

# Accounting for Climate Change

*By Maurice Roos, DWR*

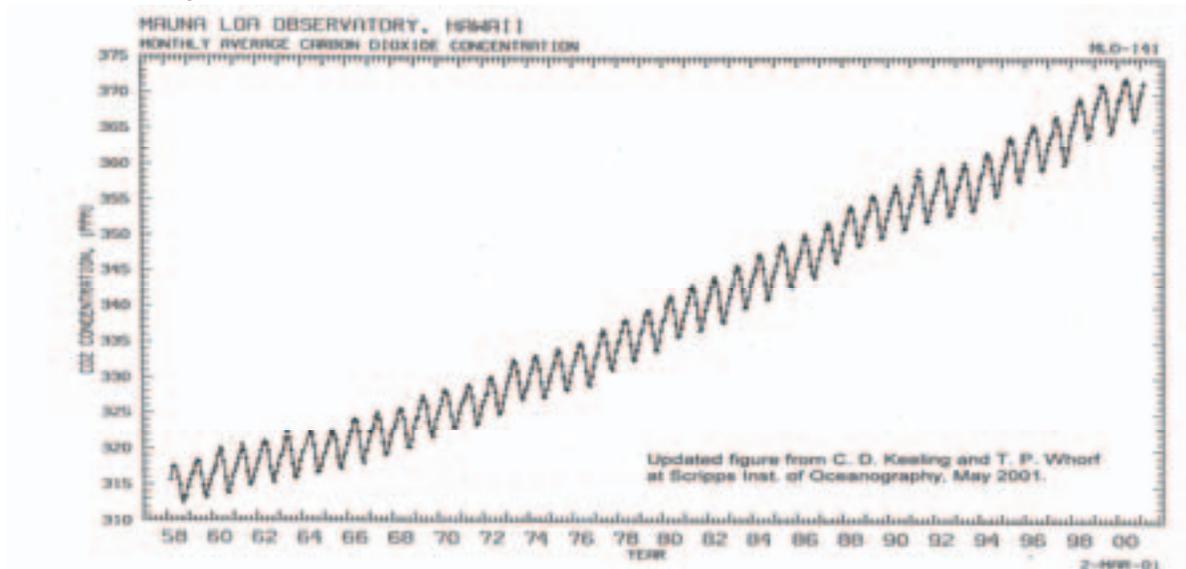
In recent years, evidence that global climate will have significant effects on water resources in California has continued to accumulate. Climate change can affect the amount, timing, and form of precipitation, whether rain or snow, that California receives, as well as the sea level of the Pacific Ocean. Moreover, changes in weather, especially temperature, and atmospheric composition can affect water use and consumption. Changes in climate have occurred during the 20<sup>th</sup> century, with noticeable warming in the last two decades.

Most scientists feel that changes during the last several decades are likely mostly due to human activities, but natural causes and variability cannot be ruled out as a significant component. Likewise, projections of amount of warming and other climate changes during the 21<sup>st</sup> century are wide ranging, depending on assumptions and models.

A major cause of expected climate change is the increasing amounts of greenhouse gases, such as carbon dioxide, in the atmosphere as a result of man's activities. These gases, as well as water vapor, allow solar radiation to pass inward through the atmosphere, but trap the longer wave infrared radiation reflected back from the earth's surface. Greenhouse gases are accumulating in the atmosphere; the following chart shows the gradual build up in carbon dioxide at Mauna Loa in Hawaii, as measured by Scripps Institution of Oceanography scientists. The annual cycle is caused by northern hemisphere vegetation uptake during the growing season. Other significant greenhouse gases are methane, nitrous oxide, halocarbons (like freon and its replacements), and, of course, water vapor itself. Cloud cover is an important element in the global radiation balance.

Whatever the causes, the prospects of significant changes warrant examination of how the State's water infrastructure and natural systems can accommodate or adapt to climate changes and whether more needs to be done to detect, evaluate and respond to water resource system effects. Many uncertainties remain, primarily on the degree of change to be expected. Responsible planning requires that the California water planning community work with climate scientists and others to reduce these uncertainties and to begin to prepare for those impacts that are well understood, already appearing as trends, or likely to appear. In this section we review possible impacts and address some of the responses appropriate for water planners and managers.

**Figure 1.**  
**Atmospheric Carbon Dioxide Concentration as measured at Mauna Loa, Hawaii**



By and large, reservoirs and water delivery systems and operating rules have been developed from historical hydrology on the assumption that the past is a good guide to the future. With global warming, that assumption may not be valid.

Significant changes in climate are projected for the latter part of this century due to global warming. These potential changes are expected to affect many of our water resources systems. Some of the more important changes would arise from temperature increases, which would raise temperate zone snow elevations and change the pattern of runoff from mountain watersheds, thereby affecting reservoir operation. Other consequences include sea level rise, which could adversely affect the Sacramento San Joaquin River Delta, a major source of water supply for the State; possibly more extreme precipitation and flood events; changes in water consumption by crops and wildlands; and water temperature problems for anadromous fish.

