Colorado River Basin Water Management: Evaluating and Adjusting to Hydroclimatic Variability (2007)

Chapter: 3 Climate and Hydrology of the Colorado River Basin Region

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Climate and Hydrology of the Colorado River Basin Region

The Colorado River basin contains climate zones ranging from alpine to desert and exhibits significant climate variability on a variety of time scales. These variations have important implications for snowmelt and river hydrology and are thus of interest to both scientists and water managers in the Colorado River region. Scientific research on the Colorado River basin's climate and hydrologic systems has included measurements of the river's flow, long-term studies of climate and river hydrology, reviews of statistics associated with temperature and precipitation extremes, and studies of connections to regional and global climate systems. In the 20th century, long-term water management and planning in the region generally relied upon the gaged record of Colorado River flows; specifically, great reliance was placed on measurements made at Lees Ferry, supplemented by data recorded at other stations on the mainstem and on tributary streams. Some of these gaged streamflow records for the Colorado River date back to the late 19th century, but most began during the 20th century.

Although a time frame of over 100 years may appear to offer an extensive record of climate and streamflow variability, in fact it represents a relatively short period in terms of geologic history of the region. In recent years, the once-prevailing view of climate as static and unchanging on time scales important to river managers has given way to a new understanding that the gaged record represents only a small temporal window of the variability characteristics encompassing many centuries of Colorado River hydroclimate. River management decisions are inherently forward looking and rely heavily on forecasts. These forecasts typically assume that past properties of the river system, as revealed through observations, will be replicated in future conditions. However, the prospect of changing states of atmospheric conditions and climate behavior, associated with anthropogenic emissions of greenhouse gases, calls this assumption into question. As a result, many water managers today are exploring ways of adjusting water planning and management strategies.

The study of climates that occurred before direct measurements of weather and climate data—*paleoclimatology*—can serve as part of the hydroclimatic information considered in water management decisions. This field of study draws upon indirect, or proxy, information about past climate conditions obtained from evidence contained in glacial ice, landscape features, sediment deposits in ancient lakes, pollen, species distributions, preserved organisms (e.g., mollusks), and middens. The science of *dendrochronology*, or the study of the sequences of annual growth layers (rings) of coniferous trees, is particularly relevant in the Colorado River basin. For several decades, cores from coniferous trees in the western United States have been analyzed to enhance understanding of past climate. Recent tree-ring analyses have incorporated updated chronologies and longer calibration periods to estimate annual Colorado River flows over the past several centuries. These new dendrochronological reconstructions have stimulated heightened interest in questions regarding the rarity and recurrence of drought conditions across the region.

This chapter discusses fundamental features and dynamics of Colorado River basin climate (including climate trends and future climate scenarios), the gaged record of Colorado River streamflow, and tree-ring studies of past Colorado River region streamflow. The concluding Commentary section discusses implications of this hydrologic and climatic information for water resources planning and decisions.

FEATURES AND DYNAMICS OF COLORADO RIVER BASIN CLIMATE

Precipitation Patterns and Sources

The Colorado River is primarily a snowmelt-driven system, with most precipitation in the basin falling as winter snowfall in higher

elevations of Colorado, Utah, and Wyoming. In the upper Colorado River basin, approximately 20 percent of the basin's precipitation falls in the highest 10 percent of the basin, and roughly 40 percent of the basin's precipitation falls in the highest 20 percent of the basin. Cold temperatures at high elevation cause precipitation to occur mainly as snow and to remain frozen during the winter months. This "white reservoir" drapes the mountain terrain during winter months and survives into summer at the highest locations. Some of the water in this snowpack is lost to the atmosphere through sublimation (a phase change from solid to vapor) during the cool season. Most remains, however, and as the snowpack warms, or "ripens," in the spring, meltwater is steadily metered into the soil. This process extends for several weeks to months at higher elevations, and melting occurs slowly enough to recharge the soil and allow water to enter the myriad channels that feed the Green and Colorado rivers. For these reasons, winter precipitation over the high-elevation portion of the upper basin plays an important large role in generating runoff and streamflow.

