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THE IMPACTS OF CLIMATIC CHANGES FOR WATER RESOURCES OF THE COLORADO AND SACRAMENTO-SAN JOAQUIN RIVER BASINS[1]

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ABSTRACT: A wide variety of regional assessments of the water-related impacts of climatic change have been done over the past two decades, using different methods, approaches, climate models, and assumptions. As part of the Water Sector research for the National Assessment of the Implications of Climatic Variability and Change for the United States, several major summaries have been prepared, looking at the differences and similarities in results among regional research projects. Two such summaries are presented here, for the Colorado River Basin and the Sacramento River Basin. Both of these watersheds are vitally important to the social, economic, and ecological character of their regions; both are large snowmelt-driven basins; both have extensive and complex water management systems in place; and both have had numerous, independent studies done on them. This review analyzes the models, methods, climate assumptions, and conclusions from these studies, and places them in the context of the new climate scenarios developed for the National Assessment. Some significant and consistent impacts have been identified for these basins, across a wide range of potential climate changes. Among the most important is the shift in the timing of runoff that results from changes in snowfall and snowmelt dynamics. This shift has been seen in every regional result across these two basins despite differences in models and climate change assumptions. The implications of these impacts for water management, planning, and policy are discussed.
(KEY TERMS: climatic change; water resources; watershed management; floods; droughts; modeling; water policy.)

INTRODUCTION

A wide variety of regional assessments of the water-related impacts of climatic change have been completed over the past two decades, using different methods, approaches, climate models, and assumptions. As part of the Water Sector research for the National Assessment of the Implications of Climatic Variability and Change for the United States, several major summaries have been prepared, looking at the differences and similarities in results among regional research projects. Two such summaries are presented here, for the Colorado River Basin and the Sacramento-San Joaquin River Basin. Both of these major watersheds are vitally important to the social, economic, and ecological character of their regions; both are large snowmelt-driven basins; both have extensive and complex water-management systems in place; and both have had several, independent studies done on them over the past 20 years. This review summarizes the models, methods, climate assumptions, and conclusions from these studies, and places them in the context of the new climate scenarios developed for the National Assessment. Some significant and consistent impacts have been identified for these basins, across a wide range of potential climate changes. The most important of these expected impacts are the result of rising temperatures on snow dynamics of these basins. First identified in the 1980s for the Sacramento River basin, changes in the timing and magnitude of snowmelt runoff due to higher temperatures have been seen in every subsequent study, despite significant differences in model design, climate assumptions, watershed scale, and other factors. The implications of these impacts for water management, planning, and policy are discussed.

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COLORADO RIVER BASIN STUDIES

Basin Overview

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. As we approach both the end of the 20th century and the limits of the water supply of the basin, the complicated laws and institutions developed to manage the river are reaching a crisis. Too many users are chasing too little water in a basin with one of the most complex set of legal, institutional, and physical structures in the world. Compounding the problem is that the health of the aquatic ecosystems in the Colorado River basin has seriously declined because of the way water has been allocated and used over the past century. Global climatic changes will be imposed on the Colorado on top of these non-climate related stresses.

Ironically, one of the earliest white explorers to the southwestern U.S. wrote:

> "Ours has been the first, and will doubtless be the last party of whites to visit this profitless locality. It seems intended by nature that the Colorado River, along the greater portion of its lonely and majestic way, shall be forever unvisited and undisturbed" (quoted in Dracup, 1977).

History has proven otherwise, and the Colorado can no longer be described as unvisited and undisturbed. Indeed, the Colorado River is one of the most heavily managed rivers in the world, and the current intensive use of Colorado River basin water resources is often described as unsustainable. Long-term planned use of Colorado River water exceeds the reliable available supply – considerably more water has been committed to users than the river can reliably deliver. The lower portion of the basin, in particular, is running up against its legally apportioned limits. Dramatic physical changes to the Colorado riverbed brought about by major dams and water withdrawals, along with the introduction of non-native fish species, have drastically reduced the native fish populations. Already, four native species are close to extinction, and without further action, it is almost certain that others will follow. In the last several years, it has become obvious to many that traditional water policies, which permitted the region to become the agricultural and economic force it is today, are not up to the task of meeting the challenges of the 21st century. Yet water institutions and policymakers have shown limited initiative to develop new tools and approaches to try to understand and address the nature of these new challenges (Morrison *et al.*, 1996).

Without further action, water overuse and mismanagement will destroy the Colorado River delta, along with the ecological and human communities dependent on it. Prior to major dam construction and water withdrawals, the delta was lush with vegetation and wildlife. Natural flows replenished the delta with silt, delivered nutrients for fish and other life in the Sea of Cortez/Gulf of California, and nourished the largest and most critical desert wetland in the American Southwest. Virtually the entire flow of the river is now captured and used – reducing the extent and health of the delta, drying wetlands, cutting off nutrients to the sea, reducing critical fisheries habitat, and taking a toll on the economic, social, and cultural life of the native Cucapá Indians, a 2,000-year old culture of fishers and flood-recession farmers.

The complex causes of these changes will be further affected by global climatic changes that may alter both water supply and demand in the region. Global climatic changes have the potential to change significantly both the intensity and magnitude of weather events in the western United States, leading to new and unanticipated climatic regimes. Colorado River basin water supply, hydroelectricity generation, reservoir levels, and salinity are all sensitive to both the kinds of changes that are expected to occur and to the policy options chosen to respond to them.

