CHAPTER 22
CLIMATE CHANGE CONSIDERATIONS

22.1 INTRODUCTION

Global climate change is playing an increasingly important role in scientific and policy debates related to effective water management. The most considerable impacts of climate change on water resources in the United States are believed to occur in the mid-latitudes of the West, where the runoff cycle is largely determined by snow accumulation and subsequent melt patterns. It is well documented that the effects of warmer climates on the timing of runoff in these regions likely will shift a portion of spring and summer runoff to periods earlier in the year (Vanrheenen *et al.* 2001). Despite the high degree of regulation in many water supply systems throughout the western United States, the resultant effects of these shifts on runoff seasonality generally are considered to be undesirable, because the amount of water stored in snowpack can be substantial and, under normal (i.e., historical) conditions, this stored water is relied upon to augment low stream flows during the relatively dry summers (Vanrheenen *et al*. 2001).

In the past, efforts to address climate change issues typically have focused on complex details and analytical limitations of atmospheric science and modeling. More recently, however, increasing attention is being given to understanding possible consequences to society and the types of appropriate responses given many remaining uncertainties (Gleick 1997). This is particularly true in the area of water resources, where many decisions depend explicitly on the assumptions about future climatic conditions. Long-term water planning choices, the design and construction of new water supply infrastructure, agricultural planting patterns, urban water allocations and rate structures, and reservoir operating rules all depend on climatic conditions. Thus, it is vitally important that those responsible for water planning and management, policymakers, and especially the public, begin to think about the implications of climatic change for our water systems (Gleick 1997).

Evidence is continuing to accumulate to indicate global climate change is to have a marked effect on water resources in California. More than 150 peer-reviewed scientific articles on climate and water issues in California have been published to date, with many more in preparation, addressing a range of considerations from proposed improvements in the downscaling of general circulation models to understanding how reservoir operations might be adapted to new conditions (Kiparsky and Gleick 2003). Rising temperatures and sea levels, and changes in hydrological systems are recognized as potential threats to California's economy, public health and environment (California Energy Commission 2003). In addition to the need for better understanding of the potential implications associated with these changes, it also is recognized that more research is necessary to identify which systems are most vulnerable (U.S. Climate Change Science Program Website 2005).

Because the Proposed Project/Action or an alternative would have a duration of approximately eight years, it would not be in place for a sufficient amount of time to contribute to climate change impacts, or to be potentially influenced by CVP/SWP system operations resulting from future climate change impacts. However, because of the importance of this issue with respect to California water planning and management efforts in general, it does require consideration and, thus, the following discussion is provided.

22.2 REGULATORY SETTING

While there are numerous regulations related to air quality and emission in California standards, two recent state regulations specifically address issues surrounding global climate change. A description of these regulations can be found below.

22.2.1 EXECUTIVE ORDER S-3-05

The Governor of California signed Executive Order S-3-05 on June 1, 2005. The Order recognizes California's vulnerability to climate change, noting that increasing temperatures could potentially reduce snowpack in the Sierra Nevada Mountains, which serve as one of the state's primary sources of water. Additionally, according to the Order, climate change could influence human health, coastal habitats, microclimates, and agricultural yield. To address these potential impacts, the Order mandates greenhouse gas emission reduction targets. More specifically, by 2010, greenhouse gas emissions are expected to be reduced to 2000 levels; by 2020, emissions are expected to reach 1990 levels; and by 2050, emissions are expected to be 80 percent below 1990 levels. The Secretary of the California EPA will oversee the reduction program targets and coordinate efforts to meet these provisions with numerous state agencies, such as the Resources Agency, which includes DWR. The Secretary will also provide biannual reports to the Governor and the State Legislature regarding: (1) progress toward meeting the greenhouse gas emissions targets; (2) the ongoing impacts of global warming in the state, including impacts to water supply and the environment; and (3) potential mitigation and adaptation plans to combat these impacts. In order to achieve the climate change emission targets, in June 2005, the Secretary formed the Climate Action Team, which is comprised of administrators from numerous state agencies.

22.2.2 ASSEMBLY BILL 32 – CALIFORNIA GLOBAL WARMING SOLUTIONS ACT

The California Global Warming Solutions Act of 2006 (AB 32) was signed into law on September 27, 2006. With the Governor's signing of AB 32, the Health and Safety Code (Section 38501, Subdivision (a)) now states the following:

> "*Global warming poses a serious threat to the economic well-being, public health, natural resources, and the environment of California. The potential adverse impacts of global warming include the exacerbation of air quality problems, a reduction in the quality and supply of water to the state from the Sierra snowpack, a rise in sea levels resulting in the displacement of thousands of coastal businesses and residences, damage to marine ecosystems and the natural environment, and an increase in the incidences of infectious diseases, asthma, and other human health-related problems.*"

The bill will require the CARB, in coordination with state agencies as well as members of the private and academic communities, to adopt regulations to require the reporting and verification of statewide greenhouse gas emissions and to monitor and enforce compliance with this program. Similar to Executive Order S-3-05, under the provisions of the bill, by 2020, statewide greenhouse gas emissions will be limited to the equivalent emission levels in 1990. By January 2008, the CARB will determine the statewide greenhouse gas emission level in 1990 through review of the best available scientific, technological, and economic information, as well as provide opportunities for public review and comment. To achieve the 2020 reduction goal, by January 2011, the CARB shall adopt emission limits and reduction measures, which may include a system of market-based declining annual aggregate emission limits for sources or categories of sources that emit greenhouse gases. It is anticipated that limits and emission standards adopted by the CARB will become operative beginning January 2012. In addition, the Climate Action Team established by the Governor to coordinate the efforts set forth under Executive Order S-3-05 is expected to continue its role coordinating overall climate policy.