Warm season precipitation plays a different role in the basin's hydrology. During warmer months precipitation falls more intensely, often in localized, convective thunderstorms. Plants are photosynthetically active at all elevations and utilize some of this water immediately. Furthermore, almost all the summer precipitation intercepted by vegetation canopies evaporates directly to the atmosphere. Much of the remainder of summer precipitation that infiltrates into the soil column is transpired by plants or (in the case of bare ground) evaporates, aided by warm soil. A relatively small fraction of summer precipitation makes its way into aquifers and streams. In the basin's high-elevation headwaters, summer precipitation amounts are generally less than winter values. The high-elevation winter dominance of annual precipitation is more pronounced in the Green River drainage than in the Colorado River headwaters in central Colorado. In the basin's lower and drier reaches, summer precipitation can account for a larger share of annual total precipitation, but because of higher evaporation and transpiration rates, this moisture is less effective in contributing to streamflow. In the hottest and lowest portions of the basin, summer precipitation matters greatly to local vegetation and to small runoff channels, but hardly at all to the mainstem Colorado and its major tributaries.

The main source of summer moisture is the North American monsoon, which transports moisture into the region from sources in the subtropical Pacific and Gulf of Mexico. This annual phenomenon brings drama to the southwestern desert skies, but only occasionally does it provide enough precipitation to contribute appreciably to hydrologic supplies. For the mainstem Colorado River and its major tributaries, the bulk of the precipitation that contributes to water supply falls during the winter months, primarily in the form of snows at high elevation. Summer months comprise the period of higher water demands and, except in extreme weather years, will provide at best only modest additions to mainstem reservoir water supplies. If a season of winter precipitation and water storage is "lost" because of drought conditions, there will be little opportunity to replenish supplies until the following winter.

The Tropical Pacific and ENSO

Ocean temperature patterns that have the greatest influence on Colorado River basin climate are in the tropical Pacific in a band that straddles the equator between Peru and the International Date Line. At irregular intervals of typically 2-7 years, sea surface temperatures (SSTs) in this region warm above climatological averages.[1] This phenomenon, called El Niño, is part of a complex ocean-atmosphere oscillation. El Niño has a climatic counterpart called La Niña that is characterized by below-average SSTs (La Niña events usually have smaller departures from average SST than do El Niño events). The terms El Niño and La Niña refer only and exclusively to ocean temperatures in this geographic domain and not to their effects elsewhere.

Another atmospheric feature relates to barometric pressure gradients in the South Pacific. In the 1920s, British meteorologist Sir Gilbert Walker published his seminal work describing the inverse relationship in atmospheric surface pressure between Tahiti and Easter Island in the tropical Pacific, and over Darwin in northern Australia (Walker, 1925). That is, when atmospheric pressure is high in one of these locations it tends to be low in the other region, and vice versa. Walker termed this phenomenon the Southern Oscillation. It refers only to the atmosphere. The Darwin-Tahiti pressure difference (nor-

1 Tropical Pacific SSTs are 1-3°C above average in modest El Niño events, 3-5°C above average in major episodes.

malized for variability over the past century) is the basis of the Southern Oscillation Index (SOI). Furthermore, when Tahiti has lower than average pressure and Darwin has higher than average pressure (negative SOI), a strong tendency exists for El Niño to be present. Conversely, there is a tendency for La Niña conditions to exist with higher pressure in Tahiti and lower pressure in Darwin. The oceanic (SST) and atmospheric (SOI) measures are usually highly correlated and these terms are sometimes used interchangeably (McCabe and Dettinger, 1999). For historical reasons these phenomena are often lumped together and referred to (although somewhat asymmetrically) as El Niño-Southern Oscillation, or ENSO. The ENSO phenomenon owes its existence to coupled ocean-atmosphere interactions over the equatorial Pacific and is an important contributor to interannual global climate variability. The ENSO cycle has impacts on climate over large areas of both the tropics and extratropics. Jerome Namias was the first to investigate extensively the possible relationship between SST and North American atmospheric circulation. Jacob Bjerknes identified the equatorial Pacific as the source of climate variability associated with the Southern Oscillation.