Climate Impact Studies

Because of concerns about these issues, some of the very first studies of the impacts of climate change for water resources examined the Colorado River basin and several of its major tributaries. The earliest studies used historical analogies and regression approaches to evaluate the impacts of hypothetical temperature and precipitation changes (Dracup, 1977; Stockton and Boggess, 1979; Revelle and Waggoner, 1983). Dracup discussed historical variability along the river, including tree-ring analyses that suggested that current instrumental records might be misleading, while the latter two studies were the first to discuss explicitly the possibility of anthropogenic climatic changes. Both Stockton and Boggess and Revelle and Waggoner used simple regression models to conclude that modest changes in average climatic conditions could lead to significant changes in runoff. Revelle and Waggoner concluded that a 2°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 (see Table 1).

By the late 1980s, regression analyses had been supplanted by efforts to use physically-based models more capable of evaluating climatic conditions outside of the range of existing experience and hydrologic statistics. As part of a comprehensive assessment conducted under the auspices of the American Association for the Advancement of Science (AAAS), John Schaake (1990) used a simple water-balance model to evaluate the elasticity of runoff in the Animas River - a tributary of the upper Colorado. Schaake suggested that a 10 percent change in precipitation would lead to a 20 percent change in runoff, while a 2°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 (1987c) for the Sacramento River (described below).

Around the same time, 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 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°C (Dennis, 1991).

In 1988, Gleick published a qualitative paper exploring the implications of climatic changes for the international agreement between the U.S. and Mexico over the Colorado. The 1944 treaty signed by the two countries does not address the potential for climatic changes and only partly addresses how the two countries might allocate shortages or water-quality problems in the river. The paper concludes that climate changes will put unanticipated stresses on the treaty provisions and makes recommendations for clarifying certain key points related to shortages, resolving disputes, and salinity. These issues were further explored in Goldenman (1990) and Gleick (1990a), both of which looked at how climate change might affect various international rivers and treaties. Goldenman prepared a comprehensive analysis of international treaties, including the U.S./Mexico Colorado River treaty, in the context of climatic changes. She concluded that international mechanisms for governing shared rivers under conditions of changing climate are immature at best, and non-existent in most cases.

In an early attempt to evaluate the interactions of climatic impacts with water-management systems

TABLE 1. Impacts of Hypothetical Climatic Changes on Mean Annual Runoff in Mountainous River Basins.

Precipitation Change (percent)	River Basin [Source]	Temperature Change +2°C (percent)	+4°C (percent)
-25	Carson [7]	-25	-25
	American [7]	-51	-54
-20	Upper Colorado [3]		-41
	Animas River [3]	-26	-32
	White River [3]	-23	-26
	East River [3]	-19	-25
	East River [8]	–	-30
	Sacramento [2]	-31	-34
-12.5	Carson [7]	-24	-28
	American [7]	-34	-38
-10	Great Basin Rivers [1]	-17 to -28	–
	Sacramento River [2]	-18	-21
	Inflow to Lake Powell [3]	-23	-31
	White River [3]	-14	-18
	East River [3]	-19	-25
	Upper Colorado [4]	-35	–
	Lower Colorado [4]	-56	–
	Colorado River [5]	-40	–
	Animas River [3]	-17	-23
0	Sacramento River [2]	-3	-7
	Inflow to Lake Powell [3]	-12	-21
	White River [3]	-4	-8
	East River [3]	-9	-16
	East River [8]	–	-4
	Animas River [3]	-7	-14
	Animas River [6]	-2.1	–
+10	Great Basin Rivers [1]	+20 to +35	–
	Sacramento River [2]		
	Inflow to Lake Powell	+1	-10
	White River [3]	+7	+1
	East River [3]	+1	-3
	Colorado River [5]	-18	–
	Animas River [3]	+3	-5
+12.5	Carson [7]	+13	+7
	American [7]	+20	+19
+20	Upper Colorado		+2
	Animas River [3]	+14	+5
	East River [3]	+12	+7
	East River [8]	–	+23
	White River [3]	+19	+12
	Sacramento [2]	+27	+23
+25	Carson [7]	+39	+32
	American [7]	+67	+67

Notes: Some of these models also evaluated the impacts of climate changes from general circulation models. Refer to the original references for details.

Sources:
[1] All Great Basin Rivers results from Flaschka *et al.*, 1987.
[2] All Sacramento River results from Gleick, 1986b; 1987b,c.
[3] All Lake Powell, White, East, and Animas River results from Nash and Gleick, 1993.
[4] Stockton and Boggess, 1979.
[5] Revelle and Waggoner, 1983.
[6] Schaake, 1990.
[7] Carson and American Rivers (North Fork) are from Duell, 1992, 1994.
[8] McCabe and Hay, 1995.

along the Colorado, Strzepek and Valdés (1989) presented a methodology to examine the impacts of climate change on surface runoff and the yield of water management systems for the Lower Gunnison Reservoir System. The climate scenario was a very simple increase in annual average temperature used to modify the rainfall/runoff ratio in the Gunnison basin. They concluded that target yields from the four reservoirs in the system would increasingly fail to meet a goal of 100 percent reliability as temperatures rise.

In 1991, Nash and Gleick used physically-based conceptual hydrologic models to analyze the impacts of climate change scenarios on the Colorado basin as a whole and on several major sub-basins, including the East River, the White River, and the Animas River. The East River is a major tributary to the Gunnison River, which in turn contributes about 40 percent of the flow of the Colorado at the Utah/Colorado border. Using both hypothetical temperature and precipitation scenarios and the equilibrium general circulation model (GCM) scenarios available at the time, they coupled the hydrologic changes with the U.S. Bureau of Reclamation Colorado River Simulation System (CRSS) model of the entire water-supply system of the river in order to evaluate the role of the physical infrastructure and the legal institutions in place for water management (Nash and Gleick, 1991; 1993). GCM transient runs were done as well with one of the first models to use transient greenhouse gas inputs. River flows in all the basins studied were found to be very sensitive to both precipitation and temperature, though less so than in 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, especially in the higher-altitude basins. 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. Figure 1 shows how increased flows would lead to increased reservoir volume and hydroelectricity generation and decreased salinity. In contrast, modest decreases in flows were projected to lead to significant decreases in water stored in reservoirs and in hydroelectricity generation. However, the most critical concern for the lower Colorado River basin is water quality – specifically salinity levels. The report concluded that under almost no climate-change circumstances could existing salinity criteria be met given projected demands and operating constraints, and that at least a 20 percent increase in runoff would be necessary to bring

