUE-Water use efficiency

# Progress on Incorporating Climate Change into Management of California's Water Resources

**1st Progress Report**
**July 2006**

# Chapter 8:
# Future Directions

### Authors:

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# 8 Future Directions

## 8.1 Introduction

This report demonstrates growth in federal and state agency capability to provide planners with relevant information on potential climate change impacts. The joint Department of Water Resources (DWR) and U.S. Bureau of Reclamation (Reclamation) Climate Change Work team has built coalitions with California climate change research groups to improve federal and state agency knowledge on climate modeling and uncertainties in future climate projections. Additional products from work team activities include identification of data and technology gaps and development of innovative analytical approaches using familiar planning tools. The work team will continue to evolve to meet the needs of water resources managers and to use new information and methodologies as they become available. Future activities will focus on probabilistic based potential effects of climate change. A summary of future directions is presented in this chapter.

## 8.2 SWP-CVP Operations Impacts

The State Water Project (SWP) and Central Valley Project (CVP) operations impacts studies presented in this report only considered climate change affects on runoff patterns. However, a warming climate may lead to changes in the seasonal pattern and magnitude of evaporation/evapotranspiration and, thereby, higher water demands. Rising sea levels would lead to greater fresh water demands in the Delta to maintain water quality. Both increased demands and increased salinity in the Delta could have significant impacts on the ability of the SWP and CVP to meet California's future needs. Impacts from a wider range of climate change effects need to be addressed.

In the climate change scenario studies presented in this report, one significant issue was the critical shortages of water in reservoirs north of the delta that occurred when present operating rules were applied. Future directions would include examining increases in carryover storage in Shasta and Oroville reservoirs to prevent loss of operational control of the Sacramento and Feather rivers during droughts. Corresponding reductions to delivery allocations would be required. If those measures weren't sufficient to provide a reliable water supply, additional measures would be investigated such as rebalancing of the water sharing mechanisms established in the Coordinated Operations Agreement.

System flexibility should be sought to mitigate climate change effects on SWP and CVP deliveries. In the current analysis, flood control spaces were left unchanged. In the future, it is planned to vary the flood control space with different climate change scenarios. Furthermore, refined flood forecasting might allow more runoff to be captured in the early spring than is otherwise possible now. Also, operational rules and regulations will have to be reassessed given a changed hydrology. Current operations studies using the CalSimII model use an Artificial Neural Network (ANN) to represent Delta water quality. Future directions include development of a new ANN or similar tool that would be incorporated into CalSimII to represent Delta water quality for sea level rise conditions.

Lastly, we need to explore ways of increasing supply to or reducing demand of SWP and CVP contractors. New reservoirs, increased pumping capacity, and groundwater banking are ways that more winter runoff can be captured for later delivery. On the demand side, CalSim-II doesn't deal with specific conservation measures. But the effects of conservation – whether from drip irrigation or low-flow toilets – can be represented in the input water demands and the effects to CVP and SWP operations simulated.

## 8.3 Delta Impacts

Improving analysis of potential effects of a rising sea level on the Delta will be a focus of future studies. Changes in salt water intrusion from the ocean need to be represented for different sea level increases. Better understanding and mathematical representation of salt water intrusion under conditions of sea-level rise should be incorporated into planning tools such as CalSim-II and DSM2. For this report, results from the sea level rise simulations could be used for levee stability analyses.

Flexibility of the existing water-conveyance system to lessen the effects of climate change will also be explored. In addition to potential changes to system operations mentioned in the previous section, mitigation measures in the Delta could include modifying Delta Cross Channel operations, changing land use patterns and temporary barrier operations. If present system flexibility can't sufficiently decrease the impacts of climate change, other measures will be investigated such as modifying operating rules or considering new system components such as gates proposed to be installed the south Delta.