22.3 TYPES OF POTENTIAL IMPACTS TO ENVIRONMENTAL RESOURCES IN CALIFORNIA RESULTING FROM GLOBAL CLIMATE CHANGE

Global climate change has the potential to impact numerous environmental resources in California through potential, though uncertain, impacts related to future air temperatures and precipitation patterns, and the resulting implications to stream runoff rate and timing, water temperatures, reservoir operations, and sea levels. Although current models are broadly consistent in predicting increases in probable global air temperatures and increasing levels of greenhouse gasses resulting from human activities, there are considerable uncertainties about precipitation estimates. For example, many regional modeling analyses conducted for the western United States indicate that overall precipitation will increase, but uncertainties remain due to differences among larger-scale General Circulation Models (GCMs)(Kiparsky and Gleick 2003). Some researchers believe that climate warming might push the storm track on the West Coast further north, which would result in drier conditions in California. At the same time, relatively newer GCMs, including those used in the National Water Assessment, predict increases in California precipitation (DWR 2005). Similarly, two popular climate models, including HadCM2 developed by the U.K. Hadley Center and PCM developed by the U.S. National Center for Atmospheric Research, also predict very different future scenarios. The HadCM2 predicts wetter conditions while the PCM predicts drier conditions (Brekke *et al.* 2004).

While much variation exists in projections related to future precipitation patterns, all available climate models predict a warming trend resulting from the influence of rising levels of greenhouse gasses in the atmosphere (Barnett *et al.* 2005). The potential effects of a warmer climate on the seasonality of runoff from snowmelt in California's Central Valley have been well-studied and results suggest that melt runoff would likely shift from spring and summer to earlier periods in the water year (Vanrheenen *et al*. 2001). Currently, snow accumulation in the Sierra Nevada acts as a natural reservoir for California by delaying runoff from winter months when precipitation is high (Kiparsky and Gleick 2003). Despite the uncertainties about future changes in precipitation rates, it is generally believed that higher temperatures will lead to changes in snowfall and snowmelt dynamics. Higher atmospheric temperatures will likely increase the ratio of rain to snow, shorten and delay the onset of the snowfall season, and accelerate the rate of spring snowmelt, which would lead to more rapid and earlier seasonal runoff relative to current conditions (Kiparsky and Gleick 2003). Studies suggest that the spring stream flow maximum could occur about one month earlier by 2050 (Barnett *et al*. 2005).

Based on consideration of future air temperature and precipitation changes and the results of recent local and regional climate change studies (see Section 22.4), the types of potential climate change effects that could be expected to occur on various resources within the Central Valley of California may include:

- ***Water Supply.*** The impacts of climate change on water supply and availability could have direct and indirect effects on a wide range of institutional, economic and social factors (Gleick 1997). Still, considerable uncertainty exists on the overall impact to future water supplies. For example, Brekke (2004) suggest two equally probable projections based on the type of model used for analyses. Based on HadCM2 projections, there would be increased reservoir inflows, increased storage limited only by current capacity, and increased river flows, relative to current conditions. In contrast, PCM models suggest decreased reservoir inflows, decreased storage and decreased river flows. Nevertheless, changes in water supply are expected and small changes in inflows could result in large changes in the reliability of water yields from reservoirs (Kiparsky and Gleick 2003). Further exacerbating potential climate change impacts, future water systems will likely already be increasingly stressed by other factors, including population growth, competition for financial resources from other sectors, and disputes over water allocations and priorities.

- ***Sea Levels.*** Existing global climate changes may already be contributing to a rise in sea level. For example, sea levels recorded at the Golden Gate Bridge in San Francisco have risen 0.2 m (0.7 feet) in the last century, and are expected to rise another 0.5 m (1.6 feet) by 2100 (DWR 2005). Impacts associated with a rise in sea level would likely be most significant in the Delta, where a rise in sea level would increase pressure on levees currently protecting low-lying lands, much of which is already below sea level. DWR (2005) reports that a one-foot rise in sea level would increase the frequency of the 100-year peak high tide to a 10-year event. Additionally, a rise in sea level would cause increased salinity intrusion from the ocean, which could degrade freshwater supplies pumped from the Delta, and necessitate increased reservoir releases upstream to dilute intruding sea water. Sea level rise could also threaten coastal aquifers (DWR 2005).