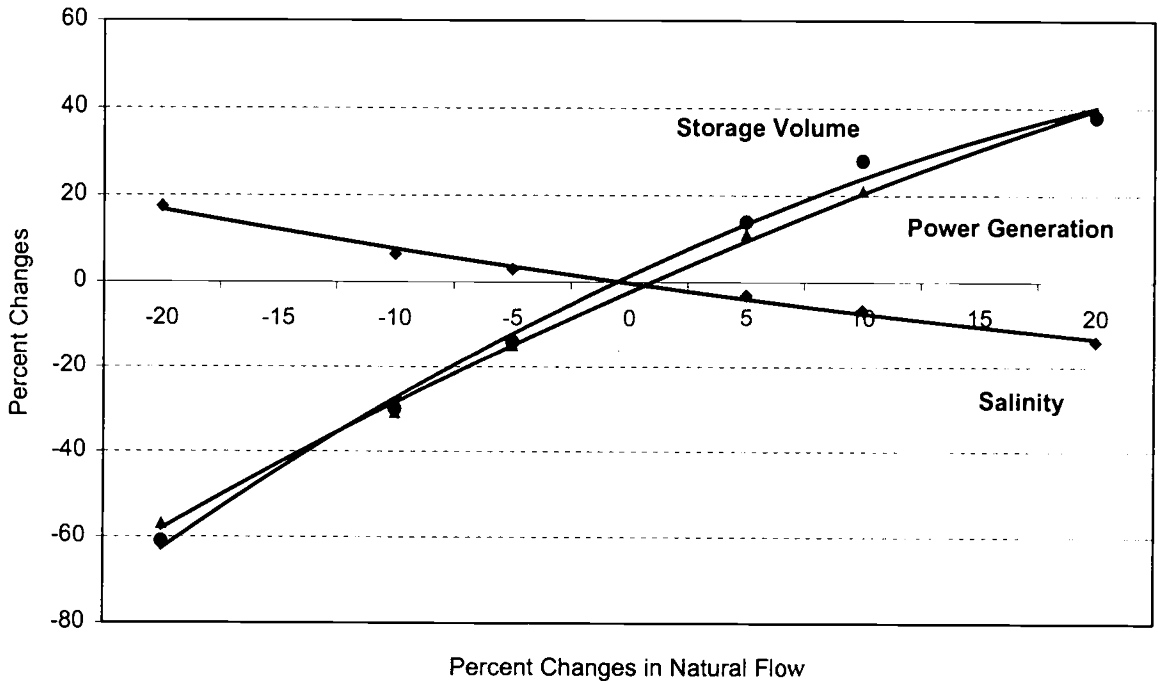


Figure 1. Percent Changes in Reservoir Storage Volume, Power Generation, and Salinity in the Colorado Riber Basin for Different Percent Changes in Natural Flow. Note the significant effects: a 20 percent drop in average natural flow led to 60 percent drops in reservoir volume and hydroelectricity generation. This study assumed no changes in the legal and institutional operating constraints in the basin, and it recommended that such changes be explored to evaluate their ability to mitigate or cope with potential impacts. Source: Nash and Gleick, 1993.

the basin into compliance. This study also looked more closely at salinity at specific points. For example, to meet water-quality standards for water delivered to Mexico, salinity was evaluated at Imperial Dam. In this case, increases in salinity were disproportionate to decreases in runoff: an 11 percent decrease in runoff at Imperial Dam resulted in a 20 percent increase in salinity while a runoff increase of 11 percent decreased salinity only 10 percent.

The Nash and Gleick study also raised the issue of non-linear effects of climate change. In evaluating the risks of flooding under different scenarios, they identified non-linear responses in the size of uncontrolled spills from reservoirs in the Upper Colorado basin. As runoff increases, both the frequency and the size of uncontrolled spills increases, with both non-linear and threshold effects observed (see Figure 2). Until runoff increases by about 20 percent, no years – in the average 78-year record available at the time – have uncontrolled spills greater than three million acre-feet. When runoff increases by 20 percent, however, 4 years out of 78 on average experience this magnitude of flood event. Similarly, the overall probability of uncontrolled spills increases from only 6 out of 78 years (8 percent) for current conditions to 33 out of 78 years (42 percent) when runoff increases 20 percent. A decrease in natural flow of 20 percent drops the frequency from 6 to 2 (from 8 to 3 percent) out of 78 years. Finally, they 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 analysis of the East River basin in Colorado was begun in 1988 by the U.S. Geological Survey and published in 1995 (McCabe and Hay, 1995). This study evaluated the sensitivity of both annual and seasonal runoff changes in temperature and precipitation. McCabe and Hay used the USGS Precipitation-Runoff Modeling System (PRMS) (Leavesley *et al.*, 1983), which is a distributed-parameter, non-calibrated, physical-process water balance model. Watersheds are divided into "hydrologic response units," and a water balance is computed daily for each unit. Similar to Nash and Gleick (1991), the USGS results indicated that changes in precipitation have a larger impact on runoff than changes in temperature, and temperature changes significantly affect the temporal distribution of runoff through the

Figure 2.
Frequency and Volume of Uncontrolled Spills in the Upper Colorado Basin Under Climatic Changes