The California Water Plan first briefly addressed climate change a decade ago in a sidebar in Bulletin 160-93 when there was less consensus that global warming was beginning. Prior to that, the California Energy Commission had produced an extensive report in 1991, in response to 1988 legislation, which had significant discussion on reduced snowpack and changing runoff patterns, sea level rise, and water temperatures. This was the first major report by a State agency on the subject.

## Climate Projections

The most well known climate change projections by year 2100, the end of the century, due to the increase in greenhouse gases have been developed by the Intergovernmental Panel on Climate Change. The IPCC was jointly established in 1988 by the World Meteorological Organization and the United Nations Environment Programme to study climate change. The IPCC has issued several reports since 1990 outlining possible global warming and other potential effects of climate change as a result of increased greenhouse gases originating from human activities.

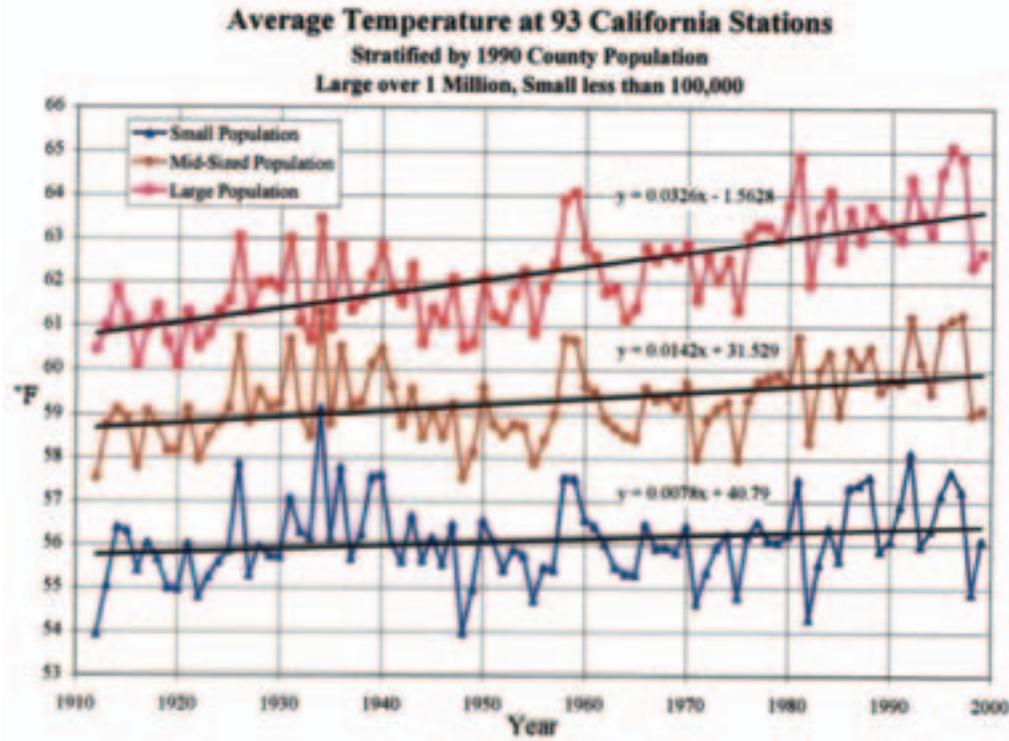
A good assessment of the state of research on the potential consequences of climate change on water resources in the United States, including what is known and what is not known, is the report of the National Water Assessment Group for the U.S. Global Change Research Program (Gleick and Adams, 2000).

The most recent IPCC Working Group I Summary Report, in its third assessment (IPCC, 2001), projects a 1990 to 2100 average surface temperature increase of around 3 degrees C, with a range of 1.4 to 5.8 degrees (2.5 to 10.4 degrees F). The increase in global temperature during the 20<sup>th</sup> century was estimated to be about 0.6 degrees C (1.0 degree F), much of which occurred by 1940, and a recent significant increase after 1980 which is believed to be primarily of human origin. Because of warmer temperatures, some increase in global evaporation and therefore more precipitation is projected for the 21<sup>st</sup> century, more likely at higher latitudes north of California.