- ***Hydropower Generation***. Hydropower production is generally a function of reservoir storage. Climate changes that decrease the quantity or alter the timing of available water (i.e., reservoir inflows), as predicted by the PCM models for example, have the potential to adversely impact the productivity of hydroelectric facilities. Alternatively, reliable increases in average flows would increase hydropower production (Kiparsky and Gleick 2003). One study (Vanrheenen *et al.* 2004) based on the PCM model, suggests potential decreases in hydropower production at Shasta Reservoir ranging from 4 to 11 percent over various time periods during the next hundred years, while total Central Valley hydropower production could decrease by 6 to 12 percent.

- ***Surface Water Quality***. Water quality depends on several variables including water temperature, flow, runoff rate and timing, and the physical characteristics of the watershed. Climate change has the potential to alter all of these variables. Depending on basin hydrology, higher winter flows could dilute pollutants, or conversely, increase erosion, sedimentation, and chemical and nutrient loads in rivers (Kiparsky and Gleick 2003). In addition, non-point source pollutants could increase due to increased urban runoff. Still, much work remains to determine the potential global climate change impacts to water quality.

- ***Groundwater***. Reduced Sierra Nevada snowpack, earlier runoff, and reductions in spring and summer stream flows would likely affect surface water supplies and may place a heavier reliance on groundwater resources, which are already depleted in many of California's agricultural areas (Hayhoe *et al.* 2004). While warmer, wetter winters could increase the amount of water available for groundwater recharge, the additional winter runoff may occur when some basins are either being recharged at there maximum capacity or are already full (Kiparsky and Gleick 2003). In contrast, reductions in spring runoff and higher evapotranspiration resulting from higher temperatures could reduce the amount of water available for recharge (Kiparsky and

Gleick 2003). Unless precipitation increases, the higher levels of evaporation accompanying warmer air temperatures could also reduce groundwater supplies in the spring (California Energy Commission 2003).

- ***Fisheries and Aquatic Resources***. If air temperatures in California rise significantly, it will become increasingly difficult to maintain appropriate water temperatures in order to manage coldwater fisheries, including anadromous salmonids. A reduction in snowmelt and increased evaporation could lead to decreases in reservoir levels and, perhaps more importantly, coldwater pool reserves (California Energy Commission 2003). As a result, water temperatures in rivers supporting anadromous salmonids could potentially rise and no longer be able to support over-summering life stages (i.e., adult and juvenile spring-run Chinook salmon, juvenile steelhead). In fact, DWR (2006) suggests that under a warmer climate scenario, water temperature standards in the upper Sacramento River likely could not be maintained.

- ***Flood Control***. Flooding depends not only on precipitation, but also on the timing and intensity of that precipitation, two characteristics that are not well-modeled at the present time (Kiparsky and Gleick 2003). Still, under most climate change scenarios, reservoir inflow is expected to increase during the winter and decrease during the spring and summer, and given existing reservoir capacities, this runoff pattern could potentially result in increased flooding (California Energy Commission 2003). Moreover, if the increased inflow during the wet season cannot be managed effectively, then dry season water supply could decrease considerably even if overall annual water quantity increases, as projected by the HadCM2 models (Zhu *et al.* 2003).

- ***Air Quality***. Air quality indices consider several constituent parameters, and these concentrations are difficult to model, particularly considering the uncertainty regarding global climate change projections. However, a study conducted by the California Energy Commission (2003) reports that in the Bay Area and the Central Valley, given no other changes in weather or emissions, a 7.2°F warming would increase ozone concentrations by 20 percent and nearly double the size of the area out of compliance with national health standards for air quality.

- ***Socioeconomics***. Because of conflicts between flood control operations and hydropower objectives, climate change in California may require the release of more water in the early spring to reduce flood potential. This change could result in a reduction in hydropower generation and its economic value. Concurrently, production of power by fossil fuels may increase to meet energy demands at a cost of hundreds of millions of dollars and result in increased greenhouse gas emissions (Kiparsky and Gleick 2003). Additionally, higher energy and water costs would likely hit low-income households the hardest because these costs makeup a larger proportion of their expenditures, relative to higher income families (California Energy Commission 2003).

22.4 CLIMATE CHANGE CASE STUDIES IN THE CALIFORNIA CENTRAL VALLEY

Projecting the regional impacts of climatic change and variability relies first on GCMs, which develop large-scale scenarios of changing climate parameters, usually by comparing scenarios with different concentrations of greenhouse gases in the atmosphere (Kiparsky and Gleick 2003). In general, conclusions drawn from the GCM results suggest that a global warming trend in California would likely lead to more severe winter storms, earlier runoff from the Sierra Nevada snowpack, and reduced summer flows in tributary streams (Quinn *et al.* 2003). However, information provided by the GCMs is typically too coarse of a scale to make accurate regional assessments (Kiparsky and Gleick 2003). Consequently, recent efforts have resulted in reducing the scale and increasing the resolution of climate models by downscaling or integrating regional models into the global models.

Both GCMs and hydrologic models (i.e., CALSIM) have been utilized in a number of California climate change studies. Many of these studies focus on stream flow response to shifts in the timing and form of precipitation, and do not address inter-annual variability or scaling issues inherent in mapping GCM model output to more detailed watershed hydrologic models (Quinn *et al*. 2003). As a result, such studies do little more than make qualitative statements about the implications of these changes to environmental impacts (e.g., water quality, agriculture, fisheries) (Quinn *et al*. 2003). However, as will be seen in the following case studies, other investigations at least attempt to quantify impacts to environmental resources, particularly water supply.

