PACIFIC INSTITUTE

Climate Change and California Water Resources: A Survey and Summary of the Literature

Michael Kiparsky
Peter H. Gleick

Pacific Institute for Studies in Development, Environment, and Security

Oakland, California
654 13th Street
Oakland, California, 94612
www.pacinst.org.

July 2003

Climate Change and California Water Resources: A Survey and Summary of the Literature

July 2003

Michael Kiparsky
Peter H. Gleick

Pacific Institute for Studies in Development, Environment, and Security

Oakland, California
654 13th Street
Oakland, California, 94612
www.pacinst.org.

Acknowledgements

This work was supported by a number of sources, including the **Dialogue on Water and Climate**, **Government of the Netherlands, the Public Interest Energy Research Program (PIER) of the California Energy Commission, the California Department of Water Resources,** and **the John D. and Catherine T. MacArthur Foundation**. We thank them for their support. All conclusions are, of course, our own.

Another product of this effort is a new, searchable, electronic bibliography of the water and climate literature. Over 3,000 citations are available to be searched by title, author, keyword, region, and more, at http://www.pacinst.org/resources.

The Public Interest Energy Research Program (PIER) of the California Energy Commission is an integrated, multidisciplinary effort to explore the potential implications of climate change for California's economy, ecosystems, and health. Designed to complement national and international studies, the project will provide California-specific but preliminary information on climate change impacts. Many efforts are already underway, and the section Research Needs describes future priorities. For example, PIER is funding a climate change research program of core research activities at UC Berkeley and UC San Diego (Scripps). Scripps is developing a comprehensive meteorological and hydrological database for the state representing historical conditions for the last 100 years. The database will be very useful for regional model inter-comparison work and the study of climatic trends. Scripps is also testing a dynamic regional climate model (Regional Spectral Model) simulating climatic conditions in California for the last 50 years a high-resolution model and they are testing new statistical downscaling techniques with the goal of capturing extreme events. Finally, they are installing meteorological and hydrological sensors in key areas/transects in California to track a changing climate and provide a richer database for future regional model enhancements and evaluations.

The authors would like to acknowledge the following individuals for their thoughts, comments, and suggestions: Guido Franco was the project manager at the California Energy Commission. His enthusiasm and patience are appreciated. Thanks also to Kelly Birkinshaw for support. We also thank:

- Dr. Dan Cayan, Scripps Institute of Oceanography, University of California, San Diego, La Jolla.
- Mr. Maury Roos, California Department of Water Resources, Sacaramento.
- Mr. Kamyar Guivetchi, California Department of Water Resources, Sacramento.
- Mr. Jonas Minton, California Department of Water Resources, Sacramento.
- Mr. Sergio Guillen, California Bay-Delta Authority, Sacramento.

Climate Change and California Water Resources:

A Survey and Summary of the Literature

July 2003

Pacific Institute for Studies in Development, Environment, and Security

Michael Kiparsky
Peter H. Gleick

Table of Contents

1. Introduction

The issue of global climate change has begun to play an increasing role in scientific and policy debates over effective water management. In recent years, the evidence that global climate change will have significant effects on water resources in California has continued to accumulate. More than 150 peer-reviewed scientific articles on climate and water in California have now been published, with many more in preparation, addressing everything from improvements in downscaling of general circulation models to understanding how reservoir operations might be adapted to new conditions.

California water planners and managers have been among the first in the nation to consider these issues, though most efforts in this field have been both modest and informal. Initial research and analysis on climate risks facing California water resources began in the early 1980s and by the end of the decade state agencies such as the California Energy Commission had prepared the first assessments of state greenhouse gas emissions and possible impacts to a wide range of sectors. The California Water Plan (Bulletin 160) first briefly addressed climate change in 1993. More recently, the Public Interest Energy Research program (PIER) of the California Energy Commission, has reinvigorated scientific research at the state level to explore a wide range of climate impacts and risks, including risks to water resources. Other state agencies, such as the California Department of Water Resources have also revived an interest in these issues (see the Acknowledgement Section and the Research Needs summary; see also a draft summary document from PIER by Wilson et al. 2003).

In recent years, the scientific consensus has broadened that climate changes will be the inevitable result of increasing concentrations of greenhouse gases. There is also a growing consensus that various anthropogenic climate impacts are already appearing worldwide. Evidence of its impacts on California's hydrologic system has also appeared in various forms. Water agencies around the State have begun to consider the implications of climate change for the reliability and safety of water systems, and professional water organizations have begun urging managers and planners to integrate climate change into long-term planning. In 1997, the American Water Works Association issued a committee report concluding that "Agencies should explore the vulnerability of both structural and nonstructural water systems to plausible future climate changes, not just past climatic variability" and "Governments at all levels should reevaluate legal, technical, and economic approaches for managing water resources in light of possible climate changes" (AWWA 1997).

Many uncertainties remain. Responsible planning, however, requires that the California water community work with climate scientists and others to reduce those uncertainties and to begin to prepare for those impacts that are well understood, already appearing, or likely to appear.

Climate change is a scientific reality. The broad consensus of the scientific community is that greenhouse gases emitted by human activities are accumulating in the atmosphere and that these gases will cause a wide range of changes in climate dynamics, especially the accumulation of terrestrial radiation (IPCC 1996, 2001; NRC 2002). Some of the most significant impacts will be on water resources – impacts that are of special concern to regions like California where water policy is already of great interest and concern (Gleick and others 2000, Wilkinson and others 2003). As concentrations of these gases continue to increase, greater amounts of terrestrial radiation will become trapped, temperatures will rise further, and other impacts will become more significant.

Substantial work has been done at the international and national level to evaluate climatic impacts, but far less information is available on regional and local impacts. This paper begins the process of summarizing some of the consequences of climate change for water resources and water systems in California. A more comprehensive assessment, supported by multiple state agencies and including the participation of a wide range of stakeholders could be a valuable tool for policymakers and planners, and we urge such an assessment to be undertaken in the near future.

2. Climate Change and Impacts on California Water Resources

Overview of Modeling

Projecting regional impacts of climatic change and variability relies first on General Circulation Models (GCMs), which develop large-scale scenarios of changing climate parameters, usually comparing scenarios with different concentrations of greenhouse gases in the atmosphere. This information is typically at too coarse a scale to make accurate regional assessments. As a result, more effort has recently been put into reducing the scale and increase the resolution of climate models through various techniques such as downscaling or integrating regional models into the global models. The resulting finer-scale output can then be analyzed for given watersheds, ideally with the incorporation of other hydrologic parameters such as local evaporation, transpiration, soil conditions, topography, snowpack, and groundwater.

Models are typically calibrated by comparing model runs over historical periods with observed climate conditions. It should be emphasized that these model results are not intended as specific predictions, but rather are scenarios based on the potential climatic variability and change driven by both natural variability and human-induced changes. Nonetheless, they are useful for assessing potential possible future conditions.

Temperature

Modeling results from GCMs are consistent in predicting increases in temperatures globally with increasing concentrations of atmospheric greenhouse gases resulting from human activity. Higher temperatures are of particular interest and concern for California water systems because of their effect on Sierra snowpack accumulation and snowmelt and other hydrologic variables, addressed below. Recent work by Snyder et al (2002) has produced the finest-scale temperature and precipitation estimates to date. Resulting temperature increases for a scenario of doubled CO_2 concentration are 1.4-3.8 degrees C throughout the region (Figure 1). This is consistent with the global increases predicted by the Intergovernmental Panel on Climate Change (2001). Sample temperature results from two different GCMs are also presented below in Figures 2a,c. In a regional model of the Western United States, Kim et al (2002) project a climate warming of around 3 to 4 degrees C. Of note in both studies is the projection of uneven distribution of temperature increases. For example, regional climate models show the warming effects are greatest in the Sierra Nevada Mountains, with implications for snowpack and snowmelt (Kim et al. 2002, Snyder et al. 2002). Similar results have been noted in Barnett et al. (2003).

Precipitation

In general, while modeling of projected temperature changes is broadly consistent across most modeling efforts, there are disagreements about precipitation estimates. Considerable uncertainties about precise impacts of climate change on California hydrology and water resources will remain until we have more precise and consistent information about how precipitation patterns, timing, and intensity will change. Some recent regional modeling efforts conducted for the western United States indicate that overall precipitation will increase (Giorgi et al. 1994, Kim et al. 2002, Snyder et al. 2002), but considerable uncertainty remains due to differences among larger-scale GCMs (Figure 1 and 2). Where precipitation is projected to increase, the increases are centered in Northern California (Kim et al. 2002, Snyder et al. 2002, Figure 1) and in winter months. More general large-scale precipitation results from two different GCMs are also presented below in Figures 2b,d. Further work is in progress to extend and improve these modeling efforts, and to use watershed-scale hydrological models that will be of more direct value to planners.

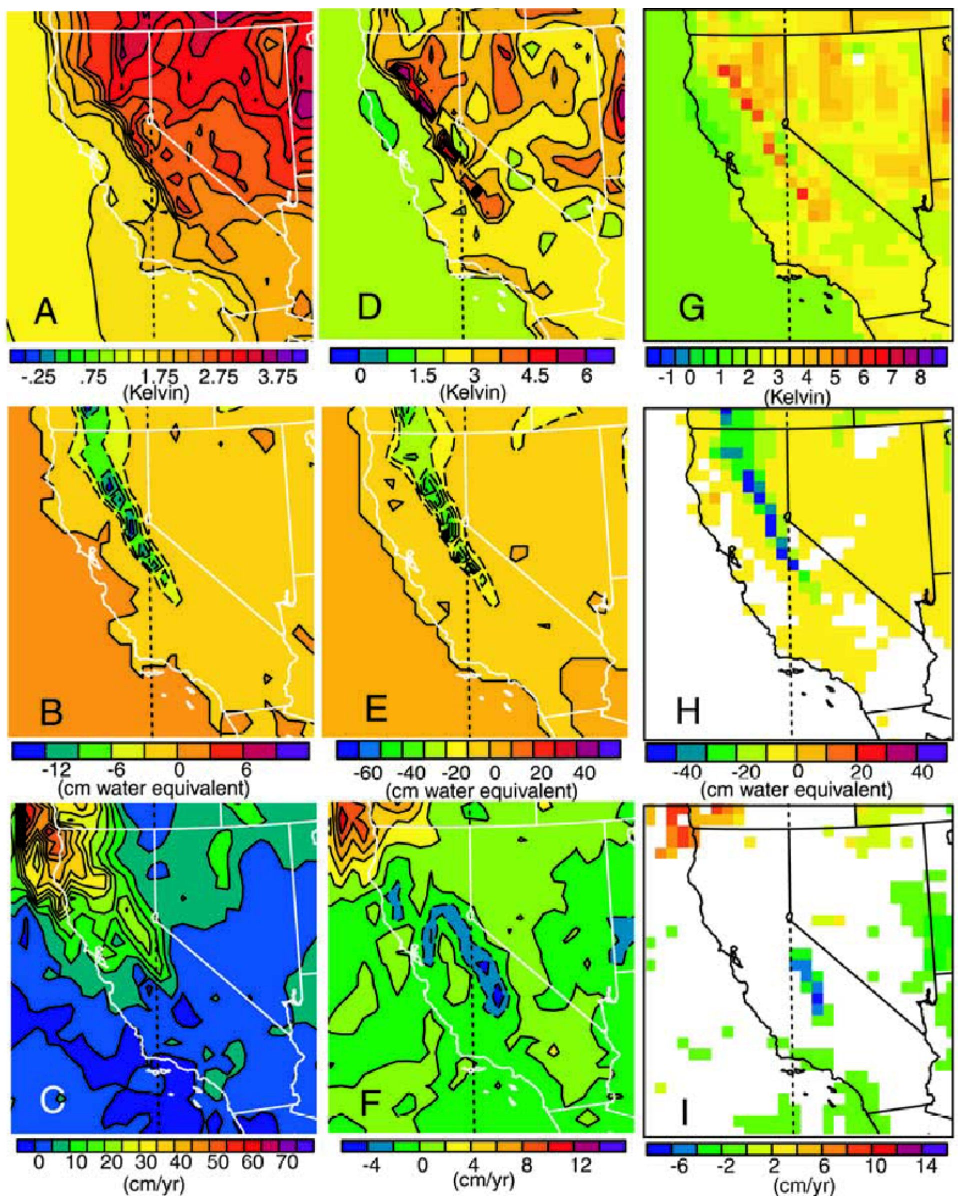


Figure 1. Comparison of modeling results for a baseline CO_2 scenario (column 1) and doubled CO_2 scenario (column 2). Column 3 shows the differences between the two scenarios. Panels A, D, and G compare modeled surface temperatures throughout the California region as represented in the model of Snyder et al. (2002). The temperature increases of 1.4-3.8 degrees C throughout the region are consistent with global modeling projections. Panels B, E, and H represent changes in April snowpack, and show a statistically significant decrease in the Sierras. Panels C, F and I show April precipitation. Note the increase in the northern part of the State, and slight decrease central California. Figure from Snyder et al. (2002).

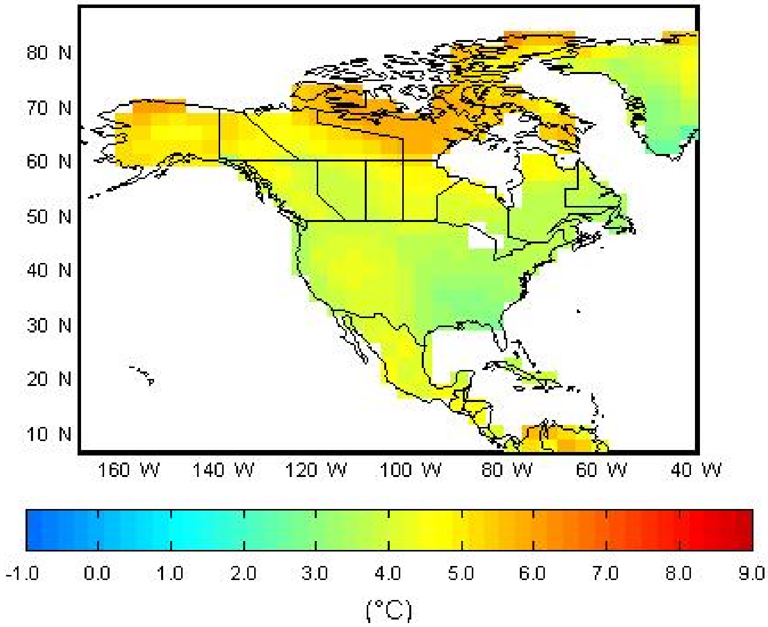


Figure 2a: Hadley2 model temperature changes for 2080 showing increases of 2 to 5 degrees C for the western United States. http://www.cics.uvic.ca/scenarios/index.cgi

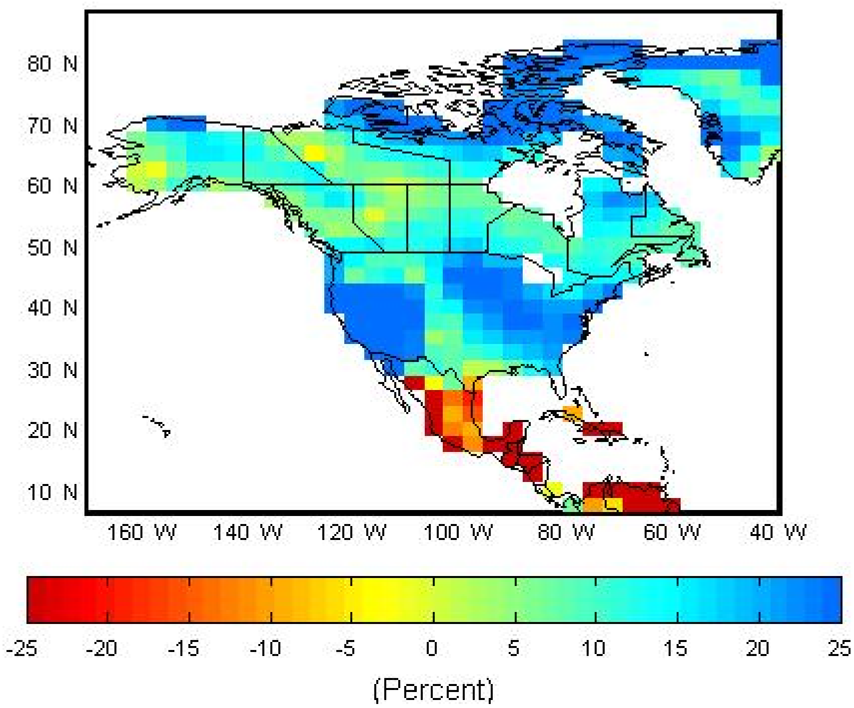


Figure 2b: Hadley2 model precipitation changes for 2080, showing projected increases in precipitation in the western United States. http://www.cics.uvic.ca/scenarios/index.cgi