## 8.4 Flood Management

In order to better understand the risks associated with global climate change on California's water resources, it is important to be able to quantify climate change effects on the ability to provide adequate flood control and to quantify climate change impacts on seasonal water supply. The Division of Flood Management at DWR will address these issues. It plans to:

1) continue the evaluation of historical data to identify trends and changes in precipitation and runoff patterns
2) periodically update frequency-based data for design computations
3) evaluate new climate change model-derived data for use in flood frequency and water supply forecasting applications
4) develop new forecasting technologies that can adapt to the changing distribution of the state's annual water supply
5) incorporate methodologies to quantify the uncertainty in the expected changes in the annual cycle of water supply into the water supply forecast process

For flood frequency analysis, future efforts at synthetic daily flow data produced from climate change model output may be suitable for traditional flood frequency analyses. As these data become available, they must be evaluated for their ability to represent present-day magnitude and variability as well as predicted changes caused by climate change. At this time, however, there are no such data that would provide meaningful results.

Another area which may produce useful flood forecasting information examines historical data in order to identify critical atmospheric circulation parameters and their threshold values associated with extreme floods. As the circulation patterns in the GCMs improve and are shown to represent present-day conditions correctly, circulation patterns under increased greenhouse gas concentrations can be examined for the flood producing patterns or critical threshold characteristics. Improved forecasting technologies will help implement adaptive strategies to decrease flood risk changes associated with climate change.

## 8.5 Evapotranspiration

To further analyze the effects of climate change on evapotranspiration (ET) future efforts will focus on improvements to the SIMETAW (Simulation of Evapotranspiration of Applied Water) model. SIMETAW development and analysis for climate change studies will be a complex process. How will a world with higher atmospheric $CO_2$ and higher temperatures influence the resistance to water vapor diffusion to the atmosphere (the boundary layer around plants)? No one knows. While we are continuing to search the literature and research programs for boundary-layer data at elevated temperatures and $CO_2$ concentrations, we need to explore the SIMETAW model's performance by using reasonable analogs for boundary-layer values. Direct measurement of boundary-layer information is limited in the near future, but we are developing an analysis to work around the limitation.

To validate the SIMETAW calculation of ET using downscaled model weather data, a set of comparative simulations is needed using historic California Irrigation Management Information System (CIMIS) data and downscaled regional model output for the same time period. Analysis periods and CIMIS sites will be chosen to obtain a range of extremes of the primary SIMETAW input variables: net radiation, wind speed, relative humidity, temperature and precipitation.

Simulations for several principal herbaceous crops, a row crop, tomatoes, and a field crop, alfalfa, will be tested with SIMETAW first at Central Valley CIMIS stations and then at other CIMIS sites throughout the state. The simulations will be analyzed at 2020 and 2050. The 2020 year is meant to correspond with the current CalSimII capabilities. The 2050 year is the far planning horizon. All four climate change scenarios selected by the Climate Action Team (see Chapter 3) will be analyzed at each location and time. An orchard crop, almonds, will then be added to contrast boundary layer and cropping patterns with the herbaceous crops. Eventually, a wider geographic range and longer list of crops is needed for a comprehensive analysis.

Currently there is no comprehensive study of crop changes or regional cropping pattern shifts in relation to climate change. There are methodologies and experts that we can reach to describe differences in climate change impacts on: (1) crop water use efficiencies (WUE) at a systems level, for the growers' water delivery on site, and as crop differences in WUE, and (2) crop production values both for growers and for water resource planners. This is a high priority need.

As an ad hoc climate change group, it might serve us to establish guidelines for managing regional climate downscaled data. Questions regarding averaging techniques including span of time to use, and quality assurance of the downscaled data are important to address. A workshop including other experts, such as statisticians, would be helpful.

For future SIMETAW studies, an average period is planned to describe the two analysis times. For 2020, we plan to use 2015 through 2025 for averaging; and for 2050, we plan to use 2045 through 2055 for averaging. If possible, we think it is useful to coordinate with the other parts of the work team to have a standard in analysis time sampling.