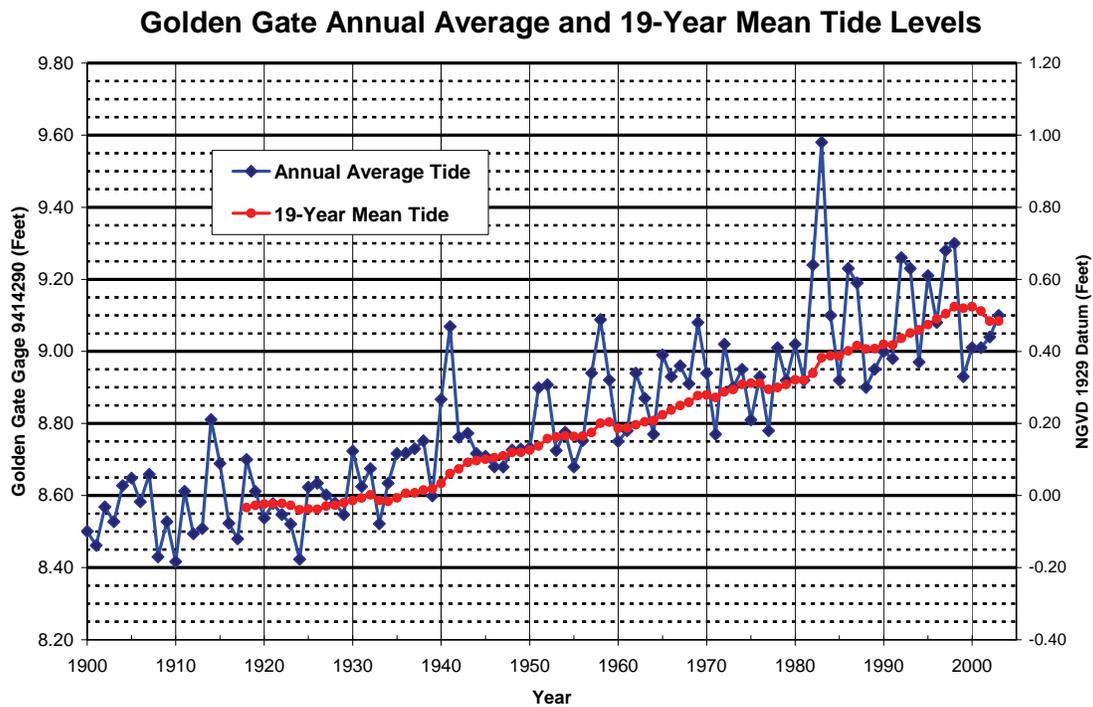
The chart shows temperature trends for three groups of stations in California during the 20<sup>th</sup> century. What is notable is the urban heat island influence, wherein the counties with large populations show more warming than rural counties. Although not directly related to greenhouse gas increases, the local urban warming does matter to local residents because it affects their lives and local environment.

Sea level (IPCC, 2001) is projected to rise around 0.5 meter (1.6 feet) by 2100, with a range of 0.1 to 0.9 meters (0.3 to 2.9 feet). The rate during the 20<sup>th</sup> century appears to have been around 0.2 meters (0.7 feet) with a range of 0.1 to 0.25 meters (0.3 to 0.8 feet). The 0.2-meter figure is consistent with the historical trend at the Golden Gate tide station, although it is possible that tectonic movement, or settlement, has influenced the stages there.

**Figure 2**  
**Long term average temperatures at different locations in California (J. D. Goodridge)**



**Figure 3:**



**Note: This figure was updated 12/08/04**

There is a general expectation that a warmer climate would lead to more intense precipitation events, potentially causing somewhat bigger floods and more intense convective storms, thereby affecting the rainfall statistics used for storm drainage design. The IPCC report rates prediction confidence in more intense precipitation events as “very likely, over many areas”. A couple of recent research studies attempting to downscale global climate model results to the watershed scale in California indicated substantial increases in the size of floods

The increase in carbon dioxide, from the current 370 ppm to perhaps 600 or 700 ppm is expected to benefit growth of many food crops, provided the water supply is adequate and temperatures don't get too hot. Higher carbon dioxide concentrations in the air could partly offset the higher water use (evapotranspiration) in agricultural production resulting from warmer temperatures.

Warmer air and less snowpack would be expected to raise average stream and estuary water temperatures. This would increase the problem for cold-water fisheries, including salmon and steelhead.

All of these projected changes, as well as some not yet identified, are likely to affect the hydrologic cycle and the water resources of California.

## **Major Consequences to Water Resources Systems**

There are a large number of potential effects on California water resources infrastructure due to global warming. Much depends on the degree of warming and whether future changes are small or large. There are potential impacts on snowpack accumulation and melting, runoff patterns, water supply, sea level, floods and droughts, water demands, water temperature, plant and animal life including livestock, hydroelectric power, wild fires, recreation, water quality, soil moisture, groundwater, and ecosystems. Only five of these will be dealt with in the section: water supply, sea level rise, extremes (primarily floods), water requirements, and river water temperature.