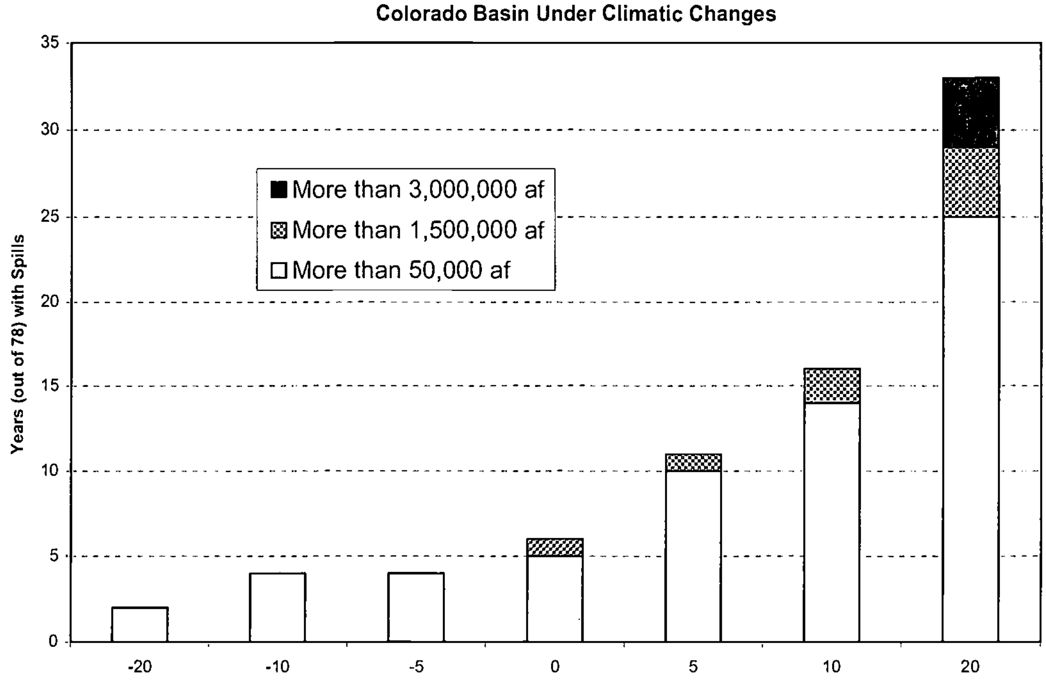


Figure 2. The Frequency of Uncontrolled Spills Greater than 50,000, 1.5 Million and 3 Million Acre-Feet in the Upper Colorado River Basin for Various Changes in Natural Flow Under Current Legal and Institutional Operating Constraints. Frequency is measured in years with spills out of the normal 78-year trace. Note the non-linearities in these results: uncontrolled spills increase from 6 out of 78 years for current conditions to over 30 years out of 78 total under an increase in natural flow of 20 percent. Decreases in natural flows only modestly reduce flood risks. In addition, no spills greater than 3 million acre-feet occur in the base case, but 5 out of 78 years have such spills when average annual runoff increases 20 percent. Source: Nash and Gleick, 1993.

year (e.g., an increase in average temperature of 4°C moved the peak spring snowmelt back one month).

A comprehensive assessment of the Colorado Basin's systems of reservoirs was also done for the Colorado River Severe Sustained Drought study (CRSSD) (Kendall and Dracup, 1991; Lord *et al.*, 1995). This work focused on the implications of long-term drought, rather than any particular climate change scenario, and concluded that the "Law of the River" – the complex, intertwined local, regional, and international legal arrangements governing water allocation, use, and management – 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 ability to reduce drought damages (Booker, 1995).

A study published in 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, 1996). Eddy concluded that changing average precipitation by simple percentages 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."

A number of general conclusions can be drawn from the numerous studies and workshops conducted on the implications of climatic changes for the Colorado River basin. [In 1990, the Pacific Institute for Studies in Development, Environment, and Security held a workshop in Denver, Colorado to bring together scientists and policymakers on this issue (Gleick, 1990c).] Colorado River runoff is sensitive to climatic variability and change in part because of the arid nature of the region, the high levels of demand for water from the river, and the way the system is operated. Despite the construction of massive physical infrastructure and development of extensive legal and institutional systems for operating the river, climatic changes could impair the reliability of supply and further damage valuable instream ecological resources (Miller, 1997). Several studies concluded that climatic changes would, under the current rules known as the "Law of the River," have dramatic effects on water availability and quality. Far less work has been done to evaluate the ability of institutional and operational changes to reduce this vulnerability.

SACRAMENTO/SAN JOAQUIN BASIN STUDIES

Basin Overview

The Sacramento and San Joaquin River basins are the largest and most important in California, together providing over 80 percent of all the runoff used in the state. These two rivers join to form the Sacramento-San Joaquin delta, which feeds into San Francisco Bay. The "Bay-Delta" is the largest remaining estuarine system on the west coast of the United States. This region also is the source of the vast majority of water that is transferred from north of the delta to south of the delta for irrigation and urban use. The pumps feeding the California aqueduct systems take fresh water out of the delta and move it south. These pumps are so powerful that at times they literally reverse the direction of natural flows in the delta. These water withdrawals have helped California's agricultural economy to become one of the most important in the world and they have satisfied the water needs of rapidly growing populations in southern California. But they have also led to severe ecological problems, threatened several aquatic species with extinction, and contributed to the ongoing controversy over water policy statewide. Addressing these problems while continuing to provide the water-related benefits needed for California is a major challenge. Imposing various climatic changes that affect the hydrology of this region on top of these problems will further complicate an already complicated system, in ways that are still not clear.