Such efforts have focused attention on the issues of water management in California associated with potential hydrologic changes that may occur as a result of climate change. More recently, there has been progress in modeling climate change and its effects on a regional basis. Although there are still differences in some model projections (e.g., amount and timing of annual precipitation), projections on other variables are becoming more consistent (e.g., reduced snowpack, shift of snowmelt timing to an earlier time period, rises in sea level, and warmer weather patterns). Though differences in the hydrological response to climate change exist among model projections, these differences can be used to bracket the magnitude of anticipated changes allowing managers to develop different response scenarios. Some of the key findings of recent research efforts in the Central Valley of California are described below.

22.4.1 2005 Update to the DWR California Water Plan

The 2005 update to the California Water Plan (DWR 2005) contains an analysis of future water demands resulting from population growth, and additionally attempts to address potential impacts resulting from global climate change, as discussed below.

DWR has developed preliminary estimates of water demands that could reasonably be expected to occur by 2030. These preliminary estimates represent the expected water demands under three different future scenarios. The three future scenarios are defined as follows:

Scenario 1 – Current Trends: Recent trends for population growth and development patterns, agricultural and industrial production, environmental water dedication, and naturally occurring conservation measures (e.g., plumbing code changes, natural replacement, actions water users take on their own, etc.).

Scenario 2 – Less Resource Intensive: Recent trends for population growth, higher agricultural and industrial production, more environmental water dedication, and higher naturally occurring conservation.

Scenario 3 – More Resource Intensive: Higher population growth rate, higher agricultural and industrial production, no additional environmental water dedication, and lower naturally occurring conservation.

The greater urban water demand projected under all three scenarios presents significant challenges to water managers. Under the Current Trends scenario, DWR estimates an additional 3.6 MAF of urban and environmental water demand per year. Though there may be commensurate reductions in agricultural demand, this demand reduction would occur in the Central Valley, while much of the additional urban demand would occur in the southern part of the state, and the ability to transfer additional water there is constrained by conveyance facilities, area-of-origin issues, environmental impacts, and other third party effects. Although these projections describe additional water demands in California by 2030, they do not consider the capability of the water management system to meet those demands under different hydrologic conditions as those predicted by climate change models.

DWR (2005) also attempts to address concerns related to climate change. More specifically, DWR recognizes the potential for significant impacts associated with climate change, and these impacts warrant an examination regarding the ability of existing water supply infrastructure and natural systems to accommodate or adapt to climatic change. DWR (2005) identifies the following needs:

- The major tool for evaluating the impact on major water project systems is CALSIM, a model developed jointly by Reclamation and DWR. CALSIM currently relies on historic monthly hydrological data to assess project impacts. The development of modified input to CALSIM from the climate models is a major task and will require help from the research community. Enabling CALSIM to utilize data from climate models will allow for more proactive planning and development of strategies and options for improving water supply and quality.
- The linking of climate and hydrologic models is a major task but will provide a tool for evaluating multipurpose reservoir flood control aspects. The screening of climate models by experts in the field will be required to select those that provide the most plausible future scenarios. Because there will be competition between flood control and other purposes at the large multipurpose reservoirs due to earlier peak snowmelt runoff, an examination of space criteria allocated for flood control in the spring is required.
- Because of a general warming in California's climate, it is anticipated that increases in water requirements for crops, wildlands and landscaping will likely occur. In order to properly measure these changes, the monitoring of evapotranspiration rates will be required. The goal is to develop likely changes in evapotranspiration rates for the 2050 and 2100 scenarios. Projections of future weather including precipitation during the growing season are required to provide projected increases in plant water requirements.
- Existing models for water temperature on the major rivers in the Sacramento River Basin will likely require improvement as the job of maintaining suitable downstream temperatures for anadromous salmonids becomes more difficult.
- Monitoring the effects of climate change on regions near California is also important. The Colorado River region is important to California and may have potential impacts on both water supply and hydropower. The Columbia River Basin is an important source of hydropower for California. Monitoring the results of research and studies in these areas is important for future planning studies.

Because only limited data and tools exist to provide answers to important questions for decision makers, water managers and resource planners, DWR is working in conjunction with others to develop a new analytical approach for the preparation of California Water

Plan Update 2010. DWR has determined that designing this quantitative approach will best be achieved through a consortium of public and private entities, with state leadership and input from stakeholders. The purpose of the consortium is to prepare a long-term plan to review data and analytical tools, as well as to develop decision-support systems to make complex technical information more accessible to decision makers and resource managers. Because time is needed to develop this new approach, most of the quantitative work will be presented in Update 2010.