### **Water Supply**

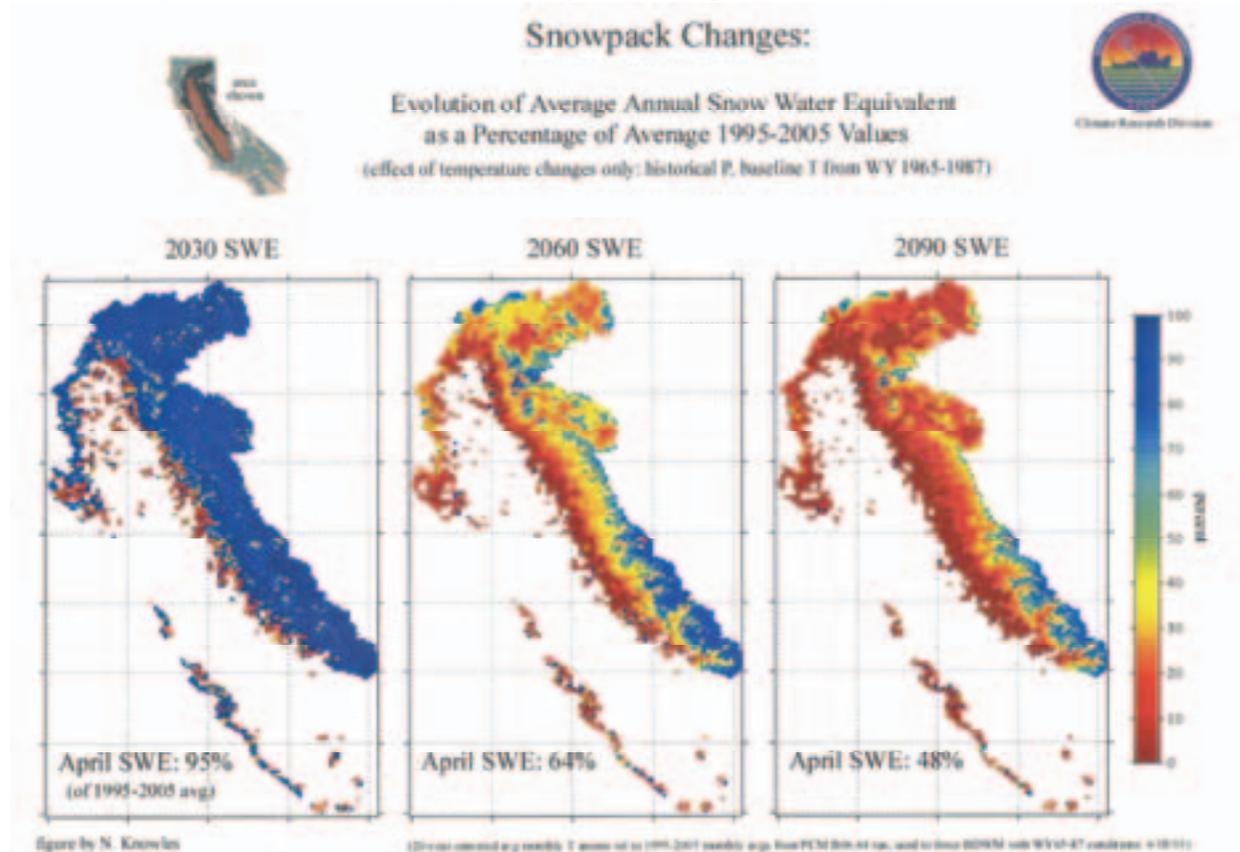
The most important parameter in determining runoff and therefore water supply is precipitation. Regional precipitation predictions in the huge general circulation models of the atmosphere have not been reliable, and vary greatly among the different models. As a general rule, a warmer world would mean more evaporation, hence more precipitation overall. But where and when the precipitations falls is all important. Some researchers think that climate warming might push the winter storm track on the West Coast further north, which would mean a drier California. On the other hand, some of the new GCM's, including the two used in the National Water Assessment, increase average California precipitation.

If warming occurs, one impact is considered relatively certain. On average, snow levels in the mountains will rise and the average amount of snow covered area and the snowpack will decrease. A reasonable estimate is about 500 feet of elevation change for every degree C rise. Many early studies, including the 1989 National Academy of Science report, have used 3°C as a benchmark of scenarios, which is still in the midrange of the new IPCC predictions, as a reasonable 100-year projection for the western states. This would mean a rise of about 1,500 feet in average snow levels. Historical average snow elevations on April 1 (the usual peak of the snow accumulation season) range from about 4,500 feet in the north above Shasta Lake to around 6,000 feet in the southern Sierra. Earlier DWR assessments some years ago came up with estimates for a rise of 1,500 feet in the average freezing level during storms and 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 nearly 3 million acre-feet of April through July runoff. The impact would be much less in the higher elevation southern Sierra. About seven tenths of the San Joaquin/Tulare Lake region snow zone would stay.

Not all the spring runoff comes from melting snow. In the northern Sierra, spring rainfall is an important contributor. The estimated average reduction in Sacramento River region April through July runoff was projected to be 43 percent, leaving 57 percent of current runoff. The southern Sierra impact was less with 23 percent reduction overall. The total runoff reduction for all watersheds was 33 percent. These results were crude and preliminary, but have been roughly confirmed by more recent work by Scripps and others. A Knowles and Cayan study (Scripps, 2001) included a 2090 projection from the Parallel Climate Model with 2.1 degrees C (3.8 F) of warming to come up with a 50 percent reduction in April snow water content and a 4.5 million acre- feet reduction in April through July runoff.