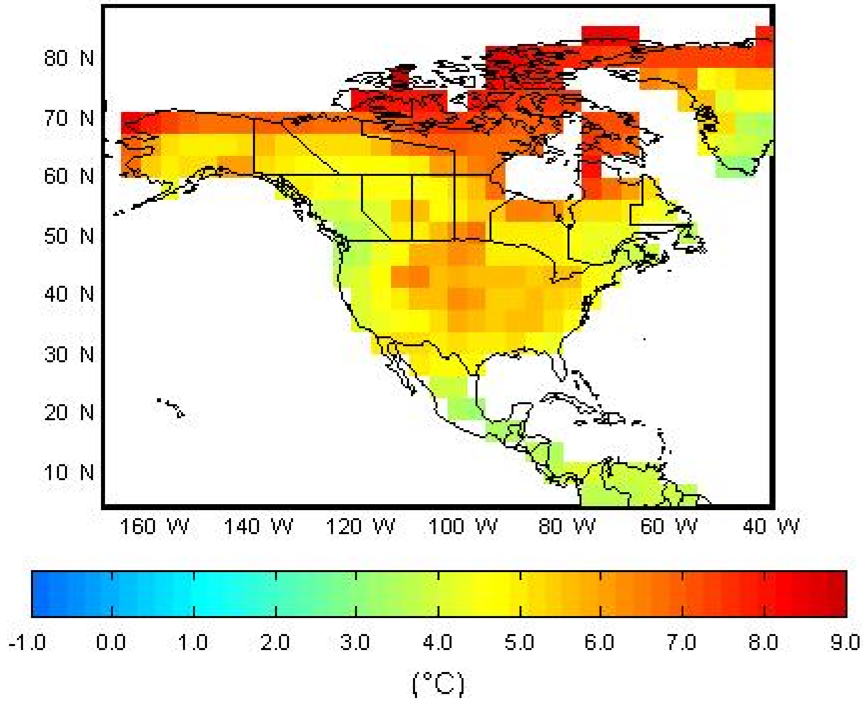


Figure 2c: Canadian model 1 showing temperature changes across North America for 2080, including 3 to 7 degrees C temperature increases in the western United States. http://www.cics.uvic.ca/scenarios/index.cgi

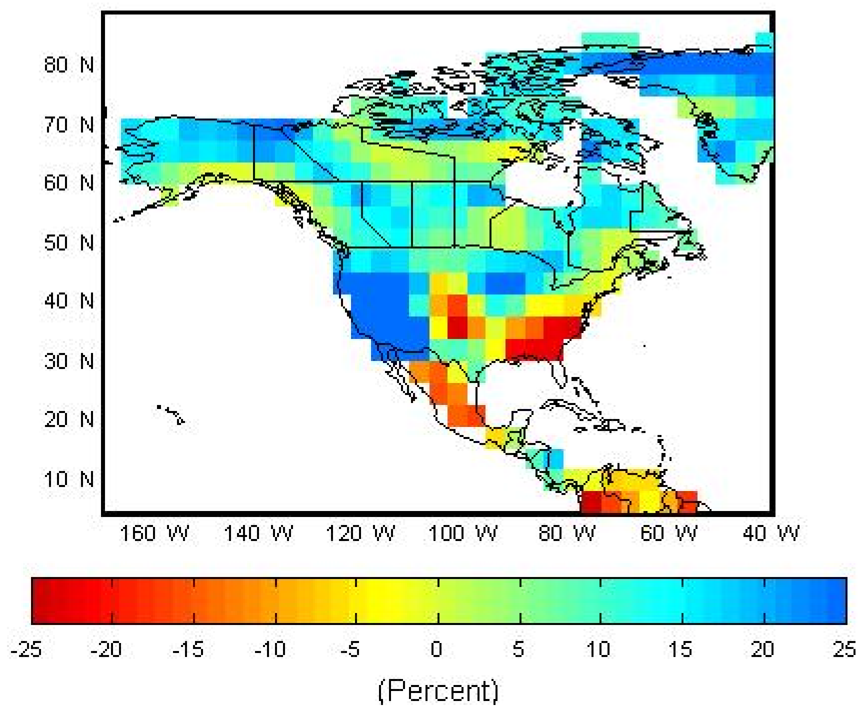


Figure 2d: Canadian climate model precipitation changes for 2080 showing substantial precipitation increases in the western United States. http://www.cics.uvic.ca/scenarios/index.cgi

Evaporation and Transpiration

Evaporation and transpiration are important aspects of the hydrologic balance affecting climate, plant growth and distributions, and water demand and use. Increasing average temperatures generally lead to an increase in the potential for evaporation, though actual evaporation rates are constrained by the water availability on land and vegetation surfaces and in the soils. In California, atmospheric moisture content can limit evaporation rates, so changes in humidity are relatively important. Vegetative cover is also important because plants intercept precipitation and transpire water back to the atmosphere. Different vegetation types play different roles in evaporation; so evaluating the overall hydrologic impacts of climate change in a region requires some understanding of current vegetation patterns and of the ways in which vegetation patterns may change.

Transpiration, the movement of water through plants to the atmosphere, is affected by variables including plant cover, root depth, stomatal behavior, and the concentration of carbon dioxide in the atmosphere. Investigations of the impacts of increased carbon dioxide concentrations on transpiration have yielded conflicting results – some assessments suggest reductions in overall water use while others indicate that some plants acclimatize to increased CO_2 levels, limiting improvements in water-use efficiency (Field et al. 1995, Korner 1996, Rötter and Van de Geijn 1999). Multiple factors related to climate change can have more complex effects when taken together, including suppressing gains in plant growth. (Shaw et al 2002). Reproducible generalizations for evapotranspiration (ET) are not yet available, and these issues are central for future research.

Climate models have consistently projected that global average evaporation would increase in the range of 3 to 15 percent for an equivalent doubling of atmospheric carbon dioxide concentration. The greater the warming, the larger these increases are expected to be (IPCC 2001).

Snowpack

By delaying runoff from winter months when precipitation is greatest, snow accumulation in the Sierra Nevada acts as a massive natural reservoir for California. Despite uncertainties about how increased greenhouse gas concentrations may affect precipitation, there is very high confidence that higher temperatures will lead to dramatic changes in the snowfall and snowmelt dynamics in watersheds with substantial snow (see summary in Gleick and others 2000). Higher temperatures will have several major effects: they will increase the ratio of rain to snow, delay the onset of the snow season, accelerate the rate of spring snowmelt, and shorten the overall snowfall season, leading to more rapid and earlier seasonal runoff.

As early as the mid-1980s and early 1990s, regional hydrologic modeling of global warming impacts has suggested with increasing confidence that higher temperatures will affect the timing and magnitude of runoff in California (see, for example, Gleick 1986, Gleick 1987a,b, Lettenmaier and Gan 1990, Lettenmaier and Sheer 1991, Nash and Gleick 1991a,b, Hamlet and Lettenmaier 1999). Indeed, over the past two decades, this has been one of the most persistent and well-established findings on the impacts of climate change for water resources in the United States and elsewhere, and it continues to be the major conclusion of regional water assessments (see, for example, Knowles and Cayan 2002, Barnett et al. 2003). Figure 3 shows hypothetical changes in hydrographs that can be expected with changing snow dynamics in the Sierra Nevada. Figure 4 shows a specific projection of changes in Sierra Nevada snowpack from a regional modeling study.

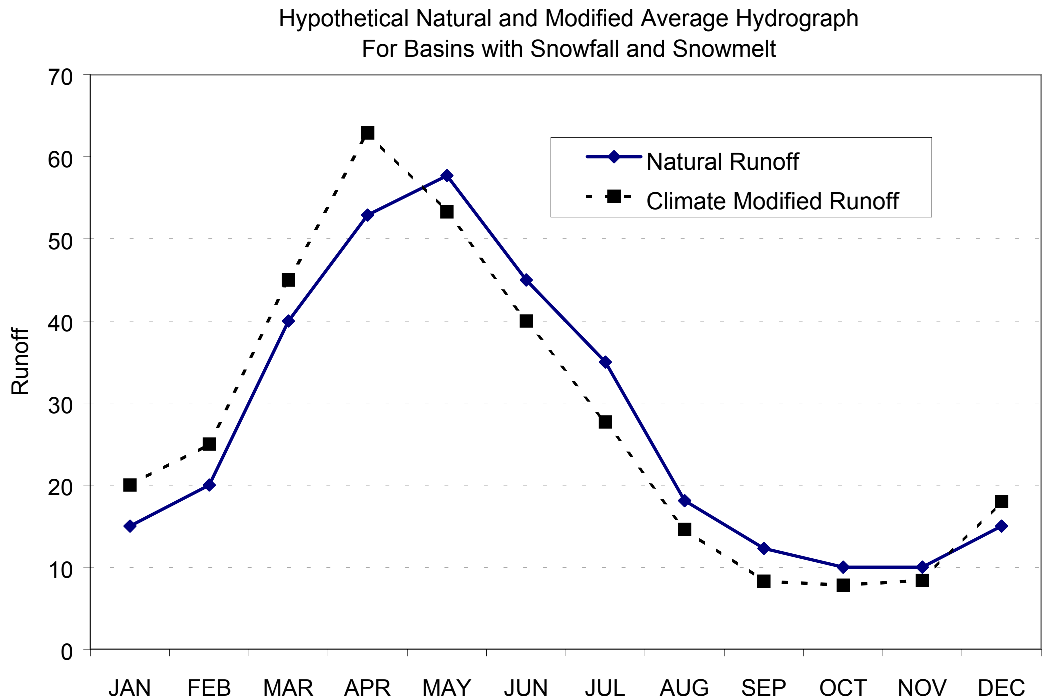


Figure 3: Rising temperatures will reduce runoff in spring and summer and increase it during winter months by affecting snowfall patterns and the timing and rate of snowmelt. (from Gleick and others 2000).

A few broad assessments have simulated the effects of climate change on snowpack in the United States (McCabe and Legates 1995, Cayan 1996, McCabe and Wolock 1999). McCabe and Wolock (1999) evaluated the links between climate conditions and snowpack for over 300 different snow sites in the western U.S., including the Sierra Nevada and the Colorado basin. They used long-term historical records to develop a snow model that used altered climatic information from GCMs. For most of the sites, strong positive correlations were found between precipitation and snowpack; strong negative correlations were found between temperature and snowpack. These correlations indicate that the supply of winter moisture is the best predictor of snowpack volume, while temperature is the best predictor of the timing of snowmelt and the overall nature of the snow season. This correlation breaks down only for those high-altitude sites where mean winter temperatures are so cold that the ratio of rain to snow is not affected.

The models used in the National Assessment (Gleick and others 2000) show large decreases in April 1 snowpack for all of the snow sites in California. In some of the extreme cases, model snowpack is completely eliminated by the end of the next century, although some snowfall and snowmelt would certainly continue in high-altitude sites. More recent work with a more detailed regional scale shows snow accumulation in February will be reduced by up to 82% in a 2xCO_2 scenario, with an almost complete melting by the end of April (Snyder et al. 2002). Figures 1 and 4 show other modeling efforts projecting that decreased snowfall and enhanced winter snowmelt could deplete most of the snow cover in California by the end of the winter (Kim et al. 2002, Knowles and Cayan 2002).

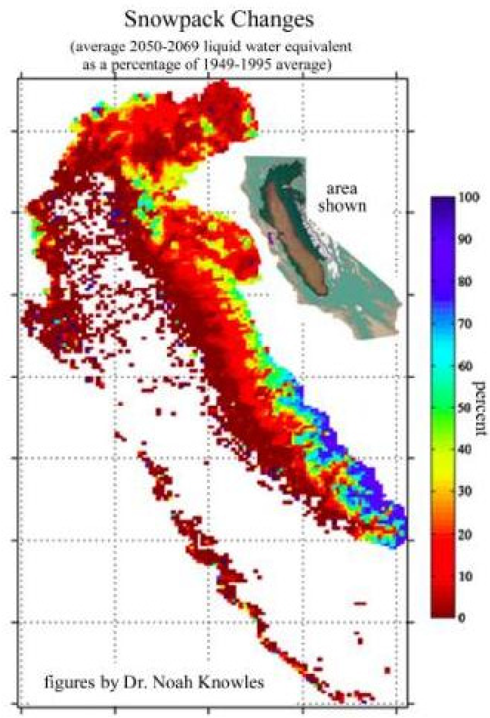


Figure 4: Possible snowpack changes from Knowles and Cayan (2002) for the Sierra Nevada, showing dramatic drops in snowpack liquid water content by the middle of this century for typical GCM projections of temperature increases. This dramatic graphic is a good illustration of the kinds of snowpack changes noted in a wide range of studies beginning in the early 1980s (see text for details).

Variability, Storms, and Extreme Events

Variability is a natural part of any climatic system, caused by processes that will continue to exert an important influence on the climate system even as changes induced by rising concentrations of greenhouse gases are felt. Efforts to understand how natural patterns of variability, such as hurricanes, intense rainstorms, and El Niño/La Niña events affect California's water resources help to identify vulnerabilities of existing systems to hydrologic extremes (McCabe 1996, Vogel et al 1997, Piechota et al. 1997, Cayan et al. 1999).

Large climatic variability has been a feature of California's past. Paleoclimatic evidence from tree rings, buried stumps, and lakebed sediment cores suggests that the past 200 years has been relatively wet, and relatively constant when compared with longer records (Meko et al. 1980; Michaelsen et al. 1987; Hughes and Brown 1992; Earle 1993; Haston and Michaelsen 1997; Meko et al. 2001; Benson et al. 2002). These longer records reveal greater variability than the historical record, in particular in the form of severe and prolonged droughts (Stine 1994). In spite of this evidence, planning and operation are generally based on the historical climate record since 1900, which may not be representative of past or future conditions.

While variability is not well modeled in large-scale general circulation studies, some modeling studies suggest that the variability of the hydrologic cycle increases when mean precipitation increases, possibly accompanied by more intense local storms and changes in runoff patterns (Noda and Tokioka 1989; Kothavala 1997; Hennessy et al. 1997). In addition, another long-standing model result points to an increase in drought often resulting from a combination of increased temperature and evaporation along with decreased precipitation (Haywood et al. 1997;

Wetherald and Manabe 1999, Meehl et al. 2000, Lambert 1995, Carnell and Senior 1998, Felzer and Heard 1999).

Models produce various pictures of increased storminess, but increased storm intensity is consistently forecast, whether or not their frequency also increases. (Carnell and Senior 1990, Hayden 1999, Lambert 1995, Frei et al. 1988)

The frequency of El Niño events may increase due to greenhouse warming. Timmermann et al. (1999) used a high-resolution global climate model to simulate the El Niño/Southern Oscillation phenomenon (ENSO) under conditions of warming. Their model indicated that the tropical Pacific climate system would undergo systematic changes if greenhouse gas concentrations doubled. In particular, their results suggest a world where the average condition is like the present-day El Niño condition and events typical of El Niño will become more frequent. Their results also found more intense La Niña events and stronger interannual variability, meaning that year-to-year variations may become more extreme under enhanced greenhouse conditions. More frequent or intense El Niños would alter precipitation and flooding patterns in the United States in a significant way.

In a study that analyzed 20 GCMs currently in use worldwide, extreme events may intensify over the next century as carbon dioxide and other greenhouse gases increase in the atmosphere. The study concludes that the West Coast will probably be less affected because of its heavier rainfall and more moist soil (Meehl and Easterling 2001). In a study that reviewed several GCM scenarios an increased risk of large storms and flood events was shown for California (Miller and Dettinger 1999). Conflicting conclusions about storms support the need for higher-spatial-resolution models with better cloud and precipitation processes.

Major floods on California's rivers are produced by slow moving Pacific storm systems, which sweep moist subtropical air from a southwesterly direction into the State. In modeling by DWR on the American River basin, increased storm temperatures of three degrees Celsius increased storm runoff by about 10 percent (personal communication, M. Roos 2003). The 1986 flood on which these experiments were based had the highest 3-day average flow on record for the American River, claimed fifteen lives, and caused more than a billion dollars in property damage (http://www.news.water.ca.gov/1997.spring/quest.html). Since existing flood control facilities in the Central Valley and elsewhere can barely accommodate such a large flood event, even a modest increase caused by climate warming could pose problems without either changes in operations or infrastructure.

Large-Area Runoff

Runoff is directly affected by changes in precipitation and temperature. However, runoff in actual watersheds is rarely explicitly evaluated in GCMs because their resolution is insufficient to include other critical watershed characteristics. Estimates of changes in runoff over large areas are thus often relatively simple evaluations of changes in large-scale precipitation and evapotranspiration patterns (Arnold et al. 1998, Arnold et al. 1999, Srinivasan et al. 1993). Despite remaining uncertainties in precipitation patterns, especially, Brown et al. (1999) concluded that the potential impact of altered precipitation and the expected increases in evapotranspiration are of large enough dimensions to require consideration in any analysis of future regional or national water supply and demand. Another important consideration is the projected change in seasonality of the hydrologic cycle that would affect the heavily managed water systems of the western U.S.