The winter storm track over the eastern Pacific Ocean shifts southward during El Niño episodes, often causing wet winters in the southwestern United States and dry winters in the Pacific Northwest and northern Rockies. La Niña winters tend to bring the opposite pattern, and moderately positive values of the SOI in the prior summer/autumn nearly guarantee a dry winter in the southwestern United States—it is the most dependable predictive climate relationship in the United States (Redmond and Koch, 1991). In Arizona and New Mexico, and extending into the San Juan Mountains of southwestern Colorado, El Niño winters are generally wetter than normal, but not always, and a few are extremely dry. Moreover, the likelihood of an extremely wet winter is much higher during El Niño winters and there are few wet winters when El Niño conditions are not present (Redmond and Koch, 1991). These patterns are accentuated in streamflow, particularly in extreme high and low streamflow (Cayan et al., 1999). Precipitation patterns in the western United States vary considerably among different El Niño events. These differences appear to depend on the particular spatial pattern of warm ocean temperatures, the magnitude of warming, and the particular months of the year when these patterns occur. Accurate forecasting of these ocean

features and their North American effects represents one of today's principal ENSO-related forecasting challenges.

Within the Colorado River basin, ENSO effects are more pronounced in the lower basin than in the upper basin. The San Juan River shows the same strong relationship to ENSO as does Arizona. By contrast, the headwaters of the Green River (in Wyoming's Wind River Mountains) tend to be slightly more influenced by the northern pole (centered over the Columbia River basin) of this winter dipole pattern (Redmond and Koch, 1991). The main source regions of Colorado River basin precipitation and streamflow—the mountains of Colorado, Wyoming, and northeastern Utah—are not greatly impacted by ENSO events. Because roughly 90 percent of the river's flows originate in mountain headwater regions with limited connection to ENSO, better forecasts of ENSO and its effects are not likely to greatly improve upper basin mainstem streamflow forecasts.

Other Ocean Connections

Another pattern of Pacific regional scale climate variability related to SST variations is the Pacific Decadal Oscillation (PDO). The term was coined in 1996 by fisheries scientist Steven Hare while he was studying connections between the Alaska salmon production cycle and Pacific climate (*http://jisao.washington/edu/pdo*). The PDO describes joint variations in SST, atmospheric pressure, and wind in the central and eastern Pacific poleward of 20°N (Mantua et al., 1997). The warm and cool phases of the PDO each historically have lasted two to three decades, for a total period of about a half-century. An abrupt jump in Pacific-wide environmental conditions known as the "1976 shift" (Ebbesmeyer et al., 1991; Trenberth and Hurrell, 1994) was identified retrospectively and helped lead to identification of the PDO. This pattern appears to alternately accentuate and counteract the effects of ENSO in the Pacific Northwest and the south-western United States and is expressed most strongly in winter. The origin of this oscillation has not been definitively determined. It is linked to periods of greater and lesser frequency of El Niño and La Niña at equatorial latitudes, even though the PDO index has only a modest correlation with the SOI (Mantua et al., 1997). Although there are intriguing statistical relationships associated with the PDO, the physical mechanisms that underlie the PDO behavior itself, and that lead to its expression within the Colorado River basin (and primarily in the lower basin, as is the case with ENSO), have not been fully explained.

In recent years another pattern has been identified that appears to have ties to the Colorado River basin. Atlantic Ocean SSTs exhibit a mode of variability that has similar departures from average for one to two decades over an area spanning low to high latitudes; this feature is known as the Atlantic Multidecadal Oscillation (AMO). That the AMO has effects on climate and streamflow in the eastern United States (Sutton and Hodson, 2005) is understandable; however, additional studies have shown some surprising results. Notably, when the North Atlantic is warm for a decade or longer, streamflow in the upper Colorado River basin tends to be lower than average, and vice versa (Gray et al., 2004; McCabe and Palecki, 2006; McCabe et al., 2004). This headwaters streamflow is largely governed by winter precipitation. The physical mechanism by which the Atlantic could influence mountain winter precipitation in Colorado and Wyoming, which are upstream in the atmospheric winter flow pattern, remains a puzzle. The evidence so far is statistical and largely dependent on just a few AMO cycles. Theory and models are just beginning to address this potential link (Delworth and Mann, 2000; Knight et al., 2005) and observational studies are continuing. For example, during warm Atlantic phases, moisture delivery to the conterminous United States is diminished (Schubert et al., 2004a).