For an understanding of ET demand there is a need to track irrigation conservation technologies and irrigation system pattern shifts including precision agriculture. This information can help anticipate probable shifts in agricultural applied water.

There is also a need to proportionally sum the evapotranspiration and evaporative demands impacted by different climate change scenarios on an annual perspective over the entire state. The precision of this analysis will improve as we improve our knowledge of evaporative processes and refine the SIMETAW model for climate change study.

## 8.6 Modeling Tool Integration

Several different mathematical models and analysis techniques can be used to assess impacts of climate change by translating changes in factors such as precipitation, sea level and crop evapotranspiration into water supply changes. Examples of modeling tools used in this report include the SWP-CVP operations model CalSim-II (Chapter 4), the Delta hydrodynamics and water quality model DSM2 (Chapter 5), and the Simulation of Evapotranspiration of Applied Water model SIMETAW (Chapter 7). Additional tools may also be available for climate change studies. Future directions include identifying 1) additional tools that could be used for climate change studies 2) input data requirements for each tool, 3) output produced by each tool and 4) more efficient ways to use these tools separately or in conjunction with other models to address water resources planning and management related climate change issues.

## 8.7 Coordination of State Climate Change Research Activities by the California Energy Commission

At the national and international levels a considerable amount of funds are being devoted to climate change science. Most of these research initiatives are designed to elucidate fundamental scientific questions such as the role of clouds on climate, or the direct and indirect effect of aerosols. The 2001 National Assessment of the Potential Consequences of Climate Variability and Change was a landmark effort resulting in a series of regional assessments that identified key vulnerabilities to a changing climate. Recently the U.S. Climate Change Science Program has embarked on the production of several synthesis and assessment products designed to support decision making on how to prepare for a changing climate.

Even though all of these national and international efforts are extremely informative, they usually are not adequate to answer policy relevant questions at the state and local levels or for detailed long-term planning in California. For this reason, The California Energy Commission through its Public Interest Energy Research (PIER) Program has created the first state-sponsored climate change research program in the nation designed to complement national and international research efforts producing policy-relevant research products. The Commission has created the California Climate Change Center (Center) with the University of California to implement its research plan on climate change. The Center is producing research products that are directly applicable for the preparation of long-term plans. Examples of such plans are the State Water Plans prepared by the Department of Water Resources and the Integrated Energy Policy Reports prepared by the California Energy Commission.

All the state agencies in California are supporting research on climate change. For example, the Air Resources Board is supporting studies on greenhouse gas tailpipe emissions from automobiles and recently has requested expanding its research program on climate change. The Department of Water Resources has an in-house effort designed to use existing planning modeling tools to better understand the potential effects of climate change on water resources in the state. CALFED is funding projects on the potential effect of climate change in the Delta region. Informally all of these efforts are being coordinated through extensive exchanges of information between technical staff from the different agencies and by the fact that some key researchers are involved in most of these research activities. The annual conferences on climate change organized by the Energy Commission and the California Environmental Protection (CalEPA) Agency are also a forum for exchange of ideas and for coordination.

Governor Schwarzenegger signed an Executive Order on June 1, 2005 requiring, among other things, the preparation of periodic assessment reports on the impacts of climate change on key sectors of the California economy. This effort, headed by CalEPA, is also serving as a catalyst for additional coordination and more intense research efforts.

In short, a great deal of coordinated research activities on climate change is already occurring in California. Formalizing these coordinated activities may be advisable, but extreme care should be taken to avoid hampering these activities with onerous requirements.

## 8.8 Risk Assessment

A major goal of the work team is to extend the analysis prospective for long-term water resources planning from "assessing impacts" to "assessing risk". Impacts assessment identifies possible outcomes resulting from a given change. Risk assessment takes the impacts assessment and investigates the likelihood or probability of occurrence that a particular outcome may occur. The work team's goal of extending our analyses from impacts assessment to risk assessment is shown in Figure 8.1. The bulls-eye nature of the figure symbolizes the work-team's goal of aiming for risk-based assessments for resource management with respect to climate change.