In California, water yields will increase in late winter/early spring because of increased runoff, as described earlier, due to the seasonality of the precipitation changes and to an earlier spring snowmelt caused by the projected warming under climate change. Rising temperatures also impact annual water yields by increasing ET, thereby reducing the contribution of lateral flow to streamflow and groundwater recharge. This combination results in a marked increase in water yield during late winter and early spring and in some cases a reduction in water yield during the summer. If there is no general increase in precipitation in these regions the early snowmelt will lead to shortages of water in summer. The hydrology is controlled by the timing and intensity of the spring snowmelt, and is impacted principally by the degree of warming during this time period.

Several different conclusions can be drawn from a review of the literature. First, the great differences in results show the difficulty of making accurate "predictions" of future runoff – these results should be viewed with as sensitivity studies and used with considerable caution. Second, runoff is extremely sensitive to climate conditions. Large increases in precipitation will probably lead to increases in runoff: such increases can either worsen or lessen water management problems, depending on the region and the nature of the problem. Third, far more work is needed, on a finer scale, to understand how climate will affect national water resources. Until GCMs get better at evaluating regional temperature and precipitation, their regional estimates of future runoff must be considered speculative and uncertain. While it is well established that changes in runoff are likely to occur, we have little confidence that we understand how specific regions will be affected. The above discussion and model results highlight many of the uncertainties surrounding the implications of climate change for overall water availability.

Regional Runoff

Detailed estimates of changes in runoff due to climate change been produced for California using regional hydrologic models. By using anticipated, hypothetical, or historical changes in temperature and precipitation and models that include realistic small-scale hydrology, modelers have consistently seen significant changes in the timing and magnitude of runoff resulting from quite plausible changes in climatic variables. In California, runoff is extremely sensitive to rainfall: a small percentage change in rainfall can produce a much larger percentage change in runoff. Considerable effort has been made to evaluate climate impacts in particular river basins, including the Sacramento, the San Joaquin, the Colorado, the Carson/Truckee, and others. Even in the absence of changes in precipitation patterns, higher temperatures resulting from increased greenhouse gas concentrations lead to higher evaporation rates, reductions in streamflow, and increased frequency of droughts (Schaake 1990, Rind et al. 1990, Nash and Gleick 1991a,b, 1993). In such cases, increases in precipitation would be required to maintain runoff at historical levels.

For California, one of the most important results for planners has also been one of the most consistent. Warming-induced change in the timing of streamflow, including both the intensity and timing of peak flows is a consistent result. A declining proportion of total precipitation falls as snow as temperatures rise, more winter runoff occurs, and remaining snow melts sooner and faster in spring (see, for example, Gleick 1986, 1987a,b, Lettenmaier and Gan 1990, Nash and Gleick 1991b, Miller et al. 1992, Knowles and Cayan 2002, Van Rheenen et al. 2003). In some basins, spring peak runoff may increase; in others, runoff volumes may significantly shift to winter months.

Shifts in runoff timing in snowmelt-fed basins are consistent in all studies that looked at daily or monthly runoff. These studies show with very high confidence that increases in winter runoff, decreases in spring and summer runoff, and higher peak flows will occur in such basins as temperatures rise. With warming, snow levels in the mountains will rise on average, and the average amount of snow covered area and snowpack will decrease. A reasonable estimate is about 500 feet of elevation change for every degree Celsius rise (M. Roos, personal communications).

Assuming the amount of precipitation remained approximately the same, in the Sacramento River region, only about one fourth of the snow zone would remain with an estimated decrease of 5 MAF of April through July runoff (Cayan 1996, Knowles and Cayan 2002, Miller and Dettinger 1999). The impact would be much less in the higher elevation of southern Sierra. For example in the San Joaquin/Tulare Lake region about seven-tenths of snow zone would remain.

Under current operating rules, less spring snowmelt could also make it more difficult to refill winter reservoir flood control space during late spring and early summer of many years, thus potentially reducing the amount of surface water available during the dry season. Lower early summer reservoir levels also would adversely affect lake recreation and hydroelectric power production, with possible late-season temperature problems for downstream fisheries. Not all river systems would be equally affected; much depends on the existing storage capacity. The storage-to-runoff ratio for the American River is only about 0.64, which makes it more vulnerable to these changes than, for example, the Stanislaus River with a ratio of 2.45.

Colorado River

The Colorado River supplies water to nearly 30 million people and irrigates more than one and a half million hectares of farmland in Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, California, and the Republic of Mexico. Spanning 2,300 kilometers and eventually running through Mexico to the Sea of Cortez, the river is the only major water supply for much of the arid southwestern United States and the Mexicali Valley of Mexico, and it plays a special role in California's water situation.

Colorado River basin water supply, hydroelectricity generation, reservoir levels, and salinity are all sensitive to both the kinds of climate changes that are expected to occur and to the policy options chosen to respond to them. Because of concerns about these issues, some of the very first river basin climate studies examined the impacts of climatic changes on the Colorado River basin and several of its major tributaries.

The earliest studies used historical regression approaches to evaluate the impacts of hypothetical temperature and precipitation changes (Stockton and Boggess 1979 and Revelle and Waggoner 1983). Both of these studies suggested that modest changes in average climatic conditions could lead to significant changes in runoff. Revelle and Waggoner concluded that a 2 degree Celsius (C) increase in temperature with a 10-percent drop in precipitation would reduce runoff by 40 percent. Stockton and Boggess' results were similar, with a projected 35 to 56 percent drop in runoff.

By the late 1980s, researchers began to use physically based models capable of evaluating climatic conditions outside of the range of existing experience and hydrologic statistics. Under the auspices of the American Association for the Advancement of Science (AAAS), Schaake (1990) used a simple water-balance model to evaluate the elasticity of runoff in the Animas River in the upper Colorado River basin. That study suggested that a 10-percent change in precipitation would lead to a 20-percent change in runoff, while a 2 degree C increase in temperature would reduce runoff by only about 2 percent. More significant, however, was the finding that changes in temperature would have significant seasonal effects on snowmelt, a finding in agreement with the earlier conclusions of Gleick (1987) for the Sacramento River (described elsewhere).

In 1991, the U.S. Bureau of Reclamation, which has responsibility for operations in the Colorado Basin, and the U.S. Geological Survey, evaluated the impacts of global climate change on the Gunnison Basin, an important tributary of the Colorado. Like the earlier Schaake study, this analysis also found significant seasonal changes in runoff due to increases in temperature, with an advance in spring snowmelt of close to a month for a temperature increase of 2 to 4 degrees C (Dennis 1991).

Nash and Gleick (1991a,b, 1993) analyzed the impacts of climate change on the Colorado basin using conceptual hydrologic models coupled with the U.S. Bureau of Reclamation Colorado River Simulation System (CRSS) model of the entire water-supply system of the river (Nash and Gleick, 1991a,b, 1993). They evaluated hypothetical temperature and precipitation scenarios as well as the equilibrium GCM scenarios available at the time. A GCM transient run was done as well with one of the first models to use transient greenhouse gas inputs. River flows were found to be very sensitive to both precipitation and temperature, though less sensitive than the earlier regression studies. As with earlier studies, major changes in the seasonality of runoff resulted from the impacts of higher temperature on snowfall and snowmelt dynamics. The effects of climate changes on water supplies were dependent on the operating characteristics of the reservoir system and the institutional and legal rules constraining the operators. The variables most sensitive to changes in runoff were found to be salinity, hydroelectric generation, and reservoir level. This study also evaluated the possible utility of increased storage capacity to address the impacts of climate changes and concluded that additional storage would do nothing to alleviate potential reductions in flow. Only if climatic changes were to increase streamflow variability without decreasing long-term supply might additional reservoirs in the Upper Colorado River Basin have any benefits.

Another comprehensive assessment of the Colorado Basin's systems of reservoirs was done for the Colorado River Severe Sustained Drought study (CRSSD) (Lord et al.1995). That analysis focused on a scenario of long-term drought, rather than a single climate change scenario, and concluded that the "Law of the River" as currently implemented would leave ecosystems, hydropower generation, recreational users, and Upper Basin water users vulnerable to damages despite the extensive infrastructure. A related study also found that water reallocation through marketing had the power to reduce drought damages (Booker 1995).

Eddy (1996) looked at extreme events in the Colorado Basin and evaluated the impact of an increase or decrease in precipitation of 10 percent on the duration of wet and dry periods. Eddy concluded that changing average precipitation would not change the number of consecutive wet or dry years by more than one year, but that about once every 20 years, some groupings of stations would experience a dramatic change in consecutive extreme years. If several portions of the Upper Colorado Basin experienced these major wet or dry periods simultaneously, "an episode of crisis proportions could occur." Recently, Christensen et al. (2002) have updated this work on the Colorado River basin and found comparable changes in snowfall/snowmelt dynamics, runoff, and sensitivity of the water resource system in the basin to climate change.

Soil Moisture

Soil moisture – a measure of the water in different depths of soil – defines vegetation type and extent, influences agricultural productivity, and affects groundwater recharge rates. The amount of water stored in the soils is influenced by vegetation type, soil type, evaporation rates, and precipitation intensity. Any changes in precipitation patterns and evapotranspiration regime directly affect soil-moisture storage. Decreased precipitation or increased temperature can each lead to decreases in soil moisture. Where precipitation increases significantly, soil moisture is likely to increase, perhaps by large amounts.

GCM results suggest large-scale regional soil drying in summer owing to higher temperatures. Drying could have significant impacts on agricultural production and on the supply of and demand for water. One consequence of this is an expected increased incidence of droughts in some regions, measured by soil-moisture conditions, even where precipitation increases, because of the increased evaporation (Vinnikov et al. 1996). Soil-moisture response has important implications for crop yield and irrigation demand (Brumbelow and Georgakakos 2000).

Modeling of the Sacramento Basin identified reductions in summer soil moisture of 30 percent or more resulting from a shift in the timing of runoff from spring to winter, a decrease in snow, and higher summer temperatures and evaporative losses (Gleick 1986, 1987a,b). Similar results are seen for the Colorado River basin, where large increases in precipitation were found to be necessary in order to simply maintain soil moisture at present historical levels as temperatures and evaporative losses rise (Nash and Gleick 1991b, 1993).

Water Quality

Water quality depends on a wide range of variables, including water temperatures, flows, runoff rates and timing, and the ability of watersheds to assimilate wastes and pollutants. Climate change could alter all of these variables. Higher winter flows of water could reduce pollutant concentrations or increase erosion of land surfaces and stream channels, leading to higher sediment, chemical, and nutrient loads in rivers. Changes in storm flows will affect urban runoff, with attendant water-quality impacts. Lower summer flows could reduce dissolved oxygen concentrations, reduce the dilution of pollutants, and increase zones with high temperatures. Less directly, changes in land use resulting from climatic changes, together with technical and regulatory actions to protect water quality, can be critical to future water conditions. The net effect on water quality for rivers, lakes, and groundwater in the future therefore depends not just on how climatic conditions might change but also on a wide range of other human actions and management decisions, as noted in modeling experiments by Earhart et al. (1999).

In a review of potential impacts of climate change on water quality, Murdoch et al. (2000) conclude that significant changes in water quality are known to occur as a direct result of short-term changes in climate. They note that water quality in ecological transition zones and areas of natural climate extremes is vulnerable to climate changes that increase temperatures or change the variability of precipitation and argue that changes in land and resource use will have comparable or even greater impacts on water quality than changes in temperature and precipitation. They recommend that long-term monitoring of water quality is critical for identifying severe impacts, as is developing appropriate management strategies for protecting water quality.

Moore et al. (1997) note that increased water temperatures enhance the toxicity of metals in aquatic ecosystems and that increased lengths of biological activity could lead to increased accumulation of toxics in organisms. Ironically, increased bioaccumulation could decrease the concentration of toxics in the water column, improving local water quality. Similarly, higher temperatures may lead to increased transfer of chemicals from the water column to sediments. However, increases in air temperature, and the associated increases in water temperature, are likely to lead to adverse changes in water quality, even in the absence of changes in precipitation.

Ecosystems influence water quality in very direct ways. Changes in terrestrial ecosystems will also lead to changes in water quality by altering nutrient cycling rates and the delivery of nutrients to surface waters (Murdoch et al. 1998). The issues of water quality and ecosystem health should be weighed together (see below).

Studies suggest that changes in precipitation will affect water quantity, flow rates, and flow timing. Decreased flows can exacerbate temperature increases, increase the concentration of pollutants, increase flushing times, and increase salinity (Schindler 1997, Mulholland et al. 1997). Decreased surface-water volumes can increase sedimentation, concentrate pollutants, and reduce non-point source runoff (Mulholland et al. 1997). Increases in water flows can dilute point-source pollutants, increase loadings from non-point source pollutants, decrease chemical reactions in streams and lakes, reduce the flushing time for contaminants, and increase export of pollutants to coastal wetlands and deltas (Jacoby 1990, Mulholland et al. 1997, Schindler 1997). Higher flows can increase turbidity in lakes, reducing UV-B penetration. More work specific to California needs to be done.

Lake Levels and Conditions

Although little California-specific work has been done, lakes are known to be sensitive to a wide array of changes in climatic conditions. Variations in temperature, precipitation, humidity, and wind conditions can alter evaporation rates, the water balance of a basin, ice formation and melting, and chemical and biological regimes (McCormick 1990, Croley 1990, Bates et al. 1993, Hauer et al. 1997, Covich et al. 1997, Grimm et al. 1997, Melak et al. 1997). Closed (endorheic) lakes are extremely sensitive to the balance of inflows and evaporative losses. Even small changes in climate can produce large changes in lake levels and salinity (Laird et al. 1996).

Other effects of increased temperature on lakes could include higher thermal stress for cold-water fish, higher trophic states leading to increased productivity and lower dissolved oxygen, degraded water quality and increased summer anoxia. Decreases in lake levels coupled with decreased flows from runoff and groundwater may exacerbate temperature increases and loss of thermal refugia and dissolved oxygen. Increased net evaporation may increase salinity of lakes. Hostetler and Small (1999) also note that climate variability may amplify or offset changes in the mean state under climate changes and may ultimately be more important that changes in average conditions. Some non-linear or threshold events may also occur, such as a fall in lake level that cuts off outflows or separates a lake into two isolated parts. Work is needed to identify threatened lakes in California and projected impacts of such events on downstream flows and groundwater recharge.

Groundwater

Groundwater withdrawals in California in the mid-1990s are estimated to be around 14.5 million acre-feet, nearly 20 percent of all the groundwater withdrawn in the entire United States. (In typical years, groundwater accounts for around 30 percent of all urban and agricultural water use in the state (http://www.waterplan.water.ca.gov/groundwater/DraftUpdate/Chapter1.pdf). In some areas current levels of groundwater use are already unsustainable, with pumping rates exceeding natural recharge. Groundwater overdrafts in California in the drier years of the 1990s averaged nearly 1.5 million acre-feet per year (California Department of Water Resources 1998).

Little work has been done on the impacts of climate changes for specific groundwater basins, or for general groundwater recharge characteristics or water quality. Changes in recharge will result from changes in effective rainfall as well as a change in the timing of the recharge season. Increased winter rainfall, expected for some mid-continental, mid-latitude regions could lead to increased groundwater recharge. Higher temperatures could increase the period of infiltration where soils freeze. Higher evaporation or shorter rainfall seasons, on the other hand, could mean that soil deficits persist for longer periods of time, shortening recharge seasons (Leonard et al. 1999). A significant portion of winter recharge comes from deep percolation of precipitation below the rooting zone, whether of native vegetation or farmland. Warmer winter temperatures between storms would be expected to increase ET, thereby drying out the soil between storms. A greater amount of rain in subsequent storms would then be required to wet the root zone and provide water for deep percolation.

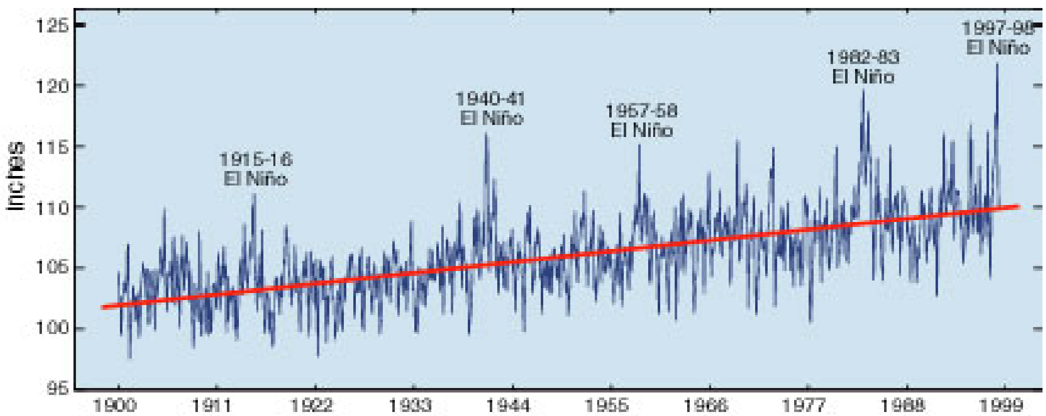
Pumping from some coastal aquifers in California has exceeded the rates of natural recharge, resulting in saltwater intrusion into the aquifers. Sea-level rise could also affect coastal aquifers through saltwater intrusion. Oberdorfer (1996) used a simple water-balance model to test how changes in recharge rates and sea-level would affect groundwater stocks and flows in a California coastal watershed. While some sensitivities were identified, the author notes that the complexity of the interactions among the variables required more sophisticated analysis.

