The Colorado River Basin and Climatic Change

The Sensitivity of Streamflow and Water Supply to Variations in Temperature and Precipitation

Linda L. Nash
Peter H. Gleick

Pacific Institute for Studies in
Development, Environment, and Security
Oakland, California

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EXECUTIVE SUMMARY

Linda L. Nash
Peter H. Gleick

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Pacific Institute for Studies in
Development, Environment, and Security
1204 Preservation Park Way
Oakland, California 94612[1]
(510) 251-1600

Growing international concern about the greenhouse effect has led to increased interest in the regional implications of changes in temperature and precipitation patterns for a wide range of societal and natural systems, including agriculture, sea level, biodiversity, and water resources. The accumulation of greenhouse gases in the atmosphere due to human activities are likely to have significant, though still poorly understood, impacts on water quality and availability. One method developed over the last several years for determining how regional water resources might be affected by climatic change is to develop scenarios of changes in temperature and precipitation and to use hydrologic simulation models to study the impacts of these scenarios on runoff and water supply. In this paper we present the results of a multi-year study of the sensitivity of the hydrology and water resources systems in the Colorado River Basin to plausible climatic changes.

The Colorado River is one of the most important river systems in the western United States. It is the principal source of water in a semi-arid basin that covers approximately 243,000 square miles, parts of seven states, and reaches into Mexico (Figure ES-1). The study was conducted in two parts: the first part evaluated the effects of changes in temperature and precipitation on runoff using a conceptual hydrologic model developed and operated by the National Weather Service. Among the impacts studied were changes in streamflow into Lake Powell and on three important tributaries of the Upper Colorado River: the White

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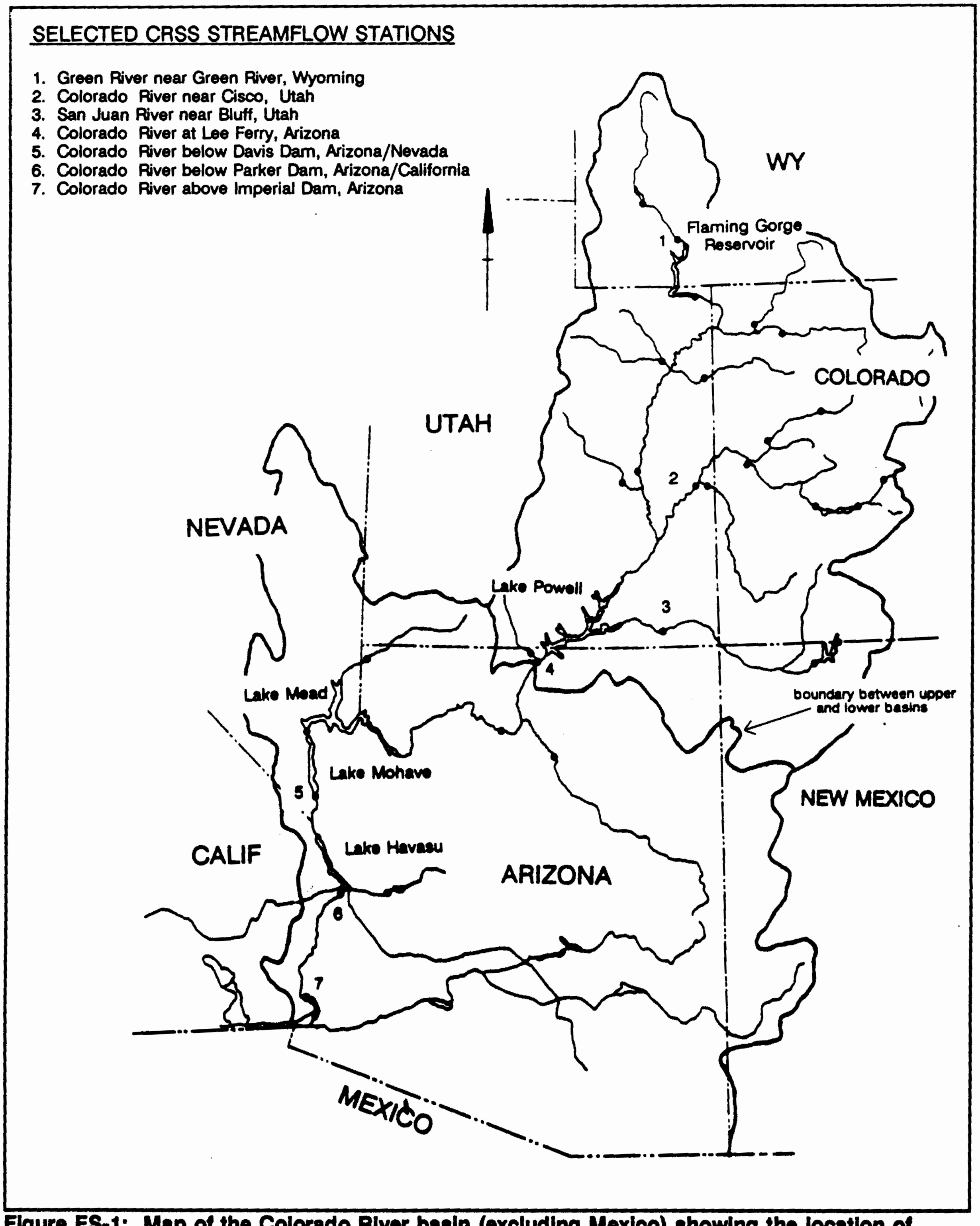

Figure ES-1: Map of the Colorado River basin (excluding Mexico) showing the location of selected CRSS stations and major reservoirs. (Source: redrawn from USDOI, 1987.)

River, the East River, and the Animas River. The second phase of the project then evaluated how these hydrologic changes might affect water supply, salinity, and hydroelectricity production throughout the entire Colorado River Basin using the Colorado River Simulation System (CRSS), a reservoir-simulation model developed and operated by the U.S. Bureau of Reclamation.

Two types of climate scenarios were used for these sensitivity studies: hypothetical temperature and precipitation scenarios, and scenarios generated by general circulation models (GCMs) of the climate. The hypothetical scenarios included increases in average temperatures of 2° to 4°C and increases and decreases in precipitation of 10 and 20 percent. The regional changes in temperature and precipitation from three GCMs were also evaluated. The scenarios chosen reflected both the best understanding and the uncertainty about the expected magnitude of regional climatic changes when the study began.

Our results suggest that certain aspects of the hydrology and water-supply system of the Colorado River Basin are extremely sensitive to climatic changes that could occur over the next several decades. Not only are significant changes in runoff possible, but the ability of the existing water supply system to mitigate the worst effects is limited. For example, the major reservoirs of the Colorado Basin lessen the impacts of reduced flows, but only for a short period of time. Under conditions of long-term flow reductions and current operating rules, these reservoirs are drawn almost completely dry, hydroelectricity production drops dramatically, and salinity in the Colorado River increases to the point where it fails to meet legal standards almost all of the time. The results strongly suggest that the current approaches to water management in the basin will have to be modified to balance the many competing demands and priorities under conditions of altered climate, and that current water allocations may well be threatened.

Changes in Colorado River Basin Hydrology

The principal impacts of changes in temperature and precipitation on runoff in the Colorado Basin are summarized below.

- Increases in temperature of 2°C alone, with no change in precipitation, cause mean annual runoff in the Colorado River Basin to decline by 4 to 12 percent.
- A temperature increase of 4°C causes mean annual runoff to decrease by 9 to 21 percent.
- Increases or decreases in annual precipitation of 10 to 20 percent result in corresponding changes in mean annual runoff of approximately 10 to 20 percent.
- A temperature increase of 4°C would require an increase in precipitation of 15 to 20 percent merely to maintain annual runoff at historical levels.
- Temperature increases shift the seasonality of runoff in the Colorado Basin, causing a distinct increase in winter runoff and a decrease in spring runoff. This is the result of a decrease in winter snowfall and snowpack, an increase in winter rain, and a faster and earlier spring snowmelt. These temperature-driven changes could increase the potential for winter and spring flooding in some regions.
- GCM temperature and precipitation scenarios modeled as part of this study suggest that

precipitation increases would be offset by increased evapotranspiration, with the net effect being a reduction in runoff ranging from 8 percent to 20 percent.

- Of the three GCMs used to develop climate scenarios in this study, the GFDL model results in the most extreme decreases in runoff for all the sub-basins studied (-10 to -24 percent) because it predicts a relatively large regional temperature increase and no change in precipitation. The least extreme effects are generated by using either the UKMO or the GISS grid points, which incorporate respective increases in precipitation of 30 and 20 percent and lead to increases in runoff of 0 to 10 percent.

- High-elevation basins appear to be more sensitive to changes in temperature and precipitation than low-elevation basins. Of the three sub-basins studied, the East River near Almont, Colorado is the most sensitive to changes in temperature and precipitation because of its higher elevation.

- In general, runoff in the Upper Colorado River basin is slightly more sensitive to a 10 percent change in precipitation than to a 2°C change in temperature. Thus, while increased temperatures will cause significant decreases in runoff, the overall response of the basin will ultimately depend upon the direction and magnitude of changes in precipitation.

In summary, the hydrologic modeling results suggest that large changes in streamflow may occur in the Colorado River basin as a result of plausible climatic changes. GCM scenarios indicate that runoff in the basin is likely to decrease. The impacts of these potential changes in streamflow would be felt throughout the basin as changes in water deliveries, reservoir storage, and hydroelectricity production.

Changes in the Colorado River Water Supply System

The changes in runoff determined in the first part of the project were then used to evaluate impacts on several water-supply parameters, including salinity, reservoir levels, deliveries to users, and hydroelectricity generation. Some quite severe effects were seen, assuming no changes in the operating rules of the basin. For example, a 20 percent reduction in natural runoff would cause mean annual reductions in storage of 60 to 70 percent, reductions in power generation of 60 percent, and an increase in salinity of 15 to 20 percent. In contrast, a moderate increase in temperature (2°C) and a large increase in precipitation (20 percent) would result in roughly a 20 percent increase in mean annual runoff, a 30 to 60 percent increase in storage, a 40 percent increase in power production, and a 13-15 percent decrease in salinity. The principal impacts on water supply identified with the CRSS model include the following:

- Changes in mean annual actual streamflow along the River range from -31 percent to +32 percent for the scenarios studied. Decreases in runoff are relatively smaller in magnitude in the Lower Basin because they are cushioned by additional reservoir releases. For example, a decrease in natural flow of 20 percent causes a 31 percent decrease in mean annual streamflow at the Upper Basin station of Green River, but only an 11 percent decrease at Imperial Dam near the Mexican border.

- Decreases in natural runoff cause severe changes in minimum runoff. For example, the -10% scenario causes mean annual runoff in the Upper Basin to decline by about 15%, but minimum flows at Lees Ferry drop 86%.

- In the base case (i.e., under current hydrology), annual releases from Lake Powell never drop below the objective minimum of 8.23 million acre-feet per year (maf/yr); however a runoff decrease of 10% causes releases from Lake Powell to fall below 8.23 maf/yr in several years.

- Reservoir storage and power generation are the variables most sensitive to changes in runoff. Changes in long-term mean storage in Lake Mead on August 1 are on the order of -70 percent, or -8,700 thousand acre-feet (taf) for the -20 percent runoff scenario, to +60 percent, or +7,400 taf for the +20 percent runoff scenario.

- Lake Powell falls below minimum power pool 20 percent of the time when runoff drops by 5 percent; this frequency rises to nearly 60 percent when runoff decreases by 20 percent. The -20 percent (runoff) scenario causes Lake Mead to go completely dry roughly 25 percent of the time.

- The sensitivity of storage to changes in runoff suggests how carefully the system is currently managed and that consequently there may be little room for error in forecasting seasonal flows should the hydrologic regime undergo any significant changes.

- High salinity levels, already a critical concern for the Lower Basin, would be severely exacerbated by any decreases in runoff.

- While the runoff scenarios modeled in this study may appear extreme, streamflow in the region may have a much higher variability than is commonly recognized. For instance, the most extreme scenario modeled in this study, a 20 percent decrease in mean annual runoff, may not even be incompatible with the current (non-greenhouse) hydrologic regime. Tree-ring reconstructions suggest that over the last 500 years, the lowest 80-year mean at Lee Ferry is less than 11 maf, which corresponds to a 27 percent decrease in natural flow, compared to the 1906-83 instrumental record.

The impact of changes in natural runoff on several water-supply parameters is summarized in Table ES-1 and in the sections below.

Table ES-1: Sensitivity of water-supply variables to changes in natural flow in the Colorado River Basin [1].

Change in Natural Flow (%)	Change in Actual Flow [2] (%)	Change in Storage [3] (%)	Change in Power Generation [4] (%)	Change in Depletions [5] (%)	Change in Salinity [6] (%)
-20	(10-30)	(61)	(57)	(11)	15-20
-10	(7-15)	(30)	(31)	(6)	6-7
-5	(4-7)	(14)	(15)	(3)	3
5	5-7	14	11	3	(3)
10	11-16	28	21	5	(6-7)
20	30	38	39	8	(13-15)

Notes: [1] Average change compared to the base case over a 78-year simulation run. Numbers in parentheses represent DECREASES.
[2] Changes in flow represent the range of changes at five points: Green River, Cisco, Bluff, Lee Ferry, and Imperial Dam.
[3] Mean storage throughout the basin on August 1.
[4] Mean annual power generation throughout the basin.
[5] Depletions are summarized over the entire basin, although depletions are defined differently in the upper and low basins. See Hundley (1975) for details.
[6] Changes in salinity represent the range of changes at three points: Davis, Parker, and Imperial Dams.

Water Deliveries to Users

Delivery of water to different users are affected dramatically by different scenarios, depending on streamflow changes and the application of the law of the river. For example, in the base case, deliveries to the Central Arizona Project would ordinarily fall to their minimum level 20 percent of the time and scheduled deliveries are met or exceeded 40 percent of the time. If runoff drops 5 percent, our results suggest that full scheduled deliveries will be met in only 25 percent of the years and that in half of the years, only minimum levels are delivered.

Although the delivery data suggest that Mexico is affected only in extreme cases, the quality of Mexican water decreases significantly. In fact, all Lower Basin users would suffer a significant decline in water quality (see Salinity).

Hydroelectricity

Under current operating rules, hydroelectricity production, like reservoir storage, is extremely sensitive to changes in runoff. If flows in the Upper Basin were to decrease by 10 percent, average annual storage decreases by 30 percent and power production drops by 26 percent. A decrease in flows of 20 percent would reduce storage by 63 percent and power production by nearly 50 percent. An increase in flows of 10 percent would increase storage by 28 percent and power generation by 21 percent.

In the Lower Basin, a 10 percent decrease in runoff reduces storage by 30 percent and power production by 36 percent. A drop in runoff of 20 percent reduces Lower Basin storage by 50 percent and power production by 65 percent.

Salinity

The most critical concern for the Lower Basin is salinity and salinity is the only water-quality parameter studied. Even in the base-case scenario salinity criteria are consistently exceeded at all points in the Lower Basin for most years. Decreases in runoff of only 5 percent cause salinity criteria to be exceeded in virtually all years. Even if average flows were to increase by 20 percent, salinity criteria are exceeded continuously for long periods.

Under almost no climate-change circumstances can existing water-quality criteria be met given projected demands and operating constraints. Our results suggest that at least a 20 percent increase in natural runoff would be necessary to bring the salinity levels in the Lower Basin into compliance with existing criteria, in the absence of other activities to reduce salinity in the river.

Seasonal Timing of Runoff

A variety of recent hydrologic analyses have suggested that changes in the seasonality of runoff may be a major impact of climate change in hydrologic basins dependent on snowfall and snowmelt. One scenario was run to study the effects of shifts in the seasonality of runoff. The results suggest that an increase in temperature of only 2°C would shift peak runoff one month earlier, to May, in the Upper Basin. Under current operating conditions, such a shift in timing reduces the overall efficiency with which the system is operated, reducing effective storage and deliveries, and increasing the average annual salinity. We recommend that changes in operations to account for changes in the timing of runoff should be evaluated.

Summary and Discussion

The results of this assessment suggest that violations of the Colorado River Compact are likely to occur under all scenarios of decreased runoff, assuming that no changes in the operating parameters of the system occur. For instance, storage strategies and targets work extremely well in the base case scenarios but are substantially less effective under alternative scenarios. Thus, violations of the Compact would potentially occur even if runoff dropped only 5 percent. The sensitivity of storage to changes in runoff reflect how carefully the current system is operated and how little room there is for forecast error if water supply is to be maximized without resulting in damaging flood-control releases or uncontrolled spills.

As might be expected, the reservoir simulation results presented here suggest that many of the procedures and inputs used in the Bureau of Reclamation model are closely tuned to the historic hydrologic record. While it is likely that many of the severe impacts noted here could be avoided under different operating conditions and rules, we were constrained in the current study from evaluating any alternative operating criteria.

The problem of planning water management in the face of a high degree of climate and hydrological uncertainty cannot be easily resolved; nonetheless, it may be possible to increase flexibility in water management. This flexibility will need to be reflected in technical and operational decisions, as well as in the legal and economic institutions that govern water use in the basin.

The problem of planning is compounded by the fact that we cannot say with certainty whether runoff in the basin will increase or decrease. Most people with an interest in the basin have focused on the prospect of long-term decreases in runoff and the shortages that would result, which is a logical reflection of the region's preoccupation with drought. The fact that average temperatures in the region will almost certainly increase suggests that, if we assume no knowledge about changes in precipitation, we would expect runoff to decrease as a result of increases in evaporation and vegetative water use. This may be reason enough to plan for supply shortages; but increased water storage must be traded off against the need for flood-control space. The greatest risk of climatic change is the potential for streamflow <u>variability</u> to increase substantially, increasing the frequency of both sustained drought events and high-flow events.

Beyond the scope of this study were several important issues that policymakers and water-supply managers will have to consider. First, the environmental and ecological impacts of changes in water supply have not been addressed here. In general ecosystems are more sensitive to seasonal, monthly, daily, and even hourly changes in streamflow and water quality than to long-term changes. Unlike water supply, the impacts on the environment cannot be adequately assessed using aggregated time periods or large-scale models. Undoubtedly, however, given the predicted rate of climatic change and the potential magnitude of runoff changes examined here, serious ecological problems would occur.

This study has also not taken projected future economic developments nor some future demands into account. Currently the issue of reserved water rights and Native American claims have obscured future demand scenarios in the basin. Because of the large amounts of water involved, these unresolved claims could have dramatic impacts on water allocation throughout the region and thus add to the uncertainty that the basin faces.

Finally, while this study has suggested what the impacts of climate change could be on water supply, it has not addressed the impacts of climate change on water demand. In fact, demands will change both in time and space. Obviously, agricultural water demand will vary as crops and production patterns are altered in response to climatic changes. Ecosystem water requirements will also vary, both in response to increased temperature and as a result of ecological and environmental changes. Urban and industrial usage will change as a result of both changes in climate and changes in population. It is quite possible that changes in demand over the next 50 to 100 years will equal or exceed changes in supply. In all likelihood, the greatest possibilities for adapting to climatic change lie in the area of demand management, particularly in the agricultural and urban sectors, and the potential for conservation and water transfers needs to be assessed from both a quantitative and an institutional perspective. If we are to plan adaptation strategies, future research must address the integrated impacts of climatic change on demand and supply across sectors.

Given the prospect of future climatic changes, it is imperative that we consider how we can increase the resiliency of our existing water-management systems and minimize the social and environmental impacts of changes in water availability. We need to identify those responses that will provide us with the greatest flexibility in the coming decades and to develop management schemes that recognize both the variability and the dynamic nature of our climate.

THE SENSITIVITY OF STREAMFLOW AND WATER SUPPLY IN THE COLORADO RIVER BASIN TO CLIMATIC CHANGES

INTRODUCTION

Background

Human activities are substantially increasing the atmospheric concentration of greenhouse gases. These gases, in turn, are expected to increase the overall average temperature of the Earth's surface and alter precipitation patterns worldwide. The magnitude of increases in global average temperature is predicted to range from 1.5° C to 4.5° C over the next century (IPCC, 1990). The regional impacts of these changes will vary and cannot yet be predicted with much confidence; however, existing global climate models indicate that temperature increases in central North America will exceed the increase in the global mean, and will be accompanied on average by reduced summer precipitation and soil moisture (IPCC, 1990; Manabe and Wetherald, 1980; Rind, et al., 1990).

Such global climatic changes may have substantial impacts on water resources. Higher temperatures, new precipitation patterns, rising sea level, and changes in storm frequency and intensity will alter water availability, quality, and demand. Despite recent advances in modeling the atmosphere, large uncertainties remain about the details of regional hydrological changes. Until large-scale climate models improve both their spatial resolution and their hydrologic parameterizations, information on the effects of global climatic changes on hydrologic sub-basins can best be produced using detailed, basin-specific hydrologic models. In this study, we analyze the potential impacts of climatic change on the hydrology and water resources of the Colorado River Basin. First, we use a regional hydrologic model to study the effect of changes in temperature and precipitation on runoff in several sub-basins of the Upper Colorado. Subsequently, we analyze the impact of changes in runoff on water supply, water deliveries, and water quality using the Colorado River Simulation System (CRSS), a reservoir-simulation model developed and operated by the U.S. Bureau of Reclamation (Figure 1).

The Colorado River is one of the most important river systems in the United States. Although not a large river, even in comparison to other rivers in the US, the Colorado flows through some of the most arid regions of the country and is the primary source of water for a region with extensive agriculture, large cities, and a diverse ecosystem. The Colorado River Basin covers approximately 243,000 square miles, parts of seven states, and reaches into Mexico. Annual unimpaired runoff of the Colorado River at Lee Ferry has ranged from 5.6 (million acre-feet) maf to 24.0 maf since regular streamflow recording was initiated in the early part of this century.[2] Over the same period, mean annual unimpaired runoff has been about 15.1 maf; however, tree-ring analyses dating back to 1512 have suggested that the long-term mean may be closer to 13.5 maf (Stockton and Jacoby, 1976).

The apportionment of the Colorado River has been more complete than that of the waters of any other river through many hard-fought lawsuits, negotiations, political battles, and an international treaty. The Colorado River Compact of 1922 divided the basin into two sections. The upper basin, in which most of the region's runoff originates, includes those parts of Wyoming, Colorado, Utah, New Mexico, and Arizona that drain into the Colorado River above Lee Ferry, Arizona.[3] The more arid lower basin encompasses most of Arizona, southeastern Nevada, southeastern Utah, western New Mexico and portions of southern California. The lower basin states were guaranteed that the upper basin states would deliver an annual average of 7.5 maf of water (over a ten year period) to Lee Ferry, a point on the river approximately on the Arizona-Utah border. The upper basin states received a right to use an equivalent amount of water (if it was

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[2]For convenience to US water managers, water volumes are presented here in acre-feet, the standard unit of measurement in the western United States. One acre-foot is equivalent to 1,233 cubic meters. A flow of one cubic meter per second (cms) is equal to 70.02 acre-feet per day.

[3]Lee Ferry, Arizona, also known as the "compact point" is the point at which the Colorado River passes from the upper to the lower basins as established by the Colorado River Compact of 1922. It is located approximately 16 miles downstream of Lake Powell and one mile downstream of the Paria River. It should not be confused with Lees Ferry, which is a point further upstream on the river, near Glen Canyon Dam.

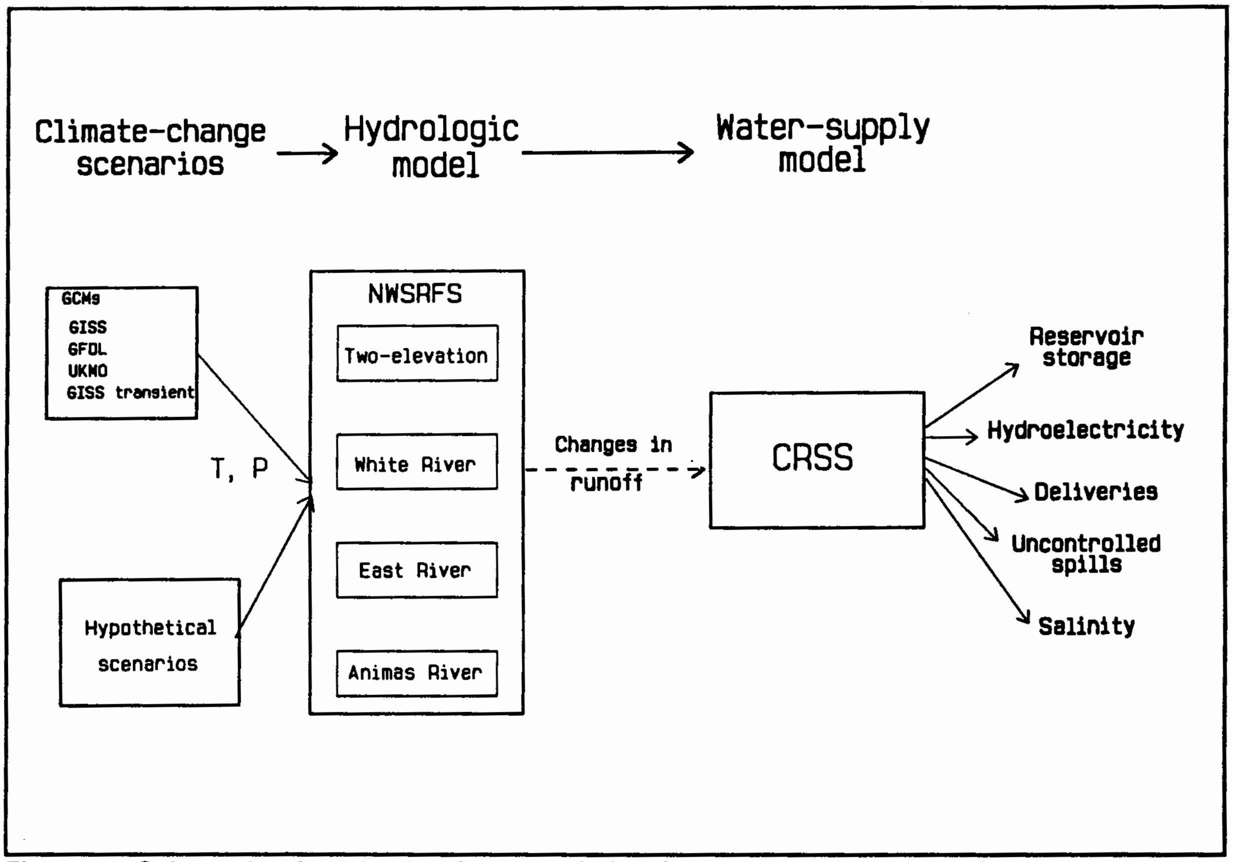

Figure 1: Schematic of study showing the relationship among various models.

available). The parties contemplated each basin eventually using equal quantities of water (7.5 maf), plus up to another one million acre-feet for the lower basin. Subsequently, the 1944 Treaty signed by Mexico and the United States guaranteed an annual flow into Mexico of not less than 1.5 maf, except in times of severe shortage. Under the Compact, the upper basin in not actually required to deliver a fixed quantity of water at Lee Ferry in any particular year, though current operating criteria adopted by the Bureau of Reclamation provide for releases of 8.23 maf from Lake Powell annually.If the Mexican Treaty obligation is assumed to be shared equally by both basins (although this remains a disputed point), then the required delivery from the upper to the lower basin is 82.5 maf in every 10-year period, except in those periods when Mexican Treaty obligations are reduced.

The water apportioned between the basins has also been rather precisely divided among the states within each basin by the Boulder Canyon Project Act (1928), the Upper Colorado River Basin Compact (1949), and several court decisions handed down in Arizona v. California. In addition, water delivered to California is divided among users by the Seven Party Agreement. (These agreements and allocations are also discussed in Appendix B.)

Water allocation continues, however, to be a contentious issue in the basin. Future demands for Colorado River water are predicted to outstrip supplies. The population of the region is more than 19 million; and, despite the fact that the area is approaching the limits of its water supply, population and economic activity have continued to expand. Although severe shortages have not yet been felt in the basin, there is growing concern that the pressures of increased demand and the potential for periodic supply shortages will create problems in the future.

Droughts in the Colorado River Basin have generally been considered as isolated, temporary events that can be overcome through storage and short-term conservation strategies. The validity of this assumption is challenged by paleoclimatic data which indicate that the region has experienced much more severe and sustained droughts in previous centuries than in our own (Stockton, et al., 1991). Now the prospect of anthropogenically induced climatic change offers the unsettling prospect that the region may face both permanent and more extreme changes in its climate than previously considered. Enhanced greenhouse warming will almost certainly cause increases in the region's average temperature, and could cause either increases or decreases in average annual precipitation (IPCC, 1990; Mitchell and Qingcan, 1991). As a result, the basin could experience changes in the likelihood and severity of prolonged droughts or extreme floods. In any case, the storage and supply facilities and institutions that have evolved in the basin are predicated on streamflow data gathered within the last 80 years. In fact, the Colorado River Compact of 1922 was based upon less than 20 years of data, and as a result allocated more water than is likely to be available in an average year. The ability of this system to function under altered climatic conditions has not been seriously considered.

Scenarios of Climate Change for Impact Assessment

To assess the implications of global warming for water resources, regional-scale details of future changes are needed for temperature, precipitation, evaporation, wind speed, and other hydroclimatological variables. Because our ability to predict these details is limited, climate-impact analysis must rely upon the development of scenarios. Such scenarios can be either hypothetical or derived from General Circulation Models (GCMs), paleoclimatic reconstructions, or recent historical climate analogues (WMO, 1987; USEPA, 1989).

Hypothetical scenarios are simple combinations of changes in variables (usually temperature, precipitation, and potential evapotranspiration) that are consistent with global changes expected as a result of the greenhouse warming. While such scenarios are limited by the fact that they may not be internally consistent, they provide a very useful means of testing hydrologic vulnerabilities. If constructed systematically, hypothetical scenarios can be used to develop sensitivity studies that delineate the relative importance of changes in temperature and precipitation to changes in runoff. Subsequently, as estimates of future temperature and precipitation improve, the impacts on water resources can be easily estimated.

Table 1 lists the range of hypothetical scenarios used in a variety of studies. The values chosen typically reflect best estimates of changes in important climatic variables, although extreme values are occasionally chosen to explore where a system might fail to perform as expected or designed. Thus, the practice of using hypothetical temperature increases of 1, 2, 3, or 4° Celsius reflects the consensus that greenhouse warming will produce temperature rises in this range, given an equivalent doubling of atmospheric carbon dioxide (IPCC, 1990).[4] Given the greater uncertainty about both the magnitude and the direction of regional precipitation changes, both increases and decreases in precipitation are frequently modeled.

Much of the effort to understand climate has focused on the development of computer models that simulate many of the intricate and intertwined phenomena that make up the climate. The most complex of these models, GCMs, are detailed, time-dependent, three-dimensional, numerical simulations that include atmospheric motions, heat exchanges, and important land-ocean-ice interactions (IPCC, 1990). Climate models, however, are still simple when compared with the complexities of the real climate system. For instance, current GCMs handle cloud formation and ocean currents quite primitively, although these are important climatic processes (Ramanathan, 1981). Oceans are generally modeled as simple slabs, and only some of the GCMs take heat transport by currents and circulation into account. In addition, the models use a smoothed topographic profile that precludes an accurate representation of regional orographic effects. Despite these limitations, general circulation models currently provide the best information available on the response of the atmosphere to increasing concentrations of greenhouse gases, as well as valuable insights into the potential impacts across broad regions (IPCC, 1990).