**Figure 4**  
**Projected Snow Pack as a percentage of Average 1995-2005 (Knowles and Cayan)**



Some GCM studies project significantly more winter season precipitation in California, some models are drier. It is possible for the southern Sierra snowmelt runoff to increase in the wetter scenarios, albeit from less area. All models so far show less snowmelt runoff in the northern Sierra.

Less spring snowmelt could 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

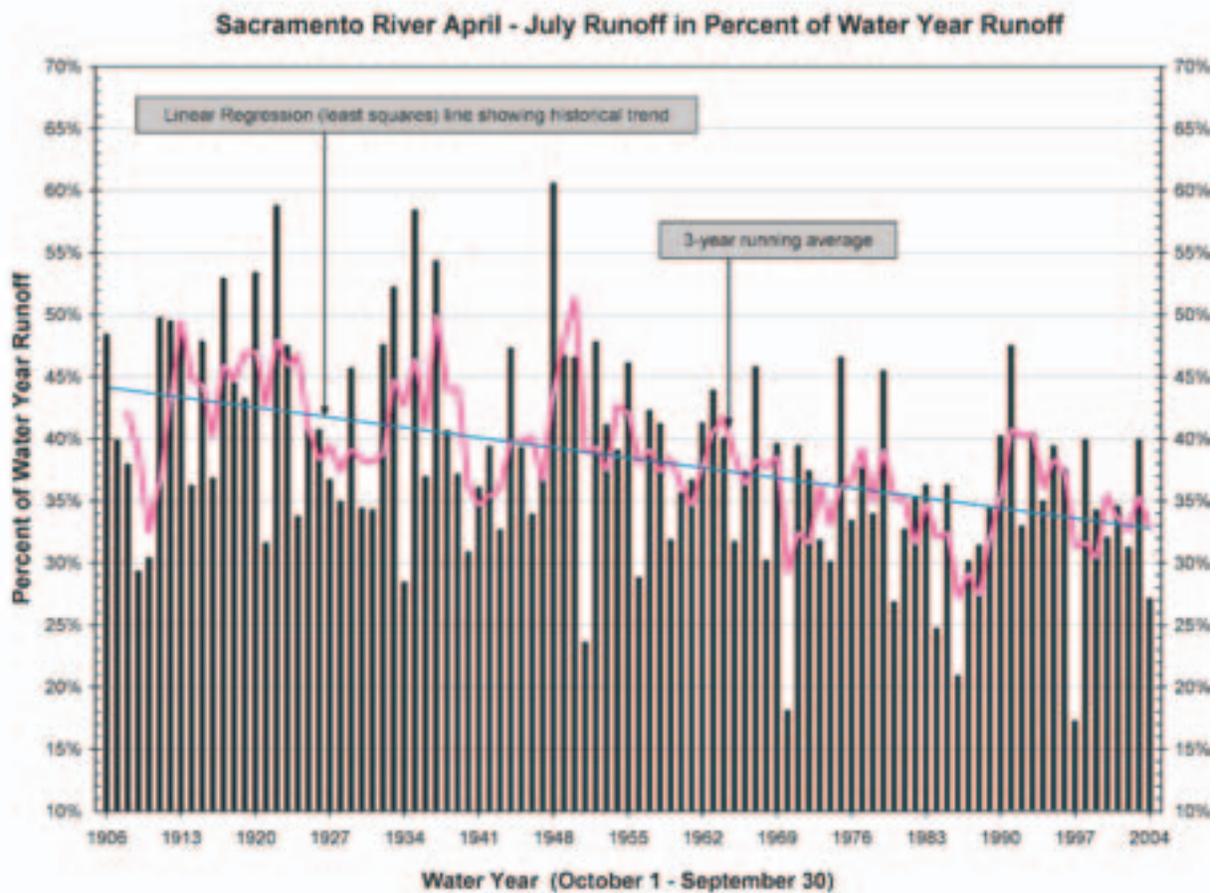
during the dry season. Lower early summer reservoir levels also would adversely affect lake recreation and hydroelectric power production, with possible late season temperature problems for downstream fisheries.

April-July runoff, primarily snowmelt, in California major rivers (including the Trinity River which supplies water to the Central Valley Project) amounts to about 14 million acre-feet on average. This is about 40 percent of the estimated total State net demand for agricultural and urban water use. Replacing that would take about 4 to 5 MAF of reservoir storage, increased conveyance facilities and other measures. Of course, if precipitation increases, reductions in runoff would be less, especially in the higher elevation southern Sierra.