This report represents an example of an impacts assessment based on four scenarios defining an expected range of potential climate change impacts. Such assessments are good for informing managers of potential future issues that may require management action. However in order for managers to make decisions related to potential climate change impacts, they need information on the probability that any particular scenario will occur relative to other scenarios under consideration.

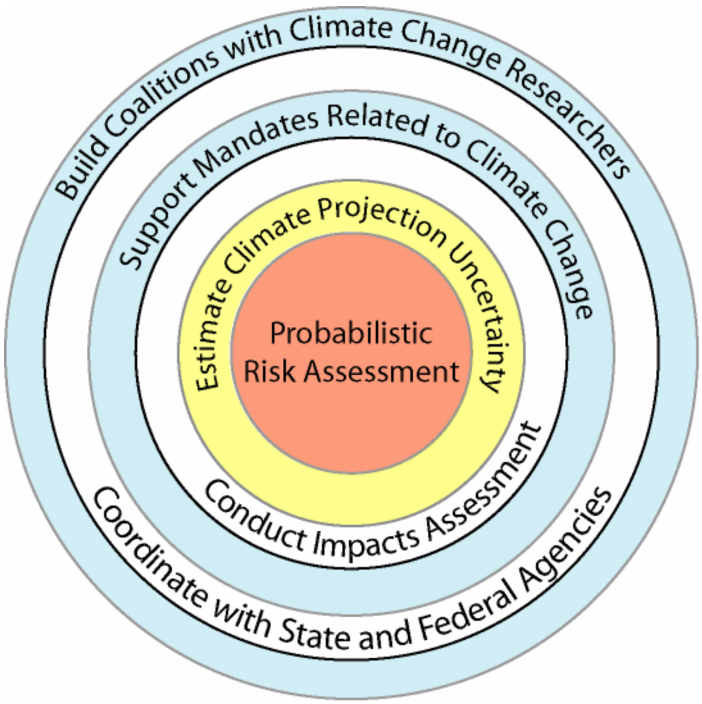



**Figure 8.1: DWR-Reclamation Climate Change Work Team Goals**
Yellow and red shading indicates future directions.

### 8.8.1 Compilation of Additional Climate Change Scenarios

An integral component of risk assessment is having as large of a data set as possible to define the range of potential outcomes. The work team plans to collaborate with climate change research groups on the selection of an ensemble of climate change scenarios for analysis, representing a spectrum of climate models and emission scenarios. For this report, analysis focused on four scenarios reflecting two greenhouse gas (GHG) emissions scenarios each represented by two Global Climate Models (GCM's) (see Chapter 3). However, many other emissions scenarios and climate models may be considered for generating future climate scenarios.

**Greenhouse Gas Emissions Scenarios**

The Intergovernmental Panel on Climate Change's (IPCC's) emissions scenarios cover a wide range of main demographic, economic, and technological driving forces GHG and sulfur emissions and are representative of the literature (IPCC, 2000). Four main storylines representing possible future evolutions of these factors were identified (see Chapter 3).

Scenarios were developed that represent a specific quantitative interpretation of one of the four storylines. All of the scenarios within a given storyline are referred to as a scenario family.

Following an integrated assessment framework, initially six global climate models (GCMs) were used to represent the various climate change scenarios. One advantage of a multi-model approach is that the resultant 40 SRES (Special Report on Emissions Scenarios) encompass the current range of uncertainties of future GHG emissions arising from different characteristics of these models. In addition, the current knowledge of uncertainties that arise from scenario driving forces such as demographic, social and economic, and broad technological developments that drive the models, are described in the storylines. Figure 8.2 shows the SRES emissions scenario tree starting with the four storylines and showing the 40 specific scenarios modeled.