Climate Impact Studies

As with the Colorado River basin, considerable work has been done on the impacts of climate change on the Sacramento and San Joaquin river basins. In the early 1980s, Gleick developed a detailed water-balance model for the Sacramento Basin and evaluated the effects of both hypothetical and GCM scenarios of climate change for annual and monthly runoff and soil moisture (Gleick, 1985; 1986a,b; 1987a,b). This analysis indicated that annual, and especially seasonal, flows would be dramatically affected by warmer temperatures, that summer flows and soil moisture could decline substantially, even with increased annual precipitation, and that winter flows and flood frequency would tend to increase. This study may be the first one to identify dramatic impacts on snow conditions as a likely impact of climatic change in basins with substantial snowfall and snowmelt. Six major temperature-driven effects were identified:

- an increase in the ratio of rain to snow, even if total precipitation amounts stay the same;
- an increase in winter runoff as a fraction of total annual runoff;
- an earlier start and faster spring snowmelt;
- a shorter snowmelt season;
- a decrease in late spring and summer runoff as a fraction of total annual runoff; and
- an earlier drying of summer soil moisture.

Figure 3 offers a graphical representation of these effects. It shows two monthly hydrographs for a hypothetical basin dependent on snow for seasonal runoff. Both hydrographs have identical annual runoff totals. The first hydrograph represents the natural unimpaired average flows; the second hydrograph represents the impacts of a warming on snowfall and snowmelt dynamics. Peak runoff occurs earlier. winter runoff has higher maxima, summer runoff has lower minima, and summer drying begins earlier. Every regional modeling study has found temperature-driven hydrograph changes of this form.

Riebsame and Jacobs (1988) conducted an early study of how water management might be affected by global climate changes. They looked at three major issues facing California, with a focus on the Sacramento-San Joaquin region. The first was whether water infrastructure could cope with changes in variability in the timing or magnitude of runoff, given tradeoffs among water supply, flood control, hydropower, and recreation. The second was the double risk of hydrologic changes and sea-level rise for the levees and "islands" of the delta region, where much of the water withdrawals for southern California occur. The third issue was how climatic changes might affect water quality due to changes in timing and magnitude of runoff and increased intrusion of salt water from the San Francisco Bay. Riebsame and Jacobs concluded that a new form of integrated regional planning might be needed to deal with climatic impacts on Sacramento-San Joaquin basin systems. They also note that "even small shifts toward earlier runoff or more extreme rainfall events would make the supply/flood-control trade-off more difficult." As demand levels rise closer and closer to the limits of supply, they concluded that the system is likely to become more sensitive to climate-induced fluctuations, requiring more effective coordination of water agencies and managers, and they raised doubts about whether this could be achieved.

Williams (1985; 1988) and the San Francisco Bay Conservation and Development Commission (BCDC) (1988) also addressed the issue of salt-water intrusion into the San Francisco Bay-Delta region due to sea-level rise. While these assessments focused on the impacts to ecosystems and coastal margins, they also

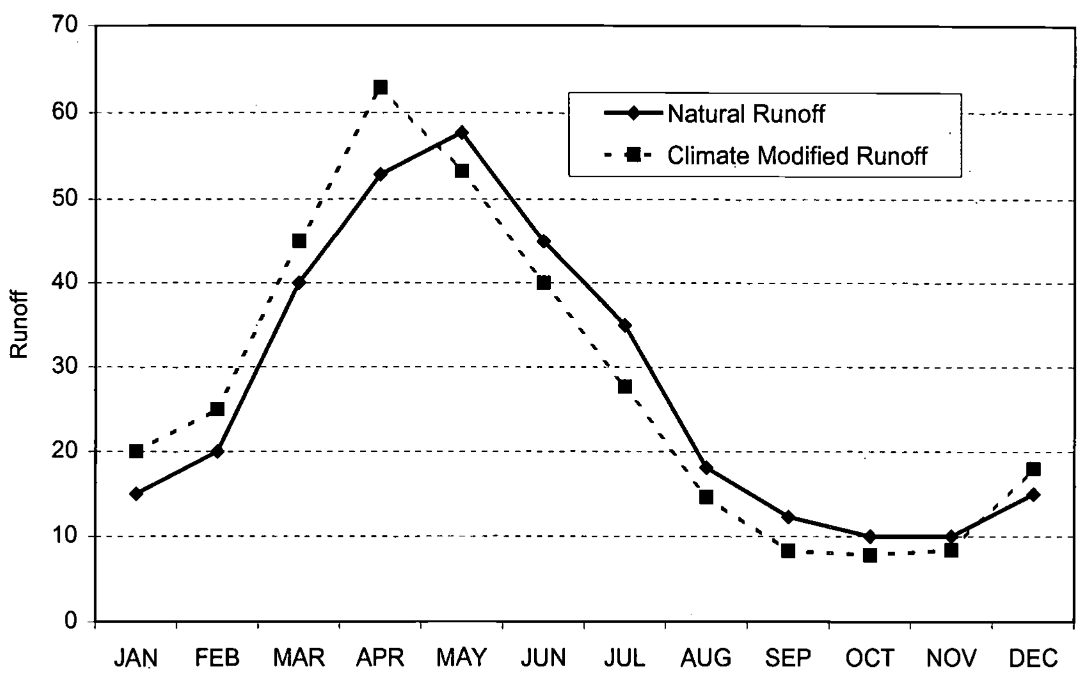


Figure 3. Hypothetical Average and Climate-Modified Hydrographs for a Basin with Snowfall and Snowmelt. Natural runoff (solid line) peaks in May as winter snows melt. Under conditions of climate change (dashed line), runoff peaks earlier, is higher in winter, and lower in summer. Both curves assume the same total annual runoff volume.

addressed concerns about salinity intrusion near the Sacramento-San Joaquin water-supply pumps in the Delta, where the major aqueducts take their water. Both of these assessments concluded that sea-level rise might threaten levee stability in the region, and that more salinity intrusion could affect water quality. The failure of levees could alter flow patterns in the Delta and permit more salt water to reach water intakes. Higher sea level and greater penetration of the salt front into the estuary system might require greater releases of freshwater from reservoirs to repel salinity away from water-supply intakes. In addition, Peterson *et al.* (1999) noted that in northern and central California, early snowmelt also means reductions in downstream summer discharge and a risk of salinity encroachment into the Sacramento-San Joaquin Delta. This is already observed to occur during naturally warm spring periods (Cayan and Peterson, 1993).