Diagnostic studies of the global pattern of ENSO cycle variability clearly have revealed that the atmosphere acts as a bridge linking SST anomalies in the equatorial Pacific to yet larger patterns of atmospheric and ocean variability. Variations in SSTs in the tropical Pacific may herald changes in jet stream patterns, strength and track of Pacific winter storms, and future water supply conditions across the Colorado River basin. Different patterns may accentuate or counteract each other. For example, the effect of Indian Ocean temperatures acting in concert with La Niña has been demonstrated as helping produce “the perfect ocean for drought” in the southwestern United States (Hoerling and Kumar, 2003). Research has shown that the American Dust Bowl of the 1930s was in part caused by tropical ocean temperature departures from normal (Schubert et al., 2004b; Seager, 2006; Seager et al., 2005). Other western droughts, such as the droughts during the Civil War era and in the 1890s, may have similar explanations (Seager, 2006; Seager et al., 2005). Linkages among these patterns suggest modest predictability, enough that they may merit consideration in water supply planning across the western United States.

CLIMATE TRENDS AND PROJECTIONS

Climate Records and Past Trends

In a previous era of Colorado River water management there was an implicit assumption that the main features of future climate states would closely resemble those of the past century. Over time, additional research has enhanced understanding of the variability of past climate over longer time scales. Moreover, increasing levels of atmospheric greenhouse gases and steadily increasing global mean surface temperatures have heightened awareness of the potential for human activities to impact the global climate system (Houghton, 2004). The assumption that future climate conditions will largely replicate past conditions is now frequently being called into question.

Variations in precipitation and water supply have long been of interest to water managers for daily, monthly, and annual operations. Less widely appreciated are the impacts that temperature has on water availability, through effects on both supply and demand. Temperature affects the quantity of and timing of snowmelt runoff in spring and summer, the occurrence of large floods, and rates of evapotranspiration. Anything that affects basin temperatures in a long-term, systematic way thus should be of considerable interest, regardless of its origin. The observed time series of basin-averaged precipitation and temperature are important for assessing regional impacts of global climate change and are discussed in the following section.

Precipitation

Colorado River basin precipitation exhibits high year-to-year (interannual) variability. Figure 3-1 shows interannual precipitation variability across the upper Colorado River basin, spatially averaged over the basin upstream of Lees Ferry and aggregated to annual resolution (Kittel et al., 1997; updated data from *ftp://ftp.ncdc.noaa.gov/pub/data/prism100*).

For example, after a period of less variability for several decades in the mid-20th century, there has been a tendency toward greater variability in the latter decades of the 20th century. The past 30 years of data include the highest and lowest annual precipitation in the 100-year record, and there has been a tendency toward multiyear episodes of both wet and dry conditions. Some years in the early and mid-1980s were at least as wet as the period that preceded the signing of the Colorado River Compact. Prior to the early 21st century drought, the driest comparable 5-year consecutive interval was the 1950s drought. The only other comparable 5-year dry period was at the end of the 19th and beginning of the 20th century. Despite these variations, there is no significant trend in interannual variability of precipitation over the past 110 years.