In theory, GCM estimates of changes in hydrologic variables, such as runoff, could be used directly to estimate changes in water resources (see, for example, USEPA, 1984). In practice, however, GCM-generated hydrologic data suffer from two major limitations. First, the spatial resolution of GCMs is too coarse to provide hydrologic information on a scale typically of interest to hydrologists.[5] Present

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[4]Regional temperature changes, however, may be higher or lower.

[5]GCM resolution is unlikely to dramatically improve for many years because of the extreme cost of high-speed computer time--a factor of two increase in resolution requires approximately a factor of eight increase in computer time [Somerville, 1987]. With a typical model resolution of 4.5 degrees latitude by 7.5 degrees longitude and nine vertical layers in the atmosphere, computing one year of weather at 30-minute intervals takes 10 hours of computer time on a Cray XMP computer--one of the fastest in the world.

Table 1: Hypothetical climate scenarios used in regional hydrologic studies.

Study [1]	Temperature	PET [2]	Precipitation
Stockton and Boggess [1979]	±2°C		±10%
Nemec and Schaake [1982]	+1°C, +3°C		±10,25%
Revelle and Waggoner [1983]	+2°C, +4°C		−10%
Flaschka et al. [1987]	±2°C		± 10,25%
Gleick [1986, 1987a,b]	+2°C, +4°C		±0,10,20%
Fitzgerald and Walsh [1987]		± 0,5,15%	± 0,10,20%
Schaake [1990]	+2°C	+10%	+10%
This study	+2°C, +4°C		± 0,10,20%

Notes: [1] All studies use different methods and assumptions. Please refer to individual sources for details.
[2] Potential evapotranspiration.

resolutions are usually between 4 to 7.5 degrees latitude by 5 to 10 degrees longitude -- grid areas of hundreds of thousands of square kilometers. Yet, hydrologists are often interested in climatic events that occur on the scale of tens or hundreds of square kilometers -- a scale several orders of magnitude finer than current GCM resolution.[6]

Second, hydrologic parameterizations in GCMs are very simple and often do not provide the detailed information necessary for water-resource planning (WMO, 1987). For example, the GCM soil-moisture budget is typically computed by the so-called "bucket method", in which the field capacity of the soil is assumed to be uniform everywhere (Manabe, 1969a,b). Runoff occurs when the soil moisture exceeds this capacity, and the rate of evaporation is determined as a simple function of the soil moisture and the potential evaporation rate (Manabe and Wetherald, 1985). Efforts are being made to improve GCM hydrology (Dickinson, 1984; IPCC, 1990), including improvements in vegetation parameterizations and the behavior of soils. Until such improvements occur, however, other methods must be used to evaluate hydrologic impacts.

Temperature predictions are considered to be the most reliable GCM output relative to precipitation, and other climatic variables (IPCC, 1990). More generally, GCM predictions of changes in temperature, precipitation, and other climatological variables are considered much more reliable than predictions of runoff or soil moisture (IPCC, 1990; WMO, 1987). Consequently, several investigators have emphasized using temperature and precipitation estimates for a doubled-CO_2 environment as inputs to more detailed regional models (e.g., USEPA, 1990; Lettenmaier and Gan, 1990; Bultot, et al., 1988; Gleick, 1987a,b).

Under the guidance of the U.S. Environmental Protection Agency, a set of climate-change scenarios was developed for use in evaluating the impacts of the greenhouse effect on water availability in

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[6]This is not meant to imply that increasing GCM resolution alone will resolve the bulk of the problems with GCMs, which suffer from several other limitations. Nonetheless, the resolution problem is critical for hydrologic analysis, particularly in regions where hydrologic processes are dominated by orography.

the Colorado River. These include several combinations of hypothetical changes in temperature and precipitation and scenarios derived from three state-of-the-art GCMs were used to develop inputs for use in modeling the Colorado River Basin. The use of more than one GCM has two advantages: first, reliance on one GCM may give a false impression of accuracy; and second, the use of more than one GCM highlights model differences and similarities and permits a broader analysis of outcomes and sensitivities. The data on temperature and precipitation changes due to a doubling of carbon dioxide come from the Goddard Institute for Space Studies (GISS) model, the Geophysical Fluid Dynamics Laboratory (GFDL) Q-flux model, and the United Kingdom Meteorological Office (UKMO) model (Hansen, et al., 1983, 1988; Manabe and Stouffer, 1980; Manabe and Wetherald, 1987; Wilson and Mitchell, 1987). Each of these models is an equilibrium run, i.e. carbon dioxide is doubled all at once in the models and a new equilibrium climate is established.

In addition, data from a GISS transient run were incorporated into our analysis. In the transient run, the GISS model was started with same amount of greenhouse gases in the atmosphere as measured in 1958, and the concentration of gases was gradually increased. We developed a climate scenario that reflected the decadal average of temperature and precipitation changes that occur in the years 2030 to 2039. These data were presumed to provide an indication of how much change will occur over the next 40 years, given the assumptions in the GISS model concerning the future rate of greenhouse-gas emissions (Hansen, et al., 1988). The changes in temperature and precipitation predicted for the Colorado River Basin by each of these GCM runs is given in Table 2.

METHODS OF ANALYSIS I: HYDROLOGIC MODELING

Background

Once scenarios of climate change are developed, hydrologic models can be used to estimate impacts on water resources. If accurate estimates of future water availability are to be calculated, regional hydrologic evaluations need to incorporate the complexities of snowfall and snowmelt, topography, soil characteristics, natural and artificial storage, and monthly or seasonal variations.

Table 2: Changes in temperature and precipitation in the Colorado River Basin predicted by general circulation models (GCMs). [1]

	Δ Temperature (°C)	Δ Precipitation (%)
Equilibrium [2]		
GISS 1	+4.8	+20
GISS 2	+4.9	+10
GFDL	+4.7	0
UKMO 1	+6.8	+30
UKMO 2	+6.9	+10
Transient [3]		
GISS 1	+3.2	+10
GISS 2	+2.5	+20

Notes: [1] For the GISS and UKMO GCMs, the upper Colorado River basin was interesected by two different grid points. The more northern grid point is labeled "1"; the more southern is labeled "2".
[2] Equilibrium GCM runs, in which greenhouse gas concentrations have stabilized at roughly twice current levels.
[3] The GISS transient run, in which greenhouse gases are increasing gradually. The numbers presented here represent the avearge over the decade 2030 to 2039.

The use of hydrologic models, rather than GCMs, for assessing the regional impacts of climatic changes has several attractive characteristics. First, diverse modeling techniques exist. This permits flexibility in identifying and choosing the most appropriate approach for evaluating any specific region. Second, hydrologic models can be chosen to fit the characteristics of the available data. Third, hydrologic models are regional in scale and are far easier to manipulate and modify than are GCMs. Fourth, regional models can be used to evaluate the sensitivity of specific watersheds to both hypothetical changes in climate and to changes predicted by large-scale GCMs or climatic analogues. And finally, methods that incorporate both detailed regional characteristics and output from GCMs can take advantage of the continuing improvements in the resolution, regional geography, and hydrology of global climate models (Gleick, 1989).

Past studies of the hydrologic impacts of climatic change can be divided into two categories: (1) stochastic methods that rely primarily on statistical techniques for evaluating the hydrologic characteristics of a region or for extending the existing hydrologic record (such as Schwarz [1977], Revelle and Waggoner [1983], and Stockton and Boggess [1979]); and (2) deterministic or conceptual methods that use physically based, mathematical descriptions of hydrologic phenomena (Nemec and Schaake, 1982; Gleick, 1986, 1987a,b; Mather and Feddema, 1986; Cohen, 1986; Flaschka, et al., 1987; Bultot et al., 1988; Lettenmaier and Gan, 1990). To date, climate-impact studies of the Colorado River Basin have been limited to stochastic methods (Revelle and Waggoner, 1983; Stockton and Boggess, 1979). These studies necessarily assume, however, that the relationships among temperature, precipitation, and streamflow will remain unchanged under future climatic conditions. In contrast, this study used a conceptual hydrologic model to study the sensitivity of the basin to greenhouse warming. A recent attempt to use a deterministic model to study climatic impacts on a small sub-basin of the Colorado River is presented in Schaake (1990). In this project we expand upon that work by incorporating additional climate scenarios and modeling additional sub-basins. By modeling actual hydrologic processes (e.g. percolation, soil-moisture storage, snowmelt, etc.), deterministic techniques incorporate an additional level of complexity. So long as these hydrologic processes do not change significantly under a CO_2-altered climate, deterministic models should be more robust than derived statistical relationships between meteorologic variables and streamflow. In fact, however, all attempts to study the impacts of climatic change using hydrologic models are limited by their dependency on historic data, which may not be applicable to future conditions.

Description of the Model

The large size of the Colorado River Basin complicates the development of a physically based hydrologic model; indeed, no completely satisfactory basin model exists. As a result, we modeled several sub-basins in the Upper Colorado River Basin, using a conceptual hydrologic model developed and operated by the National Weather Service River Forecasting Service (NWSRFS) in Salt Lake City, Utah. These models simulate the hydrologic processes important for river forecasting, including soil moisture, snowfall, and snowmelt.

The NWSRFS is comprised of two linked models: a soil-moisture accounting model that calculates gains and losses of water in the soil through various processes (e.g. evaporation, transpiration, infiltration); and a snow accumulation and ablation model that calculates the accumulation of snow and the contribution of snowmelt to soil moisture and runoff. The soil-moisture accounting model is a modified version of the Sacramento Model described in Burnash et al. (1973). The Sacramento Model is widely used and generally accepted as one of the most reliable in varied climatic conditions on several continents, including both arid and humid regions (Nemec and Schaake, 1982). The model distributes soil moisture into an upper and lower zone. Movement between zones is controlled by a physically based percolation equation whose parameters are controlled by the free water in the upper zone and the soil-moisture deficiency in the lower zone. The snowmelt model uses air temperature as the sole index to energy exchange at the snow-air interface and is described in detail in Anderson (1976). The inputs to the model are areal temperature and precipitation data; the output is streamflow (runoff) on a 6-hourly basis.

The NWSRFS models the Upper Colorado River Basin as a series of approximately 50 small sub-basins that are linked together. For forecasting purposes, all of the sub-basins are modeled simultaneously. For calibration purposes, however, each of these sub-basins is modeled separately. In this study, we modeled three sub-basins which were selected based upon: (1) the existence of an adequate historical streamflow record (at least 35 years), (2) a relatively high volume of streamflow, (3) streamflow records classified as "good" or better by the U.S. Geological Survey (USGS), and (4) the presence of only limited withdrawals and upstream regulation. These three basins are the White River at Meeker, the East River at Almont, and the Animas River at Durango. In addition, the NWS has developed a composite model (referred to here as the "Two-elevation model") that divides the entire Upper Colorado River Basin into two elevation zones and uses a limited number of data stations to predict inflow into Lake Powell. Given the constraints of this study, it was not possible to study all of the Upper Colorado River sub-basins. Yet by studying smaller, detailed sub-basin models, only limited information on the entire basin could be generated. Thus, we used the composite Two-elevation model to obtain an overview of the impacts on the entire upper basin. The Two-elevation model has an additional advantage of being highly correlated with streamflow nodes in the CRSS water-supply model.

All three sub-basins are high-elevation, snowmelt-driven watersheds, with no significant rainfall showing up in the average hydrograph. Streamflow measurements for the White River model come from the USGS gauging station located 2.5 miles east of Meeker at an elevation of 6300 feet. The drainage area of the White River covers approximately 770 square miles. The period of record for the White River dates from 1909. Mean annual discharge computed over the period 1949-1983 is about 435 thousand acre-feet (taf). East River measurements are made at the Almont station, which has an elevation of 8006 feet. The period of record dates from October, 1934. Streamflow measurements for the Animas River are made at an elevation of 6502 feet at the station of Durango. Records date from 1912. In all cases, monthly and annual streamflow records are classified as "good".[7] Streamflow into Lake Powell, which is used to calibrate the Two-elevation model, is calculated by the Bureau of Reclamation based on reservoir outflow, changes in reservoir storages, and evaporative losses, and is checked against the combined flows of three upstream USGS gauging stations (the Colorado River at Cisco, the Green River at Green River [Utah], and the San Juan River at Bluff).

As stated above, the NWSRFS is a forecasting model that was developed for the short-term forecasting of streamflows. For this purpose snow-pack conditions, daily observations of temperature and

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[7] USGS classifications are defined as follows:

Excellent -- 95% of daily discharges are within 5% of their true value.
Good -- discharges are within 10% of their true value.
Fair -- discharges are within 15% of their true value.
Poor -- discharges do not fall within 15% of their true value.

precipitation, and present streamflow information are used as inputs into the model, and future streamflow forecasts are produced as outputs. For the purposes of this study, however, the model was run in calibration (or simulation) rather than forecasting mode. To calibrate the model, past records of temperature and precipitation are correlated with concurrent streamflows. Independent parameters (associated with soil moisture accounting, snow ablation and snowmelt, and streamflow routing) are subsequently modified to improve the fit of simulated to observed data. By altering historic temperature and precipitation data, future climate scenarios and their resulting streamflows can also be simulated. The comparison of simulations obtained from actual historic data and altered data provides information about the changes in streamflow that might be expected from changes in climatic conditions.

Model Calibration

The standard test for credibility of a given hydrologic simulation model is verification with data not used in model calibration. In many cases, however, the data set is too limited to permit this type of testing. Because the model used in this study is a forecasting model used daily for operational purposes, all model testing and calibration has been done by the National Weather Service in Salt Lake City. The entire 35-year record (1949 to 1983, inclusive) was used to calibrate each of the sub-basins.

The World Meteorological Organization model intercomparison program suggests that various criteria be used to test general purpose streamflow models, including differences between simulated and observed flows, mean flow, characteristics of maximum and minimum flows, and seasonal characteristics (WMO, 1985; WMO, 1987). A set of these criteria are evaluated for the NWSRFS model calibration runs. The results are summarized in Table 3 and are presented in detail in Appendix A. In all cases, the model has a fairly good fit. The analysis of daily streamflow data for all models shows a consistent bias of overpredicting low flows and underpredicting high flows. In general, however, the model appears to perform satisfactorily so long as predicted flows are within about 20% to 25% of the mean.

Because the entire streamflow record was used to calibrate the NWSRFS model, independent tests of validation could not be undertaken as part of this study. The success of the NWSRFS as a forecasting tool, however, suggests that the model has the capability to simulate the effects of changes in temperature and precipitation. In addition, a critical assumption of this research is that the NWSRFS model is able to simulate adequately runoff under climatic conditions different from those for which the model has been calibrated. While there are reasons for believing that the model possesses this capability for moderate climatic changes, the use of this model (or any model) may be problematic if simulated conditions differ significantly from calibrated conditions. For example, changes may occur in plant-transpiration rates and in vegetative cover under a CO_2-altered climate. These types of changes and their effect on streamflow are

Table 3: Summary of calibration results for the NWSRFS model

Model	r^2 Daily Flows	r^2 Monthly Flows	Mean Annual Flow % Bias	Monthly Volume RMS Error (taf)
Two–elevation	0.94	0.92	−1.25	3.62
White River	0.92	0.88	−0.36	7.98
East River	0.93	0.91	1.05	6.98
Animas River	0.93	0.93	1.14	10.9

not accounted for in a model calibrated on current climatic conditions. Nevertheless, the short time-ste used (6-hourly) implies that the model's storage behavior beyond calibrated conditions is only for limite periods and should have a relatively minimal impact on average annual runoff outputs. And, to the exter that studies focus on relatively short-term and "moderate" changes in climate, significant changes in mod parameters would not be expected (Nemec and Schaake, 1982).

Another assumption of the model is that water withdrawals are not significantly affecting runofi Because withdrawals are not accounted for in the model directly, they are implicit in the values chosen fo other parameters. Thus, as withdrawals increase in a particular basin, the calibration of all parameters fo that basin change to account for the decrease in streamflow. So long as withdrawals remain a relatively small factor in basin streamflow, this omission should not be critical to the model's ability to simulate different climate scenarios. To minimize this problem, sub-basins were selected in which withdrawals were known to be relatively minor.[8]

A further weakness of the Two-elevation model is that model parameters have been averaged spatially. In general, the strength of the NWSRFS model is its use of physically based parameters to describe hydrologic processes. Thus, while the exact value of parameter may not be known, a reasonable range of values can be determined from existing data. This becomes increasingly difficult as the scale of the model is increased. For example, it is much more problematic to choose infiltration parameters for the entire Upper Colorado River Basin than for a small (and presumably more homogenous) sub-basin. Thus, while the Two-elevation model may "fit" the data as well as any sub-basin model, these results should be treated more skeptically. Nonetheless, because of the time and resources required to study the more than 50 sub-basins, the Two-elevation model was included in this study because it provides the only means of assessing the potential impacts of climate change on the entire Upper Colorado River Basin.

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[8]The inability to account for withdrawals explicitly is of greater concern for the Two-elevation model because substantial withdrawals are occurring.

Application of Climate Scenarios to the NWSRFS Model

The hypothetical scenarios used in each of the model runs are shown in Table 4. In the absence of information on the distribution of annual changes throughout the year, mean annual changes were applied uniformly to all the historical data. Temperature changes were applied as absolute amounts, while precipitation changes were interpreted as percent differences:

$$\delta T = T_{new} - T_{old} \quad (1)$$

$$\delta P = \frac{P_{new} - P_{old}}{P_{old}} \quad (2)$$

Potential evapotranspiration (PET) rates were assumed to follow the general relationship to temperature of 4 percent per degree Celsius as derived by Budyko (1982:119). Wetherald and Manabe (1975) found that global evaporation increases by 3 percent when temperature increases by 1° C. Accordingly, for the Two-elevation model, additional sensitivity runs were done using a potential evapotranspiration rate of 3% per degree Celsius. As expected, the potential evapotranspiration rate is most important for temperature-dependent scenarios (i.e. increases in temperature with no net change in precipitation). For a temperature increase of 4° C and no net change in precipitation, the use of a 4% per degree potential evapotranspiration rate rather than a 3% per degree rate decreases mean monthly runoff by an additional 3%. For other scenarios, the effect of the potential evapotranspiration rate was much less important.

Temperature data in the model were altered by changing the mean elevation of the basin relative to the existing station data using an appropriate lapse rate. For standard calibration runs, the model normalizes temperature station data to the mean elevation of the basin being modeled. To convert this station data, the model uses minimum and maximum lapse rates (to convert minimum and maximum temperature data, respectively) For climate change runs, the elevation of the sub-basin was altered using an average lapse rate, usually between 0.5 and 0.7° C per 100 meters. It is important to note that model results are very sensitive to the lapse rates used for modifying temperature data. The use of higher (lower) lapse rates would reduce (increase) the effect of temperature changes on runoff.

The GCM scenarios used in the model runs are also listed in Table 2. In all cases at least two GCM grid points intersect the Colorado River Basin and, at the same time, include vast areas outside of the basin. Figure 2 shows the approximate location of grid points and the modeled hydrologic sub-basins. The grid points represent spatially averaged data and, as such, misrepresent any particular point within the box. In selecting GCM grid-point data for use in hydrologic modeling, we chose not to modify the data in any way (i.e. through interpolation) because we found little justification for doing so.

Each of the sub-basins (White, Animas, and East Rivers) fell well within a specific GCM grid box, although not always the same grid box, depending upon the GCM. The Two-elevation model, on the other hand, was spread across two different grid boxes in each GCM. In the case of the GISS and GFDL models, there was little difference in the scenarios generated by the adjacent grid points, and thus only one point from each model was used. In the case of the UKMO model, however, the adjacent grid points yielded substantially different scenarios so that data from both points (labeled UKMO 1 and UKMO 2) were applied to the Two-elevation model.

The available GCM data consist of mean monthly changes in temperature and precipitation developed from a historical baseline that encompasses years 1951 through 1980. These data were averaged to obtain mean annual changes in temperature and precipitation and then applied uniformly to the long-term historical data. As in the case of the hypothetical scenarios described previously, changes in temperature

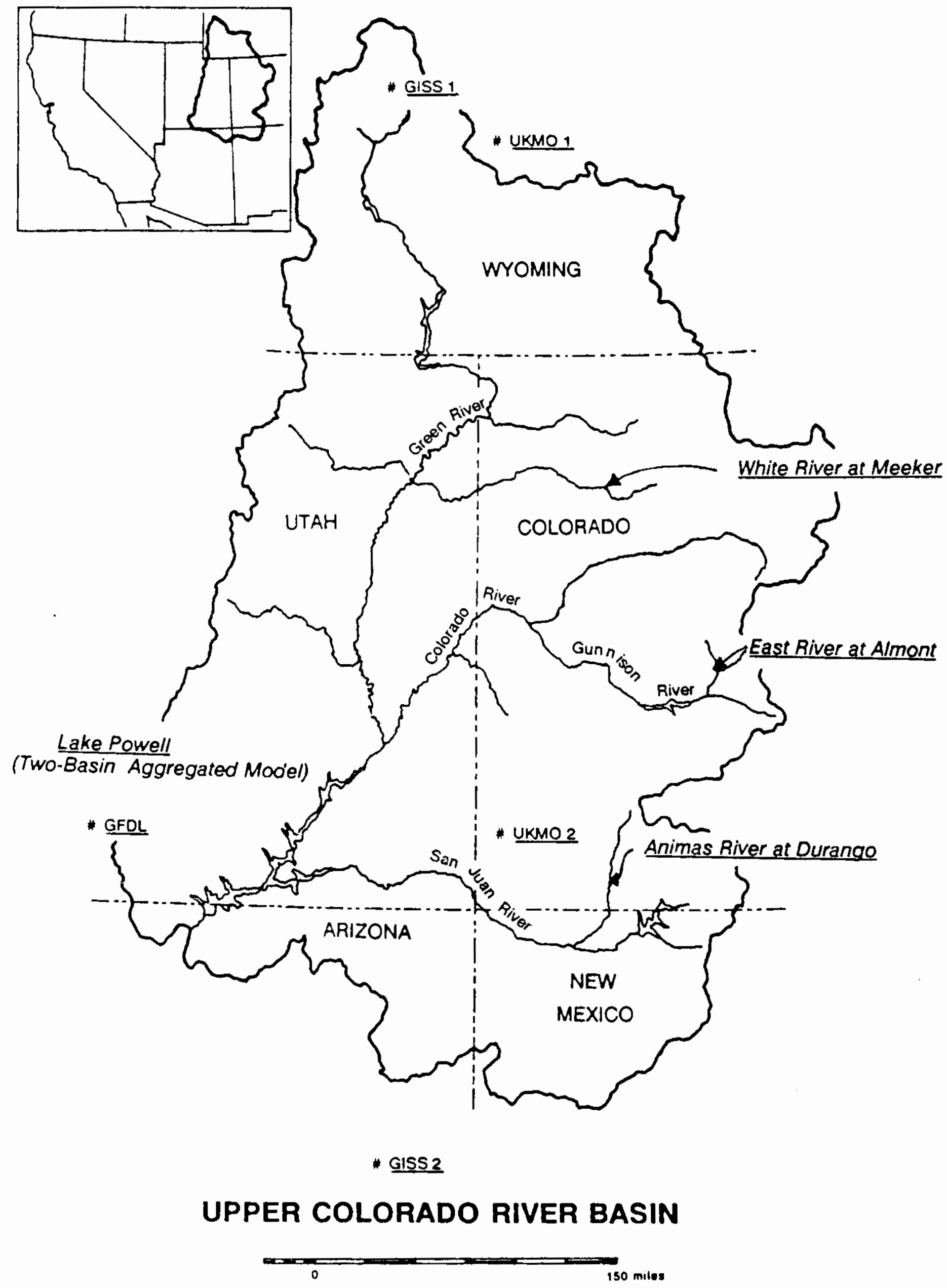

Figure 2: Map of the Upper Colorado River basin showing the location of modeled sub-basins and GCM grid points. (Source: redrawn from Upper Colorado Region Comprehensive Framework Study, Main Report, June 1971.)

Table 4: Climate–change scenarios used in the NWSRFS model.

		Two–Elevation	White River	East River	Animas River
Hypothetical					
T+2°C, P–20%		--	X	X	X
T+2°C, P–10%		X	X	X	X
T+2°C, P+0		X	X	X	X
T+2°C, P+10%		X	X	X	X
T+2°C, P+20%		--	X	X	X
T+4°C, P–20		X	X	X	X
T+4°C, P–10%		X	X	X	X
T+4°C, P+0		X	X	X	X
T+4°C, P+10%		X	X	X	X
T+4°C, P+20%		X	X	X	X
GCM [1]					
GISS 1:	T +4.8°C, P+20%	--	X	--	--
GISS 2:	T +4.9°C, P+10%	X	--	X	X
GFDL:	T +4.7°C, P+0	X	X	X	X
UKMO 1:	T +6.8°C, P+30%	X	X	--	--
UKMO 2:	T +6.9°C, P+10%	X	X	X	X

Note: [1] All GCM scenarios represent annual average changes for an equilibrium (2XCO2) run.

were applied as absolutes (i.e. +2° C), while changes in precipitation were applied as percentages (i.e. +10% of precipitation in the base case).[9]

RESULTS OF HYDROLOGIC MODELING

Annual Runoff

For the three Colorado River sub-basins, the magnitude of changes in mean annual runoff induced by the hypothetical scenarios ranged from decreases of 33% to increases of 19%. The greatest decrease in runoff was seen in the East River for a 4° C increase in temperature in conjunction with a 20% decrease in precipitation. The greatest increase was seen in the White River basin when a 2° C increase was combined with a 20% increase in precipitation. In all cases, at least a 10% increase in precipitation was required to offset the effect on annual runoff of a 2° C temperature rise. A 20% increase in precipitation caused runoff to increase in every case. For the Two-elevation model, mean annual runoff decreased by 12% and 21% when the respective hypothetical scenarios of T+2° C and T+4° C were applied with no change in precipitation. Tables 5 through 8 show these results. In general, the Two-elevation model was more sensitive to increases in temperature than the three sub-basin models. While this may be an artifact of the Two-elevation model itself, it may also be explained by the increased importance of evaporation in the lower elevation zones that the model encompasses.

For the Animas and East rivers, all GCM scenarios led to decreases in runoff, ranging from -8% to -20%, which reflects the dominant effect of increased evaporation. For the White River, two out of the four GCM scenarios showed increases in runoff (of 10% to 12%), while the other two scenarios resulted in

[9] Mean monthly changes (rather than mean annual changes) cannot be used in the NWSRFS without modifications to the model. All historical temperature and precipitation data are stored in data files that are called upon by the calibration program. The program then normalizes these data for the basin being modeled using a single coefficient. Mean annual temperature and precipitation data can therefore be easily modified by altering these coefficients. In order to incorporate monthly changes, however, it would be necessary to alter the data associated with particular months by different amounts. While this can be done, it requires access to the actual program files, which were not available for this study.

decreases in runoff (of -8% to -10%); this is related to the grid point used. Using the Two-elevation mode three of the four GCM scenarios resulted in decreases in mean annual runoff ranging of -14% and -24%. Th fourth scenario resulted in an increase of less than 1%.

Table 5: Annual inflow (taf) into Lake Powell (Two-elevation model) for all scenarios.

Scenario	Mean [1]	SD	CV	Minimum	Maximum
Base	10940	2983	0.27	4481	17040
T+2° P-10%	8386 (-23.3%)	2418	0.29	3357 (-25.1%)	12940 (-24.1%)
T+2° P+0	9656 (-11.7%)	2727	0.28	3924 (-12.4%)	14330 (-15.5%)
T+2° P+10%	11000 (0.6%)	3046	0.28	4504 (0.5%)	16350 (-4.0%)
T+4° P-20%	6447 (-41.0%)	1970	0.31	2520 (-43.8%)	11480 (-32.6%)
T+4° P-10%	7522 (-31.2%)	2260	0.30	2892 (-35.5%)	12480 (-26.8%)
T+4° P+0	8668 (-20.7%)	2554	0.30	3373 (-24.0%)	13490 (-20.8%)
T+4° P+10%	9879 (-9.7%)	2854	0.29	3911 (-12.7%)	14530 (-14.8%)
T+4° P+20%	11150 (2.0%)	3162	0.28	4443 (-0.9%)	16180 (-5.1%)
GISS 2	9444 (-13.6%)	2804	0.30	3624 (-19.1%)	14220 (-16.5%)
GFDL	8369 (-23.5%)	2514	0.30	3180 (-29.0%)	13270 (-22.1%)
UKMO 1	10950 (0.2%)	3240	0.30	4107 (-8.3%)	16070 (-5.7%)
UKMO 2	8639 (-21.0%)	2693	0.31	3173 (-29.2%)	13926 (-18.3%)

Note: [1] Numbers in parentheses represent percent change from the base case.

Table 6: Annual flow (taf) of the White River for all scenarios.

Scenario	Mean [1]	SD	CV	Minimum	Maximum
Base	434.9	104.5	0.24	242.8	670.5
T+2° P-20%	335.1 (-22.9%)	70.6	0.21	193.6 (-20.3%)	474.7 (-29.2%)
T+2° P-10%	374.6 (-13.9%)	82.9	0.22	214.6 (-11.6%)	541.1 (-19.3%)
T+2° P+0	417.0 (-4.1%)	97.5	0.23	234.7 (-3.4%)	608.7 (-9.2%)
T+2° P+10%	465.1 (7.0%)	114.8	0.25	255.0 (5.0%)	697.1 (4.0%)
T+2° P+20%	515.7 (18.6%)	132.9	0.26	279.0 (14.9%)	788.6 (17.6%)
T+4° P-20%	320.9 (-26.2%)	70.0	0.22	180.7 (-25.6%)	468 (-30.2%)
T+4° P-10%	357.6 (-17.8%)	80.6	0.23	200.6 (-17.4%)	532.4 (-20.6%)
T+4° P+0	396.9 (-8.7%)	92.9	0.23	221.5 (-8.8%)	599.7 (-10.6%)
T+4° P+10%	440.4 (1.3%)	107.9	0.24	241.7 (-0.5%)	666.9 (-0.5%)
T+4° P+20%	487.9 (12.2%)	126.2	0.26	264.0 (8.7%)	756.2 (12.8%)
GISS 1	476.2 (9.6%)	122.9	0.26	252.9 (4.2%)	746.2 (11.3%)
GFDL	389.7 (-10.4%)	91.7	0.24	214.1 (-11.8%)	599.7 (-10.6%)
UKMO 1	488.5 (12.3%)	128.3	0.26	250.2 (3.0%)	790.1 (17.8%)
UKMO 2	401.3 (-7.7%)	97.4	0.24	211.8 (-12.8%)	640.4 (-4.5%)

Note: [1] Numbers in parentheses represent percent change from the base case.

Table 7: Annual flow (taf) of the East River for all scenarios.