In 1990, Lettenmaier and Gan applied three climate scenarios generated from GCMs to four subbasins of the Sacramento-San Joaquin system: the Merced, the North Fork of the American River, the McCloud, and Tomes Creek. Although these four basins differ in elevation and geophysical characteristics, some consistent results were found in the reduction of snow water equivalent in all the basins. As with the Gleick studies, flood frequencies rose and summer soil moisture declined. Separate analyses of the American (a tributary of the Sacramento River), Carson, and Truckee river basins also showed similar changes in seasonality (Dennis, 1991; Duell, 1992, 1994; Pupacko, 1993).

Lettenmaier and Sheer (1991), and separately, Sandberg and Manza (1991) examined the implications of climate change scenarios for the performance of the State Water Project and the federally run Central Valley Project – the two major aqueducts delivering water from the Sacramento-San Joaquin basins to central and southern California. Both studies concluded that the shifts in runoff without accompanying operational changes will challenge the systems and perhaps reduce the reliability with which the systems could meet current demands. They concluded that changes in operation could, in theory, reduce the overall impacts, but noted the complex political environment that made such operational changes difficult to implement.

In the mid-1990s, the USGS used the Precipitation-Runoff Modeling System (PRMS), a physically-based, deterministic, distributed-parameter model to evaluate 25 climate change scenarios for the American and Carson river basins (Jeton *et al.*, 1996). The American River basin is on the western slope of the Sierra Nevada and is generally warmer than the higher-altitude Carson River basin. The PRMS, described above, was also used for evaluating climate impacts in various Colorado River basins. It permits a far more detailed assessment of river basins than earlier water-balance models, and includes basin altitude, slope, aspect, vegetation, soil, geology, and climate. The climate scenarios studied reflected temperature changes of ± 4.4°C and ± 25 percent of mean precipitation. Increases or decreases in precipitation, without changes in temperature, lead to relatively straightforward increases or decreases in streamflow. Changes in temperature were observed once again to lead to changes in the timing of hydrologic fluxes (as represented in Figure 3) in the two basins. The authors concluded that annual streamflows are more sensitive to precipitation than temperature, that streamflow timing is sensitive to temperature in snowmelt basins, and that basin sensitivities depend on altitude more than slope, aspect, or rain shadow.

In a more recent study trying to extend our understanding of adaptation, Risbey (1998) evaluated GCM outputs in an effort to evaluate how easy or successful water-management responses might be in the Sacramento Basin. He concludes that optimism about the robustness of present planning systems in the face of potential climate change is not warranted and that climatic changes may occur that are far outside the range current water systems are prepared to handle.

CROSS-BASIN ISSUES

Research to date supports the conclusion that climate changes will have significant impacts on the hydrology and water-management systems in major watersheds. Increases in temperature and changes in precipitation will affect runoff throughout the western U.S. Table 1 and Figure 4 summarize annual runoff changes projected by many different modeling studies for western U.S. basins to result from increases in average temperature of 2 and 4°C and both increases and decreases in precipitation.

For both of the major basins reviewed here, numerous independent model results also suggest consistent changes in snowfall and snowmelt timing and magnitude, which directly influence decisions about system design and operation. A difference in the timing of spring discharge alters the volume and seasonality of natural water storage. Flood probabilities change as snowmelt rates and volumes change. For both basins, more research has been done on hydrologic modeling than on operational studies, water management responses, and policy options for addressing climate change, but some work is available on these issues.

In addition to specific watershed analyses, several more comprehensive regional or national studies of