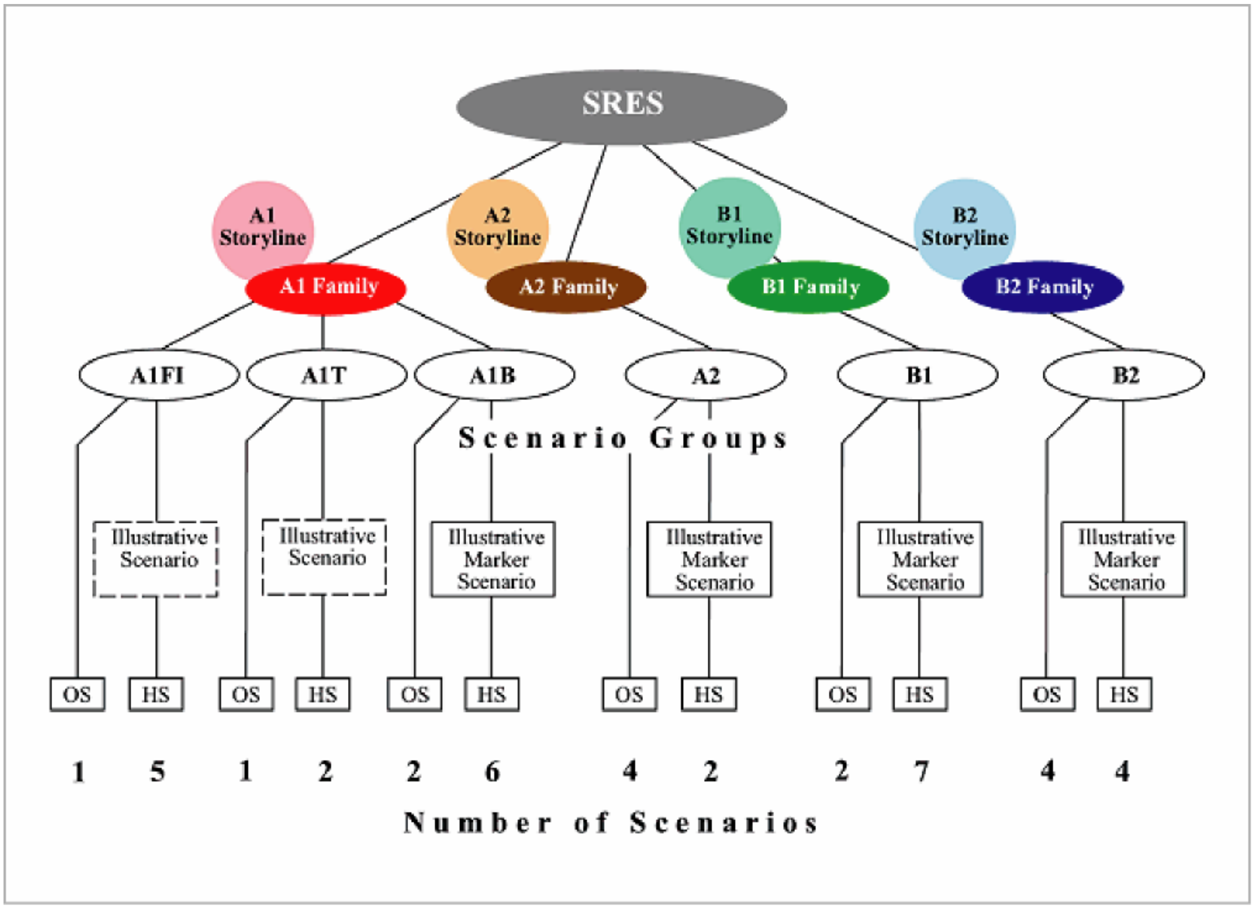