Scenario	Mean [1]	SD	CV	Minimum	Maximum
Base	230.7	84.9	0.37	76.9	477.0
T+2° P-20%	165.8 (-27.6%)	60.6	0.36	60.2 (-22.8%)	358.6 (-24.8%)
T+2° P-10%	186.9 (-18.7%)	69.1	0.37	66.4 (-14.0%)	401.8 (-15.8%)
T+2° P+0	209.4 (-9.1%)	77.8	0.37	72.5 (-5.8%)	446.1 (-6.5%)
T+2° P+10%	233.5 (1.3%)	86.2	0.37	79.1 (2.8%)	490.5 (2.8%)
T+2° P+20%	258.7 (12.3%)	94.3	0.36	86.4 (12.2%)	535.0 (12.2%)
T+4° P-20%	153.8 (-33.1%)	58.8	0.38	54.4 (-29.3%)	348.9 (-26.8%)
T+4° P-10%	172.8 (-25.0%)	66.9	0.39	61.6 (-19.9%)	388.4 (-18.6%)
T+4° P+0	192.8 (-16.5%)	74.9	0.39	68.8 (-10.6%)	428.6 (-10.2%)
T+4° P+10%	223.4 (-3.4%)	86.3	0.37	77.6 (0.8%)	487.0 (2.1%)
T+4° P+20%	246.4 (6.6%)	93.8	0.38	84.7 (10.1%)	528.3 (10.8%)
GISS 2	205.6 (-11.2%)	80.9	0.39	70.2 (-8.8%)	456.2 (-4.4%)
GFDL	187.0 (-19.1%)	73.4	0.39	64.6 (-16.1%)	420.2 (-11.9%)
UKMO 2	187.6 (-19.0%)	76.2	0.41	64.2 (-16.6%)	438.9 (-8.0%)

Note: [1] Numbers in parentheses represent percent change from the base case.

Table 8: Annual flow (taf) of the Animas River for all scenarios.

Scenario	Mean [1]	SD	CV	Minimum	Maximum
Base	550.6	192.5	0.35	240.4	941.7
T+2° P-20%	406.6 (-26.1%)	143.5	0.35	165.9 (-31.0%)	682.6 (-27.5%)
T+2° P-10%	458.6 (-16.7%)	162.3	0.35	188.8 (-21.5%)	762.2 (-19.1%)
T+2° P+0	512.3 (-7.0%)	181.6	0.35	212.3 (-11.7%)	853.0 (-9.4%)
T+2° P+10%	568.4 (3.2%)	200.8	0.35	238.0 (-1.0%)	947.8 (0.6%)
T+2° P+20%	628.2 (14.1%)	220.5	0.35	264.4 (1.0%)	1051.5 (11.7%)
T+4° P-20%	376.8 (-31.5%)	133.2	0.35	150.5 (-37.4%)	640.1 (-32.0%)
T+4° P-10%	424.3 (-22.9%)	150.8	0.36	170.6 (-29.0%)	715.8 (-24.0%)
T+4° P+0	473.3 (-14.1%)	168.8	0.36	191.5 (-20.3%)	791.8 (-15.9%)
T+4° P+10%	525.0 (-4.7%)	187.1	0.36	214.6 (-10.7%)	874.2 (-7.2%)
T+4° P+20%	578.9 (5.1%)	205.5	0.35	240.2 (-0.1%)	961.5 (2.0%)
GISS 2	505.5 (-8.4%)	182.4	0.36	205.0 (-14.7%)	847.2 (-10.0%)
GFDL	459.3 (-16.7%)	165.7	0.36	184.8 (-23.1%)	775.1 (-17.7%)
UKMO 2	465.3 (-15.7%)	169.2	0.36	182.1 (-24.2%)	798.8 (-15.2%)

Note: [1] Numbers in parentheses represent percent change from the base case.

All relationships between runoff and precipitation are nearly linear for the range of scenarios studied (Figure 3), with the exception of the T+4°C scenarios on the East River. In this case, runoff increases more slowly than precipitation. Model biases undoubtedly affect this relationship. Percent changes in runoff are dominated by low-flow years, which are generally underpredicted; thus percent increases in runoff are probably underestimated and percent decreases are overestimated. If this is in fact the case, the actual relationship is somewhat curvilinear and concave up, and runoff is still more sensitive to increases in precipitation than these results indicate.

Annual flows are normally distributed in the Two-elevation and East River models and approximately log-normally distributed in the White and Animas River models. In all cases, the climate

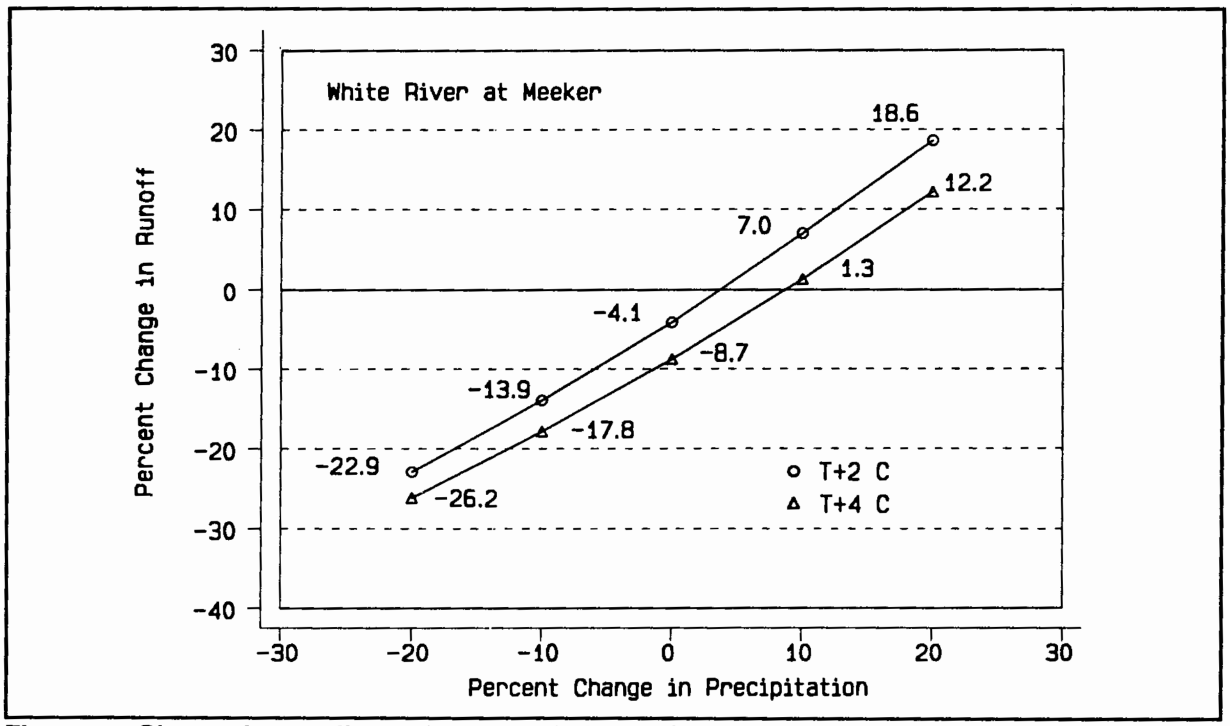

Figure 3: Change in runoff as a function of change in precipitation for the White River model. The relationship is nearly linear for the range of hypothetical scenarios modeled here.

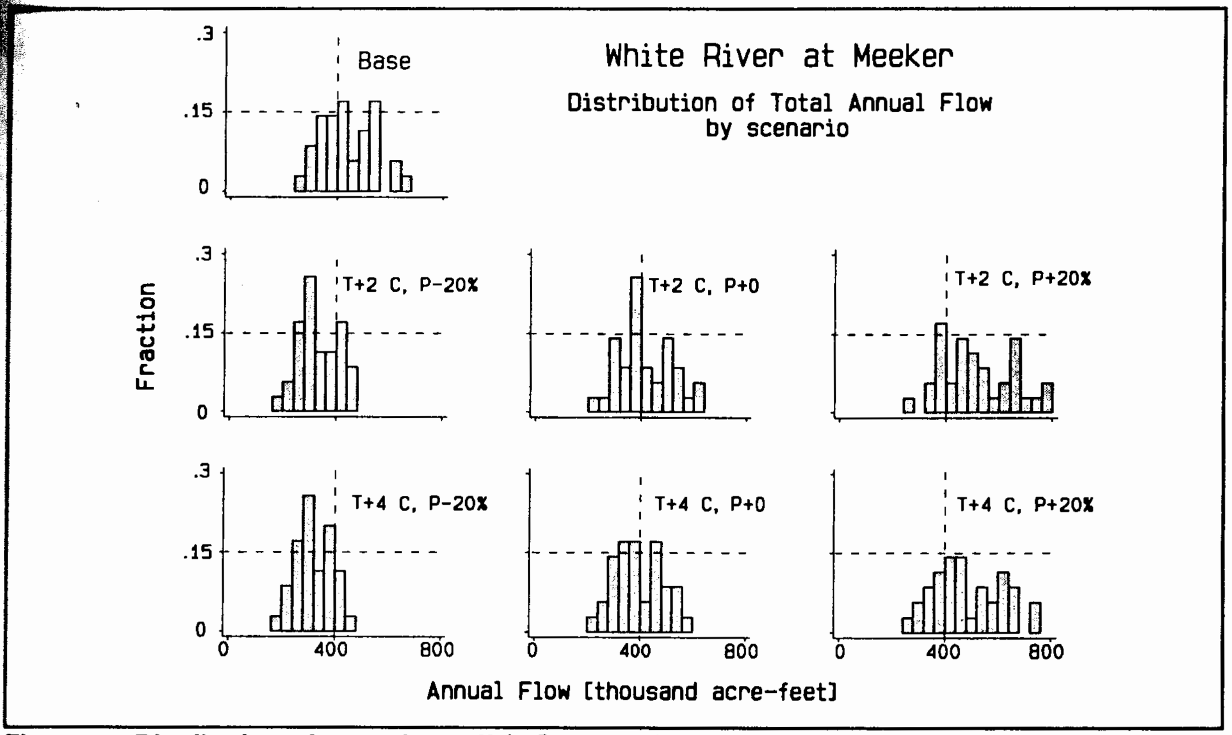

Figure 4: Distribution of annual runoff (taf) for the White River model for selected hypothetical scenarios.

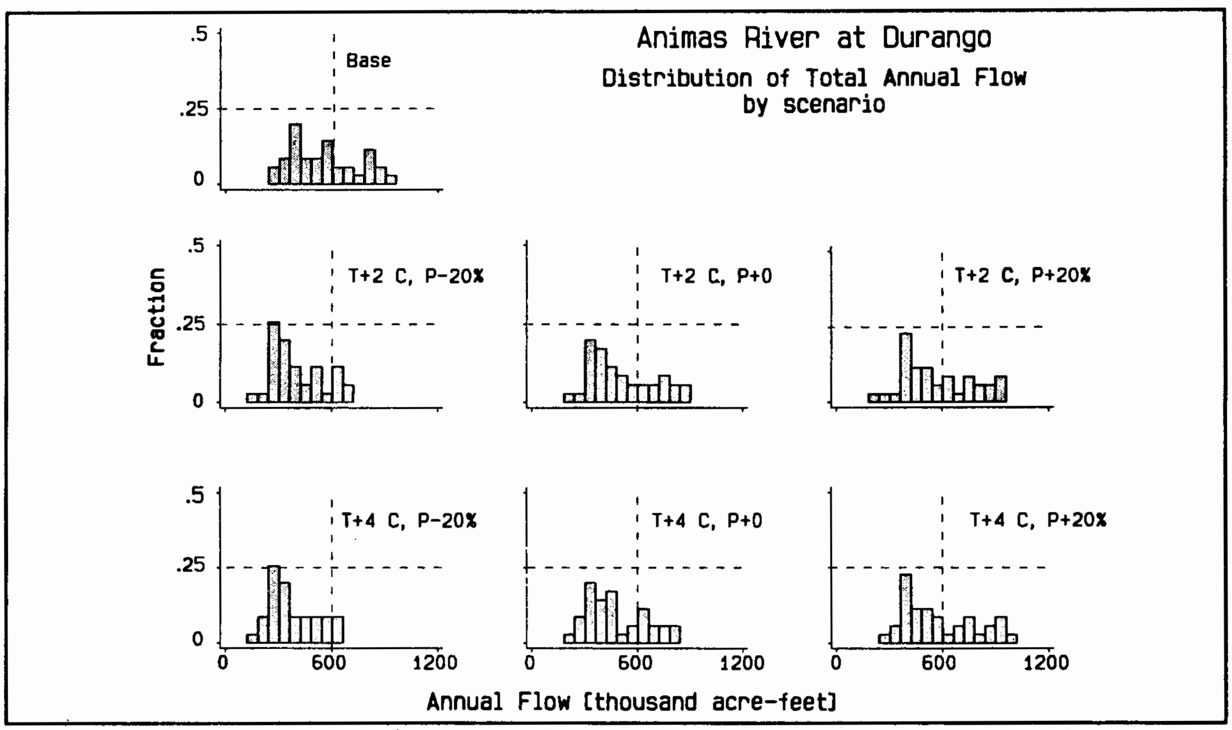

Figure 5: Distribution of annual runoff (taf) for the Animas River model for selected hypothetical scenarios.

change scenarios result in distributions of annual streamflow that are roughly log-normal (Figures 4-5). Temperature increases cause annual flows to decrease and to consolidate, i.e. the distribution narrows, and low-flow years become more frequent. Precipitation increases of 20% spread the distribution at the upper end. This result is also evident in the coefficient of variation, which increases in most of the scenarios that incorporate a 20% precipitation increase (Tables 5-8). The implication is that increased flows are likely to increase variability on an annual basis.

The statistical significance of these results was estimated following the method used by Klemes (1985: App. B). For each scenario, the mean and standard deviation (μ, σ) of the annual streamflow series were treated as perfect estimates of the true mean and standard deviation for the distribution of annual flows. Subsequently, 125 series of 35-year flows were randomly generated from a log-normal distribution defined by μ and σ. The mean and standard deviation of each 35-year series were then plotted (σ versus μ), and the 90% confidence region was defined to be the ellipse that contained 90% of these points. These confidence regions are illustrated for the White River model in Figure 6.

Using the above method, only three scenarios were significant for all basins at the 90% confidence level: T+4° C, P-20%; T+4° C, P-10%; and T+2° C, P-20%. For the White River, one additional scenario, T+2° C and P+20%, was also significant. None of the GCM scenarios were significant at the 90% level. The statistically significant scenarios correspond to a minimum change in mean annual streamflow of 18% on the White River, 25% on the East River and 22% on the Animas River (Nash and Gleick, 1991).

Seasonal Runoff

Temperature increases cause peak runoff to occur earlier in the year. A temperature increase of 2° C shifts peak runoff from June to May for the White and Animas rivers. For the East River, peak runoff still occurs in June, although it is not nearly so exaggerated. For all three basins, the 2° C rise creates a double peak, with high runoff occurring in both May and June. When temperature is increased by 4° C, the

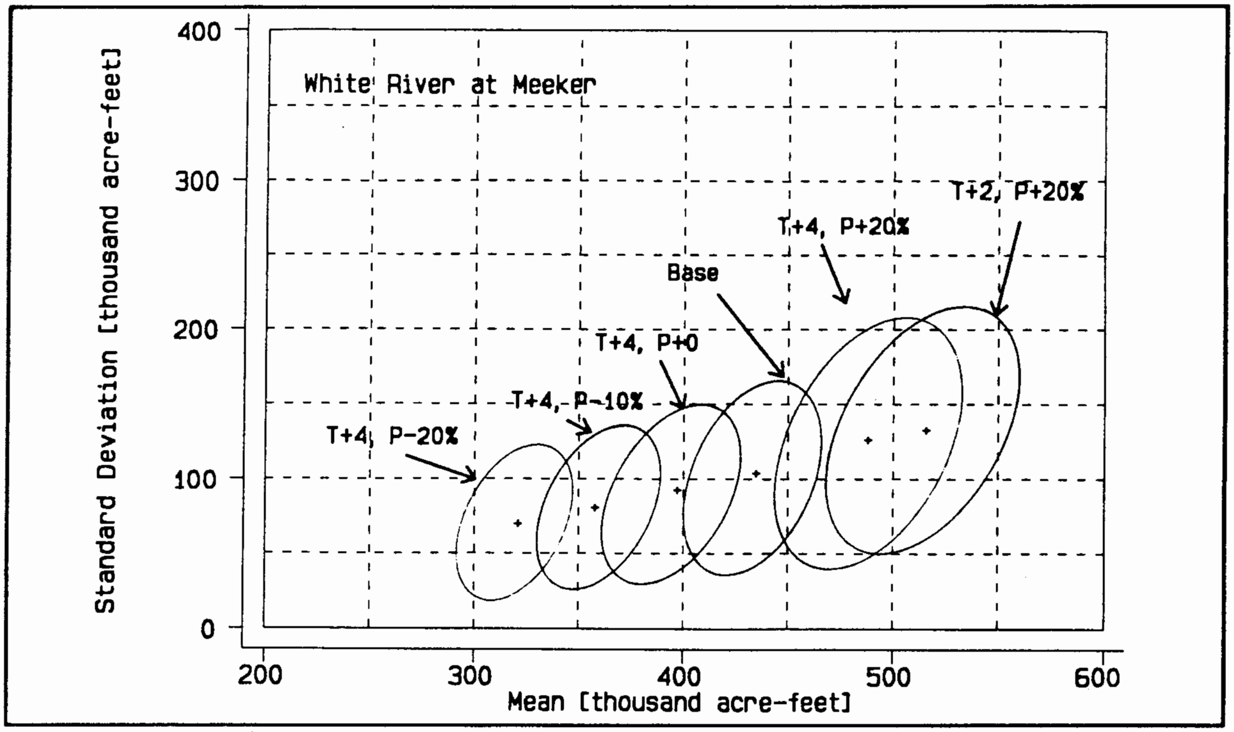

Figure 6: Point estimates of annual flow (mean and standard deviation) for the White River, with approximate 90% confidence regions for the base case and selected hypothetical scenarios.

East River also undergoes a distinct shift in the timing of peak runoff, from June to May. The UKMO scenario for the Animas and White rivers shifts peak runoff from June to April, which reflects the 6.8° C temperature rise. Figure 7 illustrates the general effect of temperature on the timing of peak runoff for the East River. In all cases, the sub-basins remain snowmelt-driven, although peak runoff is occurring earlier in the year.

Histograms of January and June runoff are presented for the Animas River in Figures 8 and 9. The distribution of January runoff becomes much more flat as a result of increases in temperature and/or precipitation. This is indicative of the higher flows which are occurring during the winter, as more precipitation falls as rain rather than snow. Still, flows in January are very low compared to typical spring or summer flows. The impact of climate-change scenarios on June runoff is the opposite. Increases in

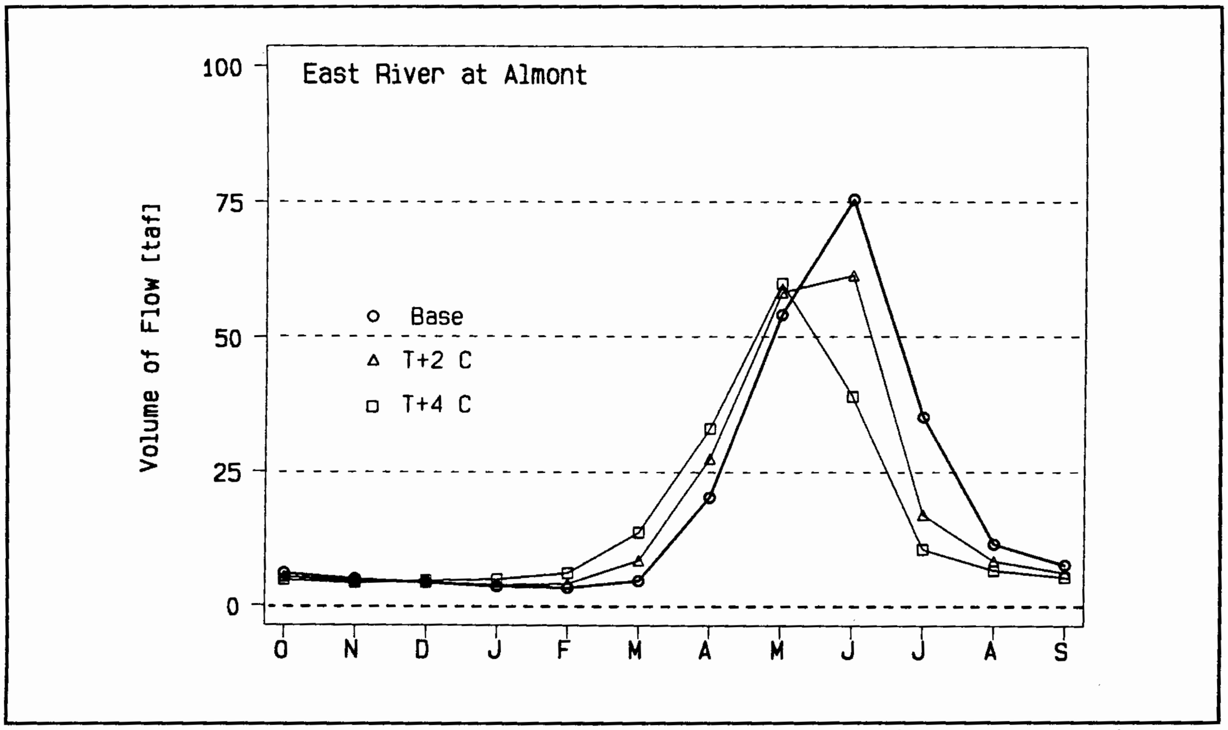

Figure 7: Effect of temperature increases on the average hydrograph (East River model). A temperature increase of 4°C shifts peak runoff from June to May.

temperature cause the distribution to narrow. Whereas in the base case, June runoff ranges from approximately zero to 400 thousand acre-feet (taf), a temperature increase of 4°C cuts this range in half, from zero to 200 taf.

Figure 10 illustrates mean runoff as it varies between high- and low-flow seasons for the White River. Spring runoff is averaged over three months of high runoff (April, May, June) and fall runoff over three months of low runoff (October, November, December). These results suggest less extreme seasonal flows as a result of climate change in most cases. The effect of an evenly applied increase in temperature is to reduce the seasonal variation in runoff, primarily as a result of reduced streamflow in the spring. In the Animas River model, climate scenarios diminish the difference between spring and fall flows because spring runoff decreases in all cases. When substantial precipitation increases are incorporated into the model, however, seasonality becomes more pronounced. In the White and East River models, climate scenarios do not decrease spring runoff as dramatically, while scenarios that incorporate precipitation increases of 20% augment spring runoff substantially.

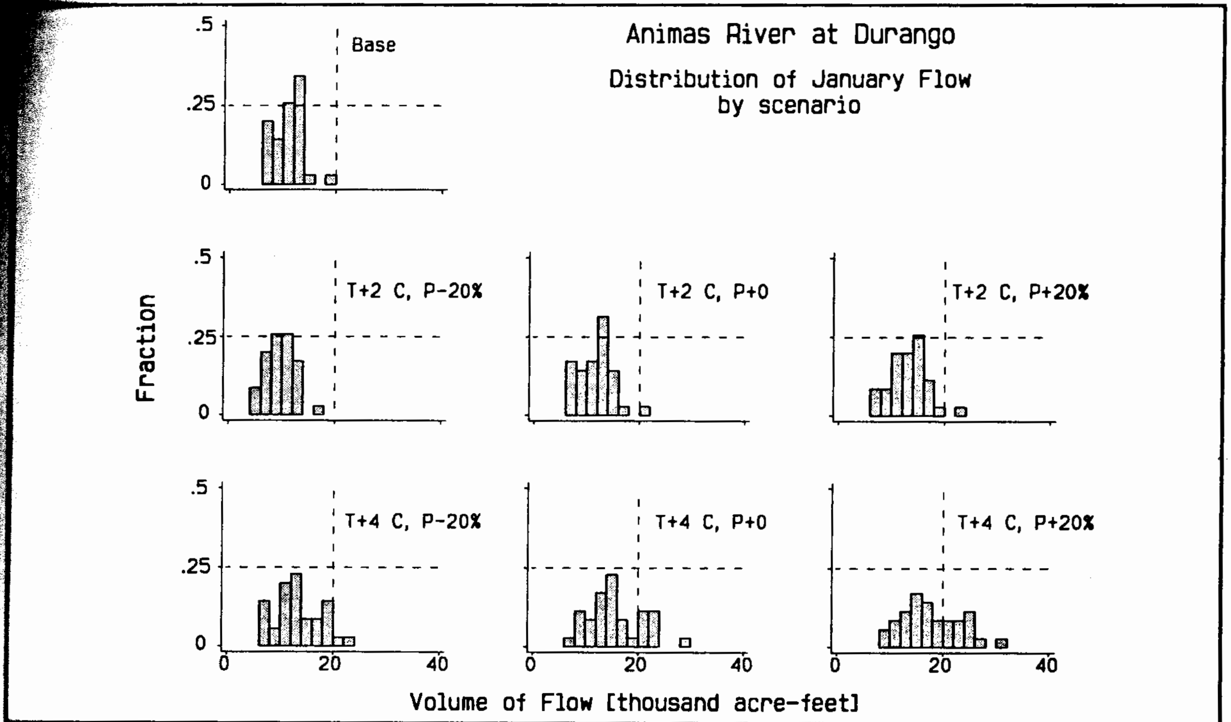

Figure 8: Distribution of January runoff (taf) for the Animas River model for selected hypothetical scenarios.

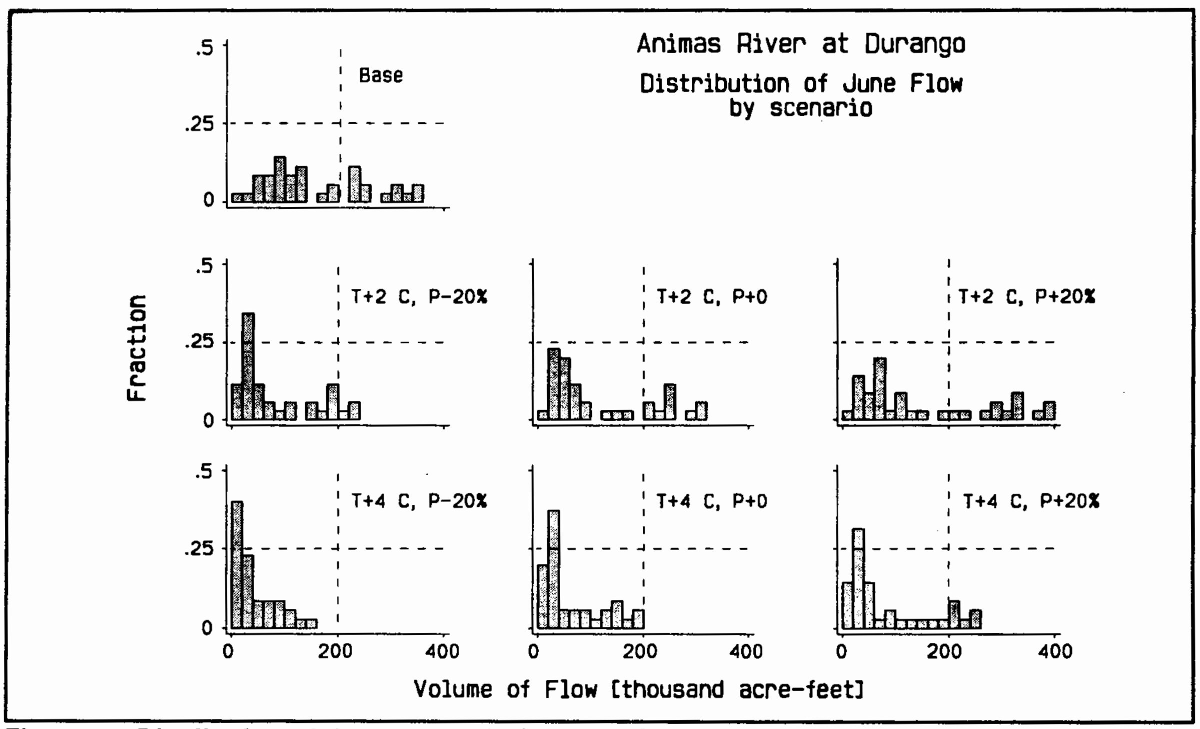

Figure 9: Distribution of June runoff (taf) for the Animas River model for selected hypothetical scenarios.

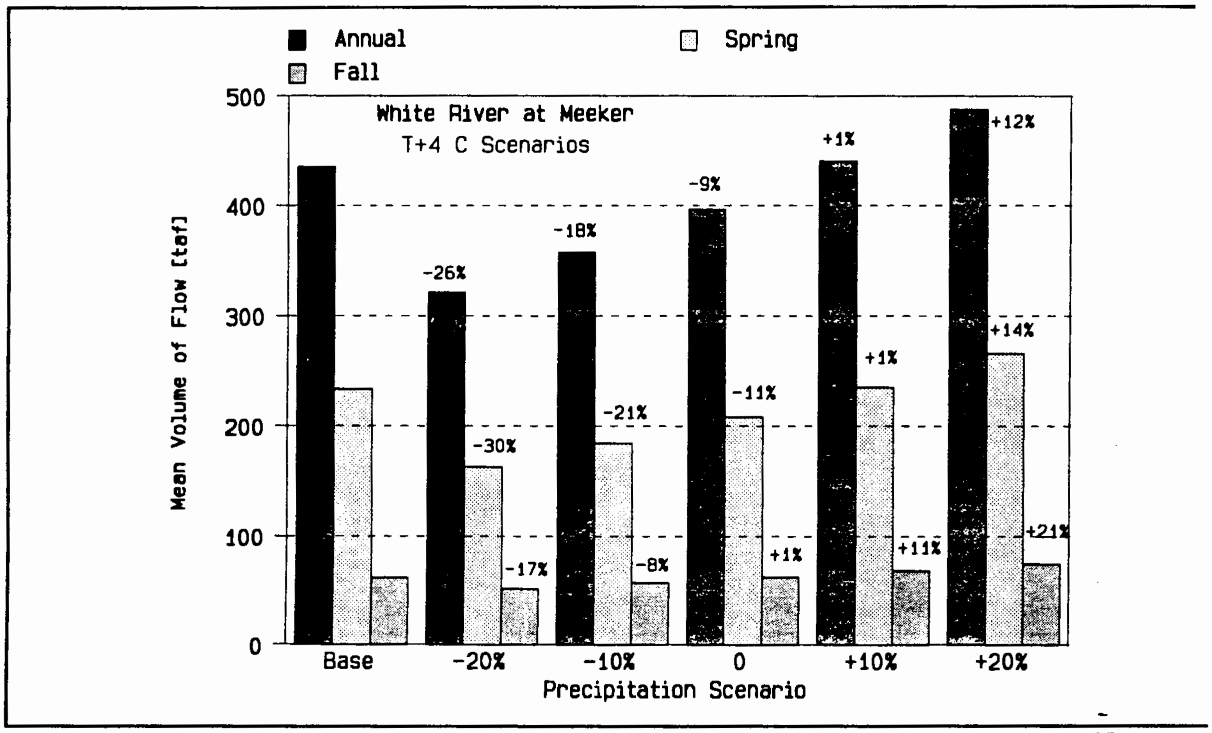

Figure 10: Mean annual runoff, mean spring (April, May, June) runoff, and mean fall (October, November, December) runoff for the White River at Meeker. The base case and T+4°C scenarios are shown.