22.4.2 PRELIMINARY CLIMATE CHANGE IMPACTS ASSESSMENT FOR CVP/SWP OPERATIONS AND THE DELTA

In responding to Executive Order S-3-05, and as a first step in addressing the limitations presented above, DWR (2006) describes the Department's progress toward incorporating climate change modeling into existing water resources planning and management tools and methodologies. While the report describes numerous efforts, Chapters 4 and 5 present the potential impacts of climate change scenarios on CVP/SWP operations and deliveries, and Delta water quality and water levels using the hydrologic models CALSIM II and DSM2, respectively. Each impact analysis considers four scenarios predicted by pairings of two global climate models (i.e., PCM and GFDL) and two carbon dioxide emissions rates (A2 and B1), and illustrate projected hydrologic conditions centered around 2050 (i.e., 2035 through 2064). All four climate change scenarios predict a general warming trend for California; however, three of the four scenarios predict modestly drier climates, while one (i.e., PCM-B1) predicts a weak precipitation increase. Monthly river inflow data for use as CALSIM II input is generated by downscaling and adapting global climate model results, using a regional hydrologic model, derivation of climate change runoff perturbation ratios, and application of these perturbations ratios to CALSIM II historic reservoir inflows. The hydrologic estimates associated with each climate change scenario are then compared to a base scenario, which is designated as the 2020 level of development outlined in Reclamation's OCAP (Reclamation 2004).

The results of the analysis for CVP/SWP operations and deliveries indicate several potential impacts related to global climate change. For example, during the three drier year climate scenarios, there are a significant number of months in which Shasta and Folsom reservoirs fall to dead storage, with these occurrences concentrated during critical and drought year conditions. During these months, stream flow requirements in the Sacramento and American rivers could not be met, and the CVP was unable to meet its share of water for the Coordinated Operations Agreement. In contrast, the base scenario had only one month which resulted in attainment of dead storage in these locations. These reservoir shortages influence the remaining analyses within the model, and hence, CVP/SWP system deliveries also are influenced by global climate change. Relative to the base scenario, changes in annual average south-of-Delta SWP Table A and CVP deliveries ranged from a slight increases associated with the wetter-climate scenario up to about 10 percent reductions for drier year scenarios. In addition, carry-over storage for both the CVP and SWP reservoirs is negatively impacted under the drier climate scenarios and mildly increased under the wetter climate scenario. Additional reservoir operations impacts are evident by a reduction in the CVP/SWP power generation capacity during summer months and warming of water temperatures in rivers downstream of project reservoirs under the drier climate scenarios.

Using the same methodology and reservoir operation output described above, DWR (2006) also describes potential impacts of climate change on Delta water quality and water levels. The CALSIM II output reflecting adjustments in reservoir operation and Delta exports due to shifting precipitation and runoff patterns are utilized in the DSM2 model for each of the four scenarios. Because one of the key assumptions in the CALSIM II model prioritizes Delta water quality standards, the impact assessment for the Delta inherently mitigates for climate change by modifying upstream system operations to maintain Delta water quality standards. Hence, Delta water quality effects for all four climate change scenarios are relatively minor. When considering a one-foot rise in sea level, either alone or combined with the effects of climate change, Delta water quality standards are met about 90 percent of the time, particularly during dry and critical years. In real-time, operational adjustments would be required and translate into impacts to the CVP and SWP, although these impacts cannot yet be quantified. Finally, DWR (2006) predicts that levee overtopping could be an issue during a one-foot sea level rise scenario, although no overtopping events are predicted for the current sea level condition.

As noted in DWR (2006), the purpose of this study is to demonstrate how various analysis tools currently used by management agencies could be used to address issues related to climate change. All of the results are preliminary and do not reflect the likelihood of occurrence for potential impacts, and as such, are not sufficient by themselves to make policy decisions. In addition, the study contains several key assumptions that may not reflect operational realities. For instance, the study assumes that no changes will be made to system structures or facilities, reservoir operating rules, stream flow requirements, water quality standards, or operations to account for sea level rise or salt water encroachment. Future work will focus on further elucidating not only the magnitude, but also probability, of potential impacts, as well as investigating possible changes in system operations to avoid these impacts.

22.4.3 WEIGHTED ESTIMATION OF CLIMATE PROJECTION DISTRIBUTIONS OVER CALIFORNIA

Reclamation has also initiated studies regarding the potential impacts of climate change on water management in California. The Reclamation studies attempt to expand previous studies that identify and enumerate potential impacts, by assigning a relative probability to each potential impact, thereby creating risk-based planning principles. To achieve this objective, Brekke (2006) utilizes an ensemble analysis of 18 different model projections for three future climatologic periods, including 2011 through 2040, 2041 through 2070, and 2071 through 2100. Precipitation, temperature, and joint precipitation-temperature distribution functions are developed using ensemble member weighting factors that indicate each model's performance during model-to-reference comparisons (i.e., pre-climate change model results compared to 20th century observations). The project distributions are expected to illustrate projection-specific likelihoods relative to the consensus. Further results related to this risk-based analysis are forthcoming, as it is anticipated that Reclamation will issue a report by late-2007.

22.4.4 CLIMATE WARMING AND WATER SUPPLY MANAGEMENT IN CALIFORNIA

Tanaka *et al.* (2006) focuses on the likely effects of a range of climate warming estimates on the long-term performance and management of California's water system. The study incorporates a wide range of hydrologic effects and resources, and includes the inter-tied water supply system such as groundwater and surface water, agricultural and urban water supply users, environmental flows, hydropower, and potential for changing infrastructure and management. In addition, Tanaka *et al.* (2006) employs the California Value Integrated Network (CALVIN), a large-scale economic-engineering optimization model for California's water supply, to examine the ability of the complex water supply system to adapt to significant changes in climate and population.