Not all river systems would be equally affected; much depends on the existing storage capacity. One would expect only a slight impact on the Stanislaus River, for example, where the ratio of storage to average annual runoff is about 2.5 and winter spills on flood control releases are uncommon. The American River ratio is about 0.64 so it is likely to be more affected.

One can look at our recent hydrologic history to see if any trends are evident. The chart shows the record for the Sacramento River system for the 20<sup>th</sup> century. April through July runoff is plotted as a percentage of total water year runoff. There really was not much trend until the last half of the century, when the percentage of April through July runoff begins to show a progressive decline. Changes in North Pacific ocean current patterns, known as the Pacific Decadal Oscillation may explain part of the trend. The same effect is noted on the southern Sierra rivers, but the decrease is less. The same downward pattern in Sacramento River snowmelt runoff can be seen on a chart plotting volume with years, but the fit is poorer and a consistent trend not as evident.

Figure 5



*Note: This figure was updated 12/08/04*

## Sea Level Rise

A second potential impact is sea level rise. This would lead eventually to problems in certain coastal areas with low-lying salt marshes and other lands protected by dikes. But the big impact on California water supply could be in the Sacramento-San Joaquin Delta. There the problem would be two-fold: (1) problems with the levees protecting the low-lying land, much already below sea level and (2) increased salinity intrusion from the ocean which could degrade fresh water transfer supplies pumped at the southern edge of the Delta or require more fresh water releases to repel ocean salinity.

Many of the central Delta levees are built on unstable peat soil and are vulnerable to high water peaks. The potential impact of sea level rise on these levees depends on the rate of increase. A small rise can probably be tolerated by the levee system; a major rise of one foot or more could cause significant problems. Extrapolating current trends yields about 0.4 foot by year 2050. The IPCC median projection is about 1.6 feet by 2100. One perspective is that a one-foot rise would transform the current 100-year high tide peak at Antioch, a western Delta station, into about a 10-year event. Thus the rare high event could become a more frequent threat to the Delta levees and the role they play in protecting the sensitive Delta.

Since California is tectonically active, it is the net combined effect of geologic change, rising or falling land, and sea level rise, which matters. The effect of a rising ocean would be magnified where land subsidence is occurring and decreased where uplift is happening.

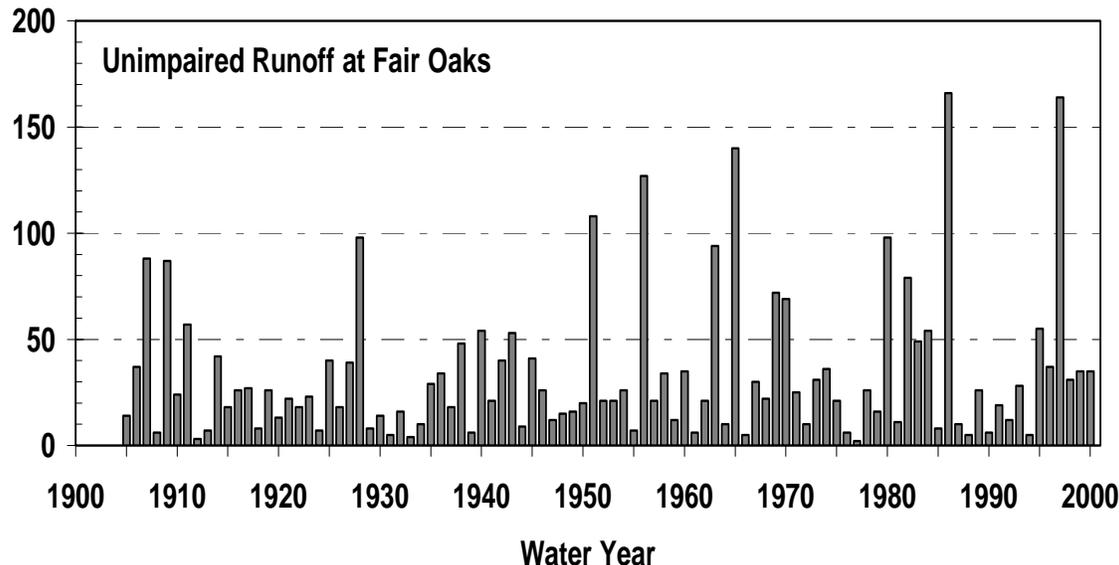
Salinity intrusion is a function of channel depth and time, increasing rapidly with depth. Climate change induced sea level rise could increase overall channel depths, potentially increasing salinity intrusion and diminishing water quality for south of Delta users. Reduced excess snowmelt in the spring would also mean a longer dry season, that is, more time, for saltwater intrusion. However, depths in the upper estuary and the western Delta may not change that much if the sea level rise is small.

## **More Extreme Events**

A third possible effect could be more extreme events: (1) larger floods and more intense precipitation events, particularly if the wetter winter scenario of the National Water Assessment materializes, and (2) longer drier droughts if other model scenarios are considered.