Transient Scenario

The changes in temperature and precipitation generated by the GISS transient scenario for th year 2030 fall within the range established by the hypothetical scenarios in which runoff varies linearly wit changes in precipitation. Thus, using the data generated by the hypothetical scenarios, we interpolated t find corresponding changes in runoff for the transient scenario. For the more northern GISS grid poin which encompasses the White River basin, temperature increases by 3.2° C and precipitation increases b 10%. This corresponds to an increase in mean annual streamflow of about 4% on the White River at Meeke and a significant shift in seasonality. For the southern grid point, which encompasses the Animas and Eas river basins as well as the Lake Powell inflow (Two-elevation model), temperature rises by 2.5° C anc precipitation increases by 20%. This corresponds to an increase in mean annual runoff of 12% on the Animas River, 11% on the East River, and 9% in the Two-elevation model (inflow into Lake Powell) (Table 9).

Table 9: Changes in runoff generated by GCMs and the NWSRFS hydrologic model

	Δ Runoff (%)	
	GCM	NWSRFS
Equilibrium [1]		
GISS 1	+20	+10
GISS 2	+5	-8 to -14
GFDL	+5	-13 to -16
Transient [2]		
GISS 1	-5	+4
GISS 2	+30	+10 to +12

Notes: [1] Equilibrium GCM runs, in which greenhouse gas concentrations have stabilized at roughly twice current levels.
[2] The GISS transient run, in which greenhouse gases are increasing gradually. The numbers presented here represent the avearge over the decade 2030 to 2039.

GCM Runoff Scenarios

GCM runoff scenarios are compared with the NWSRFS modeling results in Table 9. GCM runoff predictions do not necessarily agree even in direction with those suggested by the hydrologic modeling of GCM changes in temperature and precipitation. In the GISS equilibrium runs, runoff increases by 20% at the more northern grid point (GISS 1) and by 5% at the more southern grid point (GISS 2). Hydrologic modeling results that used the GISS temperature and precipitation inputs suggest that runoff would increase by 10% in the White River basin (GISS 1) and decrease between 8 and 14% in the GISS 2 region. For the GFDL model, the runoff outputs indicate a increase of 5%, while hydrologic modeling suggests runoff decreases between 16 and 23%. For the GISS transient scenario, GCM runoff decreases by 5% at the more northern grid point, while the White River model suggests that equivalent temperature and precipitation changes would result in a 4% increase in runoff. In the lower basin, represented by the

GISS 2 grid point, GCM runoff increases by 30%. Hydrologic modeling using temperature and precipitation inputs from the same grid point indicate that runoff would increase only between 10 and 12%. In general, GCMs underestimate decreases in runoff and overestimate increases when compared to corresponding outputs from the NWSRFS hydrologic model.

Discussion of Hydrologic Modeling Results

In the first study to analyze the impacts of climatic change on the Colorado River, Stockton and Boggess (1979) used Langbein's relationships (Langbein and others, 1949) to estimate the effects of a 2° C temperature rise and a 10% decrease in precipitation. Their results suggested that streamflow in the upper basin would decline by about 44%. Following up on that work, Revelle and Waggoner (1983) developed a linear regression model of runoff, using precipitation and temperature as independent variables. Their results indicated that a 2° C temperature increase would decrease mean annual streamflow by 29%, while a 10% decrease in precipitation would decrease runoff by about 11%. In combination, these changes would result in a 40% decrease in runoff, in close agreement with Stockton and Boggess's earlier result.

In contrast, our studies with a conceptual model suggest less severe impacts on runoff and a relatively greater sensitivity of annual runoff to precipitation rather than temperature changes. A 2° C temperature rise decreases mean annual runoff by less than 10% in the three sub-basins studied. When combined with a 10% decrease in precipitation, runoff decreases are on the order of 20%. These results are comparable to other studies of arid and semi-arid basins that have used conceptual hydrologic models (e.g. Gleick, 1987b; Flaschka, et al., 1987), supporting Karl and Riebsame's (1989) conclusion that the Langbein relationships overstate the role of evaporation.

In a recent study, Schaake (1990) modeled the Animas River altering temperature, precipitation, and potential evapotranspiration independently. (In contrast, in this study, changes in PET were linked to changes in temperature.) Schaake found that a 2° C temperature rise and a 10% increase in PET resulted a 9% decrease in mean annual runoff. Our results show a 7% decrease in mean annual runoff for a 2° C temperature rise and an 8% increase in potential evapotranspiration (refer to Table 8), which is in close agreement with the results from Schaake. For the range of scenarios presented here, mean annual runoff changes nearly linearly with precipitation, although this relationship begins to break down as precipitation increases by 20% at which point runoff begins to increase relatively faster. Results from Schaake indicate that, in the absence of temperature and potential evapotranspiration increases, this non-linearity occurs for a precipitation increase of only 10%, which causes a corresponding increase in runoff of 19%. Overall, our results are within the range reported by other investigators for semi-arid river basins (Table 10).

The results derived from GCM scenarios fall within the range established by the hypothetical scenarios. Of the three GCMs, the GFDL model (T+4.9° C, P+0) results in the most extreme decreases in runoff for all basins (-10% to -24%) because it predicts a relatively large regional temperature increase and no change in precipitation. The least extreme effects are generated by either the UKMO 1 or the GISS 1 grid point, which incorporate respective increases in precipitation of 30% and 20% and lead to increases in runoff of 0 to 10%. Overall, however, the GCM scenarios suggest that decreases in runoff are much more likely than increases in this region. This is consistent with the work of Rind, et al. (1990), who have analyzed the frequency of droughts using GCM outputs other than soil moisture and have found increased drying. Moreover, it is only the GCM grid points which incorporate large increases in precipitation (20 to 30%) in which runoff does not decrease. The greater uncertainty associated with precipitation changes should be kept in mind. All the GCM scenarios suggest large regional increases in temperature, which would lead to decreased runoff, unless offset by precipitation increases of 20% or more.

The GISS transient scenario implies increases in runoff in all three sub-basins and in the Two-elevation model. These range from 4% in the White River basin to 12% in the Animas River basin. In contrast, the GISS equilibrium scenarios imply decreases in runoff of -8% to -14%, except on the White River where runoff increases by 10%. This suggests the potential for short-term increases in runoff (due to

Table 10: Impacts of climatic changes on mean annual runoff in semi–arid river basins. [1]

Change in Precipitation	Change in Temperature: T+1°C		T+2°C		T+3°C		T+4°C	
-10%	Pease River [2]	-50%	Great Basin Rivers [3]	-17 to -28%	Pease River	-50%		
			Sacramento River [4]	-18%			Sacramento River	-21%
			Inflow to Lake Powell [5]	-24%			Inflow to Lake Powell	-32%
			White River	-13%			White River	-17%
			East River	-19%			East River	-25%
			Animas River	-17%				
0			Sacramento River	-3%			Sacramento River	-7%
			Inflow to Lake Powell	-12%			Inflow to Lake Powell	-21%
			White River	-4%			White River	-8%
			East River	-9%			East River	-16%
			Animas River	-7%			Animas River	-14%
+10%	Pease River	+50%	Sacramento River	+12%	Pease River	+35%	Sacramento River	+7%
			Inflow to Lake Powell	+1%			Inflow to Lake Powell	-10%
			White River	+7%			White River	+1%
			East River	+1%			East River	-3%
			Animas River	+3%			Animas River	-5%

Notes:
[1] Each study uses different assumptions; refer to references for details.
[2] All Pease River results from Nemec and Schaake, 1982.
[3] All Great Basin Rivers results from Flaschka, et al., 1987.
[4] All Sacramento River results from Gleick, 1986, 1987b.
[5] All Lake Powell, White, East, and Animas River results from this study.

changed precipitation patterns) that may obscure a long-term trend towards decreases in runoff for some sub-basins.

Runoff results taken directly from GCMs show poor correspondence with results generated by the NWSRFS model using GCM temperature and precipitation scenarios. In general, runoff and soil moisture outputs from GCMs suggest less drying than the NWSRFS model, despite increased air temperatures and PET. Rind, et al. (1990) have concluded that soil moisture deficits and vegetation dessication are understated in the GCM simulations because of their lack of realistic land surface models. Thus, even though GCM estimates of PET may be quite high (reflecting higher temperatures), actual evapotranspiration remains quite low in the models due to inadequate assumptions about evapotranspiration efficiency. Overall, GCM predictions of runoff should be considered less reliable on a regional basis than those results obtained by hydrologic modeling (WMO, 1987).

The statistical significance of these results cannot be assessed in a definitive manner. On the one hand, because data generated by the sensitivity runs are highly correlated with data generated by the base runs, sensitivity estimates of changes in the mean and standard deviation would be expected to be reasonably accurate and statistically significant with respect to one another. At the same time, however, the streamflows generated by the scenarios may not be significantly different from values compatible with the historic streamflow series. Using the method put forth by Klemes (1985, App. B), our analysis suggests that precipitation changes of more than 10% would be necessary before changes in runoff would be significantly different from the historic streamflow series, even if the streamflow distribution were to remain stationary. Moreover, temperature changes of 4° C would not produce a statistically observable impact on runoff, unless accompanied by precipitation decreases. This is consistent with the finding of Klemes (1985) that precipitation changes of 15 to 20% would be required to generate statistically significant changes in runoff in the Pease River (Texas) and the Leaf River (Missouri). This conclusion does not imply that the impacts of climatic change are insignificant but does suggest the difficulty inherent in <u>detecting</u> the impacts of climatic change on runoff, given a relatively short and variable streamflow record. Thus, it is likely that long-term changes in the hydrologic regime on the Colorado River attributable to climatic change would be interpreted as extreme events (e.g. as droughts) for some time and may delay adaptation as a result.

Although all the scenarios studied alter the annual and monthly distribution of flows, annual variability is not strongly affected. This is as we expected, given that we did not alter the distribution of the model inputs, but merely transposed them. In addition, the differential effect of the scenarios on high- and low-flow years is relatively moderate. While the percent change in mean annual runoff with respect to the base case is higher for low-flow years than it is for high-flow years, in all cases these differences are within 10 percent. Of potentially greater concern is the increased frequency of extreme events; however, better information is needed from GCMs before changes in interannual variability can be properly evaluated (Mearns, et al., 1990).

The analysis of seasonal impacts is constrained by the fact that changes in temperature and precipitation were applied uniformly to all daily data. Actually these annual changes would be distributed unevenly throughout the year. While GCM results provide some insights into seasonal changes, they are not definitive. The GISS and UKMO models suggest that absolute temperature increases in the Colorado River Basin are greater in winter, while the GFDL model indicates that temperature increases are greatest in the summer and fall months. All three GCMs are in agreement with respect to the prediction that percentage increases in precipitation are likely to be greatest in the winter and spring. Because these are the seasons with the greatest precipitation under current conditions and because there is likely to be a considerable loss of snowmelt storage due to higher temperatures, a relative increase in winter and spring precipitation could substantially increase the probability of flooding, particularly if operational procedures are not rapidly adjusted.

Our results suggest that an increase in temperature will shift the seasonality of runoff, with peak runoff occurring in May rather than June. This change reflects the fact that under higher temperatures more precipitation falls as rain rather than snow, and snowmelt runoff occurs earlier in the year. This result has been seen in several other regional studies (e.g. Gleick, 1986; Bultot, et al., 1988). Moreover, because this seasonal result is induced by changes in temperature, rather than more uncertain changes in precipitation, the authors believe it is fairly robust. Temperature increases had a much smaller effect on the White River than on the other basins, which is due to the lower elevation of the White River basin. The NWSRFS model reduces evapotranspiration when snow is on the ground by an amount proportional to the areal snow cover. Because a rise in temperature causes less ground to be covered with snow for fewer days out of the year, evapotranspiration increases while runoff decreases. We would expect this effect to be most significant in higher elevation basins which have proportionately more snow cover. This is in fact the case for the three sub-basins modeled here. The highest elevation basin, the East River at Almont, also shows the greatest sensitivity to temperature increases. Overall, the Two-elevation model showed an even greater sensitivity to changes in temperature, which may reflect a greater sensitivity to evapotranspiration, although it is difficult to draw a comparison because of the vastly different scale of the Two-elevation model. On a percentage basis, the sensitivity of runoff to temperature in the White River was less than one-half that in the Two-elevation model. All four models showed nearly an equal sensitivity to changes in precipitation. Relative seasonal changes are most significant for the East River, in which 10% and 20% increases in precipitation increase the absolute variation in runoff between spring and fall months. The interpretation of NWSRFS model results in this study must be tempered by three principal caveats. First, as described above, the ability of the NWSRFS model to accurately simulate runoff under conditions of altered climate is subject to some question. Secondly, all climate scenarios were applied on an annual basis, which may be a reasonable approximation for temperature increases but undoubtedly skews seasonal precipitation patterns which are likely to change dramatically under conditions of altered climate. Finally, the historical record was limited to 35 years, which is too short to allow a substantive analysis of natural (non-greenhouse) variation.

Yet notwithstanding these limitations, the authors believe that the NWSRFS results provide the best information currently available on the sensitivity of runoff in the basin to climatic changes.

In summary, the hydrologic modeling results suggest that significant decreases in runoff are a likely impact of climatic change in the Upper Colorado River Basin. These results are consistent with similar studies of semi-arid basins. The potential water-supply implications of these changes are evaluated in the following section.

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METHODS OF ANALYSIS II: WATER-SUPPLY MODELING

Description of the Model

The impacts of changes in runoff on water supply and delivery were analyzed using the U.S. Bureau of Reclamation's Colorado River Simulation System (CRSS). The CRSS is a reservoir-simulation model that tracks streamflow, reservoir storage, and water supply throughout the Colorado River Basin using a monthly time-step. It uses adjusted, historical hydrologic inputs ("natural streamflow"), projected water demands, reservoir characteristics (e.g., area-capacity relationships), and operating policies (e.g., scheduled releases, reservoir target storages) to determine levels of water deliveries to various users. All the major hydrologic and storage features of the Colorado River Basin are modeled. The model was designed to simulate the operating policies that are currently used by the Bureau of Reclamation. The outputs of the model are actual streamflow and salinity, reservoir levels, hydroelectricity generation, uncontrolled spills, and water deliveries on a monthly basis. The CRSS serves as the Bureau of Reclamation's primary tool for studying the operation of the river and the impact of projected developments in the basin. The model is documented in USDOI (1987). By changing either inputs (e.g., natural streamflow) or operating parameters (e.g., reservoir target storages), modelers can study the response of the whole system. In no sense does the model "predict" future shortages or surpluses, but it does portray the sensitivity of those outcomes to changes in inputs or operating parameters.

The hydrologic inputs to the model are natural streamflow and salinity data, which are defined as historical data adjusted to remove the effects of human development. Historical streamflow data for most stations on the Colorado River exist from 1906. Gaps in the data base have been filled by regression estimates. To derive natural streamflow data, changes in river flow and water use due to human demands, changes in vegetation, and changes in basin evaporation are calculated, and historic flows are adjusted accordingly. Historical salinity data were developed by the USGS using a regression procedure that calculates salt load as a function of historical streamflow and several variables representing development, including upstream adjustments to streamflow, consumptive use, diversions, and irrigated acreage. Adjusted data for streamflow and salinity at the time of this study were available only through 1983; thus this study uses a 78-year historical streamflow record, consisting of years 1906 through 1983, inclusive.

Demand data used in the model are derived from current usage and estimates of future usage. The Bureau of Reclamation has developed a series of projected demands that increase stepwise until the year 2040, at which time the basin states are projected to have fully utilized their water allocations. The annual demands used in the model runs are given in Table 11.[10] These demand projections are based on a number of assumptions made by the Bureau of Reclamation and are not necessarily accepted by all the affected parties. Moreover, future demands will be affected by climatic changes. For example, climate change may result in the population migrations in or out of the region and will certainly alter agricultural patterns and crop-water usage. Although the effect of climate change on future water demands in the region is a very important issue, it was beyond the scope of this study.

River operations in the model are determined by a variety of reservoir operating criteria that are designed to reflect the legal and administrative requirements that govern water supply in the basin. The series of compacts, treaties, laws, court decisions, and regulations that establish the priorities among the Colorado River's multiple users is known collectively as the "law of the river". These requirements are summarized in detail in Hundley (1975) and Getches (1991) and are presented briefly in Appendix B. The law of the river dictates certain reservoir operating criteria, which are modeled by the CRSS. The principal operating parameter in the model is a minimum objective release of 8.23 maf/year from Lake Powell.[11] In addition, the model incorporates storage and flood-control requirements and implements the Bureau of

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[10] The Bureau revises demand schedules on a periodic basis. Documentation is scattered, but the primary sources are the Bureau of Reclamation publications, Projected Water Supply and Depletions in the Upper Colorado River Basin and Consumptive Use of Diversions from the Main Stem.

[11] A minimum objective release from Lake Powell of 8.23 maf/year plus an expected additional 0.02 maf/year from the Paria River should meet the requirements of the Colorado River Compact and the Mexican Treaty obligation, as they are viewed from the perspective of the lower basin states (8.25 maf/year) [See Hundley, 1975].

Table 11: Scheduled demands [taf] used by the Bureau of Reclamation in the CRSS model. [1]

Year	Upper Basin	Lower Basin MWD	Lower Basin CAP	Lower Basin Other [2]	Mexico	Total
1990	3,916	518	1,515	5,772	1,515	13,236
2000	4,490	497	1,488	5,911	1,515	13,901
2010	4,801	497	1,464	5,935	1,515	14,212
2020	4,973	497	1,464	5,960	1,515	14,409
2040	5,245	497	1,467	5,992	1,515	14,716

Notes: [1] Demands are defined as total withdrawals minus return flows. Although trended demands are given here for the years 1990 to 2040, demands were held constant at 2040 levels in the model runs analyzed.

[2] Lower Basin demands other than those of MWD and CAP.

Reclamation's shortage and surplus strategies. The primary operating constraints that affect operation of the model are documented in USDOI (1987) and are given in Appendix B.

The Bureau of Reclamation has tested the model against a 16-year period of actual data (1968-1983) for which the results are presented in Appendix C. Calibration was limited to this 16-year period because the operation of Glen Canyon Dam, which the model simulates, did not begin until 1968. In these calibration runs, simulated end-of-month reservoir levels were forced to match historical end-of-month levels (USDOI, 1987). Thus, errors in simulation were not allowed to accumulate but were corrected for every month. Similar corrections cannot be made in normal simulation runs; therefore, the calibration results potentially overstate the ability of the model to perform multi-year simulations. In addition, the calibration results presented for the model indicate that errors tend to be systematic rather than random: low flows are underpredicted, and high flows are overpredicted.[12]

Modeling Assumptions

For this study, hydrologic inputs were developed using the Index Sequential Method (ISM), in which the historic record is wrapped around itself and run through the model using different starting dates. The existing record can be thought of as a piece of tape in which the year 1906 appears on one edge and 1983 appears on the other. In the ISM method, the ends of the tape are connected and the record becomes continuous, with year 1983 immediately preceding year 1906. The starting point for modeling purposes can now be chosen from among any of the years. Every year in the record may be used as a separate starting point, or, for convenience, some limited set may be selected, such as every fifth year. The use of historic data in the ISM rests on the assumption that past streamflows are indicative of the future, i.e. that the geophysical processes governing streamflow are both stationary and well-described by existing data. Accordingly, the past record is assumed to provide reliable information about the statistical properties of future flows, including mean, variance, and skewness, even though the sequence of future flows will undoubtedly be different from the past. The ISM allows the historic data to maintain its statistical characteristics (e.g., mean, variance, and skewness); but it also introduces some uncertainty with respect to the timing of specific streamflow sequences, allowing an analysis of the effects of the hydrologic starting point on results, e.g., the effect of having the 1920s' "wet period" early or late in the simulation period. In this study, the hydrologic record was staggered by 5 years, and 15 sets or "sequences" of data were simulated. Trace 1 begins with data from 1906, trace 2 with data from 1911, and so on. The Index Sequential Method is frequently used to generate probabilities of occurrence in any single year or set of

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[12]See USDOI (1987), Section IV, "Validation", especially plot no. 2.

years. Thus, if the information of interest is the probability of water shortages in the year 2020, potential flows in the year 2020 are generated by a set of historical traces. The traces are then treated as independent observations, and the probability that a shortage will occur is inferred.[13]

In contrast, in this study we were interested not in the performance of the system at a particular date, but in how it would function over the long-term under scenarios of climate change at some unspecified time in the future. Because climatic change is an incremental, but not necessarily linear, process that will occur gradually over the next century and beyond, the timing of its occurrence cannot be predicted with any accuracy. Thus, our aims for this study were to compare a limited number of scenarios under hypothetical "normal" conditions and under conditions of altered streamflow in order to ascertain the sensitivity of the system to possible climatic changes.

We selected three historical sequences that were analyzed independently in order to: (1) assess the impact of different trace starting points on the statistics of interest (i.e. the difference in results among sequences 1, 2, and 3); (2) bound the plausible results that might be generated by different historical data sequences; and (3) analyze the impact of changes in runoff inputs on seasonal and annual streamflow statistics (e.g. how a 10% decrease in natural streamflow inputs compares to the base case for a given historical sequence). The results presented here should thus be interpreted not as probabilities but as sensitivities. They suggest how a number of water-supply variables would change if a given historical data sequence were altered in the manner specified in each scenario; they say nothing about the likelihood of occurrence.

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[13] In actuality, the historic record cannot be used to develop probabilities of future events, given that the distribution of future streamflows is unknown. Despite this fact, the term "probability" is commonly used in such studies.

The CRSS is capable of running up to 150 years in single simulation. In this study, we chose to analyze 78 years of data because we felt that it provided a long enough sequence of years for our analyses without forcing us to selectively repeat some, but not all, of the historic data. Thus, our base period for this portion of the study consists of the historical hydrology from 1906 to 1983. In order to alleviate the inconsistency created by varying demands during the operation of the model, we elected to analyze only those years in which demand is constant. There are two reasons for this: (1) varying demands obfuscate the effect of the trace starting point on model results; and (2) the climate-change scenarios refer to an equilibrium condition (e.g. in the case of the GCM scenarios, a point at which atmospheric CO_2 has doubled) at some unspecified future date, thus we did not want the analysis to be dependent on how demands might vary in the period 1990 to 2040. We report our results as monthly or annual frequencies derived from a 78-year model run ("Years 1 to 78"), with demands constant at year 2040 predicted levels.[14]

We were also constrained in this study to use October 1989 reservoir levels as our starting point for each simulation run. Because of the large storage-to-annual-flow ratio on the River (approximately four-to-one), starting storage levels can have a significant effect on results. After 50 years of simulation, different sequences produced very different reservoir levels. Thus, by choosing to analyze only the last 78 years of a 128-year run, starting storages were varied implicitly by sequence.[15] Of the 15 sequences

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[14]Because the model is run in "real-time" mode (i.e. 1989 was equal to Year 1 in our model runs), in order to maintain demands at constant levels, the model was run for 130 years (1989-2119). Demands are scheduled to become constant in Year 2040. Thus, we analyzed the last 78 years of a 130-year simulation (2041-2119).

[15]Ideally we would have preferred to run the exact same sequence of historic data with different starting storages in order to analyze independently the impact of initial reservoir storage levels. This would allow us to see explicitly how water-supply variables are affected by initial storage levels. This was not possible for this study. Although the method used here allowed us to vary starting storage levels, it did not allow us to analyze their impact because starting storages are implicitly related to the starting point of each historic data trace (i.e., a high level of initial storage results from the wetter periods having occurred recently in the model run, and thus these very wet sequences will not occur again for several decades.) Thus, as we note later, the difference in results among sequences was not great.

produced by the CRSS model, we selected three to analyze, which correspond to low, medium, and high starting storage levels. A description of these sequences is given in Table 12.

For this part of the project, hypothetical scenarios of runoff were constructed as percent changes. The hypothetical scenarios analyzed include changes in natural runoff of ± 5%, ± 10%, and ± 20%. The magnitude of these changes corresponds roughly to the results generated by the NWSRFS model, which suggested that changes in runoff in the higher elevations of the upper basin were likely to range from -30% to +10%. Because the model generates extreme results for the -20% scenario, we did not attempt to model a decrease in runoff of -30%. We chose to vary streamflow inputs systematically in order to generate information about the sensitivity of the system to variations in runoff inputs. Percent changes were applied uniformly to all the input data used in the model, e.g. natural (historic) streamflows were decreased by 10% at all points and then run through the model.[16] This resulted in a new set of natural runoff numbers in which the mean was altered by a specific percentage and the variance was altered in proportion to the mean (i.e., the coefficient of variation remains unchanged). Although the variability of climate and runoff may change as a result of the greenhouse affect, at present, very little is known about how future climatic changes will affect variability. Neither GCMs nor historical data give a clear indication of how variability will change, nor is there any reason to expect a homogenous response to warming in terms of changes in variability (ICF, 1989; IPCC, 1990; Mearns, et al., 1990).

In addition, in order to assess the effect of a shift in the timing of runoff, a time-shifted scenario was modeled in which runoff inputs were shifted backward by one month; thus, historic flows for February were fed into the model as January runoff. This simulates the seasonal effects of increases in temperature on snowfall and snowmelt as discussed above. (See discussion of seasonal runoff under Results of Hydrologic Modeling, above).

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[16]Percent changes in runoff were applied to years 53 through 130 (i.e. Years 2042-2119). The model was run for the first 50 years without any alteration in inputs. (See FN #14 above.)

Table 12: Description of input sequences.

Sequence Number	Starting Storage (taf) [1]	Historic Input Data [2]
1	20,995	1967–1983; 1906–1966
2	36,482	1944–1983; 1906–1943
3	54,647	1929–1983; 1906–1928

Notes: [1] Total system storage (Upper and Lower basins) at beginnning of period of analysis.

[2] This shows the order in which historic hydrology was run through the model for each sequence. Year 1 in the model runs uses natural flow data from 1967 for sequence 1, 1944 for sequence 2, and 1929 for sequence 3.

RESULTS OF WATER-SUPPLY MODELING

Runoff

Changes in runoff were analyzed at five points in the system: Green River at Green River, Wyoming ("Green River"); the Colorado River at Cisco ("Cisco"); the San Juan River at Bluff ("Bluff"); the Colorado River at Lees Ferry ("Lees Ferry"); and the Colorado River below Imperial Dam ("Imperial"). Green River, Cisco, and Bluff are all upper basin points. Lees Ferry is located near Glen Canyon dam, about 16 miles upstream of the Compact Point. Imperial Dam is located in the lower basin (Figure 11).

Changes in the mean, standard deviation, maxima, and minima of annual runoff at Green River, Lees Ferry, and Imperial Dam are summarized in Tables 13-15. Generally the differences in annual statistics generated by different sequences were not significant, in part because starting storage levels and hydrologic trace were not varied independently.[17] Thus, those sequences that had low starting storages also had relatively high flows early in the simulation run. Because of the small differences generated by the different sequences, the results of only one sequence, sequence number two (s2), which represents a middle scenario, are presented here. (For comparative purposes, the annual statistics at Lees Ferry are given for all three sequences in Appendix C, Table C2. Differences in the mean among sequences are within 2% for all scenarios.)

A 20% decrease in natural runoff causes between an 11% to 31% decrease in modeled runoff among the five points analyzed. A 20% increase in natural runoff causes a 31% increase in modeled runoff at each of the five points analyzed. For the upper basin points, a 5% change in natural runoff causes a 7 to 8% change in actual runoff, and the effect of changes in natural runoff is essentially linear over the range of scenarios examined. This is not true in the lower basin where storage has a greater mitigating effect on decreases in natural runoff.

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[17]See FN #15 above.

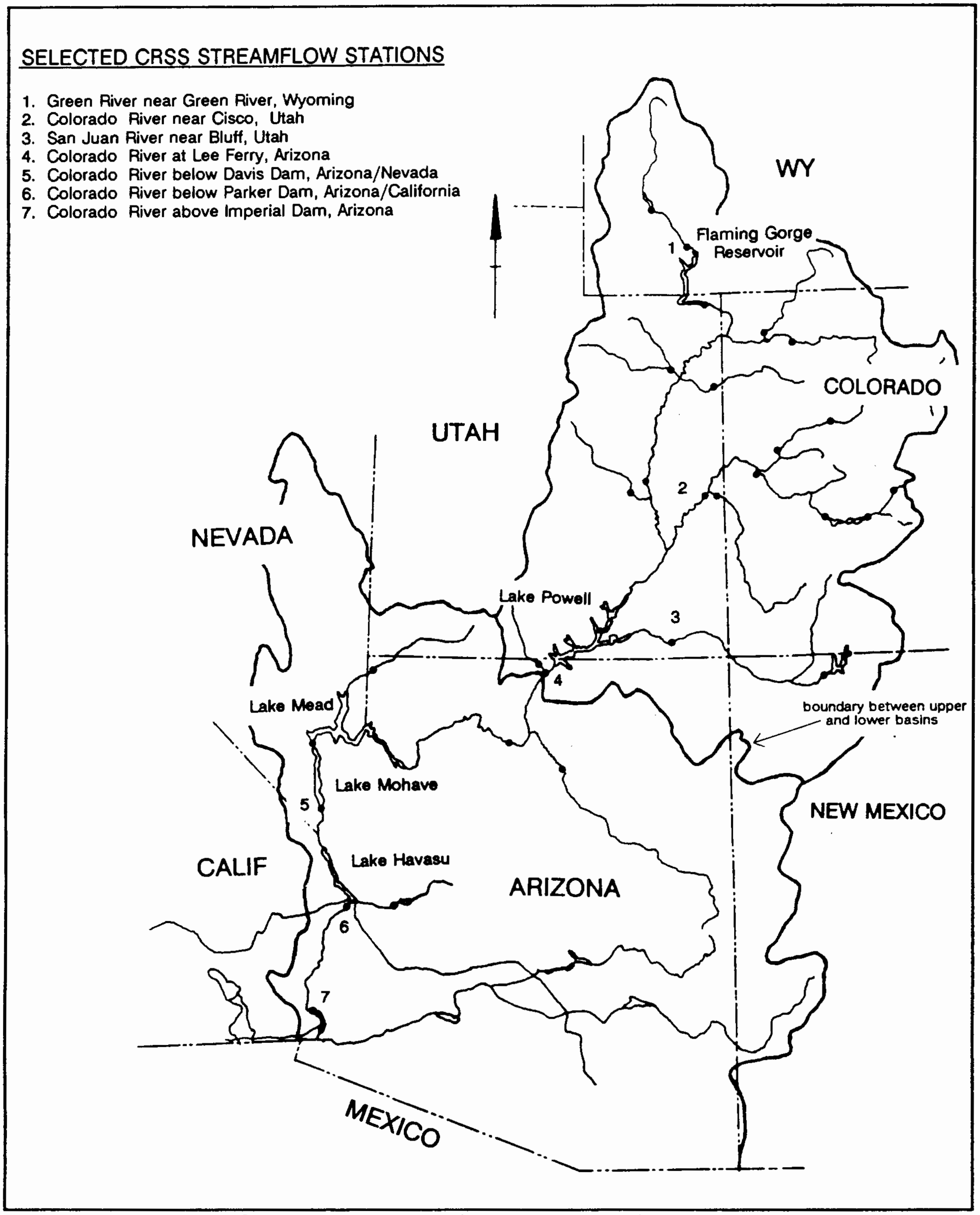

Figure 11: Map of the Colorado River basin (excluding Mexico) showing the location of selected CRSS stations and major reservoirs. (Source: redrawn from USDOI, 1987.)