Warmer, wetter winters would increase the amount of runoff available for groundwater recharge. However, this additional runoff in the winter would be occurring at a time when some basins, particularly in Northern California, are either being recharged at their maximum capacity or are already full. Conversely, reductions in spring runoff and higher evapotranspiration because of higher temperatures could reduce the amount of water available for recharge. The extent to which climate will change and the impact of that change are both unknown. A reduced snowpack, coupled with increased rainfall may require a change in the operating procedures for our existing dams and conveyance facilities.

The most recent California groundwater report from the Department of Water Resources notes that these possible changes may require more sophisticated conjunctive management programs in which the aquifers are more effectively used as storage facilities. They also recommend that water managers consider evaluating their systems to better understand the existing snowpack-surface water-groundwater relationship, and identify opportunities that may exist to optimize groundwater storage capability under new hydrologic regimes that may result from climate change (http://www.waterplan.water.ca.gov/groundwater/DraftUpdate/Chapter1.pdf

Sea Level

Sea-level rise, caused by thermal expansion of ocean waters and melting of ice from land surfaces, will affect groundwater aquifers and coastal ecosystems. Mean sea level (msl) data for stations along the coast of California show msl rising. Figures 5a and b show the increase as measured at Fort Point/the Golden Gate in San Francisco over the past 100 years. Early studies of the impacts of sea-level rise in California show that estuarine impacts of sea-level rise will be felt in the San Francisco Bay and the Sacramento-San Joaquin River delta in northern California (Williams 1985, 1987, SFBCDC 1988). Among the risks will be threats to levee integrity and tidal marshes, the salinity of water in the Delta region, and intrusion of salt water into coastal aquifers.



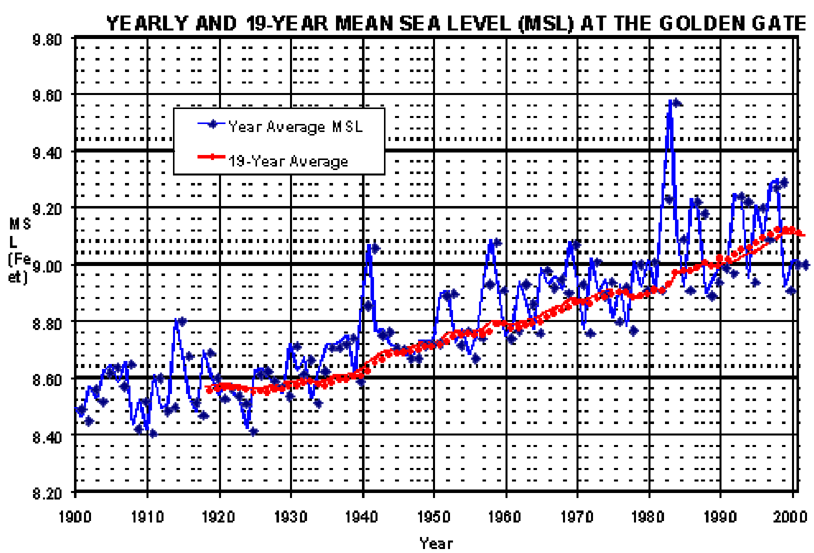


Figure 5a and b: Yearly and mean sea-level rise at the Golden Gate, California, from 1900. Sea level rise at Fort Point, San Francisco. This is the longest continuous record of sea level rise on the west coast of the United States. Source: The U.S. Geological Survey, http://geopubs.wr.usgs.gov/fact-sheet/fs175-99/.

Delta levees protect transportation systems, agriculture, and homes in the region. Williams projected that levees would fail at a higher rate, sediment movements would be changed, mudflats and salt marshes would experience more erosion, and ecosystem impacts could be substantial (Williams 1985, 1987). In addition, tidal marshes in parts of the San Francisco Bay would be submerged by a one-meter sea-level rise (SFBCDC 1988). One analysis showed that only a 15-centimeter (6 inch) rise would transform the current 100-year high tide peak in San Francisco Bay into about a 10-year event (Gleick and Mauer 1990). Severe high tides could thus become a more frequent threat to the delta levees and their ability to protect land and water systems there.

Williams (1985, 1987) also concluded that the average salinity level could migrate roughly 15 kilometers upstream, impacting the State's water-supply infrastructure. This could degrade fresh water transfer supplies pumped at the southern edge of the Delta or require more fresh water releases to repel ocean salinity. Salinity is already a problem in the Delta. Both the Central Valley Project and the State Water Project are operated under water quality constraints. Most of the time, salinity constrains the project operations in late summer and early fall when the availability of water in the reservoirs are at its lowest. Therefore, to mitigate an increase in salinity due to sea level rise pumping has to be cut during these months. The project operations are further constrained by X2 standards in months of February through June. (X2 is the distance in kilometers of tidally and depth averaged 2 psu isohaline from the Golden Gate bridge.) More reservoir releases or reduced pumping would be required to push the increased salinity intrusion caused by the sea level rise back towards the bridge.

Earlier snowmelt runoff in the spring would allow more time for summer saltwater intrusion. Preliminary modeling studies indicate that increase in sea level and changes in freshwater inflows would affect salinity throughout the Sacramento-San Joaquin Delta (see, for example, Knowles and Cayan 2002).

Ecosystems

Humans are dependent upon ecosystem processes to supply essential goods and services such as primary productivity and inputs from watersheds, fish for commercial and recreational purposes, decomposition and biological uptake, and water purification. The health and dynamics of ecosystems are fundamentally dependent on a wide range of climate-sensitive factors, including the timing of water availability, overall water quantity, quality, and temperature. All of these factors may be altered in a changed climate. Freshwater systems are rich in biological diversity, and a large part of the fauna is threatened in California – 150 species of animals are listed as endangered or threatened under state and federal law, and more than 200 species of plants are facing similar threats (http://www.dfg.ca.gov/hcpb/species/t_e_spp/tespp.shtml). A changing climate may intensify these threats in many ways, such as by accelerating the spread of exotic species and further fragmenting populations (Firth and Fisher 1991, Naiman 1992). Experience with ecosystem dynamics strongly suggests that perturbing ecosystems in any direction away from the conditions under which they developed and thrive will have adverse impacts on the health of that system (Peters and Lovejoy 1992, IPCC 2001).

The direct effects of climate change on ecosystems will be complex. Previous assessments have established a wide range of possible direct effects, including changes in lake and stream temperatures, lake levels, mixing regimes, water residence times, water clarity, thermocline depth and productivity, invasions of exotic species, fire frequency, permafrost melting, altered nutrient exchanges, food web structure, and more (for a review see Gleick and others 2000, Wilkinson and others 2003).

The ecological response to a modification in natural flow regime resulting from climate change depends on how the regime is altered relative to the historical conditions (Meyer et al. 1999). For example, a system that has historically experienced predictable, seasonal flooding, such as snowmelt-dominated streams and rivers, may show dramatic changes in community composition and ecosystem function if the seasonal cycles are eliminated or substantially altered, as has been documented for the loss of riparian trees along western watercourses (Auble et al. 1994).

It is likely that the ecosystems at greatest risk from climate change are those that are already near important thresholds, such as where competition for water is occurring, where water temperatures are already near limits for a species of concern, or where climate change will act with other anthropogenic stressors such as large water withdrawals or wastewater returns (Meyer et al. 1999, Murdoch et al. 2000).

There will be both positive and negative direct effects of increasing temperatures on aquatic and terrestrial ecosystems. In general, while many uncertainties remain, ecologists have high confidence that climatic warming will produce a northward shift in species distributions, with extinctions and extirpations of temperate or cold-water species at lower latitudes, and range expansion of warm-water and cool-water species into higher latitudes (Murdoch et al. 2000).

If California water temperatures rise significantly, the difficulty of managing the state's already threatened salmon and steelhead fisheries would increase. Higher atmospheric temperatures will make it more difficult to maintain rivers cold enough for cold-water fish, including anadromous fish. With reduced snowmelt, existing cold-water pools behind major foothill dams are likely to shrink. As a result, river water temperature could warm beyond a point that is tolerable for the salmon and steelhead that currently rely upon these rivers during the summer. Under this scenario, there is concern about how to maintain the existing, cold-water temperature standards in the upper Sacramento River.

Nutrient loading generally increases with runoff, particularly in human-dominated landscapes (Alexander et al. 1996). Delivery of constituents like phosphorus, pesticides, or acids in pulses can have adverse consequences for fishes. Increased numbers of water-quality excursions that exceed ecological thresholds will limit the effectiveness of policies designed for average conditions (Murdoch et al. 2000).

Peak flows occurring much earlier in the season (Leong and Wigmosta 1999, Hay et al. 2000) could result in washout of early life-history stages of autumn-spawning salmonids. Changes in sediment loading and channel morphology in an altered climate can impact processes regulating nutrient cycling and community composition (Ward et al. 1992).

Burkett and Kusler (2000) reviewed likely climate change impacts on wetlands. They concluded that expected changes in temperature and precipitation would alter wetland hydrology, biogeochemistry, plant species composition, and biomass accumulation. Because of fragmentation resulting from past human activities, wetland plants often cannot migrate in response to temperature and water-level changes and hence are vulnerable to complete elimination. Wetland plant response to increased CO_2 could also lead to shifts in community structure with impacts at higher trophic levels. Small changes in the balance between precipitation and evapotranspiration can alter groundwater level by a few centimeters, which can significantly reduce the size of wetlands and shift wetland types. Burkett and Kusler (2000) note that there are no practical options for protecting wetlands as a whole from rising temperature and sea level and changes in precipitation. Some management measures could be applied to specific places to increase ecosystem resilience or to partially compensate for negative impacts, but there is often no explicit economic or institutional support for doing so. Among the options for mitigation are development setbacks for coastal and estuarine wetlands, linking fragmented ecosystems to provide plant and animal migration routes, using water-control structures to enhance ecosystem function, and explicit protection and allocation of water needed for ecosystem health. Some research has been done on these issues, but far more is needed, including modeling and experimental work on the interactions with food webs and hydrological regime (Power et al. 1995, Carpenter et al 2000).

Increased concentrations of greenhouse gases has been observed to both either increase and decrease plant growth, depending on species and the availability of other key growth conditions (Field et al. 1995). Availability of water at a critical time of the plant life will determine actual plant growth. Predicted drier summers might adversely affect drought sensitive plants. Further research has to be done in translating possible increase plant growth to increase in yield.

Water Demand

There are likely to be changes in water use, as well as in water supply. In general, plant ET increases with temperature. Higher carbon dioxide levels, however, reduce water consumption (at least in laboratory tests), and seem to increase yield (Korner 2000, but see Shaw et al. 2003). The higher water consumption with warmer temperatures will likely only be partially offset by the carbon dioxide-based reductions. Thus, the net result could be slightly higher agricultural water requirements. Assessing the potential impacts to agriculture is complicated for some of the annual crops because it may be possible to adjust the planting season to adapt.

The whole subject of potential crop ET and water requirements is an important area of investigation for university and agriculture extension service people. In view of further cuts in water availability to California agriculture, changes in ET would be of great importance. Further modeling and experimental work is needed.

3. Is Climate Change Already Affecting California's Water?

Temperature and Related Trends

The average surface temperature of the Earth has increased by around 0.6 degrees Celsius over the past century (NRC 2000). The fifteen warmest years this century have all occurred since 1980 and, the 1990s were the warmest decade of the entire millennium (Mann and Bradley 1999). Temperatures in the United States have also increased. Pronounced warming has occurred in winter and spring, with the largest increases in the period March-May over the western U.S. (Lettenmaier et al 1994, Dettinger et al. 1995, Vincent et al. 1999). Figures 6 and 7 show global and hemispheric temperature trends.

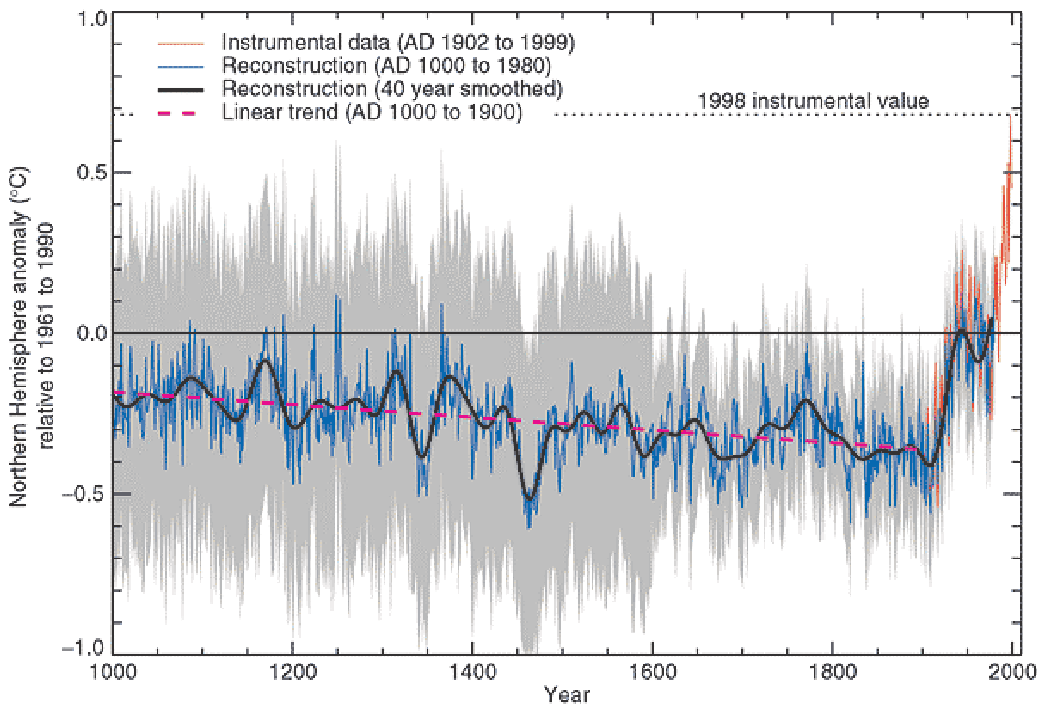


Figure 6: Global temperatures have been rising sharply in the northern hemisphere since the industrial revolution. This graph shows Northern Hemisphere temperature reconstruction from paleoclimate data (blue) and instrumental data (red) from AD 1000 to 1999, adapted from Mann et al. (1999). Smoother version of NH series (black), linear trend from AD 1000 to 1850 (purple-dashed) and two standard error limits (grey shaded) are shown.

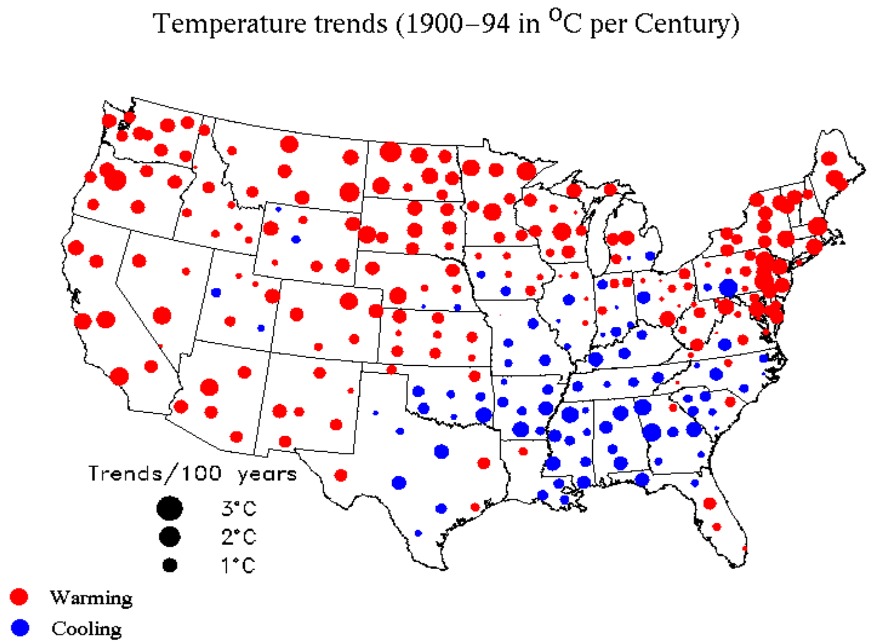


Figure 7: Temperature Trends in the Continental United States (1900 to 1994)

Precipitation Trends

Karl and Knight (1998), updated by Groisman et al. (2001) show an increase in precipitation in the continental United States, with most of the increase in the highest annual one-day precipitation event – a potentially worrisome trend in regions where flooding is a problem (Figure 8). By analyzing long-term precipitation trends in the United States, they determined that:

- Precipitation over the contiguous U.S. has increased by about 10 percent since 1910;
- The intensity of precipitation has only increased for very heavy and extreme precipitation days;
- Increases in total precipitation are strongly affected by increases in both the frequency and the intensity of heavy and extreme events, measured as the highest 1-day annual precipitation event;
- The probability of precipitation on any given day has increased;
- The proportion of total precipitation from heavy events has increased at the expense of moderate precipitation events.