Generally confirming earlier studies, Tanaka *et al.* (2006) illustrates that a wide range of climate warming scenarios could significantly increase wet season flows and significantly decrease spring snowmelt. The magnitude of the climate warming effects is comparable to population-driven water demand growth in the coming century. Agricultural water users in the Central Valley are the most vulnerable to climate warming, with the driest climate scenarios predicting delivery reductions of up to one-third, with much of the agricultural water being diverted for urban uses. While the study suggests California's water systems can adapt to meet the predicted future requirements, the costs could be substantial, and could have major effects on the agricultural and environmental sectors.

22.4.5 HYDROLOGIC FORECASTING AND WATER RESOURCES MANAGEMENT FOR FOLSOM LAKE WATERSHED IN CALIFORNIA

Reclamation and the Scripps Institute of Oceanography have provided funding to demonstrate the utility of modern hydrologic forecasting and water resource management concepts and ideas combined with climate information to provide improved management of the Folsom Lake waters (Hydrologic Resource Center Website 2005). The work is a joint effort among the Hydrologic Research Center at Scripps, the Scripps Institute of Oceanography, and the Georgia Water Resources Institute. Throughout the study, the development team will be working in collaboration with Reclamation's Central Valley Operations and NMFS' Regional River Forecast Center in Sacramento, California.

By investigating different long-term weather forecasting scenarios, initial findings indicate that Folsom operations would benefit significantly from long-lead seasonal forecasts. The project team is currently developing methodologies for incorporating climate forecasts into models to develop hydrologic forecasts. Currently, within the study area, there are significant differences in the climate model forecasts from node to node which result in significant hydrologic forecast differences. The research and development work includes the following activities:

- Hydrologic modeling of the watershed;
- Modeling of reservoir operations in Folsom Lake;
- Development of models for hydrologic forecast uncertainty;
- Development of methods for downscaling global climate model information; and
- Development of retrospective studies to demonstrate feasibility and utility.

22.4.6 SIMULATED HYDROLOGIC RESPONSES TO CLIMATE VARIATIONS AND CHANGES IN THE MERCED, CARSON, AND AMERICAN RIVER BASINS, SIERRA NEVADA, CALIFORNIA (1900 – 2099)

Hydrologic responses of daily stream flow to simulated climatic variations over a 200-year period for the Merced, Carson and American River basins are described by Dettinger *et al.* (2004) in a study funded by the U.S. Department of Energy, NMFS, Scripps Institution of Oceanography and the USGS. Dettinger *et al.* (2004) utilizes a PCM model to simulate future hydrologic conditions under three different scenarios. The first scenario is a historical simulation based on the climate during the 1870 to 1999 period. The second simulation is for the 1995 to 2048 period with greenhouse gasses fixed at 1995 levels and is referred to as the 'future control" simulation. The final simulation is for the 1995 to 2099 period with increasing greenhouse gas concentrations and is referred to as the "business as usual" simulation.

Over northern California, simulated temperatures have risen in the last part of the 20th century. Mean precipitation rates remain fairly constant under all three simulations. In contrast to the "future control" scenario, the "business as usual" future climate conditions continue the trend of the late 20th century, with additional warming of about 2.4°C and a five percent increase in precipitation by 2100. Simulations show that "business as usual" trends become significantly different by 2025. Simulated hydrologic responses to the PCM simulated climates include small increases in total stream flow and evapotranspiration and a large, clear trend toward earlier snowmelt and reduced summertime flows and soil moisture. Dettinger *et al* (2004) concludes that

> *"…even the relatively modest changes in climate predicted by the PCM model would be sufficient to induce significant and disruptive changes in the hydrology and ecosystems for these three representative Sierra Nevada river basins. The PCM climate change projections are actually near the lower edge of the available climate change simulations in terms of warming (ranging from 2°C to 5°C) and yield only modest changes in overall precipitation. If even these modest climate change projections are sufficient to cause the important hydrological changes in the Sierra Nevada simulated here, then prospects for climate change impacts in California can rightly be taken quite seriously, despite large remaining climate change uncertainties. "*

22.4.7 POTENTIAL IMPLICATIONS OF PCM CLIMATE CHANGE SCENARIOS FOR SACRAMENTO-SAN JOAQUIN RIVER BASIN HYDROLOGY AND WATER RESOURCES

In a study similar to Dettinger *et al.* (2004), VanRheenen *et al.* (2004) employs five different PCM scenarios to simulate potential hydrological changes associated with climate change. The first three scenarios are runs from 1995 through 2099 using "business as usual" global emissions simulations, each with a different initialization. The fourth scenario is a control climate scenario with greenhouse gas emissions set at 1995 levels, and the fifth scenario uses an evolving greenhouse gas concentration based on 1870 to 2000 data. For purposes of this study, a simulation model of the system, named CVMod (Central Valley Model), was developed. CVMod simulates the movement and storage of water within the Sacramento-San Joaquin River Basin, given current operational procedures. The model operates on a monthly timestep of stream flows, which come from either observed historic stream flows (for studies representing past climate) or from predicted stream flows under future climate scenarios.