Decreases in natural runoff cause severe changes in annual minimum runoff. For instance, the -10% scenario causes mean annual runoff in the upper basin to decline by about 15%. Minimum flow, however, declines by between 32% (at Cisco) and 86% (at Lees Ferry). Even the -5% scenario causes runoff at Lees Ferry to fall considerably below the objective minimum release of 8.23 maf in 6 years, while the -10% scenario causes streamflows to fall below this level in 15 of the 78 years. Also interesting is the fact that increased-flow scenarios do not change the annual minimum streamflow at Lees Ferry and Imperial Dam. Even in the +20% scenario, annual deliveries at Lees Ferry still fall to 8.23 maf in 14 of the 78 years. The increased-flow scenarios cause maximum flows in the upper basin to increase by up to 27% (in the +20% scenario). The +20% scenario causes the maximum annual runoff at Lees Ferry to jump by 35%, from 17 maf to nearly 23 maf. At Imperial Dam, this same scenario raises the maximum annual runoff to 17.8 maf.

Model outputs are closely correlated with patterns in the historical data that are used as model inputs. In Figures 12 and 13, annual runoff at Green River and Lees Ferry has been smoothed (using 3-year moving averages) and plotted as a function of time (year). At the upstream point of Green River some extremes are evident. A sequence of low-flow years occurs between years 9 and 20 and again between years 63-68. When correlated with model inputs, these periods correspond to the actual years of 1953-1964 and 1929-1933, respectively. Similarly a high-flow period is obvious between years 38-50, which correspond to the historical years 1983 and 1906-1917 and which, in fact, were the highest runoff periods in the existing instrumental record. These patterns are even more obvious at Lees Ferry, where annual flows are tightly controlled (see Figure 13). In the base case, annual releases from Lake Powell never drop below the objective minimum of 8.23 maf/year; however, a runoff decrease of 10% causes releases from Lake Powell to fall below 8.23 maf in years 9-20, resulting in shortages to lower basin users. Historically, this period (1953-64) is the most critical dry period on record in terms of water supply. Similarly the effect of the "wet period" that occurred in the early part of the century is also very evident; even streamflows in the -10% scenario rise above the 8.23 maf level for several years. Thus, when interpreting these results, the historical hydrology needs to be kept in mind.

Table 13: Annual flow (taf) of the Green River at Green River, WY.

Scenario	Mean Flow [1]		Standard Deviation	Minimum Flow		Maximum Flow	
-20 %	679	(-30.5 %)	303	91	(-63.9 %)	1,424	(-27.5 %)
-10 %	827	(-15.3 %)	353	151	(-40.1 %)	1,693	(-13.8 %)
-5 %	902	(-7.6 %)	378	197	(-21.8 %)	1,826	(-7.0 %)
Base	977		404	252		1,964	
+5 %	1,051	(7.7 %)	429	282	(11.9 %)	2,098	(6.8 %)
+10 %	1,126	(15.4 %)	454	287	(13.9 %)	2,231	(13.6 %)
+20 %	1,277	(30.8 %)	503	304	(20.6 %)	2,502	(27.4 %)

Note: [1] Numbers in parentheses represent percent change compared to the base case.

A more meaningful way to look at annual runoff is to consider how runoff frequency changes across scenarios. Figure 14 shows the cumulative frequencies of annual runoff at Lees Ferry. The cumulative frequency diagram shows a sharp discontinuity at 8.23 maf, which represents the objective minimum release from Lake Powell. In the base case scenario, no years have a streamflow less than 8.23 maf, but in the -5% scenario about 6% of the years fall below 8.23 maf; in the -10% scenario, this increases to 17%; and in the -20% scenario, 36% of the years fall below this targeted level.

Reservoir Storage

Much of the difference in runoff generated by the climate-change scenarios, rather than being passed through the system, is being cushioned through increased water storage or increased releases. While the natural streamflow data that are input into the model refer to a condition in which no storage

Table 14: Annual flow (taf) of the Colorado River at Lees Ferry (below Glen Canyon Dam).

Scenario	Mean Flow [1]		Standard Deviation	Minimum Flow		Maximum Flow	
-20 %	6,929	(-26.1 %)	2,024	832	(-89.9 %)	8,230	(-51.2 %)
-10 %	8,205	(-12.5 %)	1,784	1,143	(-86.1 %)	15,790	(-10.0 %)
-5 %	8,801	(-6.1 %)	1,693	3,710	(-54.9 %)	14,514	(-14.0 %)
Base	9,372		2,089	8,230		16,869	
+5 %	10,037	(7.1 %)	2,572	8,230	(0)	18,671	(10.7 %)
+10 %	10,774	(15.0 %)	3,023	8,230	(0)	20,307	(20.4 %)
+20 %	12,289	(31.1 %)	3,549	8,230	(0)	22,756	(34.9 %)

Note: [1] Numbers in parentheses represent percent change compared to the base case.

Table 15: Annual flow (taf) of the Colorado River at Imperial Dam.

Scenario	Mean Flow [1]		Standard Deviation	Minimum Flow		Maximum Flow	
-20 %	5,381	(-11.1 %)	511	2,565	(-54.6 %)	5,656	(-49.7 %)
-10 %	5,605	(-7.4 %)	279	3,524	(-37.6 %)	6,270	(-44.2 %)
-5 %	5,818	(-3.9 %)	611	5,650	(0)	6,057	(-19.4 %0
Base	6,053		1,112	5,650		11,241	
+5 %	6,366	(5.2 %)	1,527	5,650	(0)	13,646	(21.4 %)
+10 %	6,742	(11.4 %)	2,013	5,650	(0)	15,186	(35.1 %)
+20 %	7,954	(31.4 %)	2,873	5,650	(0)	17,773	(58.1 %)

Note: [1] Numbers in parentheses represent percent change compared to the base case.

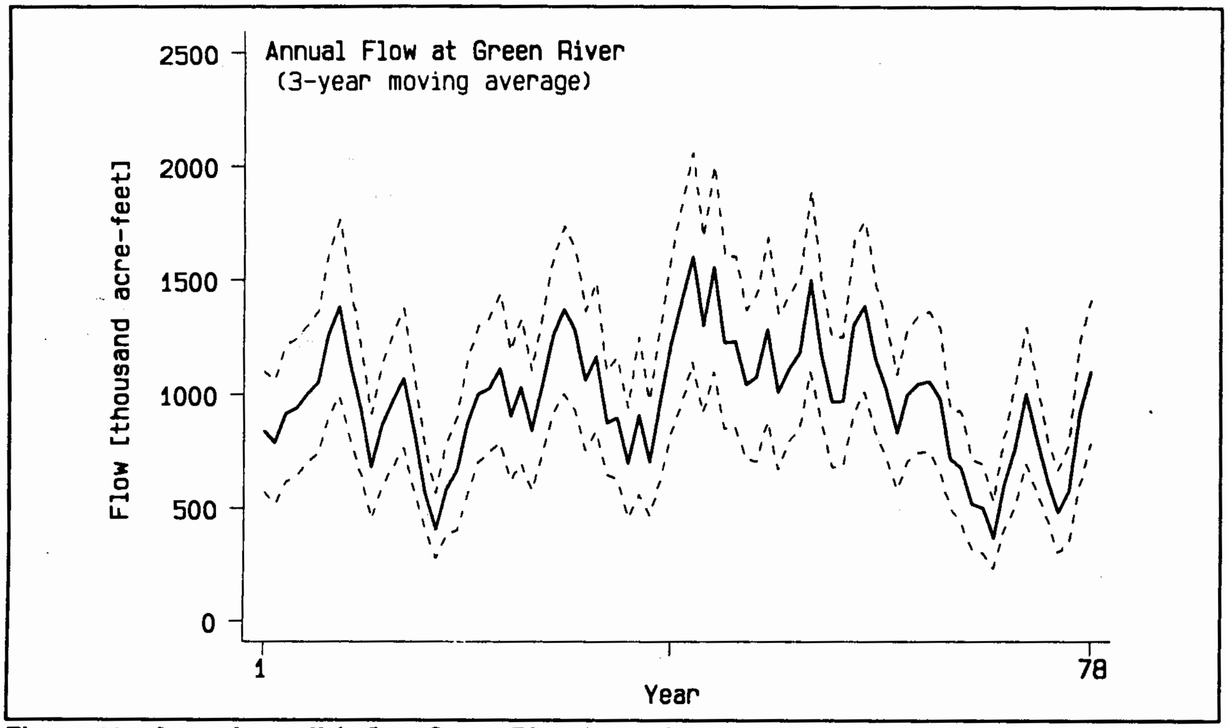

Figure 12: Annual runoff (taf) at Green River in the base case and the ±20% runoff scenarios. Runoff is plotted as a three-year moving average.

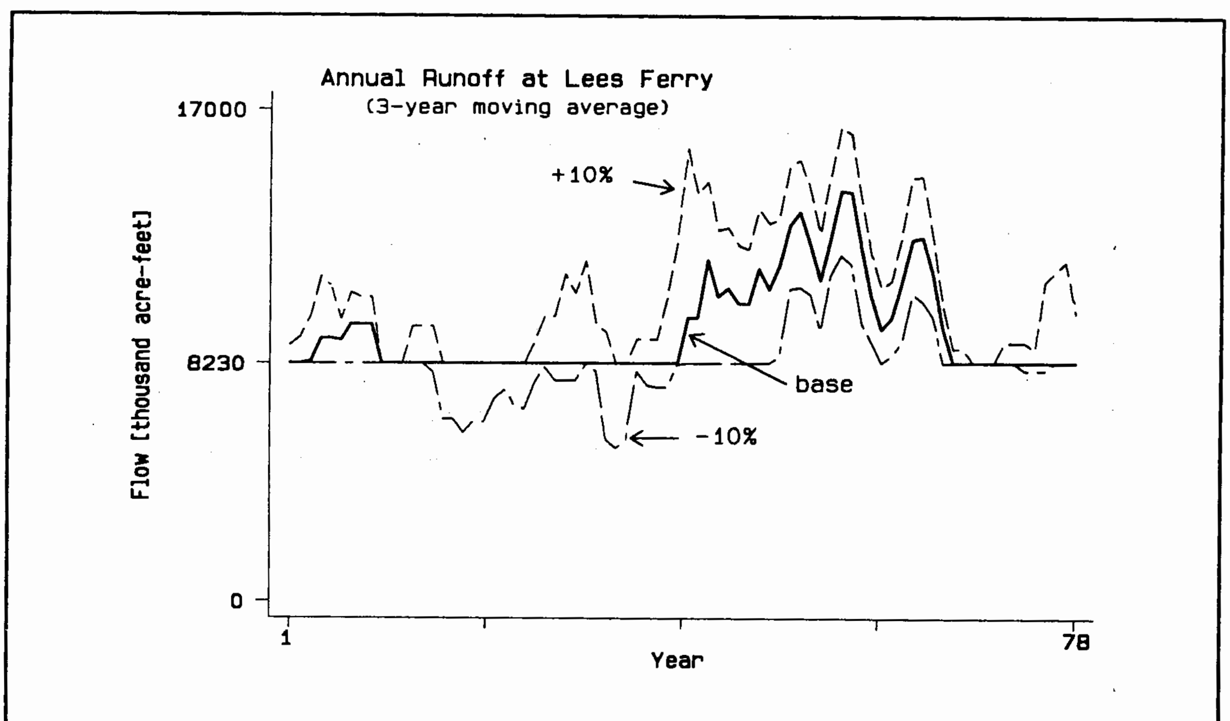

Figure 13: Annual runoff (taf) at Lees Ferry in the base case and ±10% runoff scenarios. Runoff is plotted as a three-year moving average.

Table 16: Major reservoirs in the Colorado River Basin.

Reservoir	Live Capacity [1] (taf)	Annual Evaporation [2] (feet)	Bank Storage (%) [3]	Power Generating Capacity (MW)
Blue Mesa	830	1.05	---	60
Fontenelle	345	2.27	---	10
Flaming Gorge	3,724	2.10	3.30	108
Navajo	1,642	1.80	---	
Lake Powell	24,454	3.96	8.00	950
Lake Mead	27,019	6.50	6.50	1,345
Lake Mohave	1,810	7.31	---	240
Lake Havasu	619	7.39	---	120

Source: USDOI, 1987; Weatherford, 1990:61.

Notes:
[1] Live capacity is the volume of water that can be withdrawn by gravity.
[2] Evaporation is calculated on a monthly basis by multiplying a monthly evaporation coefficient by the surface area of the reservoir. The numbers given here represent the average of 12 monthly evaporation coefficients and are in units of feet.
[3] Bank storage is calculated as a percent of monthly storage.

exists, actual storage throughout the entire Colorado River system is about 60 maf, or approximately four times the average annual streamflow of the river at Lee Ferry. It is this storage capacity that is cushioning annual changes in streamflow, particularly in the lower basin. The system's major reservoirs are summarized in Table 16. While the upper and lower basins have nearly equal storage capacities, because the major upper basin reservoir --Lake Powell-- is located so far downstream, its releases primarily serve lower basin water users. For this project, we elected to analyze changes in three reservoirs as well as in overall storage changes in the upper and lower basins. The reservoirs selected include one upper reach reservoir, Flaming Gorge; the major upper basin reservoir, Lake Powell; and the major lower basin reservoir, Lake Mead.

The effect of hypothetical changes in runoff on reservoir storage is shown in Tables 17 through 19. Reservoir storage is reported as storage on August 1, which corresponds to the end of the spring runoff season and is roughly when peak storage occurs in the Colorado system. In the upper basin, decreases in runoff of 5, 10, and 20% generate respective decreases in mean storage on August 1 of 16, 30, and 65%.

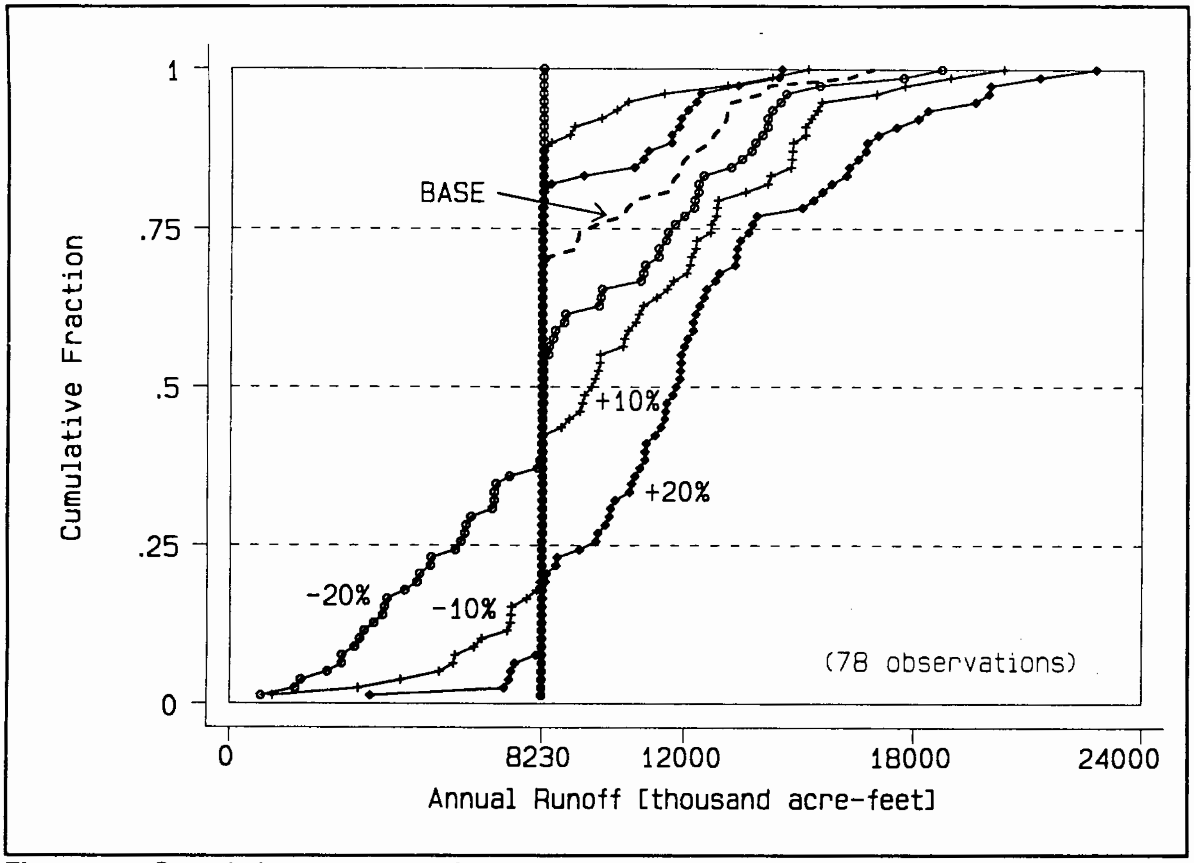

Figure 14: Cumulative frequency of annual runoff at Lees Ferry for all scenarios. The plot shows the frequency (y-axis) with which annual runoff is equal to or less than a given volume (x-axis).

While less likely under scenarios of climate change, increases in runoff of 5, 10, and 20% generate respective increases in mean storage on August 1 of approximately 18, 25, and 30%. For Lake Mead, the major lower basin reservoir, these figures are comparable (see Table 19). Decreases in natural runoff of 20% reduce mean storage on August 1 in Lakes Powell and Mead to less than 25% and 15% of their respective capacities. In both the -10% and the -20% scenarios, Lake Mead is completely drained in some years. For both the upper and lower basins, a 20% increase in natural runoff generates completely full reservoirs.

A rough water-balance of the lower basin indicates that decreases in flow/storage are being partially offset by decreases in evaporation and bank storage (i.e. water that is stored in the surrounding soils). A 10% decrease in natural runoff causes average annual storage in the lower basin to decrease by

Table 17: Storage (taf) in Flaming Gorge reservoir on August 1 for various scenarios.

Scenario	Mean Storage [1]		SD [2]	Minimum Storage		Maximum Storage	
-20 %	757	*(-70.0 %)*	629	77	*(-92.7 %)*	2,640	*(-27.2 %)*
-10 %	1,689	*(-33.0 %)*	1,134	97	*(-90.8 %)*	3,545	*(-2.3 %)*
-5 %	2,085	*(-17.3 %)*	1,063	142	*(-86.5 %)*	3,544	*(-2.3 %)*
Base	2,522		780	1,055		3,627	
+5 %	2,963	*(17.5 %)*	486	1,946	*(84.5 %)*	3,627	*(0)*
+10 %	3,150	*(24.9 %)*	368	2,119	*(100.9 %)*	3,627	*(0)*
+20 %	3,306	*(31.1 %)*	282	2,348	*(122.6 %)*	3,627	*(0)*

Notes [1] Numbers in parentheses represent percent change compared to the base case.
[2] Standard deviation.

Table 18: Storage (taf) in Lake Powell on August 1 for various scenarios.

Scenario	Mean Storage [1]		SD [2]	Minimum Storage		Maximum Storage	
-20 %	5,915	*(-62.9 %)*	3,614	1,904	*(-73.8 %)*	19,312	*(-13.3 %)*
-10 %	11,260	*(-29.4 %)*	6,684	2,627	*(-63.8 %)*	21,326	*(-4.3 %)*
-5 %	13,434	*(-15.8 %)*	6,628	2,736	*(-62.3 %)*	21,800	*(-2.1 %)*
Base	15,949		5,046	7,265		22,277	
+5 %	18,790	*(17.8 %)*	3,045	12,145	*(67.2 %)*	22,509	*(1.0 %)*
+10 %	19,978	*(25.3 %)*	2,188	14,193	*(95.4 %)*	22,885	*(2.7 %)*
+20 %	20,873	*(30.9 %)*	1,533	16,137	*(122.1 %)*	22,970	*(3.1 %)*

Notes [1] Numbers in parentheses represent percent change compared to the base case.
[2] Standard deviation.

Table 19: Storage (taf) in Lake Mead on August 1 for various scenarios.

Scenario	Mean Storage [1]		SD [2]	Minimum Storage		Maximum Storage	
-20 %	3,674	*(-70.3 %)*	2,853	0	*(-100.0 %)*	8,385	*(-59.5 %)*
-10 %	8,071	*(-34.7 %)*	5,317	0	*(-100.0 %)*	19,687	*(-8.5 %)*
-5 %	10,545	*(-14.7 %)*	4,889	2,888	*(-51.7 %)*	21,891	*(-0.4 %)*
Base	12,366		5,027	5,975		22,170	
+5 %	14,166	*(14.6 %)*	5,068	7,688	*(28.7 %)*	22,426	*(0.2 %)*
+10 %	17,211	*(39.2 %)*	3,678	9,258	*(54.9 %)*	22,716	*(1.8 %)*
+20 %	19,808	*(60.2 %)*	2,512	10,597	*(77.4 %)*	23,623	*(3.0 %)*

Notes [1] Numbers in parentheses represent percent change compared to the base case.
[2] Standard deviation.

4348 taf (30%). In the absence of changes in evaporation and bank storage, runoff decreases of that magnitude would be expected to cause substantially greater decreases in storage. In fact, decreases in bank storage and evaporation of approximately 500 taf/year occur as a result of a 10% decrease in runoff (See Appendix C, Table C5). Evaporation effects, however, are underestimated here because evaporation rates will increase in a warmer climate. This would be reflected in higher evaporation coefficients for each of the reservoirs and still greater decreases in water availability.

Figures 15 and 16 show plots of August 1 storage as a function of time. Most obviously these plots reveal how the variability of the flow-input data affects storage. Also they suggest how lesser quantities of runoff could result in extended shortages if we assume the same historical variability of runoff. In the upper basin, the -5% scenarios causes storage to fall below 10 maf for a period of nearly 20 years. In the -10% scenario, this period extends to 30 years. In the -20% scenario, nearly all years have less than 10 maf of storage. In the lower basin, a 10% decrease in runoff causes lower basin storage to fall below 6 maf for a period of 20 years. The exceedingly high flows that follow this period (corresponding to the historical period of the 1920s), however, allow the reservoirs to recover quickly and to reach near maximum capacity. Only in the -20% scenario do reservoirs fail to recover to functional levels. The -5% scenario takes storage in the lower basin to new low levels, although reservoirs recover to median levels within a few years. The -10% scenario causes extended periods of very low storage, and recovery takes 15 to 20 years. In the -20% scenario, reservoirs are unable to recover to average levels over the modeled period. In fact, the -20% scenario causes Lake Mead to run completely dry roughly 25% of the time.

These figures also show the impact of reservoir sedimentation over time. While not specifically related to climatic change, sedimentation is likely to have an impact on system operations over the next several decades. For the largest reservoirs, the CRSS calculates loss of storage capacity due to sedimentation as an absolute amount per month. Over a 78-year run, Lake Powell loses 4760 taf or nearly 20% of its capacity, and Lake Mead loses 3000 taf or 11% of capacity. This represents a significant loss of storage capacity that needs to be considered when assessing the system's future effectiveness.

More interesting than average changes in storage is how frequently critical storage levels are reached under various scenarios. For instance, in the base case, Lake Powell never falls below minimum power pool (the minimum volume necessary to generate hydroelectricity). Cumulative frequency diagrams for Lakes Powell and Mead are presented in Appendix C (Figures C6 and C7) and are summarized here. The -5% scenario causes Powell to fall below its minimum power pool (4.1 maf) roughly 20% of the time; this frequency increases to nearly 60% under the -20% scenario. Similarly, in the base case, the frequency with which Lake Powell contains two or more years worth of storage (roughly 16.5 maf) is just under 50%. This frequency rises to 70% under the +5% scenario, and to 90% under the +20% scenario. Lake Mead has an active storage capacity of roughly 26 maf and a minimum power pool of 10 maf. When storage falls below the minimum power pool, deliveries to downstream users are reduced to their minimum allowable levels. Even in the base case, monthly storage falls below minimum power pool 50% of the time. And with a 5% increase in flow, releases are still reduced to their minimum level in 30% of the months. A decrease

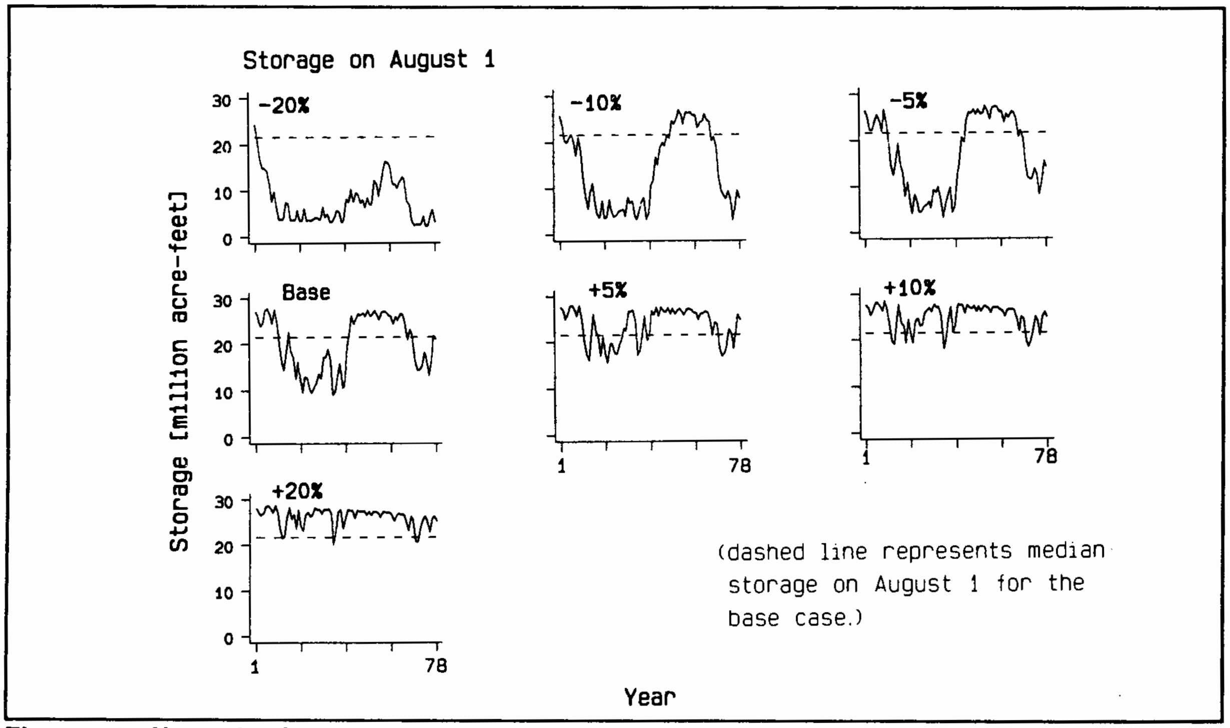

Figure 15: Upper basin storage on August 1 plotted as a function of year, for all scenarios.

in runoff of 20% leaves the reservoir essentially empty in about 30% of the years, while the minimum storage level required for power generation is never attained.

Depletions and Deliveries

Consumptive water use in the basin is reported in terms of depletions and deliveries to major users. Reservoir evaporation is modeled explicitly by the CRSS and is not considered a depletion. Scheduled depletions are those shown in Table 11. In addition, for some users, deliveries are constrained so that they never fall below a minimum level. In this study, the minimum deliveries for the Central Arizona Project (CAP) and the Metropolitan Water District of Southern California (MWD) were 451 taf and 500 taf,

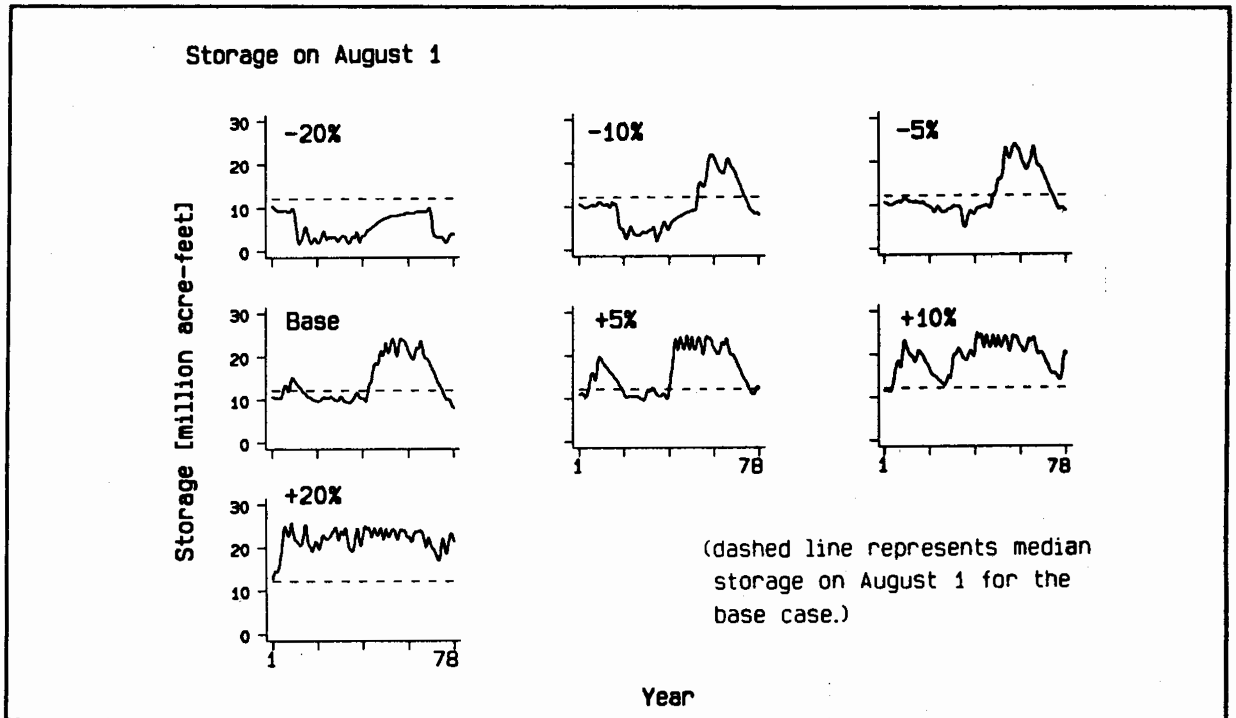

Figure 16: Lower basin storage on August 1 plotted as a function of year, for all scenarios.

respectively.[18] The CRSS has no provisions for allocating shortages in the upper basin. Thus when shortages occur and storage is exhausted, the model imposes these shortages on lower basin users, even though this may result in violations of the Colorado River Compact during the simulation run. The method by which the model allocates shortages among lower basin users is given in USDOI (1987) and summarized in Appendix B.