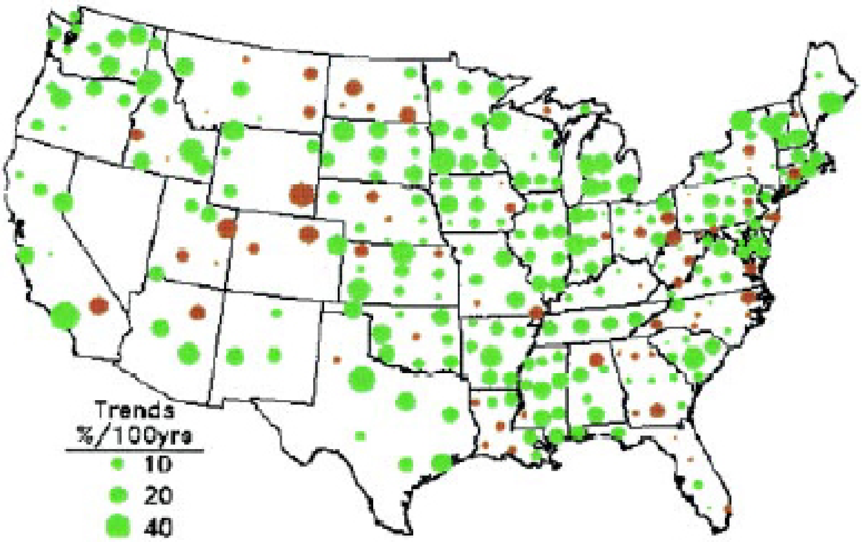


Figure 8. From Groisman et al. (2001). Linear trends in percent per 100 years of annual precipitation. Green dots indicate increase precipitation; brown dots indicate decreasing precipitation.

Runoff Trends

River runoff or discharge reflects multiple climatic factors, which makes it an important indicator of climatic variability and change. Discharge also integrates numerous human influences such as flow diversions for irrigation and municipal use, natural streamflow regulation by dams and reservoirs, and baseflow reduction by groundwater pumping. Detecting a climate signal in the midst of these complicating factors can be difficult (Changnon and Demissie 1996) and this is one of the most active areas for ongoing research.

Shortly after early modeling studies projected changes in the timing of runoff with increasing temperatures (Gleick 1986, 1987), DWR hydrologist Maurice Roos provided empirical evidence consistent with these projections (Roos 1987). In recent years, these changes in timing of streamflow have gained in statistical significance (shown in Figure 9).

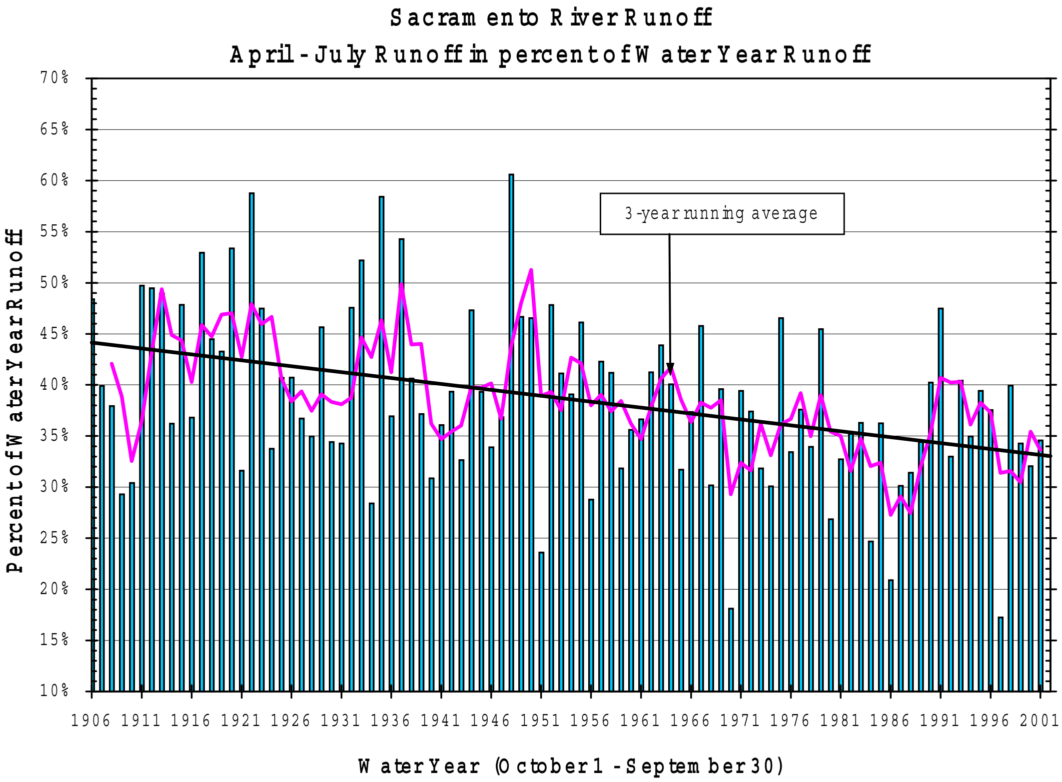


Figure 9. Historical trend in seasonal runoff for the Sacramento River. The decreasing percentage of April-July runoff indicates an earlier melting of the seasonal mountain snowpack.

Lins and Slack (1999) looked at historical trends in monthly mean flow across broad regions of the U.S., finding statistically significant increases in California. Lettenmaier et al. (1994) evaluated trends using monthly mean discharge and also found significant increases in western streamflow from 1948 through 1988. During 1948 through 1991, snowmelt-generated runoff came increasingly early in the water year in many basins in northern and central California. A declining fraction of the annual runoff was occurring during April to June in middle–elevation basins (as described above) and an increasing fraction was occurring earlier in the water year, particularly in March (Dettinger and Cayan 1995). Gleick and Chalecki (1999) observed this same basic pattern in an analysis of the Sacramento and San Joaquin Rivers over the entire twentieth century.

Groisman et al (2000) found little relation between increases in heavy precipitation and changes in high streamflow, similar to Lins and Slack (1999). More recently, however, Groisman et al (2001) have documented an increase in precipitation and especially heavy precipitation in the US as a whole, and related changes in peak streamflow. The changes were most notable in the eastern US because changes in snowcover in the west have complicated runoff studies. In the mountainous western US, snow cover has significantly retreated during the latter half of the 20th century, and there have been related shifts in seasonal discharges, but peak flows have not increased because of the changes in timing.

Snowmelt-runoff timing shifts, especially in middle-elevation mountainous river basins are important because of their sensitivity to changes in mean winter temperatures (Dettinger and Cayan 1995). However, as Dettinger and Cayan further note, the observed hydrologic shifts in these areas can involve more than simple relationships with air temperature alone.

Climate models and theoretical studies of snow dynamics have long projected that higher temperatures would lead to a decrease in the extent of snow cover in the Northern Hemisphere (see, for example, Dettinger and Cayan 1995, Cayan 1996). Recent field surveys corroborate these findings. Snow cover over the Northern Hemisphere land surface has been consistently below the 21-year average (1974 to 1994) since 1988 (Robinson et al. 1993, Groisman et al. 1994), with an annual mean decrease in snow cover of about 10 percent over North America.

Variability and Extreme Events

Extreme weather events are expected to be one of the most significant impacts of climate change. Phenomena such as the El Niño/Southern Oscillation, which is the strongest natural interannual climate fluctuation, have effects on the entire global climate system and the economies and societies of many regions and nations, including the U.S. The strong El Niños of 1982/83 and 1997/98, along with the more frequent occurrences of El Niños in the past few decades, have forced researchers to try to better understand how human-induced climate change may affect interannual climate variability (Trenberth and Hoar 1996, Timmermann et al. 1999). Analyses of flood risks are traditionally based on past data and on a fundamental assumption that peak floods are "random, independent, and identically distributed events." This assumes that climatic trends or cycles are not affecting the distribution of flood flows and that the future climate will be similar to past climate. Current concern over natural variability, anthropogenic climate change, and possible impacts on hydrology, however, calls this assumption into question (NRC 1998).

4. Climate Change and Impacts on Managed Water-Resource Systems

There is a rapidly growing literature about how climate changes may affect U.S. water resources systems (see http://www.pacinst.org/resources for a searchable bibliography). Research has been conducted on a wide range of water-system characteristics, including reservoir operations, water quality, hydroelectric generation and others. At the same time, significant gaps remain.

The Central Valley Project and the State Water Project are each operated under strict guidelines, with constraints that have to be met prior to water being available for export. Flood control storage in reservoirs, water rights in upper Sacramento and San Joaquin, minimum flow requirements in the rivers and the Delta, dissolved oxygen concentration in the Stanislaus River, 800,000 ac-ft per year reserved for restoration of fish, wildlife and habitat restoration and salinity standards in the Delta are all considered in pumping operations. Even under existing supply and demand patterns, water requirements are barely met under dry and critical water years. Modifying existing constraints and optimizing the current operation of the system should be looked into, especially due to the possibility of a reduced supply of water at critical times due to climate change.

Precipitation, temperature, and carbon dioxide levels affect both the supply of, and demand for, renewable water resources. Agricultural, urban, industrial and environmental needs will each increase at certain times of the year. For example, irrigation is particularly sensitive to climatic conditions during the growing season. Also, while indoor domestic water use is not very sensitive to temperature and precipitation, outdoor uses for gardens and parks are very climate dependent. And, higher water temperatures would reduce the efficiency of cooling systems and increase the demand for cooling water. Thus, climate will affect overall water use directly and indirectly.

Water Supply Infrastructure

A major challenge facing hydrologists and water managers is to evaluate how changes in system reliability resulting from climate changes may differ from those anticipated from natural variability and, in theory, already anticipated in original project designs. Both surface and groundwater supply systems are known to be sensitive to the kinds of changes in inflows and demands described earlier. Many regional studies have shown large changes in the reliability of water yields from reservoirs could result from small changes in inflows (Nemec and Schaake 1988, USEPA 1989, Lettenmaier and Sheer 1991, McMahon et al. 1989; Cole et al. 1991; Mimikou et al. 1991; Nash and Gleick 1991b, 1993). Lettenmaier and Sheer (1991), for example, noted the sensitivity of the California State Water Project to climate change under current operating rules. They concluded that changes in operating rules might improve the ability of the system to meet delivery requirements, but only at the expense of an increased risk of flooding. This kind of trade off is now being seen in a broader set of analyses.

Changes in runoff were the most important factors determining the climate sensitivity of system performance (Lettenmaier et al. 1999), even when they evaluated the direct effects of climate change on water demands. These sensitivities depended on the purposes for which water was needed and the priority given to those uses. Higher temperatures increased system use in many basins, but these increases tended to be modest, as were the effects of higher temperatures on system reliability.

Hydropower and Thermal Power Generation

California produces hydropower at a rate second only to the Pacific Northwest. The amount of hydropower production for a given facility is function of amount of water available, head over which the water falls, and time of operation. Changes in precipitation amount or pattern will have a direct impact on hydropower generation. If snowpack decreases, hydropower generation during these months would be reduced. However, wetter winters might enable additional hydropower generation during winter and spring if adequate flood control can be provided.

Variability in climate already causes variations in hydroelectric generation. During a recent multi-year drought in California, decreased hydropower generation led to increases in fossil-fuel combustion and higher costs to consumers. Between 1987 and 1991, these changes cost ratepayers more than $3 billion and increased greenhouse gas emissions (Gleick and Nash 1991). Because of conflicts between flood-control functions and hydropower objectives, human-induced climate changes in California may require more water to be released from California reservoirs in spring to avoid flooding. This would result in a reduction in hydropower generation and the economic value of that generation. At the same time, production of power by fossil fuels would have to increase to meet the same energy demands in California at a cost of hundreds of millions of dollars and an increase in emissions of greenhouse gases (Hanemann and McCann 1993).

Climate changes that reduce overall water availability or change the timing of that availability have the potential to adversely affect the productivity of U.S. hydroelectric facilities. In contrast, reliable increases in average flows would increase hydropower production. More sophisticated studies such as that by Lettenmaier et al. (1999) are necessary for CA. Alternative sources of energy, combined with energy conservation, may be necessary means of adapting to decreased hydropower.

Agriculture

The strong links between water-resources availability and use and agricultural productivity deserve some comment here. In particular, relatively small changes in water availability could lead to relatively large impacts in the agricultural sector. Assessing the impacts of climate change on agriculture requires integrating a wide range of factors.

In the mid-1990s, approximately 75 percent of all water consumption occurred in California’s agricultural sector. In California, the vast majority of agricultural production requires irrigation water from both surface and groundwater sources. Increases in water availability due to climate changes could help reduce the pressures faced by growers; conversely decreases in water availability are likely to affect growers more than other users for two reasons: urban and industrial users can pay more for water; and proportional reductions in water availability would lead to larger overall reductions to farmers. If irrigators holding senior water rights are allowed to sell or transfer those rights, some could actually benefit from decreases in water availability (Gleick and others 2000).

Brumbelow and Georgakakos (2000) assessed changes in irrigation demands and crop yields using physiologically based crop models, and reached several important conclusions for regional agricultural changes, though their results are dependent upon a single climate scenario and hence should be considered speculative. Durum wheat irrigation needs decreased significantly in California (82% decrease). Corn irrigation demands strongly decreased west of the 104th meridian (40% to 75% decrease) and were otherwise only slightly changed. In all regions, the length of the overall growing season increased. Economics of crop changes and quantitative water use figures are subjects for future research.

Extreme Events

Much of the analysis of climate and water impacts looks at how changes in various means will affect water and water systems, such as mean temperatures, average precipitation patterns, mean sea-level, and so on. While many factors of concern are affected by such average conditions, some of the most important impacts will result, not from changes in averages, but from changes in local extremes. Water managers and planners are especially interested in extreme events and how they may change with climate change. Unfortunately, this is one of the least-well understood categories of impacts and we urge more effort be devoted to studying it. Hydrological fluctuations impose two types of costs on society: the costs of building and managing infrastructure to provide more even and reliable flows and the economic and social costs of floods and droughts that occur in spite of these investments.

Ironically, some regions could be subjected to both increases in droughts and increases in floods if climate becomes more variable. Even without increases in variability, both problems may occur in the same region. In California, where winter precipitation falls largely as snow, higher temperatures will increase the ratio of rain to snow, shifting peak runoff toward the period of time when flood risk is already highest. At the same time, summer and dry-season runoff will decrease because of a decline in snowpack and accelerated spring melting.

Floods

Flooding is the nation’s most costly and destructive natural disaster. A change in flood risks is therefore one of the potential effects of climate change with the greatest implications for human well-being. Few studies have looked explicitly at the implications of climate change for flood frequency, in large part because of the difficulty of getting detailed regional precipitation information from climate models and because of the substantial influence of both human settlement patterns and water-management choices on overall flood risk. Floodplain development places more people and property at risk and it reduces a basin’s capacity to naturally absorb flood flows.

Future flood damages will depend on many factors. Among the most important are the rate and style of development in the floodplains, the level and type of flood protection, and the nature of climate-induced changes in hydrological conditions, sea levels, and storm surges. As noted earlier, regional and local changes in hydrological conditions attributable to a greenhouse warming are uncertain but research to date suggests that there is a risk of increased flooding in California. In any case, flooding depends not only on average precipitation but on the timing and intensity of precipitation – two characteristics not well modeled at present.

Droughts

Water managers must also be concerned about the risks of droughts. Droughts vary in their spatial and temporal dimensions and are highly dependent on local management conditions and the perceptions of local water users. No single definition of drought applies in all circumstances; thus determining changes in drought frequency or intensity that might be expected to result from climate changes is complicated. Most past studies have focused on evaluating changes in low-flow conditions and probabilities.

Quantifying the socioeconomic impacts of a drought is difficult, and comprehensive damage estimates are rarely available. Agriculture, the economic sector most susceptible to water shortages, is likely to suffer reduced crop production, soil losses due to dust storms, and higher water costs during a drought. But non-climatic factors can play an important role in limiting, or worsening, the impacts of climate. Agricultural losses during California's six-year drought from 1987-1992 were reduced by temporarily fallowing some land, pumping more groundwater, concentrating water supplies on the most productive soils and higher value crops, and purchasing water in spot markets to prevent the loss of tree crops. Direct economic losses to California's irrigated agriculture in 1991 were estimated at only $250 million, less than 2 percent of the state's total agricultural revenues (Nash 1993, U.S. Army Corps of Engineers 1994).