VanRheenen *et al.* (2004) concludes that both demand modification and infrastructure improvements will be required to account for volumetric and temporal shifts predicted to occur with future climates in the Sacramento-San Joaquin River Basin.

22.4.8 TRENDS IN SNOWFALL VERSUS RAINFALL IN THE WESTERN UNITED STATES

Knowles *et al.* (2006) addresses the well-documented shift in runoff patterns in recent decades, particularly the part of this trend attributed to more precipitation falling as rain instead of snow. The study documents a regional trend in the western United States toward smaller ratios of total winter snowfall water equivalents (i.e., the water content within snowfall) to total winter precipitation during the 1949 through 2004 period. This trend appears to be a response to warming across the region, with the most significant shift in precipitation patterns occurring in locations where wet-day minimum temperatures averaged over the study period are warmer than -5°C. Greater warming has occurred mainly at sites where the mean temperatures are cold enough that precipitation form is less susceptible to warming trends. Trends toward smaller snowfall to precipitation ratios are most pronounced in January for lower elevations throughout much of the West Coast region. The authors suggest that if these trends continue, much of the West's freshwater storage capacity from snowpack will be diminished and the risks of winter and spring flooding could increase. The combination of reduced natural storage capacity and greater flood risks threatens to augment the tension between flood control and storage priorities at major reservoirs.

22.4.9 Accelerated Climate Prediction Initiative

The University of Washington Water Resources Management and Drought Planning Group designed the Accelerated Climate Prediction Initiative (ACPI) to answer questions on how future climate variability may affect the water resource industries (particularly hydropower) along the West Coast (University of Washington, The Alpheus Group TAG Website 2005). Through the ACPI, the CVMod has been developed for use in conducting an independent evaluation of climate changes predicted to occur, as well as the potential for such changes to influence water systems in California, including the Central Valley. CVMod charts the major operations of the Trinity, Sacramento, and San Joaquin River basins by Reclamation and DWR. CVMod represents fifteen structures in all including: eleven dams, two pumping stations, and two diversion canals. The model also captures a complex and divergent set of demands and legal policies that affect allocations within the Central Valley and the Delta.

22.5 Areas of Further Research and Ongoing Activities

One of the most important areas of research associated with the potential impacts of climate change on California's water resources is the further development of tools to predict changes in the timing or amount of future water availability. Currently, CALSIM serves as the primary operations and planning model for CVP and SWP operations. The model simulates CVP and SWP operations on a monthly time-step to predict the hydrologic effects of those operations within the geographical area affected by CVP and SWP facilities, including the Delta. CALSIM routes water in the system on a monthly basis using operational decisions, which minimize a priority-based penalty function of delivery and storage targets. The weights of these penalty functions train the model to adhere to operating rules and constraints such as instream flow requirements, downstream water quality objectives and contract deliveries to agricultural and urban water districts. The end-of-period storages from each optimization step are used as initial conditions for the following month's optimization. Model outputs include monthly reservoir releases, river flows, reservoir stored water volumes, Delta export activities, and indicators of Delta water quality (California Energy Commission 2003). A baseline version of the model is set up to perform monthly operations decisions for a 73-year simulation period based on the 1922 to 1994 hydrologic years experienced in the Central Valley. Water demands and system infrastructure are modified to represent 2001 and 2020 levels of development.

Another simulation model that has been used for studies in the Central Valley is CVMod. CVMod was developed by the University of Washington and operates similarly to CALSIM. The primary input to CVMod is monthly stream flow which comes from either observed historic stream flows or from Variable Infiltration Capacity (VIC) simulations of potential future stream flows; VIC is a regional hydrologic model implemented for the Sacramento-San Joaquin River Basin (Vanrheenen *et al*. 2004). In a comparison of CALSIM with CVMod, it was shown that CALSIM was better able to predict end-of-month storage volumes in the major Central Valley Reservoirs. The period of analysis for the comparison was October of 1979 through June of 1994 (California Energy Commission 2003).

A third model used in some Central Valley studies is CALVIN. CALVIN was developed at University of California Davis and is a prescriptive optimization model that operates surface and groundwater resources and allocates water over the historical hydrologic record (California Energy Commission 2003). CALVIN maximizes the economic values of agricultural and urban water use statewide, within physical, environmental and policy constraints. Besides the Central Valley, CALVIN incorporates parameters from southern California SWP contractors, California users of the Colorado River, the Owens Valley and Mono Basin and also groundwater sources, making it the model with the broadest coverage of water users in California. Monthly operations and allocation decisions are made based on the 1922 to 1993 hydrologic period assuming perfect foresight of future inflows.

To effectively assess the potential impacts of climate change on California's water system, a model is needed that represents the operation of the system and has the ability to accept input from climate change impact studies related to the Central Valley. The model requires a descriptive, rather than prescriptive approach (California Energy Commission 2003). Of the three models described above, CALSIM provides the most robust representation of the current system in terms of coverage, spatial representation and operational rules. CALSIM's major fault is its inability to utilize hydrologic data not related to the 73 years of historical data for which the model has been validated. CVMod has the ability to accept any hydrologic inputs, however, its weakness is that some of the operations rules, and hence, the results from the model, are potentially much different from how the system is actually run. The CALVIN model is prescriptive rather than descriptive.