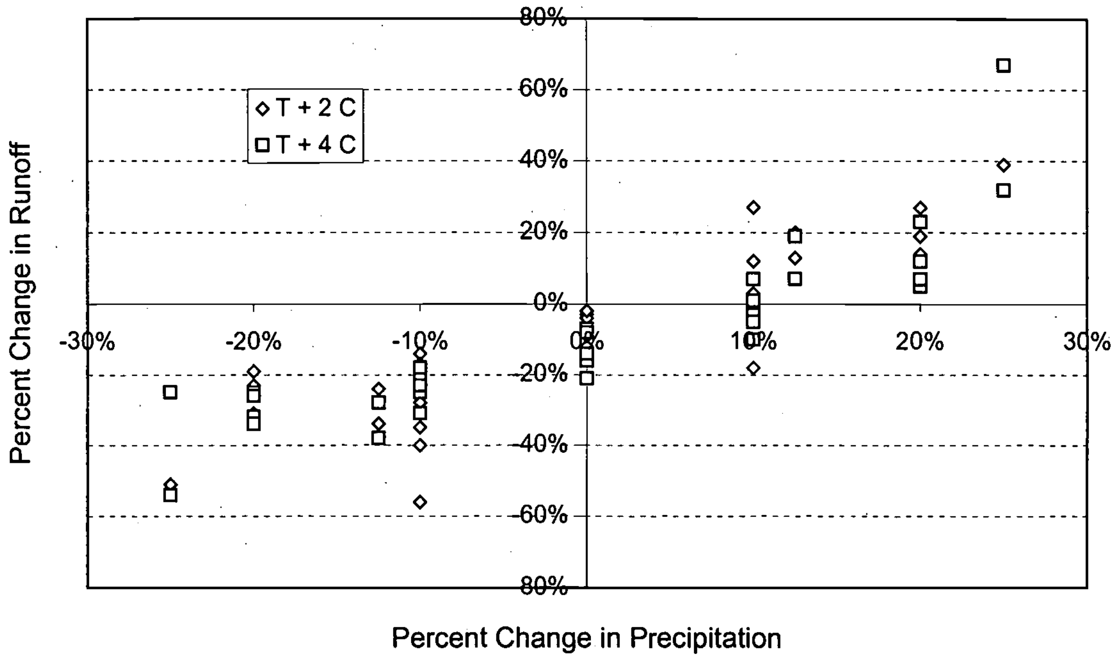
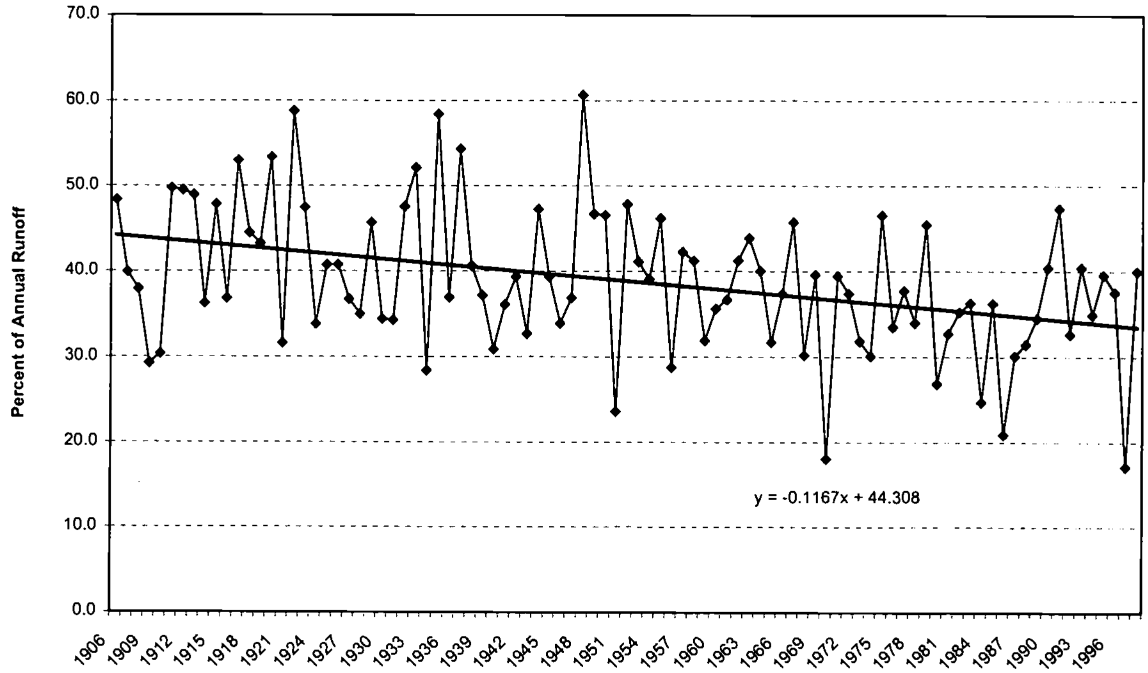


Figure 4. Effects of Hypothetical Climate Changes on Runoff are Plotted Here from Eight Separate Watershed Studies (see Table 1).

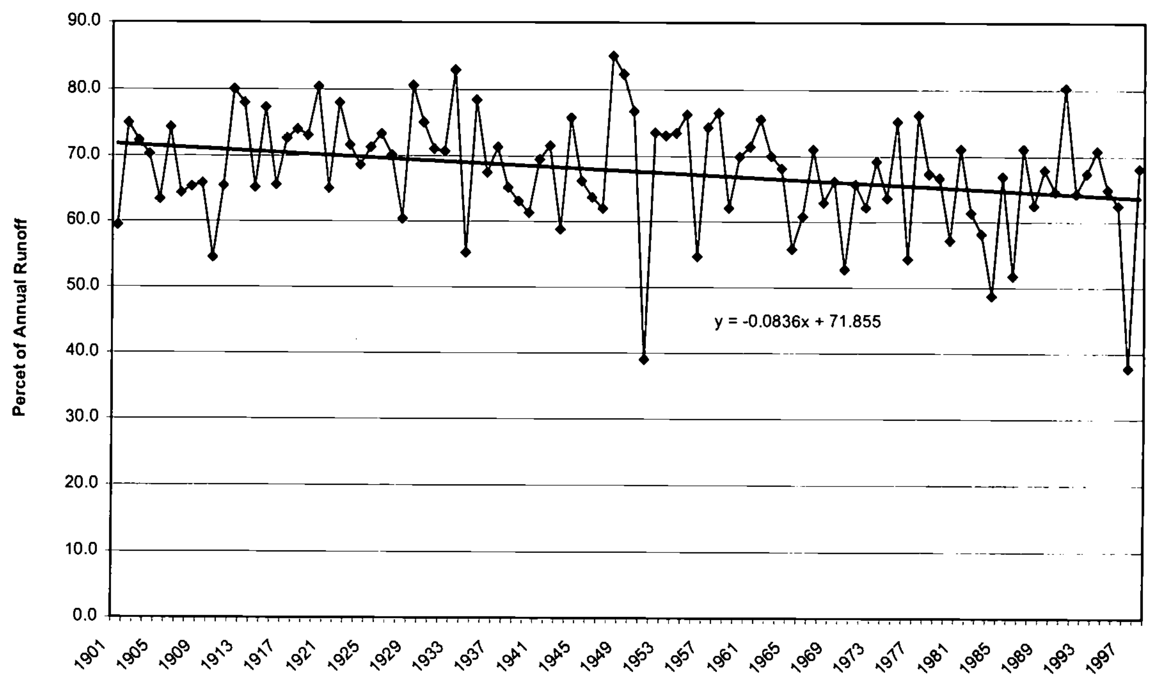
the impacts of climatic changes on water resources have been done, which also include information on impacts in these western watersheds. In an overview of the vulnerability of watersheds to climatic changes, the American Association for the Advancement of Science (AAAS) published a series of papers, including one on indicators of vulnerability that can be measured at a watershed level (Gleick, 1990b). These indicators include the ratio of storage volume to total renewable water supply, the ratio of water demand to supply, the regional dependence on hydroelectricity and groundwater, and the variability of supply. The California region had four of five indicators exceed levels of concern; the upper and lower Colorado basins had two and three, respectively. In 1999, Hurd, Smith, and Jones expanded efforts to develop indicators of vulnerability to climate change. They looked at a wide range of indicators of water supply, water quality, ecosystem sensitivity, and institutional adaptability. In this analysis, both the Colorado and Sacramento/San Joaquin basins were again shown to be highly vulnerable to a range of impacts, particularly those associated with water supply, distribution, and consumptive use. Several sub-basins in these major watersheds also had high vulnerability to water quality and ecosystem measures (Hurd *et al.,* 1999). They noted that institutional flexibility appears greater in the western U.S. than in the eastern U.S., improving the possibility for mitigating damages, but recognized the difficulty of developing quantitative measures for evaluating this kind of flexibility.