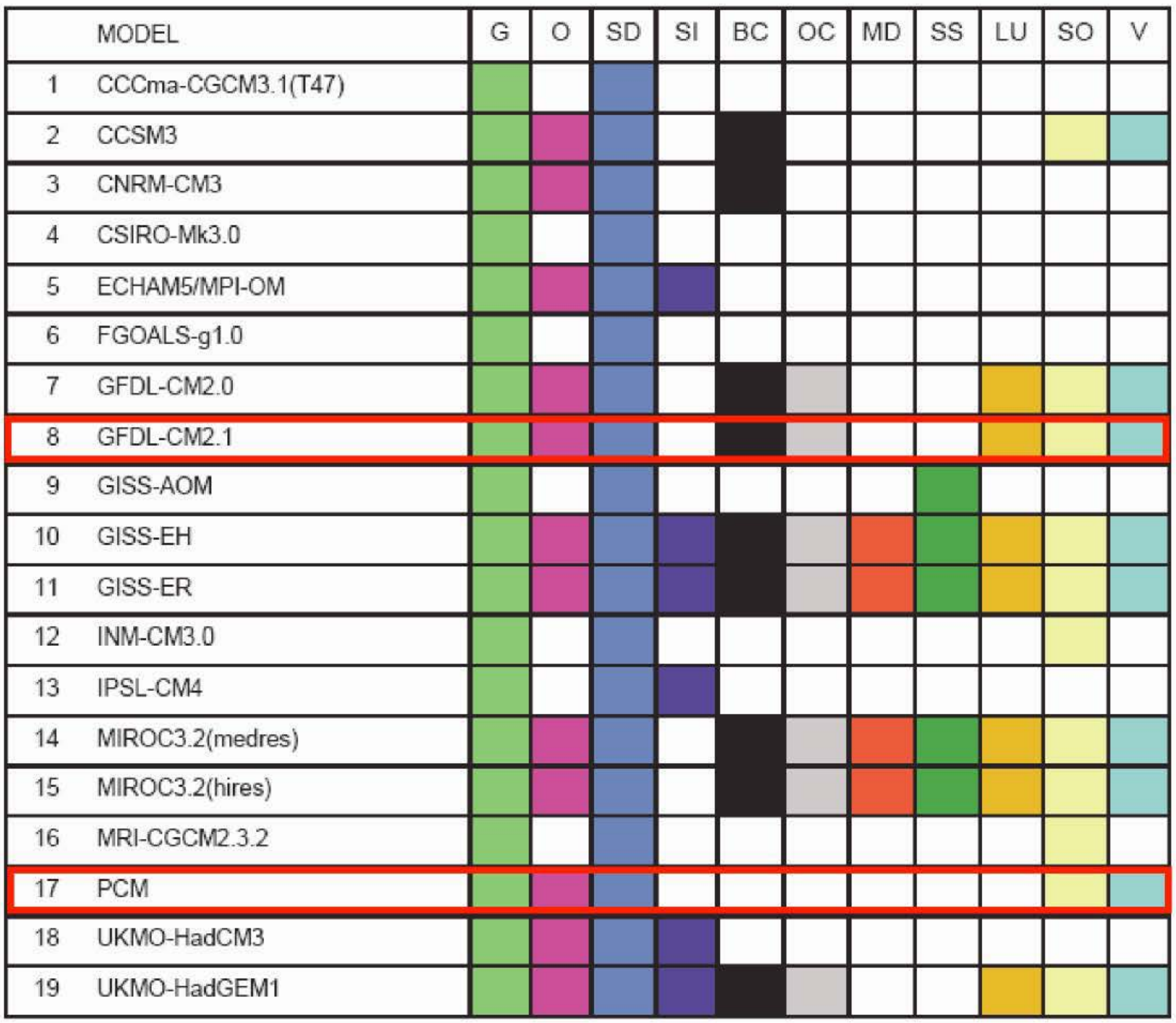