A prolonged drought affects virtually all sectors of the economy. Urban users in California paid more for water and were subject to both voluntary and mandatory conservation programs. Landscaping and gardening investments and jobs were lost. Electricity costs, as described above, rose more than $3 billion because of reduced hydropower power production. Recreation was adversely impacted. Visits to California state parks declined by 20 percent between 1987 to 1991, and water-based activities such as skiing and reservoir fishing declined (Gleick and Nash 1991). During this drought, the state's environmental resources may have suffered the most severe impacts. Most major fisheries suffered sharp declines and many trees were weakened or killed by the lack of precipitation, increasing the subsequent risk of forest fires (Nash 1993, Brumbaugh et al. 1994). Many of these ecosystem impacts are never monetized or quantified.

5. Coping and Adaptation: Policy Directions

Review of Policy Recommendations from Peer-Reviewed Sources

For over a decade, scientists have been producing formal, peer-reviewed recommendations for integrating their work into policy. We synthesize their suggestions for coping and adaptation from several key reports. Each recommendation is followed by one or more references indicating which reports included it. While only the California Energy Commission report (1991) is wholly specific to California, it should be noted that most focus on the Western United States, including California, because in general impacts of climate change on water resources are expected to be greater in areas which are already water-stressed. The following reports are used in this synthesis:

- (Waggoner 1990) – The American Association for the Advancement of Science published this volume detailing the setting, impacts, and responses for U.S. water resources. It was the most in-depth, interdisciplinary, and scientifically sophisticated report until the National Assessment (Gleick and others 2000).
- (California Energy Commission 1991) – The first report by a California State agency was mandated by AB4420 in 1988. The CEC report is specific to California, and produced under the auspices of a California Agency. It should be noted that its recommendations were based on the assumption that snowmelt timing will be the primary hydrologic variable altered by climate change, and precipitation was held constant in its scenarios.

In our interviews, California water policymakers cited it repeatedly as an influential early document.

- (American Water Works Association 1997) – The Public Advisory Forum of the American Water Works Association issued a succinct set of recommendations to water managers. As the largest U.S. professional water utilities and providers' organization, its peer-reviewed document should carry weight with water managers.
- (Gleick and others 2000) – The report of the Water Sector of the National Assessment on the Potential Consequences of Climate Variability and Change for the United States provides a regional and national overview of the impacts of climate change on water resources.
- (Wilkinson and others 2002) – The draft report of the California Regional Assessment Group of the National Assessment provides an overview of impacts for the State's ecosystems, economy, society, human health, and other areas. It includes a major chapter on water resources. In its section on recommendations for adaptation, it quotes in full the Water Sector (Gleick and others 2000) and the AWWA reports (American Water Works Association 1997). In addition, it offers other recommendations, which are cited in this summary.

These reports were all peer-reviewed, except the CEC report, which is included because of its historical influence and the degree of its specificity to California. A general theme in the recommendations is the adoption of "no-regrets" strategies, which are defined by the IPCC as policies that would have net social benefits whether or not there is anthropogenic climate change (McCarthy et al. 2001).

In the context of broad scientific consensus that global climate change is real and expected with a very high degree of confidence, these recommendations also implicitly or explicitly acknowledge that specific regional effects are not yet predictable with high certainty. This point was emphasized in the recommendations of the AAAS report (Waggoner 1990).

It is also notable that none of the reports contradict each other on any specific recommended measure. This consistency follows from the general scientific consensus on global climate change, but also from the generally conservative nature of the suggestions. Even the California Energy Commission report (1991), with its less-sophisticated scientific basis, produced recommendations that are consistent with those of later efforts. Some of the recommendations have been acted on, and some responses are currently being devised.

We divided the list below into four categories: Current No-Regrets Actions, Communication and Collaboration, Research Needs, and Information Gathering.

Current No-Regrets Actions

- Governments and agencies should reevaluate legal, technical, and economic procedures for managing water resources in the light of the climate changes that are highly likely (Waggoner 1990; American Water Works Association 1997; Gleick and others 2000; Wilkinson and others 2002).
- Governments should encourage flexible institutions for water allocation including water markets (Waggoner 1990).
- Planning should occur over appropriate regions which may or may not correspond to current boundaries (Waggoner 1990). This would elevate the importance of hydrologic boundaries over political boundaries.
- Increased funding is necessary for interdisciplinary research necessary to address the broad-based impacts and effects of climate change (Waggoner 1990).
- Flexible decisions should be encouraged, particularly in the design and construction of new projects (Waggoner 1990; Gleick and others 2000; Wilkinson and others 2002).

- Opportunities for water conservation, demand management, and efficiency should be explored and encouraged (Waggoner 1990; California Energy Commission 1991; Gleick and others 2000; Wilkinson and others 2002).
- Private enterprises should decrease vulnerabilities to the hydrologic effects of climate change through water transfers or construction of new infrastructure (Waggoner 1990).
- The State should improve both weather and flood forecasting (California Energy Commission 1991).
- The State should assess Delta levees' strength with respect to increasing sea level rise (California Energy Commission 1991).
- Water managers should carefully consider increased storage in new surface or underground storage facilities (California Energy Commission 1991; Gleick and others 2000). The California Energy Commission (1991) gave the most specific recommendation, at four million acre feet, plus storage for maintenance of Delta salinity levels. This estimate, however, should be taken in the context of the relative generality of its science.
- Existing dams should have temperature controls added for fish species that require cold water downstream (California Energy Commission 1991).
- New supply should come from both traditional and alternative places, such as wastewater reclamation and reuse, water marketing and transfers, and possibly desalination (Gleick and others 2000).
- Prices and markets should be adjusted to balance supply and demand (Gleick and others 2000).
- Water laws should be updated and improved water laws, including review of the legal allocation of water rights (American Water Works Association 1997; Gleick and others 2000).
- Managers should plan and invest for multiple benefits (e.g. Water supply, energy, wastewater, and environmental benefits result from water use efficiency increases) (Wilkinson and others 2002).
- Site-dependant application of climate change science to stormwater management strategies should be used, including approaches like increasing permeable surfaces in urban areas (Wilkinson and others 2002).

Communication and Collaboration

- Water organizations should communicate regularly with scientists, with the dual goals of communicating scientific advances to managers, and communicating what knowledge is necessary from scientists for effective management (Waggoner 1990; American Water Works Association 1997; Gleick and others 2000).
- "Those reporting about climate change bear a special responsibility for accuracy, conveying the real complexities and uncertainties, and not oversimplifying. Scientists must make extra effort to explain clearly in conservative and understandable terms." (Waggoner 1990).
- Timely flows of information between scientific community, public, and water management should be facilitated (American Water Works Association 1997; Gleick and others 2000).[1]

Research Needs

There is no shortage of research needs, several of which are listed below. The PIER project has developed a research agenda, short-term (1 to 3 years), mid-term (3 to 10 years), and long-term (10 to 20 years), to attempt to answer some of the most important questions facing California policymakers and scientists. Funding is not available for all of the necessary work. Roos (2003) describes this "roadmap" at http://www.energy.ca.gov/reports/2003-04-16_500-03-025FA-II.PDF.

[1] Several recent conferences illustrate that this is currently happening. For example, at a recent CALFED meeting detailing modeling projects, several local stakeholder groups were represented along with larger environmental groups an many branches of government.

This roadmap has been approved by the California Department of Water Resources to help it develop future research efforts.

Other research needs include:

- Climate change scientists should focus on the timeframes and spatial scales relevant to water managers, who are concerned with watershed-level predication and decadal time scales (Waggoner 1990).
- Improve GCMs to more accurately represent hydrologic impacts, water resource availability, overall hydrologic impacts, and regional impacts (Waggoner 1990; Gleick and others 2000).
- Improve downscaling of GCMs[2] (Gleick and others 2000).
- Planners should reassess water transfer plans for the Sacramento-San Joaquin Delta, particularly in light of predicted sea-level rise (California Energy Commission 1991).
- Changing land use patterns should be examined as a coping mechanism (Gleick and others 2000).
- Scientists and engineers should reexamine engineering designs, operating rules, contingency plans, and water allocation policies under a wider range of climate scenarios[3] (American Water Works Association 1997; Gleick and others 2000).
- Economists should investigate economic effects of climate change and of adaptations to climate change (Gleick and others 2000).
- Hydrologists should research effects on groundwater quality, recharge and flow dynamics has been lacking (Gleick and others 2000).
- All sectors should look into mitigation through decrease in fossil fuel use (California Energy Commission 1991; American Water Works Association 1997).

Information Gathering

- The state should improve hydrologic monitoring, including improving data on storm frequency (California Energy Commission 1991; Gleick and others 2000).
- Water quality monitoring should be increased (California Energy Commission 1991).
- The State should reevaluate risks to flood zones at intervals of 20-30 years (California Energy Commission 1991).
- Information on the relative costs and benefits of non-structural managements options, like demand management or decreased floodplain development should be produced (Gleick and others 2000).
- Agencies should explore the vulnerability of both structural and nonstructural water systems (American Water Works Association 1997).
- Economic and market tools should be explored, but Wilkinson and others (2002) caution that this should *not* be equated with privatization.

In the context of these recommendations for types of action, the following more specific items are available within several major topical categories. Among the new tools water agencies and managers are exploring are (1) incentives for conserving and protecting supplies, (2) opportunities for transferring water among competing uses in response to changing supply and demand conditions, (3) economic changes in how water is managed within and among basins, (4) evaluating how “re-operating” existing infrastructure can help address possible changes, and (5) new technology to reduce the intensity of water use to meet specific goals (Gleick and others 2000).

---

[2] This is one area that continues to see significant advances (eg. Knowles and Cayan 2002; Snyder et al. 2002). Interestingly, Knowles and Cayan (2002) acknowledge water managers at DWR for providing motivation for their work.

[3] See (cite Georgakakos…)

6. Coping and Adaptation: Specific Policy Actions

The lessons from existing efforts need to be evaluated in order to understand how they might mitigate (or worsen) the impacts of climate changes. During the 20th century dams, reservoirs, and other water infrastructure were designed with a focus on extreme events such as the critical drought periods or the probable maximum flood. This approach provided a cushion to deal with uncertainties such as climate variability (Matalas and Fiering 1977). In recent years, however, the high costs and environmental concerns that now make it difficult to get a new project approved also make it likely that the projects that are undertaken will have less redundancy built into their water supply and control facilities than the projects built earlier (Frederick 1991).

Managing water resources with climate change could prove different than managing for historical climate variability because 1) climate changes could produce hydrologic conditions and extremes of a different nature than current systems were designed to manage; 2), it may produce similar kinds of variability but outside of the range for which current infrastructure was designed; 3), it assumes that sufficient time and information will be available before the onset of large or irreversible climate impacts to permit managers to respond appropriately; 4) it assumes that no special efforts or plans are required to protect against surprises or uncertainties (Gleick and others 2000). This chapter of Bulletin 160-2003 represents an important acknowledgement by a major state agency of the realities and necessities inherent to a changing climate.

Water Planning and Management

Decisions about long-term water planning depend on climatic conditions and what humans do to respond and adapt to those conditions. In the past, these decisions relied on the assumption that future climatic conditions would have the same characteristics and variability as past conditions. Dams are sized and built using available information on existing flows in rivers and the size and frequency of expected floods and droughts. Reservoirs are operated for multiple purposes using the past hydrologic record to guide decisions. Irrigation systems are designed using historical information on temperature, water availability, and soil water requirements.

This reliance on the past record now may lead us to make incorrect – and potentially dangerous or expensive – decisions. Given that risk, one of the most important coping strategies must be to try to understand what the consequences of climate change will be for water resources and to begin planning for those changes. Emphasis on planning and demand management rather than construction of new facilities marks an important change in traditional water-management approaches, which in the past have relied on the construction of large and expensive infrastructure.

O'Conner et al. (1999) examined the sensitivity and vulnerability of community water systems to climate change by surveying 506 managers. Water-system managers do not dismiss the issue of climate change, but they have been reluctant to consider it in their planning horizons until they perceive a greater degree of scientific certainty about regional impacts. Interestingly, most managers admit that they expect disruptions in daily operations caused by changes in climate variability. Experienced and full-time water managers were more likely to consider future climate scenarios in planning than inexperienced or part-time managers. O'Conner et al (1999) offered some conclusions and discussion of policy implications of their survey:

- Moving away from exclusive reliance on surface water by integrating surface and groundwater management reduced vulnerability to climate fluctuations;
- Continued efforts to improve research and to communicate the risk of climate changes to water managers, especially at the local level, will be useful; and
- Local governments should consider creating more full-time water manager positions to attract top professionals capable of considering long-term issues and concerns in planning.

Sea Level Concerns

Five hundred and twenty miles of levees that protect the Delta Islands are non-project (outside the federal flood control project) levees that are currently built to HMP (Hazard Mitigation Plan) standards. Local districts responsible for maintaining these levees are challenged by poor foundations and regulations to protect levee wild life habitat. An estimated expenditure of from $613 million to $1.28 billion would bring the levees up to Public Law 84-99 standard (16 ft wide and 1.5 ft free board above a 100-year flood) (personal communication, Department of Water Resources, 2003).

To increase these non-project levees by one additional foot (to accommodate sea level rise) would increase the cost by about $300 million. There are currently 220 miles of project levees in the Delta region, which are mostly up to PL 84-99 standards. It will cost over $130 million to accommodate an increase of a foot in this levee system. An additional increase in the water level due to sea level rise would necessitate not only an increase in the levee height but also strengthening the levees.

Modifying Operation of Existing Systems

There are two critical issues associated with using existing facilities to address future climate change: can they handle the kinds of changes that will occur; and at what economic and ecological cost? There have been few detailed analysis of either of these questions, in part because of the large remaining uncertainties about how the climate may actually change. Also, the principle of local public participation is increasingly being implemented. Involving the public in water management decisions has taken steps forward in California through the CALFED process (cite Environment paper) and through the public advisory committee role in the production of this document.

Regardless, without precise information on the characteristics of future climate, the best that water managers can hope to do may be to explore the sensitivity of their system to a wider-range of conditions than currently experienced and to develop methods or technologies that can improve operational water management.

The work of Lettenmaier et al. (1999) and Georgakakos and Yao (2000a,b) reinforce the conclusion that effective operation of complex systems can reduce impacts of climate change, but only if implemented in a timely and dynamic manner. Lettenmaier et al. (1999) addressed this question of response to climate change for a series of water systems around the United States. They noted that reservoir systems buffer modest hydrologic changes through operational adaptations. As a result, the effects of climate change on the systems they studied tend to be smaller than the underlying changes in hydrologic variables. They concluded that significant changes in design or scale of water management systems might not be warranted to accommodate climate changes alone, although this obviously depends on the ultimate size of the changes. They urged a concerted effort to adjust current operating rules or demand patterns to better balance the existing allocated purposes of reservoirs, which requires planning and participation by water managers.

Other steps should include determining quantitative impacts from climate change on water supply and flood control including a systematic review and evaluation of all major multi-purpose reservoirs for water supply and flood control and their ability to adapt under current operating rules. Also, evaluation of alternative options for water management including evaluation of measures to improve water supply and quality, reduce demands throughout the State, maintain and restore ecosystems, re-operate reservoirs, and adapt to sea level rise in the Delta. The work will emphasize increased flexibility in both physical systems and institutional mechanisms in order to permit a greater range of response. Supply and quality measures will be particularly important in regions dependent on imported supplies.

Due to the many uncertainties in predicting peak flows under climate change scenarios, a closer look at the design practices of hydraulic infrastructure should be considered. Related to flood risk are the rainfall depth-duration-frequency data widely used for designing local storm water control and drainage facilities. It has been suggested that these statistics be updated frequently, at least every 20 years or so. In this way, climate changes will be gradually incorporated into the record and in the rainfall statistics.

New Supply Options

Traditional water-supply options, such as dams, reservoirs, and aqueducts may still have an important role to play in meeting water needs in parts of the United States. Because new infrastructure often has a long lifetime, it is vital that the issue of climate change be factored into decisions about design and operation.

While new supply options can be expensive and controversial traditional, water-supply options such as dams, reservoirs and aqueducts may still have an important role to play in meeting water needs of California. At present the Department of Water Resources in collaboration with United States Bureau of Reclamation (USBR), Contra Costa Water district (CCWD) and local agencies are looking into enlarging instream storages in Shasta and Millerton reservoirs, off stream storage options such as Red bank project, Colusa Reservoirs and Sites reservoirs, Enlarging Los Vaqueros reservoir and flooding four Delta islands namely Bacon, Web, Bouldin and Holland. These projects will increase supply reliability, improve water quality and improve some environmental issues such as providing wild life habitats and cooler water for salmon migration. Because new infrastructure often has a long lifetime, it is vital that the issue of climate change be factored into decisions about designs and operations.