Annual depletions for the upper and lower basins and Mexico, across all scenarios, are summarized in Figure 17. Much less variation occurs among scenarios in the upper basin, where the -20% scenario causes only a 5% decrease in depletions and the +20% scenario causes a 2% increase in depletions. Similarly, minimum and maximum deliveries fall within a very narrow range. In contrast, in the lower basin, the -20% and +20% scenarios result in a respective 15% decrease and a 12% increase in depletions. In the base case, deliveries to Mexico average 1918 taf/year and never fall below the 1500 taf level specified by the Treaty requirements.

Deliveries are commonly analyzed on a frequency basis (i.e. the expected frequency with which a specified level of delivery is met or exceeded). The cumulative frequency of deliveries to various users in summarized below and presented in detail in Appendix C, Figures C3 to C6. When analyzed on a 10-year average basis, deliveries from the upper to the lower basin at Lee Ferry fall below 82.5 maf 23% of the time

[18]These minimum deliveries roughly reflect the Bureau of Reclamation's estimate of minimum municipal and industrial requirements for each state.

in the base case, suggesting that either Compact calls or severe shortage provisions would be invoked.[19] In the -5% scenario this frequency rises to 41% , and in the -20% scenario to 97%.

Under current CRSS operating assumptions, MWD's scheduled deliveries are met in all years, under all scenarios (Table 20). Under the increased runoff scenarios of +5%, +10%, and +20%, scheduled deliveries are met or exceeded in 30, 35, and 60% of the years, respectively. Annual deliveries to CAP in the baseline scenario equal or exceed scheduled deliveries (1467 taf/year) 40% of the time, while deliveries fall to their minimum level of 451 taf 20% of the time. Deliveries to CAP never fall below 451 taf, which is the level at which municipal and industrial usage would presumably be impaired. The -5% scenario causes the frequency of full deliveries to CAP to fall substantially, so that in only 25% of the years is the level of 1467 taf met or exceeded. Moreover, under the -5% scenario, CAP receives only the minimum delivery of 451 taf in 50% of the years. In the increased-flow scenarios of +5, +10, and +20%, the percent of years meeting or exceeding the scheduled delivery rises to 25, 40, and 60%, respectively.

Mexico receives 1515 taf in all years in both the base case and the -5% scenario. In addition, Mexico experiences several years of surplus deliveries under these scenarios. Under the -10% scenario, only 5% of the years result in shortages to Mexico, while under the -20% scenario, shortages are experienced 20% of the time. Although the delivery data suggest that Mexico is affected only in extreme cases, this ignores the water quality impacts of decreased flows in the lower basin. In fact, all lower basin users would suffer a significant decline in water quality (i.e. an increase in salinity), which is discussed below. Cumulative frequency plots showing these results are given in Appendix C.

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[19] Interpretation of the Colorado River Compact and Mexican Treaty remains a contested issue. Generally, upper basin commitments are interpreted as requiring delivery of 75 maf every 10 years plus one-half of the Mexican Treaty obligation (0.75 maf) every year. Under this interpretation, the upper basin would be required to deliver 82.5 maf every 10 years, except in times of severe shortage when Mexican Treaty obligations might be reduced. Among the most critical interpretive issues that would reduce the upper basin's required delivery are: (1) to what extent, if any, the upper basin is responsible for Mexican Treaty deliveries, and (2) whether evaporative losses should be counted against required deliveries from the upper basin. See Getches (1991).

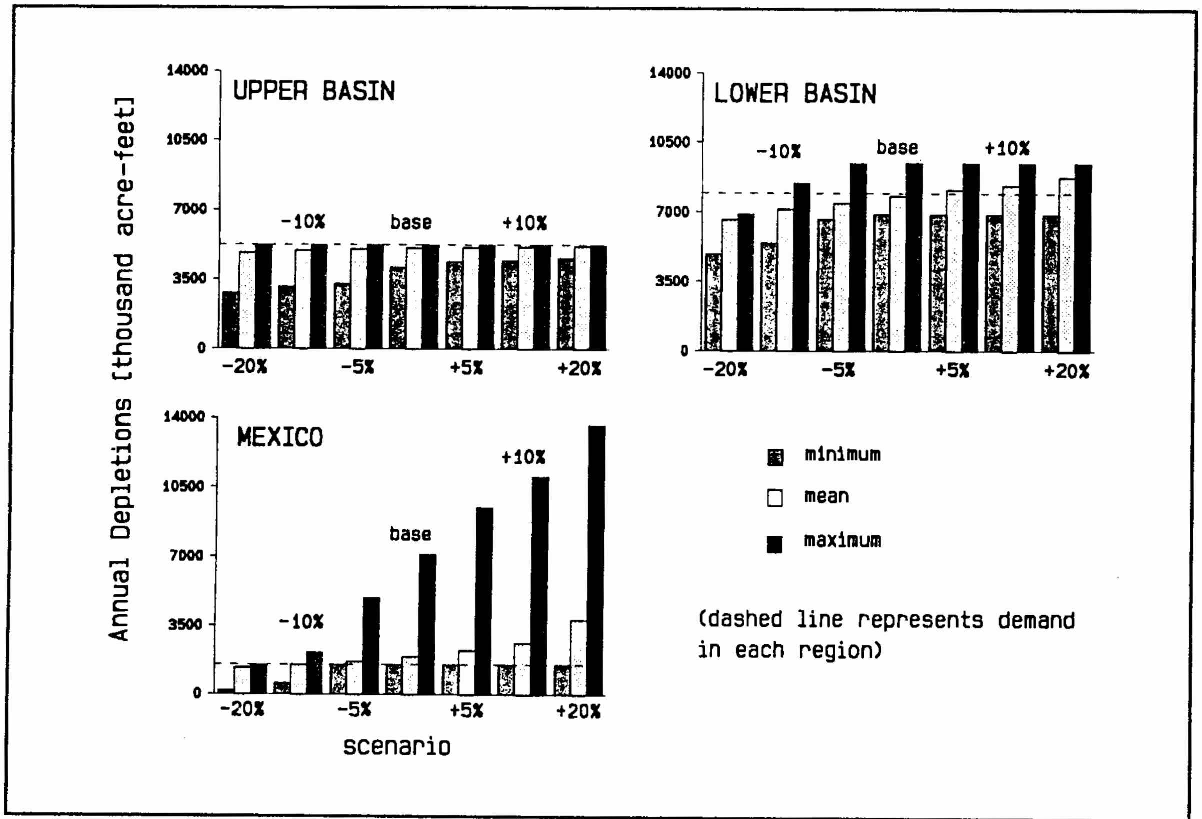

Figure 17: Minimum, mean, and maximum annual depletions in the upper basin, lower basin, and Mexico for all scenarios.

Table 20: Percent frequency with which CRSS scheduled deliveries to MWD, CAP, and Mexico are met or exceeded.

Runoff Scenario	MWD	CAP	Mexico
CRSS Scheduled delivery (taf)	500	1467	1515
-20%	100	0	64
-10%	100	28	94
-5%	100	35	100
Base	100	59	100
+5%	100	77	100
+10%	100	95	100
+20%	100	97	100

Hydroelectricity Production

Hydroelectricity production, like reservoir storage, is extremely sensitive to changes in runoff. Changes in power production are more sensitive to the historical sequence than the other variables analyzed in this study. Although differences among sequences in the base case are insignificant, in the -20% scenario, different sequences generate as much as a 10% difference in results (Table C6).

In the upper basin, power production does not decline as rapidly as storage on an average annual basis. The -10% scenario causes average annual storage to decrease by 30% while power production decreases by 26% (Figure 18). In the -20% scenario, power production drops by 49% compared to a decline in storage of 63%. Storage increases, however, tend to exceed power increases on a percentage basis. In the +5% scenario, overall power generation jumps by 1 thousand gigawatt-hours (GWh) per year, or 11%, while storage increases by 14%. In the +10% scenario, power generation increases by 21%, compared to an increase in storage of 28%.

In the lower basin, power production reductions are on par with, or slightly greater than, reductions in storage, largely because Lake Mead has a relatively high minimum power pool (10 maf). Even though the CRSS reduces deliveries to minimum levels in order to maintain some power-generating capacity, the magnitude of runoff decreases modeled in this study still reduce power production in the lower basin substantially. Although the -10% scenario causes a 12% reduction in runoff at Lees Ferry and a 30% decline in lower basin storage, it causes a 36% decline in lower basin power production. Similarly, the -20% scenario causes a 50% decline in lower basin storage and a 65% decline in power production.

Uncontrolled Spills

In this study, no uncontrolled spills occurred in the lower basin except in the +20% scenario, in which spills occur in 2 out of the 78 years. The total volume of spills for these years is 1.5 maf and 8 maf. For the upper basin, the base-case scenario generates uncontrolled spills in 7 years out of a total of 78 (9%), with the maximum volume of spills in any one year equal to 1.5 maf (Figure 19). When natural runoff is increased by 5%, uncontrolled spills occur in 11 years, with a maximum annual volume of 1.7 maf. A 10% increase in natural runoff results in 16 years that experience uncontrolled spills, with a maximum annual volume of 3 maf. In the +20% scenario, uncontrolled spills are occurring in more than one-third of the years (33). In 8 of these years, spills exceed 1.5 maf; and in 4 of these years, spills exceed 3 maf. The maximum annual volume spills in this scenario is 4.5 maf. Even though spills occur under scenarios of increased flow, the existing flood control criteria for the reservoirs, which require that 5.35 maf of storage space be available in Lake Mead or upper basin reservoirs on January 1, are never violated.

Salinity

Salinity is the only water-quality parameter estimated by the CRSS model. It is defined as total dissolved solids (TDS) and reported in units of milligrams/liter (mg/l). The model assumes uniform salinity in reservoirs, but does take into account the effects of evaporation. Existing, but not projected, salinity control projects are incorporated into the model.

Even in the base-case scenario salinity criteria are consistently exceeded at all points (Figure 20).[20] In the base case, salinity concentrations are within the criteria at all points in less than 15 years. Decreases in runoff of only 5% cause essentially all years to exceed the criteria. Moreover, even in the +20% scenario, salinity criteria are exceeded continuously for long periods, roughly 20 years. Differences in absolute salinity between stations increase as runoff decreases. For example, in the base-case scenario, salinity below Davis Dam measures 858 mg/l on an average annual basis, increasing to 1019 mg/l at Imperial Dam, a difference of 161 mg/l. In the -20% scenario, this difference increases to 208 mg/l, with salinity values at Davis and Imperial reaching 1010 mg/l and 1218 mg/l respectively.

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[20] Numeric criteria for salinity on an annual, flow-weighted basis were established in 1972 for three locations along the River:

(1) Below Hoover Dam: 723 mg/l
(2) Below Parker Dam: 747 mg/l
(3) At Imperial Dam: 879 mg/l

In addition, Minute 242 establishes a relative standard for water delivered to Mexico, which is not to exceed the salinity level measured at Imperial Dam by more than 130 ±30 mg/l.

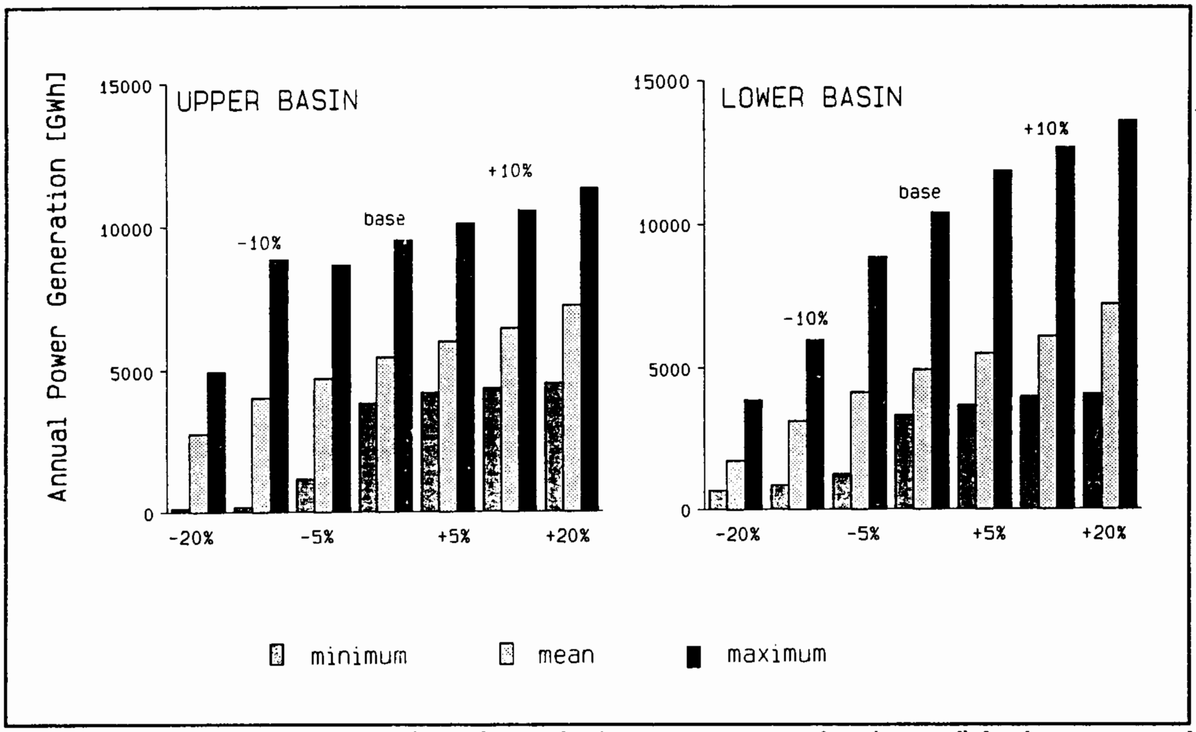

Figure 18: Minimum, mean, and maximum hydropower generation (annual) in the upper and lower basins for all scenarios.

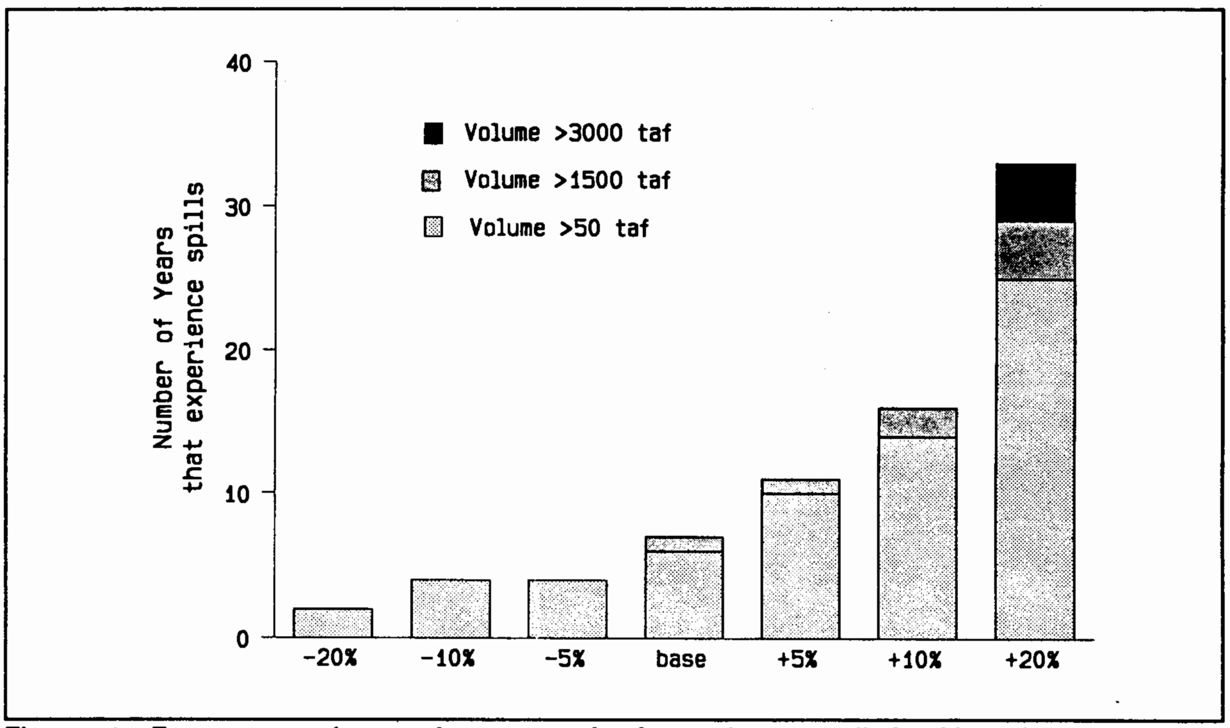

Figure 19: Frequency and approximate annual volume of uncontrolled spills which occur in the upper basin during a simulation run of 78 years.

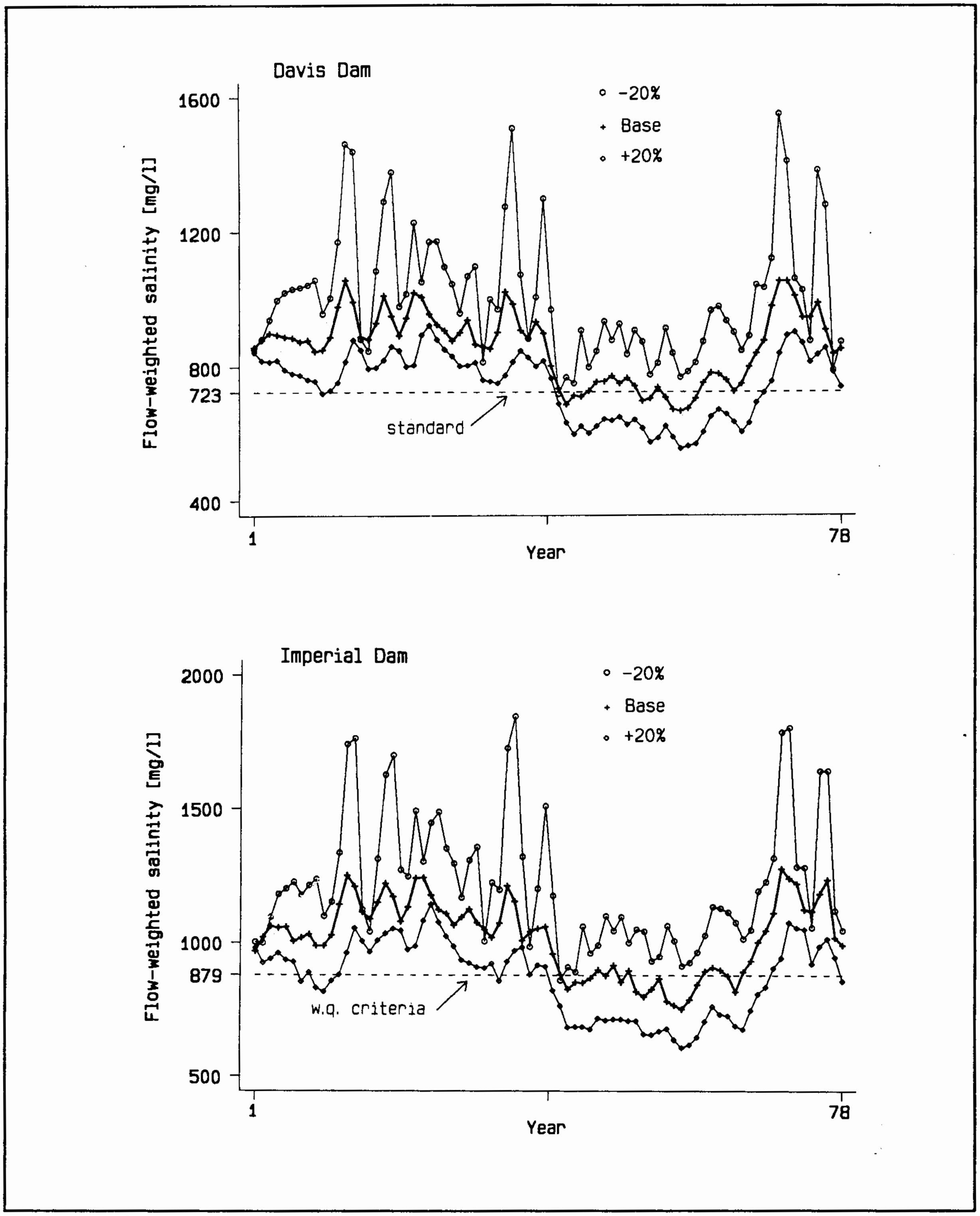

Figure 20: Salinity as a function of year at Davis and Imperial Dams. The base case and the ±20% runoff scenarios are shown. Water-quality criteria are continually exceeded in all but the +20% scenario.

Time-Shifted Scenario

In addition to quantitative changes in runoff inputs, we also ran one time-shifted scenario to study the effects of shifts in the timing (seasonality), but not quantity, of runoff. The results obtained from the NWSRFS hydrologic model suggest that increases in temperature of 2°C would shift peak runoff to the month of May rather than June in the upper basin. In general, the quantity of monthly runoff appears to shift backward by one month (refer to Figure 7). To simulate this effect in the CRSS model, natural-flow inputs were shifted backwards by one month so that June runoff was input as May runoff, July runoff as June, January runoff in year *n* as December runoff in year *n-1*, and so on.

The results of this scenario suggest that, even though the natural-flow inputs do not change on an annual basis, overall system operations are less efficient. Average annual runoff increases marginally at several points (Table 21) as do upper basin depletions, reflecting the fact that less water is being held in storage. Mean decreases in August 1 storage range from -11% in the upper basin and -4% in the lower. The effect of the time-shifted scenario on the cumulative frequency of storage is shown in Figure 21. In the base case, storage in the upper basin falls below 15 maf only with a 15% frequency; this rises to more than 30% under the time-shifted scenario. Deliveries in the lower basin also suffer somewhat, with average annual deliveries to CAP and MWD declining by 89 taf (6%) and 21 taf (3%), respectively. Scheduled deliveries to CAP are met with slightly less frequency, 60% versus 65% of the years. These changes are most likely due to the model forecasting procedure, which establishes target storages based on reservoir contents and time of year. Thus, because higher streamflows occur earlier in the year, more water is being released in the winter and early spring. Subsequent months, however, have lower-than-predicted runoff, causing most deliveries to decline on an annual basis.

The time-shifted scenario also causes a slight increase in average annual salinity. Flow-weighted salinity at Davis, Parker, and Imperial dams increases by about 20 mg/l (2.5%), which is comparable to the increase of roughly 25 to 35 mg/l (3%) for the -5% scenario. The fact that salinity increases by 2.5% is

Table 21: Annual runoff (taf) at various points for the base case and the time-shifted scenario.

Station	Mean Base	Mean TS [1]	SD Base	SD TS	Minimum Base	Minimum TS	Maximum Base	Maximum TS
Green	977	997	404	381	252	281	1,964	1,984
Cisco	4,522	4,712	1,678	1,547	1,193	1,247	8,413	8,244
Bluff	1,356	1,348	694	727	361	294	3,280	3,480
Lees Ferry	9,393	9,557	2,089	2,193	8,238	8,239	16,884	16,889
Imperial	6,098	6,053	1,161	1,112	5,650	5,650	11,597	11,241

Note: [1] Time-shifted scenario, in which all historic input data is shifted backwards by one month, e.g., January of Year "n" is input as December of Year "n-1" in order to reflect the shift in seasonality expected as a result of increased temperatures.

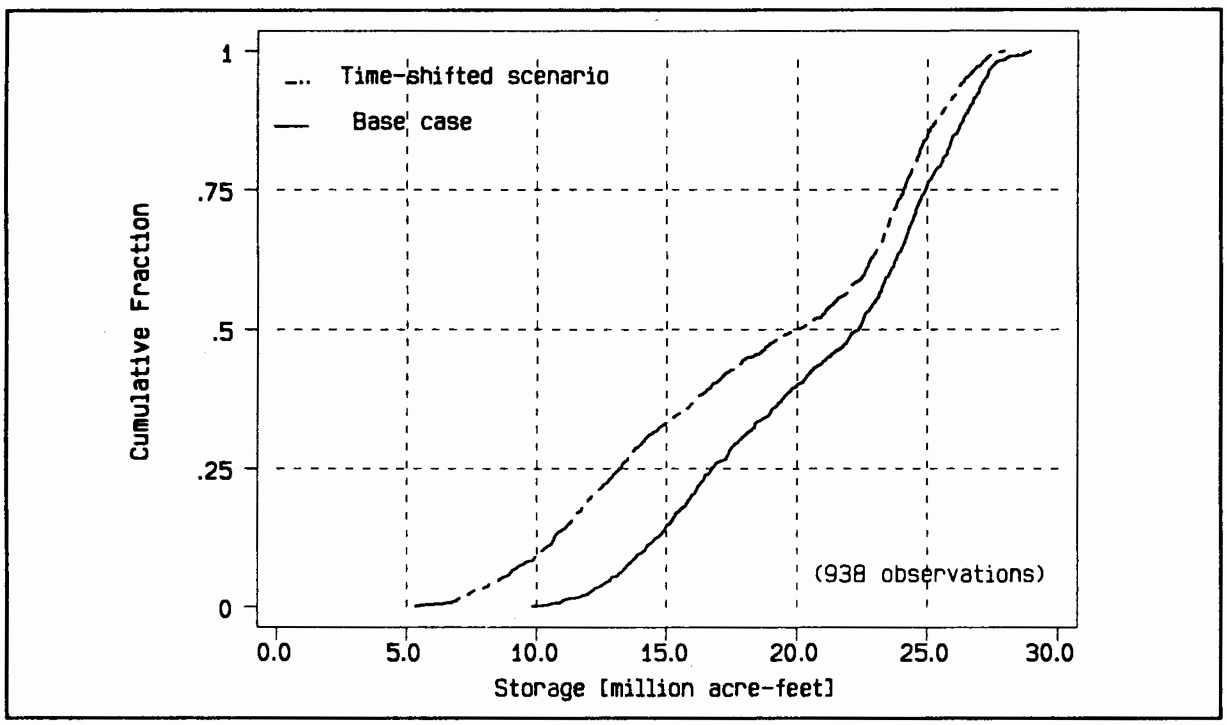

Figure 21: Impact of the time-shifted scenario on storage in the upper basin. This graph shows the frequency (y-axis) with which monthly storage is equal to or less than a particular volume (x-axis).

interesting because streamflow at Imperial decreases by <1% in the time-shifted scenario. The frequency with which the salinity criterion at Imperial Dam is exceeded increases marginally, from 75% to 78%.

Summary and Discussion of Water-Supply Modeling Results

To date, few studies have attempted to model the impacts of climatic changes on regional water-supply systems. This reflects both the lack of suitable models and the paucity of regional information on climate-induced changes in runoff. Two exceptions are the studies of the State Water Project in California and the Tennessee Valley Authority, both done as part of the US EPA study of climate impacts (USEPA, 1990; Lettenmaier and Sheer, 1991). In these studies, a limited number of GCM scenarios were analyzed using large-scale water-supply models. In both cases, water-supply systems were found to be sensitive to GCM-derived scenarios of climatic change. One of the conclusions of the California study was 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. Both studies noted that climatic changes are likely to increase the tension between flood control and water supply and/or hydroelectricity production.

Our results from the CRSS model similarly suggest that the water-supply system of the Colorado River Basin is sensitive to changes in runoff that might be plausibly associated with climatic change, and that some tradeoffs will be necessary to balance multiple purposes. Looking back at the hydrologic modeling discussed in Part I of this report, we can relate climate scenarios to the changes in the water supply variables given in Table 22. Overall, the GCM scenarios suggest decreases in runoff on the order of 10 to 20%. A 20% reduction in runoff would cause reductions in mean (August 1) storage of 60 to 70%, reductions in mean annual power generation of 60%, and an increase in mean annual salinity of 15 to 20%. In contrast, should the region experience only a moderate increase in temperature (2° C) and a large increase in precipitation (20%), this would result in roughly a 20% increase in runoff, a 30 to 60% increase in mean storage, a 40% increase in power production, and a 13-15% decrease in salinity. On the other hand, a temperature increase of 4° C coupled with a precipitation decrease of 20% would result in approximately a 30% decrease in runoff, which is more extreme than any of the scenarios modeled with the CRSS.

These CRSS results suggest that Compact violations are likely to occur under all scenarios of decreased runoff. This primarily reflects current operating parameters. The CRSS does not impose shortages on the upper basin but passes them on to the lower basin. Under the terms of the Colorado River Compact, however, the lower basin could theoretically require the upper basin to curtail usage in order to meet the Compact requirements during a period of severe drought (Hundley, 1975; Getches, 1991). Thus, the delivery and depletion results presented here reflect a potentially unlikely scenario in which the lower basin bears the brunt of any shortage, without resorting to a Compact call. For instance, although CAP deliveries should be fairly secure under all but the -20% scenario assuming that a Compact call is enforced, in these simulations some reductions to CAP are occurring even in the base case, probably in order to maintain the minimum power pool in Lake Mead. This can be seen in Figure 22, which shows that CAP deliveries fall from their scheduled level of 1467 taf to the minimum level of 451 taf as storage in Lake Mead declines to 10 maf, which is equivalent to minimum power pool. Under the operating regime modeled here, CAP would not receive their full allocation in the future without persistent increases in annual runoff.

The reservoir simulation results presented here suggest that many of the procedures and inputs used in the model are closely tuned to historic hydrology. For instance, storage strategies and targets work extremely well in the base case scenario but are substantially less effective under alternative scenarios. Thus, Compact violations would potentially occur even in the -5% scenario, even though this could most likely be avoided if the CRSS operating parameters were altered.

If operating parameters were altered, the result would be a very different allocation of shortages. According to Getches (1991:22), the upper basin has present perfected rights[21] to only about 2 maf and in cases of severe shortage, the upper basin could be required to reduce its usage to that amount so that the remaining water could flow to the lower basin and Mexico. In the model runs presented here, however, upper basin consumption never falls below 2.8 maf even though substantial shortages are occurring in the lower basin. In the -20% scenario, overall shortages to the upper basin are only about 5%; but lower basin depletions fall by 15%, which represents a 0.9 maf shortfall of lower basin entitlements on an average annual basis. But under the existing legal framework, the lower basin and Mexico would not be legally forced to endure shortages until the total water available in the basin for consumptive use fell below 11 maf.[22] This occurs in one year out of 78 in the -10% scenario, and 3 years out of 78 in the -20% scenario. Thus, if the CRSS modeled Compact calls, the lower basin would rarely suffer shortages. The upper basin, on the other hand, would suffer much more extreme shortages than those suggested by the modeling runs presented here. In the base case, upper basin depletions would be limited to 3 maf or less roughly one-third of the time, a cutback of more than 20% over present levels. In the -5% scenario, this percentage of years in which consumption would be 3 maf or less rises to 61%. In the -20% case, the upper basin would never receive more than 3 maf, and would receive only 2 maf in about 10% of the years. Of course, these frequencies are dependent upon when and how quickly reservoir storage is consumed.