Projecting regional impacts of climate change is a multi-step process. First, GCMs are used to develop large-scale scenarios of changing climate parameters. Because this information is at too coarse a scale to make regional assessments, efforts are currently being made to reduce the scale and increase the resolution of GCMs by downscaling or integrating regional models into the GCMs. Quinn *et al.* (2003) was able to downscale output from both HadCM2 and PCM models to simulate hydrologic conditions in the San Joaquin River basin from 2010 to 2100. Simulations of water deliveries were made using output from the downscaled HadCM2 and PCM models as input to CALSIM. Although Quinn *et al.* (2003) results differed significantly, depending on which downscaled GCM was used to develop CALSIM input, they do show the feasibility of linking GCMs with hydrologic models for simulating different climate change scenarios. VanRheenen *et al.* (2004) were able to incorporate output data from PCM models into CVMod to examine the Central Valley water resources, under five different PCM scenarios, by developing a technique to downscale PCM model output to a scale suitable for CVMod input. Dettinger *et al.* (2004) was able to utilize a downscaled PCM model output to simulate stream flow and water balances in the American River Basin by use of the Precipitation-Runoff Modeling System (PRMS), a model that predicts changes to runoff based on land use and climate changes. Zhu *et al.* (2003) utilized CALVIN to process 12 climate change scenarios developed by the Lawrence Berkeley National Laboratory (LBNL). In this study, LBNL data was used to alter the CALVIN base hydrology, consisting of monthly time series of rim inflows, reservoir evaporation rates local accretions and groundwater inflows, to simulate predicted hydrology under different climate change scenarios.

Although significant differences among GCMs currently exist in predicted future climate scenarios, the research described above indicates that substantial progress has been made in developing methodologies to integrate hydrologic models with climate models. Ideally, the ability to integrate GCM output with CALSIM will provide a tool to allow the proactive planning and development of options to improve water supply and quality under different climate change scenarios. Integration of the GCMs with CALSIM will likely require several intermediate steps that will include downscaling of the GCMs and may include features from CALVIN, CVMod and PRMS. DWR (2006) has made significant strides in integrating GCMs into CALSIM, although several limitations remain.

Both government agencies and the private sector have recognized the potentially adverse impacts associated with climate change. Businesses in the private sector are voluntarily cutting their greenhouse gas emissions while state and local governments are responding with efforts to cut emissions within their jurisdictions (California Energy Commission 2003). Additionally, the federal government has set a goal of reducing greenhouse gas intensity by 18 percent over the next decade. Greenhouse gas intensity is a measure of green house gas emissions per defined unit. For example, greenhouse gas intensity could be reported as tons of greenhouse gas emissions per capita or per million dollars of gross domestic product.

Within California, the Climate Action Team established by Executive Order S-3-05, coordinates all state-level actions relating to climate change. Under the umbrella of the Climate Action Team, the different state resource agencies are actively engaged in various activities specifically related to climate change. For example, DWR is helping the state prepare for climate change through its water resource planning and forecasting activities; CDFG is addressing the issue of adaptation to climate change with regional conservation planning, watershed planning, fisheries management and restoration, and biological assessment; and the California Energy Commission's Public Interest Energy Research Program is addressing climate change by leading the development of a long term climate change research program for California and is seeking to improve understanding of the implications of climate change by supporting research on potential impacts and possible adaptation and mitigation measures (State of California Website 2005). Additionally, several campuses of the University of California are actively engaged in climate change research.

Through development of a functional water management tool capable of incorporating climate change data, reductions in greenhouse gas emissions, and proper resource planning, California will continue preparing for climate change impacts.

22.6 CONCLUSIONS

According to a recently published California Energy Commission report titled, "*Climate Change and California Water Resources: A Survey and Summary of the Literature*" (Kiparsky and Gleick 2003):

> "*Managing water resources to address climate change impacts could prove to be different than managing for historical climate variability for several reasons, including: (1) climate changes could produce hydrologic conditions and extremes of a different nature than current systems were designed to manage; (2) they may produce similar kinds of variability, but that are outside of the range for which current infrastructure was designed; (3) traditional water resource management assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to*

> *permit managers to respond appropriately; and (4) traditional management assumes that no special efforts or plans are required to protect against surprises or uncertainties*."

Although considerable uncertainties regarding the exact impacts of climate change on California hydrology and water resources will remain until there is more accurate and consistent information about how precipitation patterns, timing, and intensity will change, considerable progress is being made to develop methodologies and tools to incorporate future climate change scenarios into current hydrologic models. Additionally, one of the most important results for water managers also has been the one most consistently predicted to occur. It is quite likely that there will be increases in winter runoff, decreases in spring and summer flows and higher peak flows. Therefore, managing water resources with a changing climate will likely prove different than managing for historic variability. Climate changes could produce hydrologic conditions and extremes of a different nature than current systems were designed to manage.