Aside from new water-supply infrastructure, options to be considered include wastewater reclamation and reuse, water marketing and transfers, and even limited desalination where less costly alternatives are not available and where water prices are high. None of these alternatives, however, are likely to alter the trend toward higher water costs. They are either expensive relative to traditional water costs or their potential contributions to supplies are too limited to make a significant impact on long-term supplies. Ultimately, the relative costs, environmental impacts, and social and institutional factors will determine the appropriate response to greenhouse-gas induced climate changes.

Major (1998) notes that incremental construction can allow for adaptation but adds that planners must choose robust designs to permit satisfactory operation under a wider range of conditions than traditionally considered. Designing for extreme conditions, rather than simply maximizing the expected value of net benefits, should be considered. He also suggests postponement of irreversible or costly decisions.

Demand Management, Conservation, and Efficiency

Demand management, especially in face of population increase is critical to mitigate loss of water supply. More water efficient methods in agricultural, industrial and urban water have been effective in the past in this capacity (Owens-Viani et al. 1999), and should be further developed and implemented.

As the economic and environmental costs of new water-supply options have risen, so has interest in exploring ways of improving the efficiency of both allocation and use of water resources. Improvements in the efficiency of end uses and sophisticated management of water demands are increasingly being considered as major tools for meeting future water needs, particularly in water-scarce regions where extensive infrastructure already exists (Vickers 1991, Postel 1997, Gleick 1998a, Dziegielewski 1999, Vickers 1999). Evidence is accumulating that such improvements can be made more quickly and more economically, with fewer environmental and ecological impacts, than further investments in new supplies (Gleick et al. 1995, Owens-Viani et al. 1999).

The largest single user of water is the agricultural sector and in some places a substantial fraction of this water is lost as it moves through leaky pipes and unlined aqueducts, as it is distributed to farmers, and as it is applied to grow crops. In water-short areas, new techniques and new technologies are already changing the face of irrigation. Identifying technical and institutional ways of improving the efficiency of these systems in a cost-effective manner will go a long way toward increasing agricultural production without having to develop new supplies of water (Gleick 1998a).

In an assessment of urban water use, Boland (1997, 1998) shows that water conservation measures such as education, industrial and commercial reuse, modern plumbing standards, and pricing policies can be extremely effective at mitigating the effects of climate change on regional water supplies. A number of water-system studies have begun to look at the effectiveness of reducing system demands for reducing the overall stresses on water supplies, both with and without climate changes. Wood et al. (1997) and Lettenmaier et al. (1999) noted that long-term demand growth estimates had a greater impact on system performance than climate changes in circumstances when long-term withdrawals are projected to grow substantially. Actions to reduce demands or to moderate the rate of increase in demand growth can therefore play a major role in reducing the impacts of climate changes. Far more work is needed to evaluate the relative costs and benefits of demand management and water-use efficiency options in the context of a changing climate.

Economics, Pricing, and Markets

Prices and markets are also increasingly important tools for balancing supply and demand for water and hence for coping with climate-induced changes. Economists and others are beginning to advocate an end to the treatment of water as a free good. This can be accomplished in many different ways. Because new construction and new concrete projects are increasingly expensive, environmentally damaging, and socially controversial, new tools such as the reduction or elimination of subsidies, sophisticated pricing mechanisms, and smart markets provide incentives to use less water, produce more with existing resources, and reallocate water among different users. Water marketing is viewed by many as offering great potential to increase the efficiency of both water use and allocation (NRC 1992, Western Water Policy Review Advisory Commission 1998). As conditions change, markets can help resources move from lower- to higher-value uses.

Water transfers in itself do not create new water, but simply reallocate water within a region or between regions. This process enables a better distribution of water throughout the State from areas of surplus to areas in need. In a guide to water transfer, the California State Water Resources Control Board stipulates that a person who transfers water should hold the rights to it and should not injure another water right holder or unreasonably effect instream beneficial uses. For efficient water marketing and smooth transferring of water the users should have a clear idea about the transfer costs.

Water banks acts as storage locations where excess water is held until a withdrawal is necessary. The storage location could be either a surface reservoir or a groundwater aquifer. Water banks enhance the versatility of water transfers and marketing, though many questions about equity, pricing, and operations remain to be answered.

The characteristics of water resources and the institutions established to control them have inhibited large-scale water marketing to date. Water remains underpriced and market transfers are constrained by institutional and legal issues. Efficient markets require that buyers and sellers bear the full costs and benefits of transfers. However, when water is transferred, third parties are likely to be affected. Where such externalities are ignored, the market transfers not only water, but also other benefits that water provides from a non-consenting third party to the parties to the transfer. A challenge for developing more effective water markets is to develop institutions that can expeditiously and efficiently take third-party impacts into account (Loh and Gomez 1996, Gomez and Steding 1998, Dellapenna 1999). As a result, despite their potential advantages, prices and markets have been slow to develop as tools for adapting to changing supply and demand conditions.

California's emergency Drought Water Banks in the early 1990s helped mitigate the impacts of a prolonged drought by facilitating water transfers among willing buyers and sellers. Dellapenna (1999) and others have noted, however, that the California Water Bank was not a true market, but rather a state-managed reallocation effort that moved water from small users to large users at a price set by the state, not a functioning market. More recent efforts to develop functioning markets on smaller scale have had some success (California Department of Water Resources, http://rubicon.water.ca.gov/b16098/v2txt/ch6e.html).

Temporary transfers may be particularly useful for adapting to short-term changes such as climate variability. They are less effective in dealing with long-term imbalances that might result from changing demographic and economic factors, social preferences, or climate. At some point, the historical allocation of water becomes sufficiently out of balance to warrant a permanent transfer of water rights.

State Water Law

Few analyses have tried to evaluate how climate change impacts may affect, and be affected by, water laws and regulatory structures. Water in its many different forms has been managed in different ways at different times, and in different places around the country, leading to complex and sometimes conflicting water laws. At the federal level, laws such as the Clean Water Act and the Safe Drinking Water Act have played a major role in how water is used, allocated, and treated. Yet these national tools, not to mention the many regional and local laws affecting water, were all designed without considering the possibilities of climate changes (Trelease 1977). Even without such changes, efforts are needed to update and improve legal tools for managing and allocating water resources. Tarlock (1991) evaluated how western water laws may begin to conflict as climate change affects water availability and reliability. Dellapenna (1999) argues that the current fragmented approach is obsolete and that integrated water management at the basin level is required, both with and without climate changes. He further argues, however, that climate changes are likely to exacerbate the problems that already exist under inefficient management.

Hydrologic and Environmental Monitoring

Better data on hydrology and land use are critical to California's successful adaptation to expected climate change. Changes in hydrology are among the most certain of climate change impacts and good hydro-meteorological data are the starting point for evaluating the capabilities of the current water supply and flood protection systems to continue to serve the people of California. Hydrological data are used in the design and operation of water supply systems and flood control works, the provision of environmental needs, and in design of other infrastructure. Several State agencies have ongoing climate, water, and land use/land cover monitoring programs. But there are important gaps, particularly in areas where greater changes are anticipated. At a minimum, data must be collected in several important categories, including:

- Enhance measurements of precipitation and related climate data, streamflow, snowpack, ocean and Delta water levels.
- A water quality sampling network designed to look at changes expected from climate change.
- More systematic sea-level measurements in the San Francisco Bay and Delta region, and elsewhere along California's coast.

- Enhanced land use and cover monitoring within the State.

Finally, it is important to continue to collect, maintain, and evaluate records from existing California stations, incorporating data from recent years. Efforts should be made to prevent cuts in monitoring and data collection due to budget constraints.

7. Citations

Aguado, E., D. Cayan, L. Riddle and M. Roos (1992). "Climatic Fluctuations and the Timing of West Coast Streamflow." *Journal of Climate* 5(12): 1468–1483.

Alexander, R. B., P. S. Murdoch and R. A. Smith (1996). "Streamflow-induced variations in nitrate flux in tributaries to the Atlantic coastal zone." *Biogeochemistry* 33(3): 149-177.

American Water Works Association (1997). "Climate Change and Water Resources: Committee Report of the Public Advisory Forum." *Journal of the American Water Works Association* 89(11): 107-110.

Auble, G. T., J. M. Friedman and M. L. Scott (1994). "Relating Riparian Vegetation to Present and Future Streamflows." *Ecological Applications* 4: 544-554.

Barnett, T. P., Malone, R., Pennell, W., Stammer, D., Semtner, A., Washington, W., (2002). The Effects of Climate Change on Water Resources in the West: Introduction and Overview. *Climatic Change* (in review).

Bates, G. T., F. Giorgi and S. W. Hostetler (1993). "Toward the Simulation of the Effects of the Great Lakes on Regional Climate." *Monthly Weather Review* 121(5): 1373-1387.

Benson, L., M. Kashgarian, R. Rye, S. Lund, F. Paillet, J. Smoot, C. Kester, S. Mensing, D. Meko and S. Lindstrom (2002). "Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada." *Quaternary Science Reviews* 21(4-6): 659-682.

Boland, J. J. (1997). "Assessing Urban Water Use and the Role of Water Conservation Measures under Climate Uncertainty." *Climatic Change* 37(1): 157-176.

Boland, J. J. (1998). "Water Supply and Climate Uncertainty." *Water Resources Update*(112): 55-63.

Booker, J.F. 1995. "Hydrologic and economic impacts of drought under alternative policy responses." *Water Resources Bulletin*, Vol. 31, No. 5, pp. 889-906.

Brown, R. A., N. J. Rosenberg and R. C. Izarraulde (1999). Response of U.S. Regional Water Resources to CO_2-Fertilization and Hadley Centre Climate Model Projections of Greenhouse-Forced Climate Change: A Continental Scale Simulation Using the HUMUS Model, Pacific Northwest National Laboratory: 29.

Brumbelow, K. and A. Georgakakos (2001). "An assessment of irrigation needs and crop yield for the United States under potential climate changes." *Journal of Geophysical Research-Atmospheres* 106(D21): 27383-27405.

California Energy Commission (1991). Planning for and Adapting to Climate Change. Global Climate Change: Potential Impacts and Policy Recommendations Committee Report. II: 6.1-6.18.

Carpenter, T. M. and K. P. Georgakakos (2001). "Assessment of Folsom lake response to historical and potential future climate scenarios: 1. Forecasting." *Journal of Hydrology* 249(1-4): 148-175.

Cayan, D. R. (1996). "Interannual Climate Variability and Snowpack in the Western United States." *Journal of Climate* 9(5): 928–948.

Cayan, D. R., K. T. Redmond and L. G. Riddle (1999). "ENSO and Hydrologic Extremes in the Western United States." *Journal of Climate* 12(9): 2881–2893.

Changnon, S. A. and M. Demissie (1996). "Detection of Changes in Streamflow and Floods Resulting from Climate Fluctuations and Land Use-Drainage Changes." *Climatic Change* 32(4): 411-421.

Christensen, N.S., Wood, A.W., Lettenmaier, D.P. and R.N. Palmer (2002). Effects of Climate Change on the Hydrology and Water Resources of the Colorado River Basin. Climatic Change (in revision).

Cole, J. A., S. Slade, P. D. Jones and J. M. Gregory (1991). "Reliable Yield of Reservoirs and Possible Effects of Climate Change." *Hydrological Sciences Journal* 36(6): 579-598.

Covich, A. P., S. C. Fritz, P. J. Lamb, R. D. Marzolf, W. J. Matthews, K. A. Poiani, E. E. Prepas, M. B. Richman and T. C. Winter (1997). "Potential Effects of Climate Change on Aquatic Ecosystems of the Great Plains of North America." *Hydrological Processes* 11(8): 993-1021.

Croley, T. E. (1990). "Laurentian Great Lakes Double-CO_2 Climate Change - Hydrological Impacts." *Climatic Change* 17(1): 27-47.
Dennis, A.S. 1991. Initial climate change scenario for the western United States. Global Climate Change Response Program, United States Department of the Interior, Bureau of Reclamation, Denver, Colorado.
Dettinger, M. D. and D. R. Cayan (1995). "Large-Scale Atmospheric Forcing of Recent Trends toward Early Snowmelt Runoff in California." *Journal of Climate* 8(3): 606–623.
Earle, C. J. (1993). "Asynchronous droughts in California streamflow as reconstructed from tree rings." *Quaternary Research* 39: 290–299.
Eddy, R.L. 1996. Variability of wet and dry periods in the Upper Colorado River Basin and the possible effects of climate change. Global Climate Change Response Program, United States Department of the Interior, Bureau of Reclamation, Denver, Colorado.
Eheart, J. W., A. J. Wildermuth and E. E. Herricks (1999). "The Effects of Climate Change and Irrigation on Criterion Low Streamflows Used for Determining Total Maximum Daily Loads." *Journal of the American Water Resources Association* 35(6): 1365-1372.
Felzer, B. and P. Heard (1999). "Precipitation Difference Amongst GCMs Used for the U.S. National Assessment." *Journal of the American Water Resources Association* 35(6): 1327-1340.
Field, C. B., R. B. Jackson and H. A. Mooney (1995). "Stomatal responses to increased CO_2-implications from the plant to the global scale." *Plant Cell and Environment* 18: 1214-1225.
Firth, P. and S. G. Fisher, Eds. (1992). Global Climate Change and Freshwater Ecosystems. New York, Springer-Verlag.
Frederick, K. D. (1993). "Climate Change Impacts on Water Resources and Possible Responses in the MINK Region." *Climatic Change* 24(1-2): 83-115.
Frei, C., C. Schär, D. Lüthi and H. C. Davies (1998). "Heavy precipitation processes in a warmer climate." *Geophysical Research Letters* 25: 1431–1434.
Gleick, P. H. (1986). "Methods for Evaluating the Regional Hydrologic Impacts of Global Climatic Changes." *Journal of Hydrology* 88: 97-116.
Gleick, P. H. (1987a). "The Development and Testing of a Water-Balance Model for Climate Impact Assessment: Modeling the Sacramento Basin." *Water Resources Research* 23(6): 1049-1061.
Gleick, P. H. (1987b). "Regional Hydrologic Consequences of Increases in Atmospheric Carbon Dioxide and Other Trace Gases." *Climatic Change* 10(2): 137-161.
Gleick, P. H. (1998). "Water Planning and Management Under Climate Change." *Water Resources Update(*112): 25-32.
Gleick, P. H. and E. L. Chalecki (1999). "The impacts of climatic changes for water resources of the Colorado and Sacramento-San Joaquin River Basins." *Journal of the American Water Resources Association* 35(6): 1429-1441.
Gleick, P.H. and E.P. Maurer. 1990. "Assessing the costs of adapting to sea-level rise: A case study of San Francisco Bay." Pacific Institute for Studies in Development, Environment, and Security, Berkeley, California and the Stockholm Environment Institute, Stockholm, Sweden. 57 pp. with 2 maps.
Gleick, P.H. and L. Nash. 1991. "The societal and environmental costs of the continuing California drought." Pacific Institute for Studies in Development, Environment, and Security, Berkeley, California. 66 p.
Gleick, P. H. and others (2000). Water: Potential Consequences of Climate Variability and Change for the Water Resources of the United States. Report of the Water Sector Assessment Team of the National Assessment of the Potential Consequences of Climate Variability and Change. Oakland, CA, USA, Pacific Institute for Studies on Development, Economics, and Security: 151.
Grimm, N. B., A. Chacon, C. N. Dahm, S. W. Hostetler, O. T. Lind, P. L. Starkweather and W. W. Wurtsbaugh (1997). "Sensitivity of Aquatic Ecosystems to Climatic and Anthropogenic Changes: The Basin and Range, American Southwest and Mexico." *Hydrological Processes* 11(8): 1023-1041.
Groisman, P. Y., T. R. Karl and R. W. Knight (1994). "Observed Impact of Snow Cover on the Heat Balance and the Rise of Continental Spring Temperatures." *Science* 263: 198-200.

Groisman, P. Y., R. W. Knight, and T. Karl. 2001. "Heavy precipitation and high streamflow in the contiguous United States: trends in the 20th century." *Bulletin of the American Meteorological Society* Vol. 82, pp. 219-246.

Hamlet, A. F. and D. P. Lettenmaier (1999). "Effects of climate change on hydrology and water resources in the Columbia River basin." *Journal of the American Water Resources Association* 35: 1597–1623.

Haston, L. and J. Michaelsen (1997). "Spatial and Temporal Variability of Southern California Precipitation over the Last 400 yr and Relationships to Atmospheric Circulation Patterns." *Journal of Climate* 10(8): 1836–1852.

Hauer, F. R., J. S. Baron, D. H. Campbell, K. D. Fausch, S. W. Hostetler, G. H. Leavesley and P. R. M. Leavitt, D.M. (1997). Assessment of climate change and freshwater ecosystems of the Rocky Mountains, USA and Canada. Freshwater ecosystems and climate change in North America - A regional assesment: *Advances in Hydrological Processes*. C. E. Cushing, J. Wiley: 85-106.

Hay, L. E., R. J. L. Wilby and G. H. Leavesley (2000). "A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States." *Journal of the American Water Resources Association* 36(2): 387-397.