The variables most sensitive to changes in natural runoff are reservoir storage and power generation, which are particularly sensitive to decreases in runoff (Table 22). For example, changes in mean storage in Lake Mead on August 1 are on the order of -70% (-20% scenario) to +60% (+20% scenario). It is difficult to say much about the risks of flooding to the basin based on these scenarios. Unlike water-supply

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[21] "Present perfected rights" refer to those water rights that were already established by upper basin users at the time the Colorado River Compact was signed, in 1922. These rights are not subject to compact calls. See Getches (1991).

[22] This includes 2 maf for the Upper Basin, 7.5 maf for the Lower Basin, and 1.5 maf for Mexico. See Getches (1991).

Table 22: Sensitivity of water-supply variables to changes in natural flow in the Colorado River Basin [1].

Change in Natural Flow (%)	Change in Actual Flow [2] (%)	Change in Storage [3] (%)	Change in Power Generation [4] (%)	Change in Depletions [5] (%)	Change in Salinity [6] (%)
-20	(10-30)	(61)	(57)	(11)	15-20
-10	(7-15)	(30)	(31)	(6)	6-7
-5	(4-7)	(14)	(15)	(3)	3
5	5-7	14	11	3	(3)
10	11-16	28	21	5	(6-7)
20	30	38	39	8	(13-15)

Notes: [1] Average change compared to the base case over a 78-year simulation run. Numbers in parentheses represent DECREASES.
[2] Changes in flow represent the range of changes at five points: Green River, Cisco, Bluff, Lee Ferry, and Imperial Dam.
[3] Mean storage throughout the basin on August 1.
[4] Mean annual power generation throughout the basin.
[5] Depletions are summarized over the entire basin, although depletions are defined differently in the upper and low basins. See Hundley (1975) for details.
[6] Changes in salinity represent the range of changes at three points: Davis, Parker, and Imperial Dams.

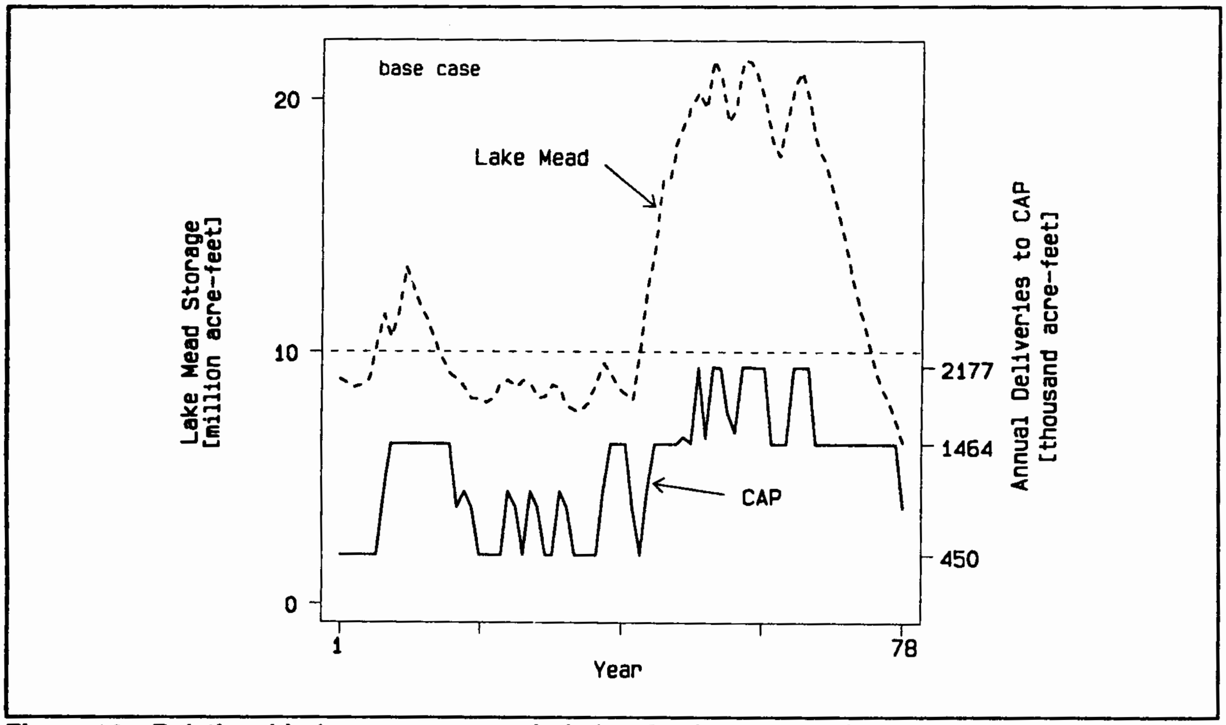

Figure 22: Relationship between storage in Lake Mead and annual delvieries to CAP. In the base case (and the +5%) scenario, CAP deliveries fall to their minimum level (450 taf) when Lake Mead falls below minimum power pool (approximately 10 maf).

shortages, which are primarily a function of average annual flows, floods are a function of the duration and severity of particular snowmelt and precipitation events. While climatic changes will in fact alter snowmelt and precipitation patterns, these effects cannot be adequately evaluated without more detailed regional information. In general, the loss of snowpack storage associated with global warming is likely to increase reservoir spills in some seasons. The Hoover Dam flood control regulations call for releases from Lake Mead not to exceed 28,000 cfs, in order to avoid damage in the flood plain below Parker Dam (USACOE, 1982). Any uncontrolled spill in the lower basin is cause for concern. Depending on their magnitude and duration, uncontrolled spills in the upper basin may be an indication of high, but not necessarily uncontrolled, runoff in the lower basin that may nonetheless be damaging. The volume of upper basin spills in the +10% scenario (up to 3 maf annually) suggests that flood control would be an issue. More generally, the sensitivity of storage to changes in runoff illustrates how carefully the current system is operated and how little is the room for forecast error if water-supply is to be maximized without resulting in damaging flood-control releases or uncontrolled spills.

The range of basin storage over which the level of power generation shows little variation is very wide, from about 5 maf to 23 maf. This insensitivity of power production to reservoir levels indicates that power plant releases are not being adjusted to reflect water-storage levels in the basin. In other words, power is generated at a relatively constant level until critical (i.e. minimum power pool) reservoir levels are reached, and then no power is generated. In the -10% and -20% (runoff) scenarios, minimum power pool is frequently breached (e.g. with respective frequencies of 75% and 100% in lake Mead), and so dramatic declines occur in hydroelectric output. An alternative, and possibly more efficient, operating strategy might make power generation more sensitive to reservoir levels, so that lower levels of power were produced over longer periods of time.

Not surprisingly, the most critical concern for the lower basin is water quality/salinity. Under almost no circumstances can existing water-quality criteria be met given projected demands and operating constraints. Our results suggest that at least a 20% increase in natural runoff would be necessary to bring the salinity levels in the lower basin into compliance with existing numeric criteria. Although the scenarios considered here result in only moderate changes in salinity, the problem is already so severe in the base case that even moderate declines in water quality are of particular concern.

Increases in salinity are disproportionate to decreases in runoff. A (modeled) runoff decrease of 11% at Imperial Dam brings a average annual salinity increase of nearly 20% (200 mg/l), while a runoff increase of 11% at the same location results in only a 10% (71 mg/l) decrease in salinity. In addition, annual maximum salinity concentrations increase dramatically. For instance, at Imperial Dam maximum annual salinity concentrations rise from 1279 mg/l in the base case to 1516 mg/l in the -10% scenario and to 1848 mg/l in the -20% scenario. This represents percentage increases of 19% and 44%, respectively. Although the model's accuracy with respect to salinity calculations may be questioned, the phenomenon of non-linearity has been established both empirically and theoretically (Vaux, 1991). These complications imply the need to continue to develop and to improve water-supply models such as the CRSS so that the multi-faceted impacts of changes in runoff can be adequately assessed. The results also suggest the importance of flow-independent sources of salinity in downstream reaches because differences in absolute salinity between stations increase as runoff decreases.

Overall, the water-supply modeling results illustrate how carefully the system must be managed in order to meet the multiple needs of the basin. Of course, this is not a surprising result; it reflects the historical over-allocation of supply as well as rapidly growing demands.

The water-supply results are unquestionably sensitive to the volume of demands used in the model. In reality, the numbers used for these runs represent probable supplies rather than actual demands. For instance, MWD's demand in the model is set to 500 taf, although MWD regularly takes and uses significantly greater quantities of Colorado River water (Getches, 1991:18). On the other hand, upper basin demand numbers embody several assumptions about growth and development that have been contested. Upper basin demands in these runs are nearly 35% greater than current demands. Were these demand projections altered, they would have substantial impacts on the operation and results of the CRSS model.

Finally, although changes in mean natural runoff of 20% may seem extreme, in fact, changes of this magnitude over a limited period of time are conceivable even without the advent of enhanced greenhouse warming. A 20% decrease in natural runoff would lower the annual mean at Lee Ferry from 15 maf to 12 maf. Tree-ring reconstructions suggest that over the last 500 years the lowest 80-year mean is less than 11 maf, which corresponds to a 27% decrease in natural flow. If climatic changes were coupled with such extreme, non-greenhouse variations, the impacts on the basin would be more severe than even the most extreme scenarios presented here.

STUDY CONCLUSIONS

To date, most hydrologic studies have been limited to analyzing changes in runoff and soil moisture These are important parameters to study, but they tell us only a limited amount about how water-supply systems may be challenged under conditions of climatic change. In order to assess the ability of the political and water-management infrastructure to distribute water in an equitable and efficient manner under a greenhouse-affected climate, we need information on the spatial distribution of water. This is the type of information provided by reservoir-simulation models such as the CRSS.

The results of this study suggest that the Colorado River Basin would be very vulnerable to potential climatic changes. Certainly a temperature increase in the range of 2-4° C is well within the range of plausibility.[23] Without any change in precipitation, these temperature changes alone imply decreases in runoff of 5 to 10 percent. This would result in average annual declines in mean annual reservoir storage and power generation of 30% to 60%. Average annual depletions would decrease by 3% to 6%, and Compact calls could potentially occur in several years. Moreover, decreases in runoff would exacerbate an already severe salinity problem in the lower basin. Should precipitation increase, some or all of these impacts might be offset; but should precipitation decrease, the impacts may exceed even those presented here. It should be borne in mind that these results reflect runoff changes of 5 to 20% imposed on the hydrology of the last 80 years. The results would be different if a different hydrologic record had been used. For instance, the hydrology of the last 400 years suggests that much more severe and sustained droughts have occurred in the past (Stockton, et al., 1991). If this hydrology were used as a basis for a similar study, decreases in runoff would have still greater impacts on the Colorado River Basin.

In this study, the current operating system fails to manage adequately long-term decreases in natural runoff of 20%. Lesser changes challenge the system; however, they do not overwhelm it. Yet over the long-

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[23] GCM predictions for this region suggest greater increases in temperature, from 4° to 7°C on an average annual basis.

term, the system appears to operate more comfortably under a slightly increased runoff regime (+5%), although it could probably still operate more efficiently. This reflects the fact that the system is likely to be over-allocated if all presently scheduled demands come on line in the next 50 years. On the other hand, relatively moderate decreases in streamflow (i.e. -5%) would pose considerable challenges to the basin. Given the assumptions that bound this study, it appears likely that any long-term decrease in streamflow would bring extended periods of drought and water-supply shortages.

Although we were not able to assess the impact of changes in operations as part of this study, our results suggest that the system would almost certainly benefit from alterations in the operating regime should the magnitude or persistence of streamflow change. The current operations are, in some sense, an artifact of historic experience. Management assumptions and the perception of risk are conditioned by recent hydrologic experience in the basin. An example of this is discussed by Dracup et al. (1985:239) in connection with the flooding experienced in the lower basin during 1983:

> The period of time that the Colorado reservoir system was filling constituted a period during which true exposure to climatic impacts, i.e. precipitation variability, did not exist.... The encroachment into the flood plain was possible because water was in storage upstream, and also because the period of filling Lake Powell was drawn out for almost two decades. Two decades are more than sufficient to affect societal perceptions of climate stability.

Water managers have traditionally relied upon historical hydrologic records and past experience in order to plan, inferring the probability of future shortages and floods from their frequency of occurrence in the past. If the existing record on the Colorado River is examined, however, it shows little ability to predict future conditions. The classic example of this is provided by the 20-year period immediately preceding the adoption of the Colorado River Compact in 1922. During this period, average annual flows at Lee Ferry were estimated to be 16.4 maf/year, of which the Compact intended to allocate 15 maf/year (Hundley, 1975). No period of similar duration and high flows has occurred since then, and the average runoff at Lee Ferry from 1906 to 1990 has been only about 15 maf/year. Tree-ring analyses suggest that the long-term average runoff may be as low as 13.5 maf/year and that the most critical period on record may have had a 20-year average runoff of only 11 maf (Stockton and Jacoby, 1976). While this is an extreme example, it nonetheless illustrates the problem of relying exclusively on the recent instrumental record as a basis for planning, and suggests that any attempt to model future water supply will be hindered by such a reliance on historic data.

Ultimately the problem is our ignorance of the underlying distribution that governs streamflow. Current operating procedures, although somewhat flexible, are strongly keyed to the existing historical record. When viewed from the perspective of climatic change, this becomes a concern. Although the existing record is now nearly 80 years in length, this is not a long record given the high variability of streamflow in the basin, our poor understanding of streamflow distributions, and the likelihood of future shifts in underlying climatic variables. The ability of a system to perform adequately in the past is at best a weak indicator of its potential to perform in the future. While certainly a system must be able to address historic variations and extremes to be effective over the long term, it must be able to address even greater variations that might reasonably be anticipated in the future. Scenarios derived from GCMs are useful in this respect because they provide additional information on changes in streamflow that might accompany climatic changes. Most of the GCM temperature and precipitation scenarios modeled as part of this study suggest that runoff will decrease even though precipitation may increase, with the magnitude of decrease ranging from 8% to 24%. The problem of planning water management in the face of a high degree of climate and hydrological uncertainty cannot be easily resolved; nonetheless, it may be possible to increase flexibility in water management. This flexibility will need to be reflected in technical and operational decisions, as well as in the legal and economic institutions that govern water use in the basin.

The problem of planning is compounded by the fact that we cannot say with certainty whether runoff in the basin will increase or decrease. Most people with an interest in the basin have focused on the prospect of long-term decreases in runoff and the shortages that would result, which is a logical reflection of the region's preoccupation with drought. The fact that average temperatures in the region will almost certainly increase suggests that, if we assume no knowledge about changes in precipitation, we would expect runoff to decrease as a result of increases in evaporation and vegetative water use. This may be reason enough to plan for supply shortages; but increased water storage must be traded off against the need for flood-control space. The greatest risk of climatic change is the potential for streamflow variability to increase substantially, increasing the frequency of both sustained drought events and high-flow events, and thus complicating management.

In addition to the uncertainty in future hydrology posed by climatic changes, any change in hydrology may pose additional policy challenges for the region. As hydrology changes, it may well become more difficult to reconcile the claims of different users and multiple purposes along the river. Institutional and operational regimes will have to respond to tensions between the upper and lower basins, between demands for hydroelectricity and water supply, and between water supply and flood control.

Inevitably the discussion of climate-change and water resources leads to the question of storage, specifically whether increased storage is a reasonable response to climate-induced changes in water supply. Reservoirs are frequently viewed as a response to supply shortages; however, given the already high levels of storage available on the Colorado, additional reservoir capacity would do little or nothing to alleviate potential reductions in flow. Reservoirs serve solely to decrease seasonal and inter-annual variability (over a limited number of years); they do not increase the volume of water available on a long-term basis. In fact, additional reservoirs in highly developed regions may actually decrease water supply over the long-term through evaporative and bank-storage losses (Klemes, 1985; Langbein, 1959). Only if climatic changes were to increase streamflow variability, without decreasing long-term supply, would additional reservoirs in the Upper Colorado River Basin have any benefits. The question of change in variability has not been addressed in this study.

In addition, the development of water resources may inadvertently reduce flexibility in some cases. For example, the decrease in the interannual variability of streamflow in the Colorado River has been accompanied by an increase in both usage and dependence, and thus the long-term vulnerability of the region to climatic changes has increased. The low variability of water supply in the lower basin has encouraged the total use of available resources, thus removing any real drought "cushion". While this generates economic benefits, it also increases the economic costs of a severe and sustained drought once storage has been exhausted. Similarly, the perceived invulnerability of flood plains has encouraged additional development that subsequently reduces operating flexibility (USACOE, 1982; Dracup, et al., 1985). On the Colorado River, ample flood-control storage exists, but as others have pointed out, the basin's concern with drought and water storage has resulted in a series of operating rules and customs that maintain reservoirs nearly full, leaving little room for forecast error or for managing extremely high flows without damage. The range in which flood control and water supply are balanced is very narrow as the system is currently operated. This is an issue that would almost certainly be exacerbated by climatic changes.

Beyond the scope of this study were several important issues that policymakers and water-supply managers will undoubtedly have to consider. First, the environmental and ecological impacts of changes in water supply have not been addressed in this study. Part of the problem lies in the lack of information. In general ecosystems are more sensitive to seasonal, monthly, daily, and even hourly changes in streamflow and water quality than to long-term changes. Unlike water supply, the impacts on the environment cannot be adequately assessed using aggregated time periods or large-scale models. Undoubtedly, however, given the predicted rate of climatic change and the potential magnitude of runoff changes examined here, serious environmental concerns would be raised.

This study has also not taken projected future developments nor some future demands into account. Currently the issue of reserved water rights and Native American claims have obscured future demand scenarios in the basin. Because of the large amounts of water involved, these unresolved claims could have dramatic impacts on water allocation throughout the region and thus add to the uncertainty that the basin faces.

Finally, while this study has suggested what the impacts of climate change could be on water supply, it has not addressed the impacts of climate change on water demand. In fact, demands will change both in time and space. Obviously, agricultural water demand will vary as crops and production patterns are altered in response to climatic changes. Ecosystem water requirements will also vary, both in response to increased temperature and as a result of ecological and environmental changes. Urban and industrial usage will change as a result of both changes in climate and changes in population. In fact, it is quite possible that changes in demand over the next 50 to 100 years will equal or exceed changes in supply. In all likelihood, the greatest possibilities for adapting to climatic change lie in the area of demand management, particularly in the agricultural and urban sectors, and the potential for conservation and water transfers needs to be assessed from both a quantitative and an institutional perspective. If we are to plan adaptation strategies, future research must address the integrated impacts of climatic change on demand and supply across sectors.

Given the uncertainty surrounding potential climatic changes and the problems encountered in trying to model impacts, care must be taken to view the results presented here in their appropriate context. While some analysts and planners, when faced with large uncertainties, may prefer to refrain from any attempt to assess the impact of climatic change on water resources, we believe that it is preferable to see how far one can get using current information and models even though they might seem inadequate to the task. The greatest danger, however, is that the numbers will be accepted uncritically or as predictions when, in fact, they are bounded by considerable uncertainty. Nevertheless, numbers may help us to represent and to comprehend the sensitivity of the basin to plausible scenarios of climatic change. In particular, the scenarios of changes in temperature and precipitation derived from GCMs provide the best information currently available on climatic change. When translated into changes in runoff and water supply, as in this study, these climate scenarios suggest that past assumptions about water-supply reliability may be severely challenged in the coming decades. By suggesting plausible future scenarios, we may find the impetus to consider what changes we can make to balance multiple purposes under varying conditions of climate. Given the prospect of future climatic changes, it is imperative that we consider how we can increase the resiliency of our existing water-management systems and minimize the social and environmental impacts of changes in water availability. We need to identify those responses that will provide us with the greatest flexibility in the coming decades and to develop management schemes that recognize both the variability and the dynamic nature of climate.

Future Work

This study has identified the overall sensitivity of the region as well as the rough magnitude of potential impacts. It has suggested concerns about basin-wide planning mechanisms, potential future conflicts, and the risks of increased variability. The results generated by the three sub-basin models suggest that additional modeling of the Upper Colorado River Basin would be useful. An important step would be to assess the region on a sub-basin-by-sub-basin basis in order to identify and categorize the response of individual watersheds. This would provide a more accurate picture of how the overall basin would respond to climatic changes. Moreover, smaller-scale studies would enable researchers to evaluate the relative sensitivities of supply and demand within sub-basins in order to identify critical regions and to focus adaptation strategies on a sub-regional basis. Potentially better generalizations could be made if the hydrologic modeling incorporated larger spatial coverage of the basin and additional climate scenarios. Additional modeling may also allow for more detailed validation of the NWSRFS (or other appropriate) model and would lend greater confidence to the results presented here.

The results of the reservoir-simulation modeling also suggest numerous opportunities for additional research. This study was limited to modeling only hypothetical scenarios of changes in natural runoff that were applied uniformly across the basin. First, this modeling could be extended by disaggregating streamflow scenarios both temporally and spatially using statistical techniques. Potentially, this type of study could provide a more accurate picture of how the basin would respond to climatic change, and also when and where critical situations are likely to occur. Secondly, additional and more complex scenarios of changes in runoff could be developed if additional hydrologic modeling of the Upper Colorado River Basin were undertaken. Thirdly, operational flexibility could be explored in detail with a modified, and potentially simpler, version of the CRSS in which operating parameters and assumptions could be more easily adjusted. This would allow a quantitative assessment of the model's sensitivity to operating assumptions as well as a more policy-oriented study of operational flexibility and opportunities for improved water management.

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APPENDIX A: CALIBRATION RESULTS FROM THE NWSRFS MODEL

APPENDIX B: THE LAW OF THE RIVER AND CRSS OPERATING PROCEDURES

APPENDIX C: ADDITIONAL RESULTS FROM THE CRSS MODEL

APPENDIX A:

CALIBRATION RESULTS FROM THE NWSRFS MODEL

Table A1: Calibration data for the Two–elevation model.

	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Monthly Bias [Sim - Obs] (taf)	Max. Error [Sim - Obs] (taf/day)	% Average Absolute Error	% Daily RMS Error	Max. Monthly Volume Error (taf)	% Avg Abs Monthly Vol Error	% Monthly Vol RMS Error
Oct	15.02	15.38	-2.37	-11.29	69.90	26.06	42.12	-387	19.66	25.58
Nov	13.24	14.53	-8.92	-38.90	23.80	17.54	23.78	-233	15.89	19.38
Dec	11.88	11.62	2.22	7.98	22.73	19.98	28.23	-159	13.76	17.87
Jan	10.81	11.62	-6.97	-25.11	19.73	21.20	28.66	-172	15.13	20.06
Feb	11.34	13.64	-16.87	-64.43	19.51	26.45	38.67	-372	23.88	30.00
Mar	17.06	17.76	-3.91	-21.51	43.52	35.24	45.76	-424	30.10	36.36
Apr	34.80	32.67	6.52	64.00	51.42	37.66	48.56	-116	32.44	40.68
May	70.61	71.65	-1.45	-32.36	65.80	25.41	32.56	-1286	19.57	25.81
Jun	94.61	99.27	-4.69	139.60	80.13	16.98	22.60	-1501	11.64	16.40
Jul	45.19	43.68	3.46	46.81	87.23	24.62	33.65	-1050	21.99	28.79
Aug	19.99	18.40	8.65	49.36	64.90	37.00	48.38	544	31.78	40.18
Sep	15.00	14.09	6.45	27.28	76.57	31.20	47.94	-237	24.21	29.13
Yr Avg	30.02	30.38	-1.25	137.70	87.23	24.88	40.47	-1501	19.88	31.69

Table A2: Calibration data for the Two–elevation model summarized by flow interval.

Flow Interval (taf/day)	No. of Cases	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Bias [Sim - Obs] (taf/day)	Maximum Error (taf/day)	% Avg Absolute Error	% RMS Error
0	28	8.14	1.55	424.03	6.59	10.88	424.00	445.30
< 2.6	922	11.44	6.60	73.23	4.84	38.51	74.70	97.10
< 8.1	8127	15.46	14.20	8.86	1.26	49.29	30.30	44.60
< 25.9	2427	45.85	8.86	-0.16	-0.07	66.39	26.00	34.20
< 81.0	1278	106.30	121.60	-12.57	-15.30	87.24	18.00	22.70
< 259.3	0							

Table A3: Calibration data for the White River model.

	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Monthly Bias [Sim - Obs] (taf)	Max. Error [Sim - Obs] (taf/day)	% Average Absolute Error	% Daily RMS Error	Max. Monthly Volume Error (taf)	% Avg Abs Monthly Vol Error	% Monthly Vol RMS Error
Oct	0.75	0.76	-0.60	-0.14	0.77	15.85	20.53	7.53	12.76	15.89
Nov	0.66	0.71	-6.52	-1.38	0.32	12.72	15.86	6.01	11.08	14.18
Dec	0.60	0.64	-5.93	-1.18	0.48	13.71	17.60	6.77	12.00	14.92
Jan	0.58	0.60	-3.02	-0.56	0.36	15.39	19.31	8.65	12.88	16.74
Feb	0.57	0.59	-4.02	-0.68	0.40	12.58	15.89	5.45	11.36	14.71
Mar	0.55	0.63	-13.99	-2.75	0.47	17.97	22.20	7.72	16.26	18.61
Apr	1.03	1.01	1.19	0.36	1.88	28.10	39.49	19.83	23.35	28.25
May	3.12	2.95	5.99	5.47	2.94	21.80	27.85	62.55	14.79	19.90
Jun	3.54	3.78	-6.45	-7.31	4.83	27.61	37.00	74.60	24.15	30.99
Jul	1.37	1.29	5.97	2.40	2.97	28.77	41.40	42.99	28.26	35.41
Aug	0.79	0.72	9.66	2.16	1.31	23.78	29.51	11.95	21.49	25.55
Sep	0.74	0.67	10.13	2.04	0.53	22.30	27.64	9.72	18.92	22.93
Yr Avg	1.19	1.20	-0.36	-1.58	1764.00	22.58	43.39	74.60	19.02	35.03

Table A4: Calibration data for the White River model summarized by flow interval.

	Flow Interval (taf/day)	No. of Cases	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Bias [Sim - Obs] (taf/day)	Maximum Error (taf/day)	% Avg Absolute Error	% RMS Error
	0.00	0							
<	0.05	2	0.46	0.16	194.90	0.31	0.31	194.90	194.90
<	0.16	1266	0.57	0.44	31.62	0.14	0.79	36.20	45.90
<	0.51	9428	0.75	0.75	0.32	0.00	2.94	20.20	32.00
<	0.60	1724	3.12	3.07	1.41	0.04	3.56	25.10	32.80
<	5.12	363	5.59	6.49	-13.90	-0.90	4.83	21.10	26.80

Table A5: Calibration data for the East River model.

	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Monthly Bias [Sim - Obs] (taf)	Max. Error [Sim - Obs] (taf/day)	% Average Absolute Error	% Daily RMS Error	Max. Monthly Volume Error (taf)	% Avg Abs Monthly Vol Error	% Monthly Vol RMS Error
Oct	0.20	0.21	-6.10	-0.40	0.66	30.73	43.28	-6.00	23.91	33.14
Nov	0.16	0.18	-10.69	-0.58	0.96	25.96	36.89	-3.38	24.05	28.97
Dec	0.14	0.14	-2.91	-0.13	0.80	25.07	35.67	-2.37	23.84	28.46
Jan	0.12	0.12	-4.51	-0.17	0.20	23.95	29.57	-1.97	22.74	27.73
Feb	0.11	0.12	-5.40	-0.17	0.37	27.60	37.38	2.60	27.12	33.47
Mar	0.15	0.12	24.83	0.94	1.04	52.93	104.78	8.39	47.83	70.00
Apr	0.66	0.44	51.23	6.74	1.40	64.59	88.27	17.56	53.24	64.13
May	1.78	1.81	-1.20	-0.70	-2.15	26.41	33.75	-24.13	16.61	20.41
Jun	2.48	2.58	-3.78	-2.92	3.25	22.42	30.48	-48.34	16.85	23.21
Jul	1.15	1.11	4.21	1.45	3.18	33.62	54.36	47.46	30.86	45.48
Aug	0.38	0.45	-15.20	-2.11	-1.15	27.94	40.67	-13.00	26.79	35.16
Sep	0.25	0.23	6.30	0.44	0.97	33.20	46.62	6.22	28.18	35.83
Yr Avg	0.63	0.63	1.05	2.41	3.25	29.13	57.99	-48.34	23.19	43.23

Table A6: Calibration data for the East River model summarized by flow interval.

Flow Interval (taf/day)	No. of Cases	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Bias [Sim - Obs] (taf/day)	Maximum Error (taf/day)	% Avg Absolute Error	% RMS Error
0.00	0							
< 0.04	2143	0.11	0.10	11.58	0.01	0.68	34.68	56.70
< 0.12	6385	0.21	0.19	9.25	0.02	1.10	38.75	70.67
< 0.38	2200	0.72	0.66	9.56	0.06	1.56	39.27	53.57
< 1.18	1811	2.20	2.22	-0.63	-0.01	3.25	25.04	33.51
< 3.78	244	3.96	4.64	-14.58	-0.68	-2.86	19.40	23.72

Table A7: Calibration data for the Animas River model.

	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Monthly Bias [Sim - Obs] (taf)	Max. Error [Sim - Obs] (taf/day)	% Average Absolute Error	% Daily RMS Error	Max. Monthly Volume Error (taf)	% Avg Abs Monthly Vol Error	% Monthly Vol RMS Error
Oct	0.75	0.66	12.76	2.62	3.34	30.25	50.15	15.71	23.48	28.75
Nov	0.59	0.52	13.41	2.10	2.53	29.87	44.19	15.30	28.06	37.70
Dec	0.43	0.43	2.21	0.29	-0.56	24.27	29.82	8.74	13.76	27.76
Jan	0.36	0.40	-8.80	-1.08	0.45	23.09	29.26	8.98	15.13	27.67
Feb	0.35	0.40	-12.93	-1.45	0.50	26.66	33.69	-8.30	23.88	31.87
Mar	0.49	0.52	-4.29	-0.69	1.90	38.47	52.41	-16.10	30.10	41.74
Apr	1.61	1.49	7.65	3.42	4.78	39.75	55.19	38.71	32.44	43.17
May	4.14	4.05	2.12	2.67	-5.56	21.26	27.55	-55.00	19.57	17.17
Jun	5.29	5.35	-1.16	-1.86	-7.47	26.51	35.90	93.24	11.64	22.81
Jul	2.30	2.25	2.11	1.47	7.56	26.62	46.85	71.19	21.99	34.49
Aug	0.98	1.02	-4.58	-1.45	3.29	26.08	39.37	19.34	31.78	26.53
Sep	0.82	0.81	0.77	0.19	6.14	28.30	54.86	-14.88	24.21	25.44
Yr Avg	1.51	1.49	1.14	6.23	7.56	26.91	52.40	93.24	20.84	34.88

Table A8: Calibration data for the Animas River model summarized by flow interval.