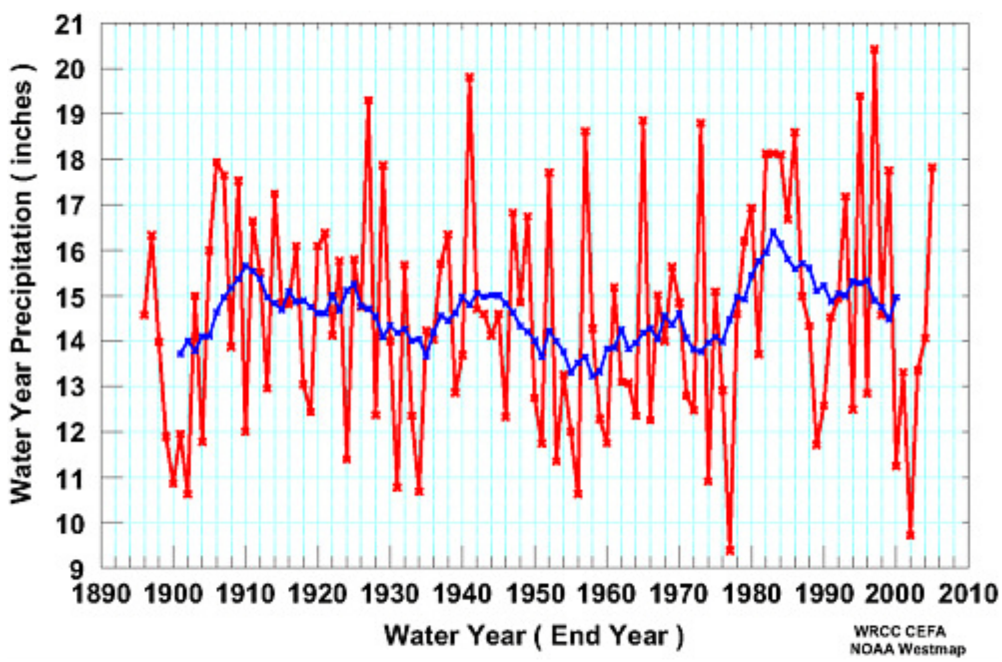

FIGURE 3-1 Annual precipitation for the Colorado River basin above Lees Ferry, 1895-2005.

NOTE: Red: annual values. Blue: 11-year running mean.
SOURCE: Western Regional Climate Center.

Temperature

Figure 3-2 shows annual mean temperatures for the entire Colorado River basin from 1895 to 2000 (adjusted for variations in elevation using the same method as for precipitation in Figure 3-1). Upper and lower basin temperature trends are similar and bear a strong resemblance to the history of temperature across the entire western United States (Redmond, in press), as well as to mean global surface temperature trends. Figure 3-2 shows that since the late 1970s the Colorado River region has exhibited a steady upward trend in surface temperatures. The most recent 11-year average exceeds any previous values in the over 100 years of instrumental records.

One striking aspect of Figure 3-2 is how much warmer the region has been in the drought of the early 2000s as compared to previous droughts. For example, temperatures across the basin today are at least 1.5°F warmer than during the 1950s drought. Increasing