There is a general relationship between rainfall intensity and the warmth of the climate. Other factors being equal, warm air holds more water vapor than cool air. For a given amount of lift of saturated air, more condensation will occur from warmer as compared to cooler air. Therefore, lifting of the air either orographically by winds blowing over a mountain range, by convective activity (thunderstorms), or by a weather system front has the potential for greater precipitation intensity. Also, higher snow levels in the Sierra Nevada and other high mountains mean more watershed area contributing direct rain runoff during winter storms and less snow accumulation.

**Figure 6**  
**American River Three Day Flood Bar Chart**



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. When these moisture-laden weather systems run into the mountains, copious amounts of rain and runoff are produced as the air is lifted by the mountain ranges. Whether the southwesterly winter storm winds would be stronger or weaker if global warming occurs has not been determined. In one simple experiment by the Department of Water Resources on the American River basin east of Sacramento, temperatures of a major storm (like that of February 1986) were raised three degrees Celsius, keeping the strength of the southwesterly winds and the relative humidity the same. The storm runoff increased about 10 percent. If storm intensities increase, it is likely the probable maximum flood used for dam spillway design would be bigger.

Research work by Dr. Michael Dettinger of Scripps Institution of Oceanography and Dr. Norman Miller and associates at Berkeley National Laboratory show an increased risk of large storms and flood events for several GCM scenarios. Since existing flood control facilities in the Central Valley and elsewhere seem to be barely able to accommodate large flood events, like the 1-in-100-year flood, even a modest increase could pose problems. An increase in winter flood control space would conflict with operations for water supply, power and recreation on many of the big multipurpose reservoirs in California. The total volume of maximum winter flood control space requirements on major Central Valley foothill reservoirs exceeds 5.5 million acre-feet.

Increasing winter flood control space generally would make it more difficult to fill reservoirs in the spring. The filling problem would be compounded if spring runoff were reduced because of smaller snowpacks.

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.

## Water Use

There are likely to be changes in water use as well as in water supply. Water consumption changes may be small, but because so much land area is involved, amounts could be very significant. Generally, a slightly warmer climate with less frost and a higher atmospheric concentration of carbon dioxide is regarded as beneficial to most food crops.

As a rule, plant evapotranspiration (ET) increases with temperature. Higher carbon dioxide levels, however, reduce water consumption (at least in laboratory tests), and seem to increase yield. In the opinion of knowledgeable researchers, the higher water consumption with warmer temperatures will probably 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 annual crops because it may be possible to change the planting season a few weeks, which may result in no net change in water use for that crop.

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.

### Warmer Water Temperature

Of considerable concern, if California temperatures rise significantly, would be managing salmon and steelhead fisheries. Warmer air 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 stay in these rivers during the summer. Under this scenario, it is doubtful that the existing, cold-water temperature standards in the upper Sacramento River would be able to be maintained. Problems are likely for juvenile steelhead, as well.

A few of the major reservoirs have multilevel outlet structures able to control discharge water temperatures. For many of the others where downstream fisheries require cold water, temperature control structures should be considered and, where feasible, installed.

## Colorado River Impacts

The Colorado River in recent years has furnished slightly over half of the total water supply for the South Coast and Colorado River regions of Southern California. With the planned reduction in California diversions to 4.4 million acre-feet it will still furnish about 45 percent of estimated current water demands, a very important portion of the State's water budget. Because total reservoir storage on the Colorado River exceeds 4 times the average annual runoff of about 15 million acre-feet, its water supplies are not very vulnerable to seasonal shifts in runoff due to less snowpack. Rather it is the total annual amount of runoff which matters. Most of the runoff is generated from a relatively small portion of the basin, on the order of 10 percent, which is the high elevation mountain region. Studies by Nash and Gleick (1993) indicate that percentage changes due to global warming may be somewhat less in the higher watersheds than when modeling the basin as a whole above Glen Canyon dam. Their 1993 report also indicates that about a 10 percent increase in precipitation would be required to offset the drying effect of about the same percentage due to a temperature rise of 2 degrees C.

Some GCM models show more precipitation in the Colorado River basin. Only a modest increase in runoff, on the order of 10 percent, can change the emphasis from water supply shortages to flood control. The message is that what happens on the Colorado River is very important to California, but more studies are needed to assess probable directions of impacts. A slightly drier scenario could rule out interim surplus over the 4.4 million acre-feet for California. Beyond that, under current law, further decreases in runoff would have to be absorbed by Arizona.

## **Adapting to Change**

Even though there are large variances in GCM model results on certain parameters, such as likely future precipitation, some effects are consistent:

- Temperatures will rise, which will affect the extent and amount of winter snowpack in the mountains.
- However, the range in projections of the amount of temperature increase to expect is still quite large.
- Sea levels will rise with a likely minimum rate of 0.2 meter (0.7 feet) in the next century (the apparent recent historical rate) and possibly more.
- Some increase in the intensity of extreme precipitation and flood events is likely.
- Because of generally higher temperatures, some increase in crop and urban greenery water requirements is likely, but not large increases.
- River and estuary water temperatures will rise with increasing problems for cold water fisheries.