Flow Interval (taf/day)	No. of Cases	Simulated Mean (taf/day)	Observed Mean (taf/day)	% Bias	Bias [Sim - Obs] (taf/day)	Maximum Error (taf/day)	% Avg Absolute Error	% RMS Error
0.00	0							
< 0.05	0							
< 0.15	4491	0.40	0.38	5.54	0.02	2.53	28.33	41.05
< 1.46	5029	0.81	0.77	5.14	0.04	4.78	33.33	51.11
< 4.66	2233	2.68	2.69	-0.46	-0.01	5.47	27.90	35.78
< 14.56	1022	7.21	7.22	-0.15	-0.01	7.56	22.38	29.59

APPENDIX B:

THE LAW OF THE RIVER
AND CRSS OPERATING ASSUMPTIONS

THE LAW OF THE RIVER AND CRSS OPERATING ASSUMPTIONS

This appendix describes: (1) the major laws and agreements that govern allocation of the waters of the Colorado River, and (2) the major operating parameters that are modeled by the CRSS model. The discussion which follows on the "Law of the River" is drawn primarily from Getches (1991) and Hundley (1977). The discussion of operating procedures is drawn from USDOI (1987).

The Law of the River

The apportionment of the Colorado River has been more complete than that of the waters of any other river. The seven states along the 1400-mile river entered into the Colorado River Compact of 1922 dividing use of the river's water between the upper basin and the lower basin. The lower basin states of Arizona, California, and Nevada were guaranteed that the upper basin states of Colorado, Wyoming, Utah, and New Mexico would deliver an annual average of 7.5 million acre-feet of water to Lee Ferry, a point on the river approximately on the Arizona-Utah border. The upper basin states received a right to use an equivalent amount of water (if it was available). The lower basin also secured the right to increase its beneficial consumptive uses by another one million acre-feet. The parties contemplated each basin eventually using equal quantities of water (7.5 million acre-feet), plus up to another one million acre-feet for the lower basin. The Compact established that future obligations to Mexico would be shared equally by both basins. A 1944 treaty with Mexico set the obligation for U.S. water deliveries from the Colorado at 1.5 maf a year.

Under the Compact, the upper basin is not actually required to deliver a fixed quantity of water at Lee Ferry for the lower basin in any particular year, though current operating criteria adopted by the Bureau of Reclamation provide for releases of 8.23 million acre-feet annually. The only annual delivery obligation in the Compact is one-half the Mexican Treaty guarantee of 1.5 maf. The water apportioned between the basins has also been rather precisely divided among the states within each basin as described below.

The Colorado River Compact required approval by Congress and ratification by each of the 7 basin states. Before California agreed to ratify the agreement, it insisted on passage of the Boulder Canyon Project Act, which authorized the construction of Boulder Canyon Dam (later known as Hoover Dam). In passing this legislation in 1928, Congress added a suggested allocation of water among the states of the lower basin, giving 4.4 maf to California, 2.8 maf to Arizona, and 0.3 maf to Nevada. Shortly after the legislation passed, both California and Utah ratified the Compact. In 1944 Arizona finally approved the Compact as a means of securing some of the benefits of Hoover Dam and of assuring that the lower basin's Mexican treaty obligations would be shared among the three lower basin states.

The Upper Colorado River Basin Compact, approved in 1948, divided the upper basin's share of water among each of the states on a proportional rather than absolute basis, except for Arizona, which has only a small area in the upper basin and which was allocated 0.05 maf/year. Colorado received 51.75% of the upper basin's share, Utah 23%, Wyoming 14%, and New Mexico 11.25%.

The lower basin's water was finally allocated among the states by the U.S. Supreme Court decision in Arizona v. California (1963), which adopted the apportionment suggested in the Boulder Canyon Project Act. In addition, this decision recognized the rights of Native American tribes to water required for irrigable acreage on reservations, although most of these rights have not yet been quantified.

California's rather firm entitlement to 4.4 maf a year, plus any surpluses to which the state is entitled, has been divided by a 1931 "Seven Party Agreement". This agreement gives the highest priority to several agricultural irrigation districts for up to 3.85 maf, then to the Metropolitan Water District of Southern California and the City of Los Angeles for up to 550,000 acre-feet, then (to the extent that water remains unused) to MWD and to the City and County of San Diego for 550,000 and 112,000 acre-feet respectively, with equal priority. There are additional allocations and priorities, but these major provisions leave little water for any other users.

Two other pieces of federal legislation complete the list of major components of the Law of the River: the Colorado River Basin Project Act of 1968 and Colorado River Basin Salinity Control Act of 1974. The Colorado River Basin Project Act authorized the Central Arizona Project. In order to obtain passage of this legislation, Arizona conceded that any annual shortages would be met from CAP's allocation before any reductions were made in the 4.4 maf of water designated for California. The Salinity Control Act requires limits on the salinity of water entering Mexico and authorizes construction of a desalinization plant at Yuma, Arizona.

CRSS Operating Assumptions

The CRSS model incorporates the Secretary of Interior's Operating Criteria for the reservoir system as laid out in the "Criteria for Coordinated Long-Range Operation of Reservoirs" (USDOI, 1980). Among the provisions which the CRSS models are:

- A minimum objective release from Lake Powell of 8.23 maf/year;
- The Mexican Treaty of 1944, which requires an annual delivery to Mexico of 1500 taf, except in times of extreme shortage during which the burden is to be shared equally by U.S. and Mexico. The CRSS model schedules deliveries to Mexico of 1515 taf to account for unavoidable over-deliveries.
- Section 602(a) of the Colorado River Basin Project Act, which allows excess water to be stored in Lake Powell to the extent reasonably necessary to assure deliveries to the Lower Basin without impairing future consumptive uses in the Upper Basin. The amount of this storage is calculated based on the length of the most critical historical flow period, projected demands in the Upper Basin, and the minimum power pool in Upper Basin reservoirs. Typically, the Bureau assumes a 12-year critical period in which no shortages were imposed on upper basin users;
- Balancing active storages in Lakes Powell and Mead at the end of the water year;

In addition, the CRSS also simulates the following procedures:

- Flood control provisions, which require that 5.35 maf of storage space be provided by January 1 of each year in Lake Mead or upstream reservoirs. Between January 1 and July 31, flood control releases are based on forecasted inflow to prevent filling of Lake Mead beyond its 1.5 maf minimum space to protect against rain floods. Minimum flood control space is to increase linearly from 1.5 maf on August 1 to 5.35 maf on January 1.
- A surplus strategy, which is input into the model as a probability in order to minimize unscheduled releases and increase hydroelectric output. For this study, the surplus strategy was set to 0.7, the level of assurance normally used by the Bureau of Reclamation in its modeling runs. Based on the historic record, an assurance level of 0.7 causes unscheduled flood-control releases to be made in not more than 30% of the years;

- The shortage strategy, which is triggered by the water-surface elevation of Lake Mead. Level 1 and Level 2 shortages are imposed on the Central Arizona Project (CAP) and the Southern Nevada Water Project (SNWP). Level 3 shortages are shared proportionately by Mexico and US users.

The CRSS does not model water-rights priorities. Thus, when shortages occur, they are implemented at their point of occurrence rather than being passed on to a user with a more junior water right. In addition, the CRSS does not model Compact calls. Thus, when annual runoff at Lee Ferry falls below 8.25 maf, shortages are borne primarily by lower basin, rather than upper basin, users.

APPENDIX C:

ADDITIONAL RESULTS FROM THE CRSS MODEL

Table C1: Calibration Data for the CRSS Model

Station	Mean Annual Bias (%) [1] Flow	Salinity [2]
Colorado River at Cisco, UT	0.15	4.45
Green River at Green River, WY	-1.61	-1.78
Colorado River at Lees Ferry, AZ	-0.67	3.08
Colorado River below Hoover Dam	-1.62	-3.15
Colorado River at Imperial Dam	-4.42	-5.28

Source: USDOI, 1987: 2.

Note [1] Bias is calculated on the basis of 16 observations of total annual flow (1968–1983) and is equal to simulated flow minus observed flow

[2] Salinity is calculated on a flow-weighted basis and is equal to total salt load for the year divided by total flow for the year.

Table C2: Mean annual runoff (taf) at Lees Ferry
-- Comparison of the results obtained for three different sequences [1]

Scenario	S1 [2]	S2 [3]	S3 [4]
Base	9,348	9,372	9,353
-20 %	6,751	6,926	6,843
-10 %	8,105	8,205	8,079
-5 %	8,769	8,801	8,728
+5 %	9,959	10,038	10,045
+10 %	10,629	10,775	10,785
+20 %	12,119	12,289	12,307

Notes: [1] The numbers given here represent the total annual flow averaged over a 78-year record.
[2] Sequence 1 has a starting storage level of 20,955 taf; input data begin with the year 1967.
[3] Sequence 2 has a starting storage level of 36,482 taf; input data begin with the year 1944.
[4] Sequence 3 has a starting storage level of 54,647 taf; input data begin with the year 1929.

Table C3: Annual flow (taf) of the Colorado River at Cisco.

Scenario	Mean Flow [1]		Standard Deviation	Minimum Flow		Maximum Flow	
-20 %	3,181	(-29.7 %)	1,227	634	(-46.9 %)	6,034	(-28.3 %)
-10 %	3,849	(-14.9 %)	1,419	802	(-32.8 %)	6,793	(-19.3 %)
-5 %	4,182	(-7.5 %)	1,540	1,095	(-8.2 %)	7,241	(-13.9 %)
Base	4,522		1,678	1,193		8,413	
+5 %	4,868	(7.7 %)	1,807	1,298	(8.8 %)	8,985	(6.8 %)
+10 %	5,214	(15.3 %)	1,912	1,410	(18.2 %)	9,551	(13.5 %)
+20 %	5,910	(30.7 %)	2,117	1,658	(39.0 %)	10,683	(27.0 %)

Note: [1] Numbers in parentheses represent percent change compared to the base case.

Table C4: Annual flow (taf) of the San Juan River at Bluff

Scenario	Mean Flow [1]		Standard Deviation	Minimum Flow		Maximum Flow	
-20 %	983	(-27.5 %)	603	99	(-72.6 %)	2,580	(-21.3 %)
-10 %	1,176	(-13.3 %)	674	114	(-68.4 %)	3,036	(-7.4 %)
-5 %	1,265	(-6.7 %)	691	140	(-61.2 %)	3,052	(-7.0 %)
Base	1,356		694	361		3,280	
+5 %	1,462	(7.8 %)	765	402	(11.4 %)	3,513	(7.1 %)
+10 %	1,571	(15.9 %)	821	423	(17.2 %)	3,755	(14.5 %)
+20 %	1,789	(31.9 %)	931	479	(32.7 %)	4,177	(27.3 %)

Note: [1] Numbers in parentheses represent percent change compared to the base case.

Table C5: Effect of changes in runoff on average annual reservoir storage, evaporation, and bank storage in Lake Powell.

Scenario	Change in Storage [1] (taf)	Change in Evaporation (taf)	Change in Bank Storage (taf)
-20 %	(9,437)	(215)	(755)
-10 %	(4,416)	(95)	(354)
-5 %	(2,388)	(50)	(191)
+5 %	2,751	55	220
+10 %	3,875	77	310
+20 %	4,720	94	377

Note: [1] All numbers refer to difference relative to the base case.

Table C6: Average annual power generation (GWh) in the Upper Basin.

Scenario	S1 [1]	S2 [2]	S3 [3]
-20 %	2,485	2,770	2,550
-10 %	3,914	4,040	3,714
-5 %	4,697	4,726	4,515
Base	5,460	5,471	5,460
+5 %	5,953	6,028	6,042
+10 %	6,377	6,479	6,493
+20 %	7,162	7,272	7,284

Notes: [1] Sequence 1 has a starting storage level of 20,955 taf; input data begin with the year 1967.
[2] Sequence 2 has a starting storage level of 36,482 taf; input data begin with the year 1944.
[3] Sequence 3 has a starting storage level of 54,647 taf; input data begin with the year 1929.

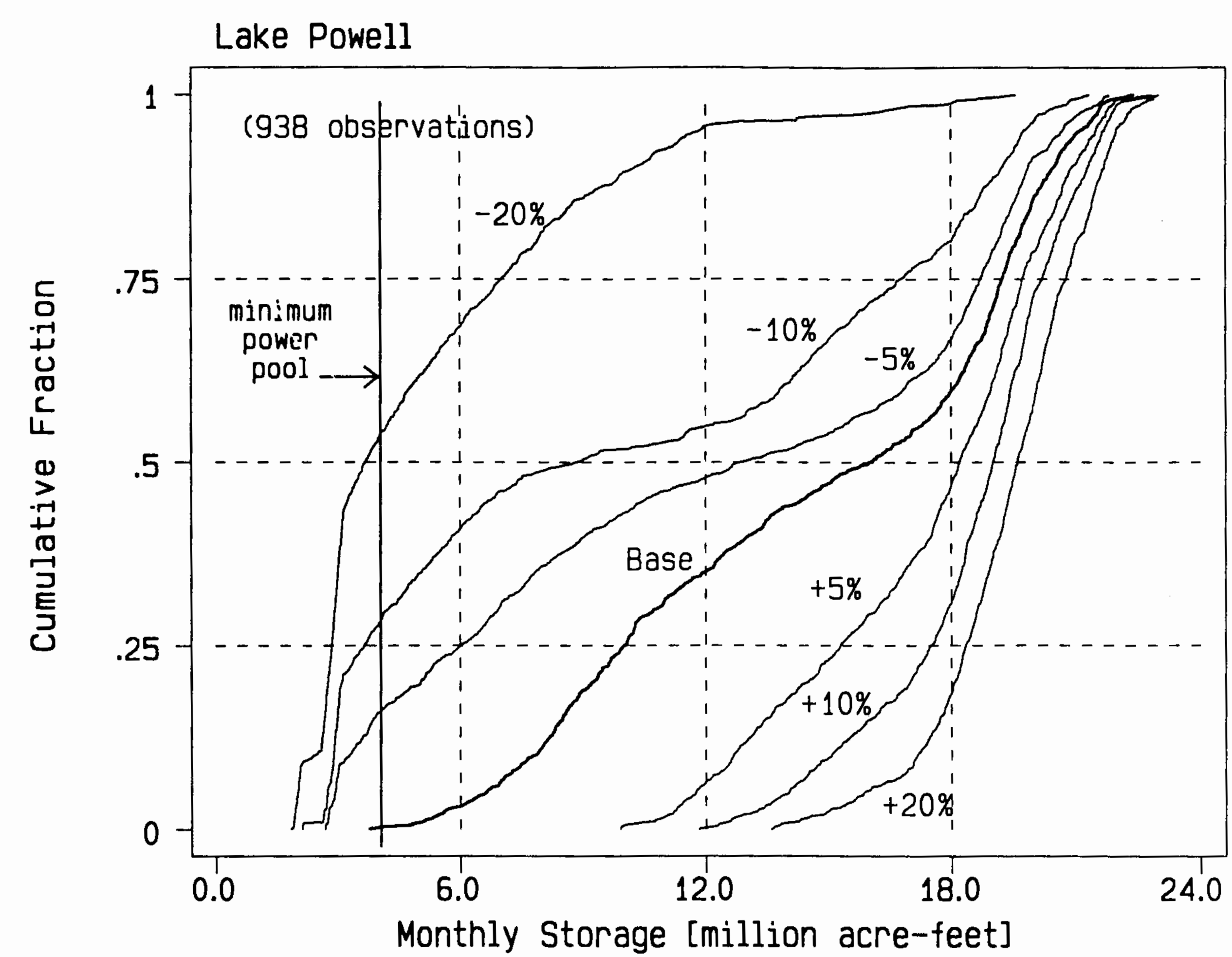

Figure C1: Cumulative frequency distribution showing the monthly storage in Lake Powell for all scenarios. Graph shows the frequency(y-axis) with which reservoir contents are equal to or less than a given volume.

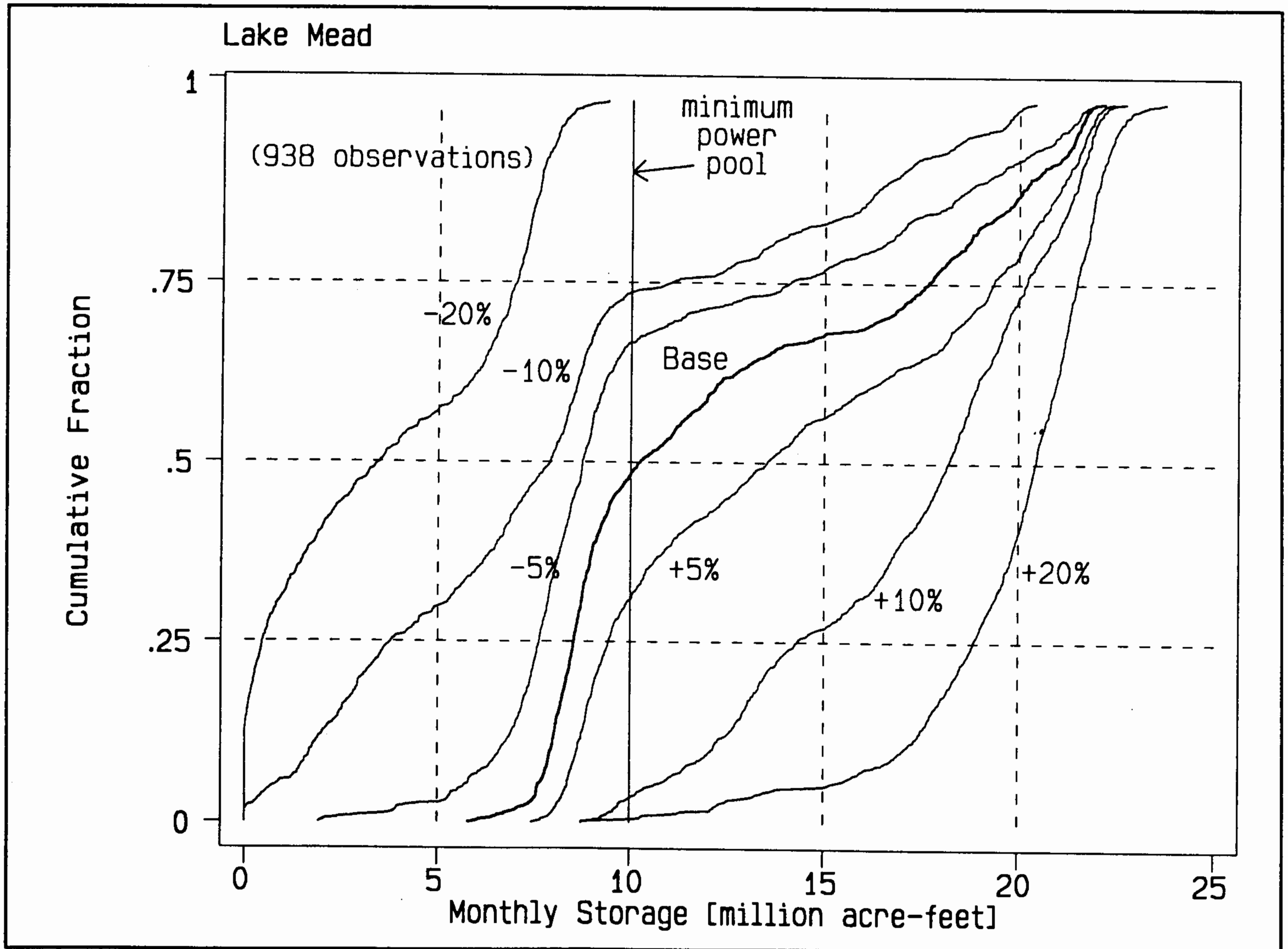

Figure C2: Cumulative frequency distribution of monthly storage in Lake Mead for all scenarios.

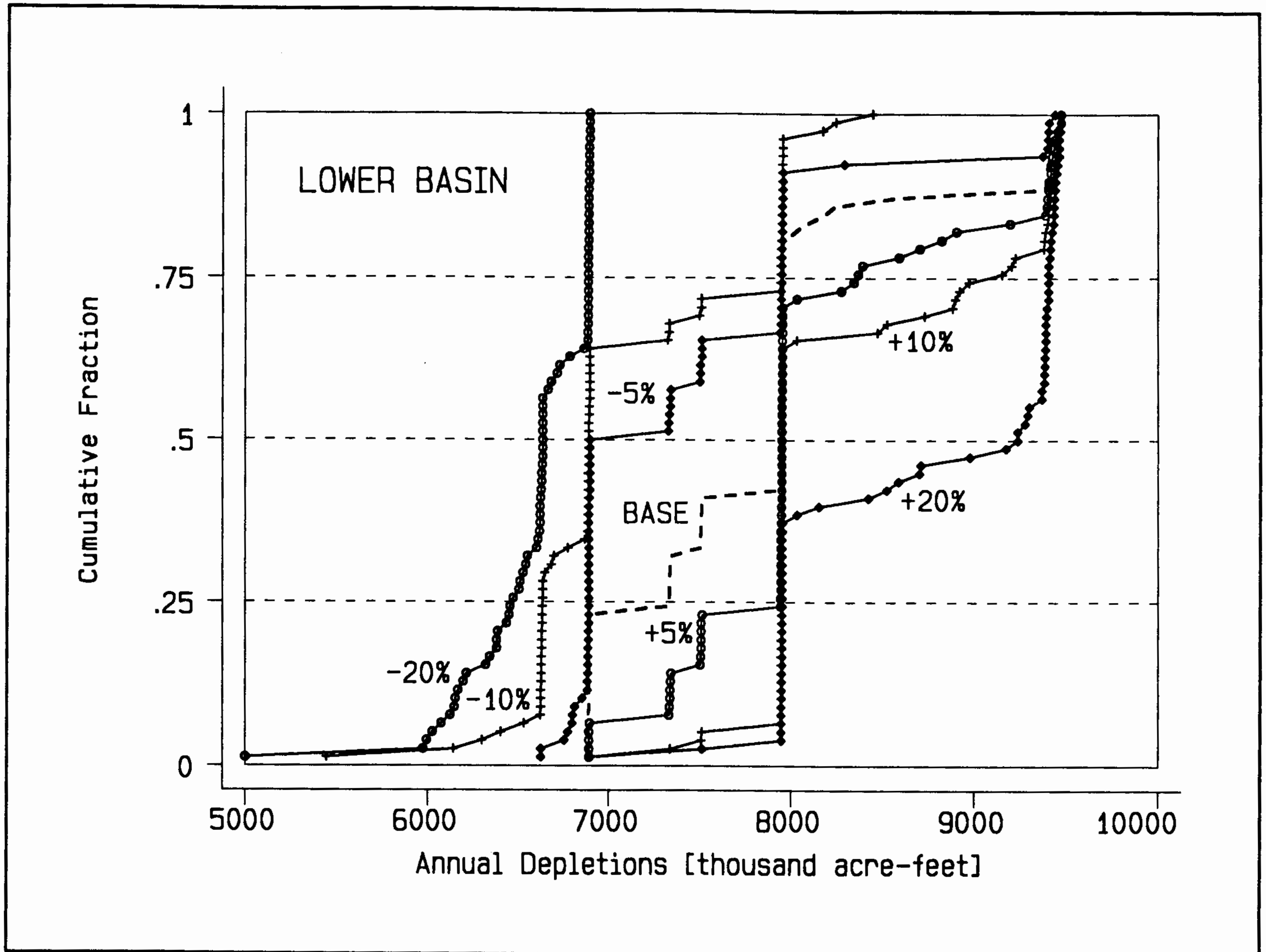

Figure C3: Cumulative frequncy distribution of annual consumptive use (depletions) in the lower basin. Graph shows the frequency(y-axis) with which consumptive use is equal to or less than a given level.

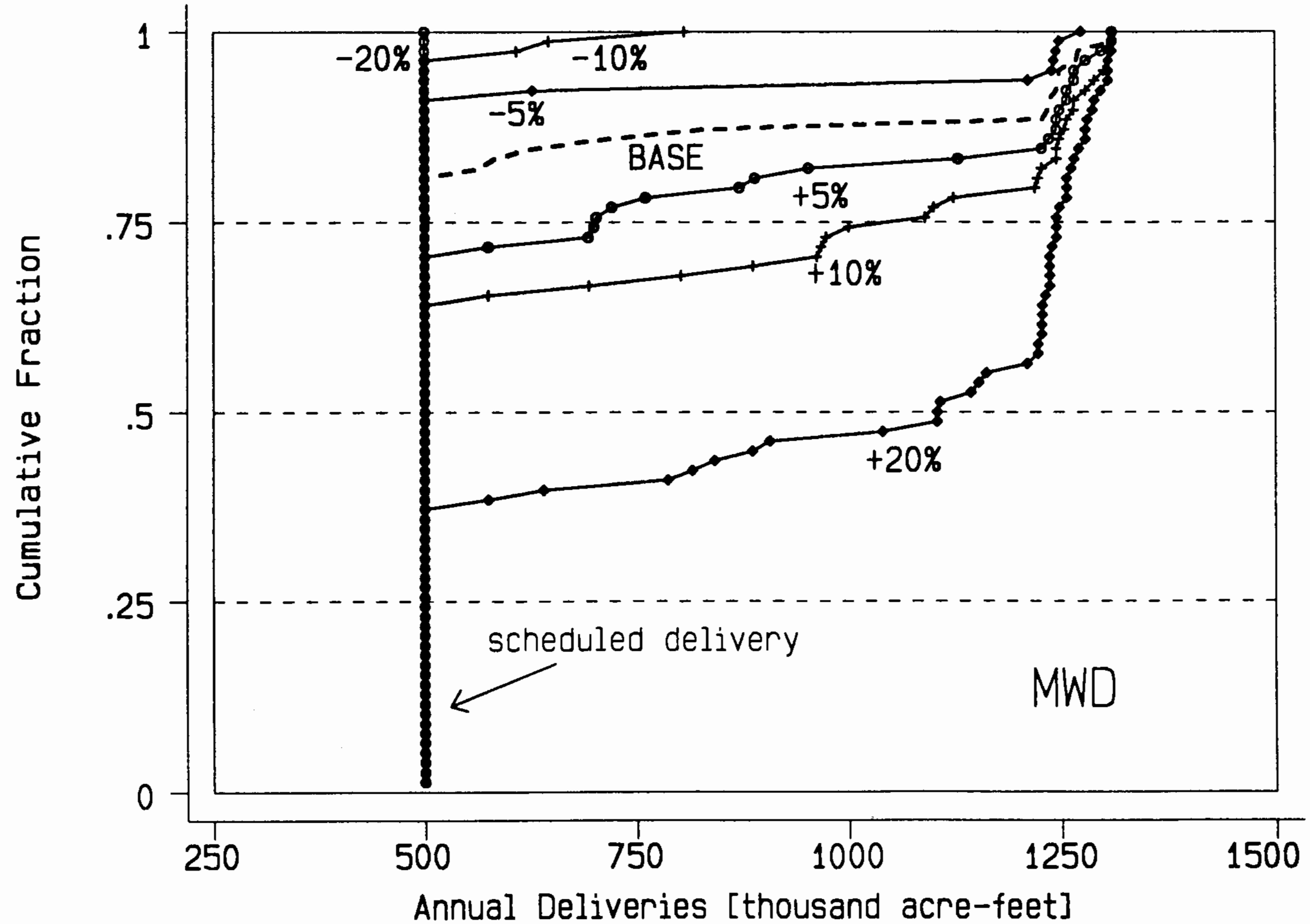

Figure C4: Cumulative frequency distribution of annual deliveries to MWD. Scheduled deliveries are approximately 500 taf/year.

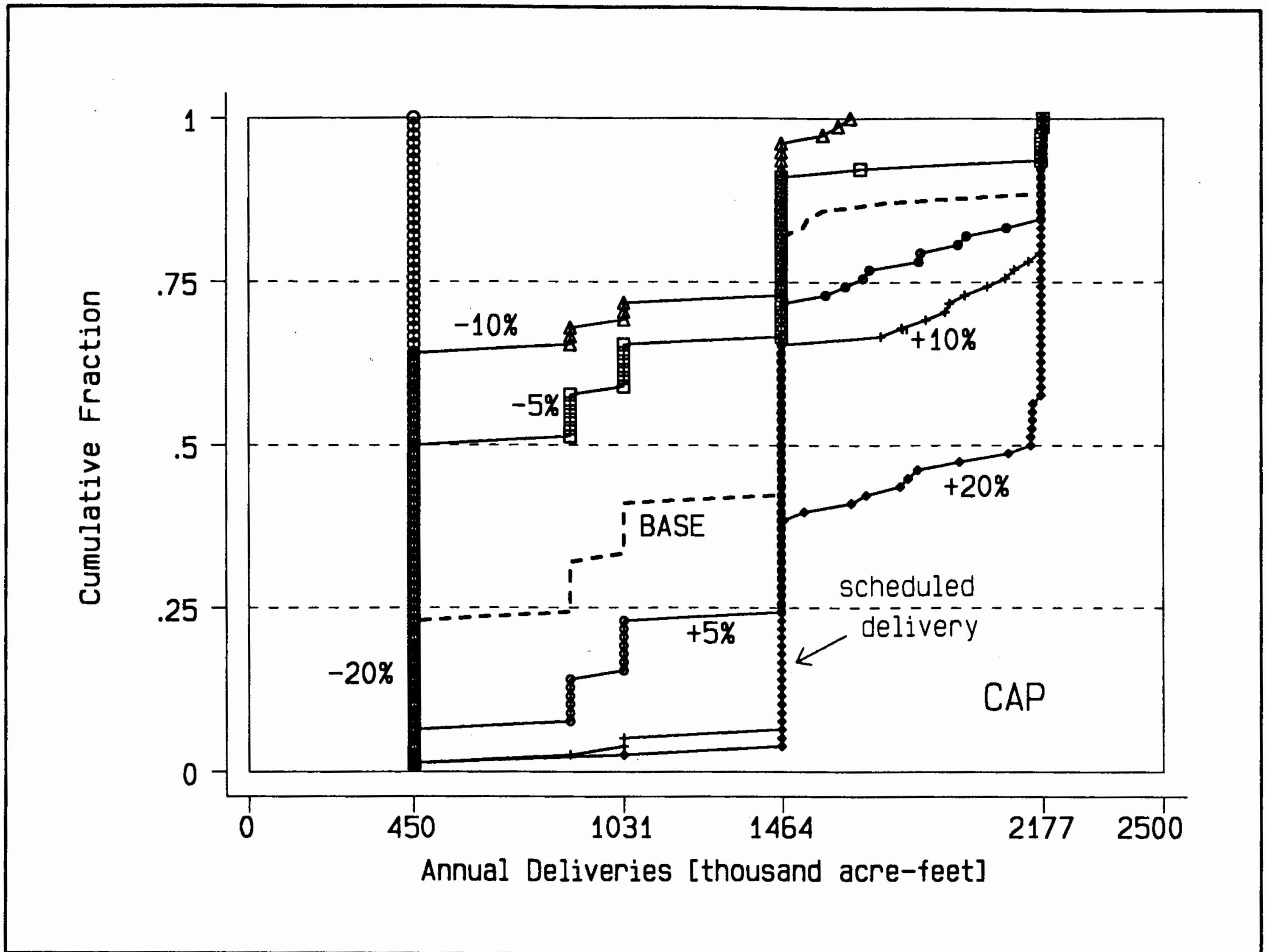

Figure C5: Cumulative frequency distribution of annual deliveries to CAP. Scheduled deliveries to CAP are approximately 1460 taf/year.