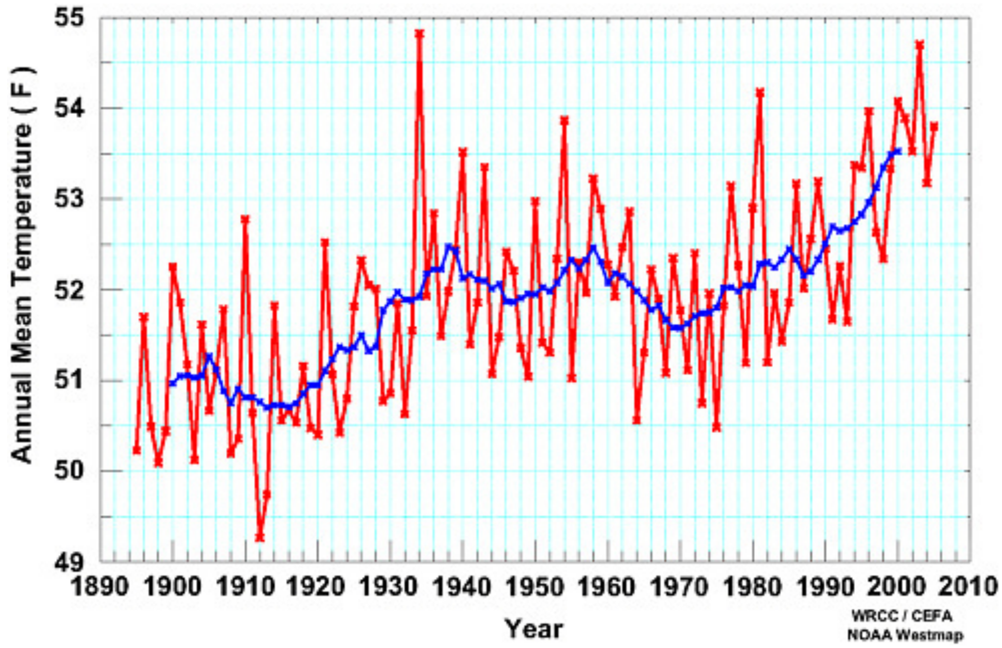

FIGURE 3-2 Annual average surface air temperature for entire Colorado River basin, 1895-2005.
NOTE: Red: annual values. Blue: 11-year running mean.
SOURCE: Western Regional Climate Center.

temperatures in the region have many important hydrologic implications, including the impacts of drought. For example, the drought of the early 2000s has taken place in particularly warm conditions. Figure 3-3 shows temperature departures for that 6-year period (2000-2005) as compared to 1895-2000 averages. Both in terms of absolute degrees and in terms of annual standard deviation, the Colorado River basin has warmed more than any region of the United States—a fact that should be of great interest throughout the region. This trend continued through the first half of 2006. This warming is well grounded in measured climatic data, corroborated by independent data sets, and widely recognized by climate scientists throughout the West.

The trend of increasing temperatures in the western United States also is seen in larger, global temperature trends. For example, a 2005 paper on western mountain snowpack trends notes that "increases in temperature over the West are consistent with rising greenhouse gases, and will almost certainly continue" (Mote et al., 2005). And in a recent review of global surface temperature records of the past 2,000 years, a committee of the National Research Council (NRC, 2006) concluded that

> It can be said with a high degree of confidence that global mean surface temperature was higher during the last few decades of the 20th century than during any comparable period during the preceding four centuries. This statement is justified by the consistency of the evidence from a wide variety of geographically diverse proxies (NRC, 2006).

Key manifestations of warmer temperatures in western North America are a shift in the peak seasonal runoff (driven by snowmelt) to earlier in the year, increased evaporation, and correspondingly less runoff. In fact, many of these changes have been documented:

> Winter and spring temperatures have increased in western North America during the twentieth century (e.g., Folland et al. 2001) and there is ample evidence that this widespread warming has produced changes in hydrology and plants.... The timing of spring snowmelt-driven streamflow has shifted earlier in the year (Cayan et al. 2001; Regonda et al. 2004 [*corr* Regonda et al., 2005]; Stewart et al. 2005), as is expected in a warmer climate (Hamlet and Lettenmaier 1999a) (Mote et al., 2005).

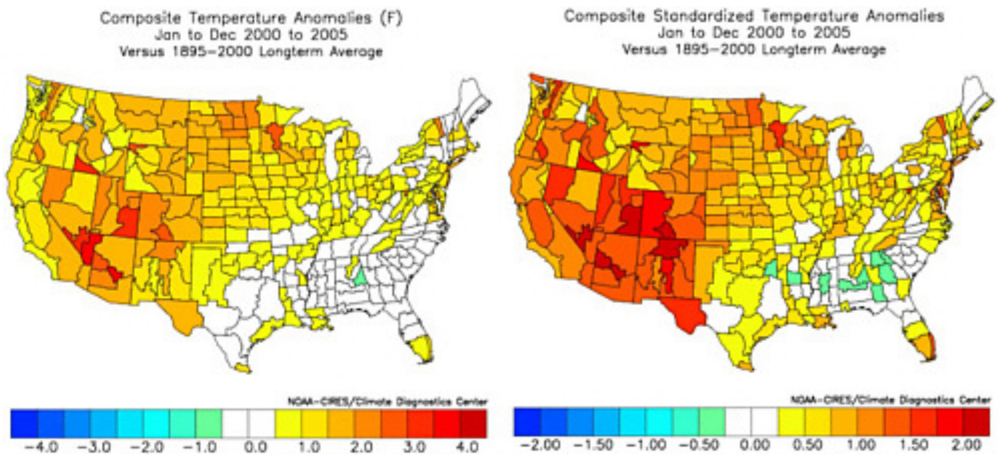

FIGURE 3-3 2000 to 2005 temperature departures from 1895-2000average. Left: Shown in temperature units (°F). Right: Shown in standardized terms (standard deviations).
SOURCE: National Oceanic and Atmospheric Administration's Climate Diagnostics Center.