During 1998 and 1999, a series of studies was undertaken for the National Assessment using the Canadian Climate Model and the Hadley, UK Climate Centre general circulation models. With temperature and precipitation simulations from these models, McCabe and Wolock (1999) concluded that despite projected increases in winter precipitation, April 1 western snowpacks are likely to be significantly reduced in both basins. Empirical evidence for this kind of change has been monitored by the California Department of Water Resources, which analyzes seasonal runoff. Figures 5a and 5b show that the fraction of total annual runoff occurring in the April-to-July period has been decreasing over the past century in the Sacramento/San Joaquin basins, with no apparent trend in total runoff. This suggests larger winter flows and decreased spring and summer flows, consistent with the snowmelt projections described above (CDWR, 1999).

A critical aspect of the impacts of climate change on water resources is the role, responsibilities, and responses of water managers. The 1990 AAAS climate and water study noted that water managers have not been as involved in either research or policy discussions around climate change as they should be and made an unsuccessful effort to bring water managers into the process (Waggoner, 1990). Others have noted this as well (Schilling and Stakhiv, 1998). In 1997, the American Water Works Association (AWWA) published a series of recommendations for water managers that included reexamining engineering design



(a)



(b)

Figure 5. Actual April to July Runoff as a Percent of Total Annual Unimpaired (natural flow) Runoff in the (a) Sacramento River Since 1906 and (b) San Joaquin River Since 1901. Both traces show a decreasing trend, suggesting that more runoff is occurring in winter months and less in spring. This observation is consistent with modeling results but no causal connection can yet be proven. Data source: CDWR ,1999.

assumptions, operating rules, and contingency planning under a wider range of climatic conditions than normally considered, as well as working with climate scientists to facilitate the exchange of information on climate change and water resources (AWWA, 1997). A critical point of these recommendations was that water managers can no longer assume that their systems will be resilient and robust under conditions of climate change, but must more aggressively re-evaluate that assumption. Baldwin *et al.* (1999) sought the views of some western U.S. water managers and noted that the kinds of information most valued by these managers, such as climatic variability at seasonal and interannual time scales, are not routinely evaluated in climate impacts studies.

SUMMARY AND DISCUSSION

Because of the importance of water for the western United States, a wide range of research has looked at possible impacts of climate change for water resources. Two of the most important river basins in the region, the Colorado and the Sacramento/San Joaquin, have been extensively studied. Both watersheds are vitally important for their regions. Their natural hydrologic cycles are strongly influenced by snowfall and snowmelt characteristics and by the probability and frequency of extreme events. Water resources in both basins are very heavily managed and controlled. Complex institutional and legal arrangements are in place to guide water use and transfers out of the basin to neighboring users.

Significant uncertainties remain about the likely impacts of climatic change on precipitation intensity and patterns. These uncertainties will not be resolved until higher resolution climate models are available that can incorporate the complex geophysical characteristics of the western U.S., including orographic effects and storm tracks originating in both the Pacific Ocean and the Gulf of Mexico. Additional work is needed to improve regional assessments at all scales and to develop appropriate policy responses in the face of uncertainty.

Despite these gaps, some consistent and important conclusions can be drawn from these assessments, with important lessons for water managers and planners. The seasonality and timing of runoff in these basins will shift as temperatures begin to rise. In particular, winter runoff is likely to increase as the ratio of rain to snow increases and as snowpacks melt faster. This increases the risk of winter flooding, which is already a serious risk in these basins. At the same time, summer water availability is likely to decrease, as spring runoff begins and ends earlier. This increases the risk that seasonal water shortages or deficits will become more likely. These possible consequences of climate change have not been taken into account in any of the traditional regional water-resources planning or policy assessments.

More work is certainly needed on the modeling side. But work is also needed to learn how to communicate the possible impacts of climatic changes more effectively to water managers. Research on adaptation strategies is also limited, such as the role conservation and demand management might play in mitigating the effects of climate change on water users. What is the value of more effective non-structural floodplain management in the context of climate change? How can we better integrate the impacts of climate changes on sectors vitally dependent on water, such as agriculture, ecosystem functioning, and industrial production? The answers to these questions will help us better set priorities for education, research, and water policy.

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