## **What We Need to Know**

There are a number of needs for better information regarding climate change on which to base water resources planning. Foremost is better hydrologic monitoring so we can assess trends and changes which are underway. Because weather and hydrology are so inherently variable, many years of consistent and accurate measurements are vital. Besides indicating quantitative changes, the proposed monitoring is necessary feedback into calibrating climate models used for future predictions. Currently there are few good climate data stations in the mountain zones where the more significant changes are expected.

For water systems in California and elsewhere, climate model precipitation is probably the most important parameter. This must be developed at the watershed level for a representative set of future scenarios. The major tool for evaluating the impact on major water project systems would be the CALSIM reservoir system operation (simulation) model developed jointly by DWR and USBR. Development of modified monthly input to CALSIM from the climate models will require help from the research community. The heart of an adaptation program to improve the State's capacity to operate its complex water management system in the face of different and perhaps a more variable climate depends on assessing simulated operation over long hydrologic time periods. This would enable proactive planning and development of options and strategies to improve water supply and quality, including adapting to sea level rise in the Delta and possibly reoperation for flood control. Initial tests of the CVP-SWP system would more practically be based on a 50-year projection of trends during the past 50 years.

The December 2002 report of the California Floodplain Task Force did take note of the potential for bigger floods and changes in flood frequency with climate change. Conceivably, if more definite

estimates of these changes can be determined from further research with GCM results, some allowance for climate change can be built into the Task Force's concept of the "reasonably foreseeable flood."

Evaluation of major multipurpose reservoir flood control aspects is another major need, which would require generation of at least daily inflow from the watersheds. Linking climate and hydrologic models can provide such inflow, but is a major task. Some screening by climate model experts will be needed to select the climate models which can provide a more plausible future. Since the big floods are rare events, simulation of long periods of climate, thence runoff, and are required to develop confidence in results. Since there will be competition at the big multipurpose reservoirs between flood control and other purposes, a thorough examination of the flood space relaxation criteria in the spring would be in order. Possibilities of basing part of the flood space requirements on weather forecasts should be tested.

It is anticipated that changes in water requirements of crops, wildlands, and landscaping will be gradual. Some monitoring of reference evapotranspiration by renovating or reinstalling a few of the lysimeters which were operating in the 1960's is recommended to see if changes in the past 30 or 40 years are measurable. This would need to be a multi-year effort, possibly for 10 years, because of the variability from season to season.

While the evapotranspiration measurements are underway, it should be possible to convene a group or task force of knowledgeable experts on plant water consumption and agricultural practices by people from the university system and government. The goal would be to develop likely changes in evapotranspiration, and perhaps some ranges for year 2050 or 2100 scenarios, with warmer average temperatures and a higher carbon dioxide content of the atmosphere. To do this, some reasonable projections of future weather, including growing season precipitation are needed from the climate modelers. Some increase in plant water requirements would be expected because of warmer temperatures, but probably not a large percentage change.

The fifth major concern would be water temperature increases. There are existing models of water temperature which have been in use for a decade on some of the Sacramento River region major rivers. These models may need improvement as the job of maintaining suitable downstream temperatures becomes more difficult. Analysis of selected foothill reservoirs and rivers is suggested to see what a different pattern of inflow and higher air temperatures would do. New or upgraded temperature modeling is being developed as part of the Oroville power plant relicensing project. Once these tools are selected or developed, researchers can apply them to other streams and reservoirs. A logical extension would be to apply the new temperature models to evaluate the affect of a changed climate and runoff scenario, beginning with Lake Oroville and the Feather River.

The last item of strong interest would be effects of climate change in regions near California, especially the Colorado and Columbia River regions. The Colorado River would be most important to California because of potential impacts on water supply, with some potential effect on hydroelectric power. The Columbia River basin is an important source of electric power for California during the summer. If conditions there turned drier, there would be an impact on electricity as happened during 2001. For these basins, the best course of action for now may be to monitor results of anticipated new research and studies on runoff and water supply in both of these regions forthcoming by interested regional parties.

Summary

The preceding items are the major expected effects of global warming on the California water resources system. Climate change is just one of the factors water planners need to face in the coming century. Other factors include dealing with an expanding population, growth, environmental needs and maintaining the quality of land on water resources. Some degree of warming and sea level rise seem reasonably certain, but with the uncertainty of current climate model precipitation, the range of possible changes is quite large. There is serious scientific evidence that global warming will pose serious challenges to our water infrastructure. It is time to try to quantify the effects of projected climate change on California's water resources. Being aware of potential climate changes should help in preparing better for an uncertain 21<sup>st</sup> century.