Hayden, B. P. (1999). "Climate Change and Extratropical Storminess in the United States: An Assessment." *Journal of the American Water Resources Association* 35(6): 1387-1398.

Hennessy, K. J., J. M. Gregory and J. F. B. Mitchell (1997). "Changes in daily precipitation under enhanced greenhouse conditions." *Climate Dynamics* 13: 667–680.

Hostetler, S. W. and E. E. Small (1999). "Response of North American Freshwater Lakes to Simulated Future Climates." *Journal of the American Water Resources Association* 35(6): 1625-1638.

Hughes, M. K. and P. M. Brown (1992). "Drought frequency in central California since 101 B.C. recorded in giant sequoia tree rings." *Climate Dynamics* 6: 161–167.

Intergovernmental Panel on Climate Change (IPCC). 2001. The Scientific Basis: IPCC Third Assessment Report, Cambridge University Press, Cambridge, UK.

Jacoby, H. D. (1990). Water Quality. Climate Change and U.S. Water Resources. P. E. Waggoner. New York, John Wiley & Sons: 307-328.

Karl, T. R. and R. W. Knight (1998). "Secular trends of precipitation amount, frequency, and intensity in the United States." *Bulletin of the American Meteorological Society* 79(2): 231-241.

Kim, J., T.-K. Kim, R. W. Arritt and N. L. Miller (2002). "Impacts of Increased Atmospheric CO_2 on the Hydroclimate of the Western United States." *Journal of Climate* **15**: 1926-1943.

Knowles, N. and D. R. Cayan (2002). "Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary." *Geophysical Research Letters* 29(18): 1891.

Korner, C. (1996). The response of complex multispecies systems to elevated CO_2. Global Change and Terrestrial Ecosystems. B. R. Walker and W. Steffen. Cambridge, United Kingdom, Cambridge University Press: 20-42.

Laird, K. R., S. C. Fritz, E. C. Grimm and P. G. Mueller (1996). "Century-scale paleoclimatic reconstruction from Moon Lake, a closed-Basin lake in the northern Great Plains." *Limnology and Oceanography* 41: 890-902.

Lambert, S. J. (1995). "The Effect of Enhanced Greenhouse Warming on Winter Cyclone Frequencies and Strengths." *Journal of Climate* 8(5): 1447–1452.

Lettenmaier, D. P. and T. Y. Gan (1990). "Hydrologic Sensitivities of the Sacramento-San Joaquin River Basin, California, to Global Warming." *Water Resources Research* 26(1): 69-86.

Lettenmaier, D. P. and D. P. Sheer (1991). "Climatic Sensitivity of California Water Resources." *Journal of Water Resources Planning and Management* 117(1): 108-125.

Lettenmaier, D. P., E. F. Wood and J. R. Wallis (1994). "Hydro-Climatological Trends in the Continental United States, 1948-1988." *Journal of Climatology* 7: 586-607.

Lettenmaier, D. P., A. W. Wood, R. N. Palmer, E. F. Wood and E. Z. Stakhiv (1999). "Water Resources Implications of Global Warming: A U.S. Regional Perspective." *Climatic Change* 43(3): 537-579.

Lins, H. F. and J. R. Slack (1999). "Streamflow trends in the United States." *Geophysical Research Letters* 26(2): 227-230.

Lord, W.B., J.F. Booker, D.H. Getches, B.L. Harding, D.S. Kenney, and R.A. Young. 1995. Managing the Colorado River in a severe sustained drought: An evaluation of institutional options. *Water Resources Bulletin*, Vol. 31, No. 5, pp. 939-944.

Major, D. C. (1998). "Climate Change and Water Resources: The Role of Risk Management Methods." *Water Resources Update*(112): 47-50.

Matalas, N. C. and M. B. Fiering (1977). Water-Resource Systems Planning. Climate, Climatic Change, and Water Supply. Washington, DC, National Academy of Sciences Press: 99-110.

McCabe, G. J. (1996). "Effects of winter atmospheric circulation on temporal and spatial variability in annual streamflow in the western United States." *Hydrological Sciences Journal* 41: 873-888.

McCabe, G. J. and D. M. Wolock (1999). "Future snowpack conditions in the western United States derived from general circulation model climate simulations." *Journal of the American Water Resources Association* 35: 1473-1484.

McCarthy, J. J., O. F. Canziani, N. A. Leary, D. J. Dokken, K. S. White and (Eds.), Eds. (2001). Climate Change 2001: Impacts, Adaptation & Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, Cambridge University Press.

McCormick, M. J. (1990). "Potential Changes in Thermal Structure and Cycle of Lake Michigan Due to Global Warming." *Transactions of the American Fisheries Society* 119(2): 183-194.

Meehl, G. A., F. Zwiers, J. Evans, T. Knutson, L. Mearns and P. Whetton (2000). "Trends in extreme weather and climate events: Issues related to modeling extremes in projections of future climate change." *Bulletin of the American Meteorological Society* 81(3): 427-436.

Meko, D. M., C. W. Stockton and W. R. Boggess (1980). "A tree-ring reconstruction of drought in southern California." *Water Resources Bulletin* 16: 594–600.

Meko, D. M., M. D. Therrell, C. H. Baisan and M. K. Hughes (2001). "Sacramento River flow reconstructed to AD 869 from tree rings." *Journal of the American Water Resources Association* 37(4): 1029-1039.

Melack, J. M., J. Dozier, C. R. Goldman, D. Greenland, A. M. Milner and R. J. Naiman (1997). "Effects of Climate Change on Inland Waters of the Pacific Coastal Mountains and Western Great Basin of North America." *Hydrological Processes* 11(8): 971-992.

Meyer, J. L., M. J. Sale, P. J. Mulholland and N. LeRoy Poff (1999). "Impacts of Climate Change on Aquatic Ecosystem Functioning and Health." *Journal of the American Water Resources Association* 35(6): 1373-1386.

Michaelsen, J., L. Haston and F. W. Davis (1987). "400 years of central California precipitation variability reconstructed from tree-rings." *Water Resources Bulletin* 23: 809–818.

Miller, N., Kim, J.W., and Dettinger, M.D., 1999, California streamflow evaluation based on a dynamically downscaled 8-year hindcast (1988-1995), observations, and physically based hydrologic models: *Eos*, American Geophysical Union Fall Meeting supplement, v. 80, p. F406.

Mimikou, M., Y. Kouvopoulos, G. Cavadias and N. Vayianos (1991a). "Regional hydrological effects of climate change." *Journal of Hydrology* 123(1-2): 119-146.

Mimikou, M. A., P. S. Hadjisavva, Y. S. Kouvopoulos and H. Afrateos (1991b). "Regional climate change impacts. II. Impacts on water management works." *Hydrological Sciences Journal* 36(3): 259-270.

Mimikou, M. A. and Y. S. Kouvopoulos (1991). "Regional Climate Change Impacts: Impacts on Water Resources." *Hydrological Sciences Journal* 36(3): 247-258.

Moore, M. V., M. L. Pace, J. R. Mather, P. S. Murdoch, R. W. Howarth, C. L. Folt, C. Y. Chen, H. F. Hemond, P. A. Flebbe and C. T. Driscoll (1997). "Potential Effects of Climate Change on Freshwater Ecosystems of the New England/Mid Atlantic Region." *Hydrological Processes* 11(8): 925-947.

Mulholland, P. J., G. R. Best, C. C. Coutant, G. M. Hornberger, J. L. Meyer, P. J. Robinson, J. R. Stenberg, R. E. Turner, F. Vera-Herrera and R. G. Wetzel (1997). "Effects of Climate

Change on Freshwater Ecosystems of the Southeastern United States and the Gulf of Mexico." *Hydrological Processes* 11(8): 949-970.
Murdoch, P. S., D. A. Burns and G. B. Lawrence (1998). "Relation of Climate Change to the Acidification of Surface Waters by Nitrogen Deposition." *Environmental Science & Technology* 32: 1642-1647.
Murdoch, P. S., J. S. Baron and T. L. Miller (2000). "Potential effects of climate change on surface water quality in North America." *Journal of the American Water Resources Association* 36: 347-366.
Nash, L.L. and P.H. Gleick. 1991. The sensitivity of streamflow in the Colorado Basin to climatic changes. *Journal of Hydrology* Vol. 125, pp. 221-241.
Nash, L. L. and P. H. Gleick (1991). The Implications of Climate Change for Water Resources in the Colorado River Basin. First National Conference on Climate Change and Water Resources Management, Albuquerque, NM, U.S. Army Corps of Engineers.
Nash, L. L. and P. H. Gleick (1993). The Colorado River Basin and Climatic Change: the Sensitivity of Streamflow and Water Supply to Variations in the Temperature and Precipitation. Washington, DC, U.S. EPA: 121 pp.
Noda, A. and T. Tokioka (1989). "The Effect of Doubling the CO_2 Concentration on Convective and Non-Convective Precipitation in a General Circulation Model Coupled with a Simple Mixed Layer Ocean Model." *Journal of the Meteorological Society of Japan* 67: 1057-1069.
O'Conner, R. E., B. Yarnal, R. Neff, R. Bord, N. Wiefek, C. Reenock, R. Shudak, C. L. Jocoy, P. Pacale and C. G. Knight (1999). "Weather and Climate Extremes, Climate Change, and Planning: Views of Community Water System Managers in Pennsylvania's Susquehanna River Basin." *Journal of the American Water Resources Association* 35(6): 1411-1420.
Owens-Viani, L., A.K. Wong, and P.H. Gleick (editors). 1999. Sustainable Use of Water: California Success Stories. Pacific Institute for Studies in Development, Environment, and Security, Oakland, California.
Piechota, T. C., J. A. Dracup and R. G. Fovell (1997). "Western U.S. streamflow and atmospheric circulation patterns during El Nino-Southern Oscillation." *Journal of Hydrology* 201: 249-271.
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, National Academy Press, Washington, D.C.
Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig and R. Ruedy (1990). "Potential Evapotranspiration and the Likelihood of Future Drought." *Journal of Geophysical Research-Atmospheres* 95(D7): 9983-10004.
Robinson, P. J., A. N. Samel and G. Madden (1993). "Comparisons of modelled and observed climate for impacts assessments." *Theoretical and Applied Climatology* 48: 75-87.
Roos, M. (1987). Possible Changes in California Snowmelt Runoff Patterns. Fourth Annual Pacific Climate (PACLIM) Workshop, Pacific Grove, CA.
Roos, M. 2003. The Effects of Global Climate Change on California Water Resources. Contractors Report, Public Interest Energy Research, California Energy Commission, P500-03-025 (April), Sacramento, California.
Rötter, R. and S. C. v. d. Geijn (1999). "Climate Change Effects on Plant Growth, Crop Yield and Livestock." *Climatic Change* 43(4): 651-681.
Schaake, J.C. 1990. From climate to flow. In P.E. Waggoner (editor) Climate Change and U.S. Water Resources, J. Wiley and Sons, New York, pp. 177-206.
Schindler, D. W. (1997). "Widespread Effects of Climatic Warming on Freshwater Ecosystems in North America." *Hydrological Processes* 11(8): 1043-1067.
Shaw, M. R., E. S. Zavaleta, N. R. Chiariello, E. E. Cleland, H. A. Mooney and C. B. Field (2002). "Grassland Responses to Global Environmental Changes Suppressed by Elevated CO_2." *Science* 298(5600): 1987-1990.
Snyder, M. A., J. L. Bell, L. C. Sloan, P. B. Duffy and B. Govindasamy (2002). "Climate responses to a doubling of atmospheric carbon dioxide for a climatically vulnerable region." *Geophysical Research Letters* 29(11): 10.1029/2001GL014431.
Stine, S. (1994). "Extreme and Persistent Drought in California and Patagonia During Medieval Time." *Nature* 369(6481): 546-549.

Stockton, C.W. and W.R. Boggess. 1979. Geohydrological implications of climate change on water resource development. U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia.

Tarlock, A. D. (1991). "Western Water Law, Global Warming, and Growth Limitations." *Loyola Law Review* 24(4): 979-1014.

Timmermann, A., J. Oberhuber, A. Bacher, M. Esch, M. Latif and E. Roeckner (1999). "Increased El NiÒo Frequency in a Climate Model Forced by Future Greenhouse Warming." *Nature* 398: 694-696.

Trelease, F. J. (1977). Climatic Change and Water Law. Climate, Climatic Change, and Water Supply. Washington, DC, National Academy of Sciences Press.

Van Rheenen, N.T., A.W. Wood, R.N. Palmer and D.P. Lettenmaier. (2002). Potential Implications of PCM Climate Change Scenarios for Sacramento - San Joaquin River Basin Hydrology and Water Resources. *Climatic Change* in press

Vogel, R. M., C. Bell and N. M. Fennessey (1997). "Climate, Streamflow and Water Supply in the Northeastern United States." *Journal of Hydrology* 198(1-4): 42-68.

Waggoner, P. E., Ed. (1990). Climate Change and U.S. Water Resources. New York, John Wiley & Sons.

Ward, A. K., G. M. Ward, J. Harlin and R. Donahoe (1992). Geological Mediation of Stream Flow and Sediment and Solute Loading to Stream Ecosystems Due to Climate Change. Global Climate Change and Freshwater Ecosystems. P. Firth and S. G. Fisher. New York, Springer-Verlag: 116-142.

Westman, W. E. and G. P. Malanson (1992). Effects of Climate Change on Mediterranean-Type Ecosystems in California and Baja California. Global Warming and Biological Diversity. R. L. Peters and T. E. Lovejoy. New Haven, CT, Yale University Press: 258-276.

Wetherald, R. T. and S. Manabe (1999). "Detectability of Summer Dryness Caused by Greenhouse Warming." *Climatic Change* 43(3): 495-511.

Wilkinson, R. and others (2002). Potential Consequences of Climate Variability and Change for California. Draft Report of the California Regional Assessment Group for the U.S. Global Change Research Program. September 2002. Santa Barbara, CA.

Wilson, T., L. Williams, J. Smith, and R. Mendelsohn. 2003. unreviewed draft report: Global Climate Change and California Potential Implications for Health, Ecosystems, and the Economy. Distributed on a CD, February 10, 2003 from the PIER Program of the California Energy Commission.

Wood, A. W., D. P. Lettermaier and R. N. Palmer (1997). "Assessing Climate Change Implications for Water Resources Planning." *Climatic Change* 37(1): 203-228.

Yao, H. and A. Georgakakos (2001). "Assessment of Folsom Lake response to historical and potential future climate scenarios; 2. Reservoir management." *Journal of Hydrology* 249(1-4): 176-196.

PACIFIC
INSTITUTE

Research for People and the Planet

About The Pacific Institute

The **Pacific Institute** is an internationally recognized research center founded in 1987 to address the complex problems of global environment, economic development, and international security. The Institute has become one of the most respected independent organizations working on problems of freshwater, climate change, globalization, and human well-being. Our goal is to do research for people and the planet – to do high-quality analysis capable of influencing policymakers and the public and to work to ensure that that information reaches the proper places to make a difference.

We address a wide range of issues related to freshwater resources, sustainability, and efficiency through the **Water and Sustainability Program.** Using an integrated approach, we are developing a new water management paradigm that has regional and international applications in water policy decision-making. Our work on quantifying the potential for water-use efficiency improvements worldwide offers a powerful tool for water policy makers concerned about water management, ecological protection, and policy. The Institute also produces ***The World's Water*** – a biennial water report on critical issues published by the nation's premier environmental publisher, Island Press (Washington, D.C)

> "You want facts, credible and incontrovertible facts? Go to the Pacific Institute. You want a dedicated concern for the earth, its inhabitants, and the future? Go to the Pacific Institute. You want a small, smart staff that is connected to policymakers in the private and public sectors around the world? Go to the Pacific Institute. You want to fund the best of the best, with academic credentials but without the academic molasses? Go to the Pacific Institute. Now." Michael Fischer, Hewlett Foundation

> "Peter Gleick and his talented staff have established the Pacific Institute as one of the world's foremost research centers on sustainable development and the manifold, interlinked aspects of the critical theme of water. I find the Institute to be a continual source of outstanding and innovative publications. The Institute has become an invaluable resource for policy makers, educators, and students." The Honorable Richard E. Benedick, Chief Negotiator of the Montreal Protocol

The **Pacific Institute's** programs focus on three objectives:

- To conduct research on water and sustainability,
- To inform policymakers and the public about risks and opportunities in this changing world, and

- To make information that previously circulated only among academic researchers and technical experts more broadly available.

Our efforts focus on a subset of the world's critical problems because of our particular skills and our perception of the priorities that need to be addressed. Our work is therefore highly targeted to where we believe we can best contribute to solving some of our shared global problems and help develop the knowledge and decision-making skills needed to address present and future problems.

For more information, visit http://www.pacinst.org

Contact information:
Pacific Institute
Preservation Park
654 13th Street
Oakland, California 94612
510 251-1600 (telephone)
510 251-2203 (telefax)