**Figure 8.2: Schematic Representation of 40 Emissions Scenarios**

## Global Climate Models

Nineteen different GGMs have been used to represent the 40 SRES greenhouse gas emissions scenarios (Santer, 2006). The climate processes in a GCM are driven by factors known as forcings, such as greenhouse gas emissions, ozone concentrations, sulfate aerosols, solar irradiance, mineral dust, sea salts, land use/land cover and volcanic aerosols. Different climate models use different combinations of these forcings to represent the evolution of the climate system (Figure 8.3). The studies presented in this report used climate change projections from two GCMs. Climate change projections produced by additional GCMs are desired to span the range of uncertainty associated with the representation of the climate system.




Shading indicates that the forcing is included on interannual or longer time scales. Forcings that only varied seasonally are not shaded Models used in this report are highlighted in red.

Climate Model Forcing Factors:

| | | | |
|---|---|---|---|
| G | well mixed greenhouse gases | MD | mineral dust |
| O | tropospheric and stratospheric ozone | SS | sea salt |
| SD | sulfate aerosol, direct effects | LU | land use/land cover |
| SI | sulfate aerosol, indirect effects | SO | solar irradiance |
| BC | black carbon aerosols | V | volcanic aerosols |
| OC | organic carbon aerosols | | |

**Figure 8.3: Forcing Factor Represented in Various Global Climate Models**
Adapted from Table 5.2 (Santer et al., 2006)
Red highlighting indicated models used in this report.

### 8.8.2 Probability Assessments

As described in the previous section, the work team will compile a larger ensemble of climate change scenarios, hopefully 20 to 30 or more scenarios. The ensemble uncertainty would then be quantified at the regional-scale in terms of probability distributions of annual shifts in precipitation and air temperature. Ensemble members' probabilistic classification (scenario probabilities) would make use of techniques such as those developed by Dettinger (2004). Assumptions would be clearly noted. These scenario probabilities would then be combined with associated impacts assessed using methodologies discussed in this report in order to produce risk information on a variety of system metrics such as annual water deliveries, end-of-September storage, or summer stream temperature. This risk information becomes the baseline for subsequent mitigation studies which look to reduce the risk of negative impacts.

This effort will provide decision makers with both ranges of impacts of climate change and their associated likelihoods. Perceived risk allows planners to make statements about the probability of impacts exceeding certain established thresholds and can be weighed against reliability levels for establishing planning directions. A better understanding of the likelihoods associated with potential climate change impacts will aid decision makers in planning appropriate response strategies. With the accomplishments to date and planned future directions, DWR is collaborating with other agencies and researchers to provide leadership in incorporating climate change impacts and risks into the planning and management of California's precious water resources.

## 8.9 References

Dettinger, M. (2004). From Climate Change Spaghetti to Climate Change Distributions, Discussion paper prepared for the California Energy Commission, pp25, http://www.energy.ca.gov/reports/2004-04-22_500-04-028.PDF

IPCC. (2000). Intergovernmental Panel on Climate Change, Special Report on Emissions Scenarios, Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. pp 570, http://www.grida.no/climate/ipcc/emission/.

Santer, B.D., J.E. Penner, and P.W. Thorne. (2006). How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes? In: Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences. A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research [Karl, T.R., S.J. Hassol, C.D. Miller, and W.L. Murray (eds.)]. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, NC, USA (in press).

## 8.10 Abbreviations

ANN-Artificial Neural Network
CalSimII-Simulation model of the SWP and CVP
CIMIS-California Irrigation Management Information System
CVP-Central Valley Project
GCM-Global Climate Model
GHG-Greenhouse Gas
IPCC-Intergovernmental Panel on Climate Change
SIMETAW-Simulation of Evapotranspiration of Applied Water Model
SRES-IPCC Special Report on Emissions Scenarios
SWP-State Water Project
WUE-Water Use Efficiency