A recent study of the timing of snowmelt in several mountain basins in the western United States concluded that "[t]he recent midlatitude warming, perhaps of anthropogenic origins, is a plausible cause for the shift in spring peak flow timing" (Regonda et al., 2005). Other studies of snowpack over the western United States find that declining trends in snow accumulation likely are not solely a manifestation of precipitation and snowfall variability, but rather reflect (at least in part) a warming signal:

> Estimates of future warming rates for the West are in the range of 2°—5° C over the next century, whereas projected changes in precipitation are inconsistent as to sign and the average changes are near zero (Cubash et al. 2001). It is therefore likely that the losses in snowpack observed to date will continue and even accelerate (Hamlet and Lettenmaier 1999a; Payne et al. 2004) (Mote et al., 2005).

Projecting Future Climate Conditions

Many studies of future climate and hydrology conditions across the western United States are based on results of computer-based, numerical models of the global atmosphere. Developed in large part to project future effects of human-induced climate change arising from increasing levels of heat-trapping greenhouse gases, these atmospheric models—referred to as general circulation models (GCMs)—are used for a variety of experiments. These numerical models of the global climate system are the primary method used by climate scientists to project global and regional atmospheric responses to a variety of perturbations, such as a doubling of atmospheric carbon dioxide levels. Seasonal to interannual weather forecasts from multiple models are generally viewed to be more accurate than individual forecasts (Krishnamurti et al., 1999). This perspective regarding "consensus" weather forecasts can be generalized to climate forecasts, and has led to a trend of using multiple GCM output scenarios to assess implications of climate variability and change.

Precipitation Projections

For reasons similar to the difficulties in making daily precipitation forecasts, long-term projections of precipitation constitute a greater modeling challenge than temperature projections. Over the West and the Colorado River basin, precipitation projections from climate models suggest a wide range of potential changes in annual precipitation. Results from multiple computer runs, over many model-scenario combinations, generally forecast precipitation futures that show relatively little annual change in the region (see Dettinger [2005] for precipitation projections that are representative of the western United States). Over the next 10-40 years, there is a tendency in the results of climate model superensembles to forecast slightly increased annual precipitation in the northwestern United States by about 10 percent above current values, and to forecast slightly decreased annual precipitation in the southwestern United States by less than 10 percent below current values, with relatively little change in annual precipitation amounts forecast for the headwaters regions of the Colorado River.

Changes in seasonality of precipitation or changes in the type of precipitation (rain or snow) can be just as important as changes in annual amounts of precipitation. A detailed study for the Sierra Nevada mountains (at the same latitude as the upper Colorado), using 11 climate models and 2 emission scenarios, projects slightly more precipitation in winter and slightly less precipitation in late winter and in spring and early summer (Maurer, 2007). To a first approximation, no appreciable trend in annual Colorado River basin precipitation has been detected (Figure 3-1) or currently is projected. The accuracy of climate model precipitation forecasts is a topic of great interest and will continue to be an important focal point in climate science research.

Temperature Projections

Figure 3-4 compares multiple climate model projection results for temperature across the Colorado River region. Key points from these projections are the unanimity among the different models that temperatures will rise in the future, and relatively small differences across projections during the first part of the 21st century. Differences among these model results are modest until roughly 2030, with increasing divergences among them moving toward the year 2100. All these changes and model results are so far broadly consistent with recorded temperature data for the region. Taken as a whole, these future projections and past trends point to a strong likelihood of warmer future climate across the Colorado River basin.

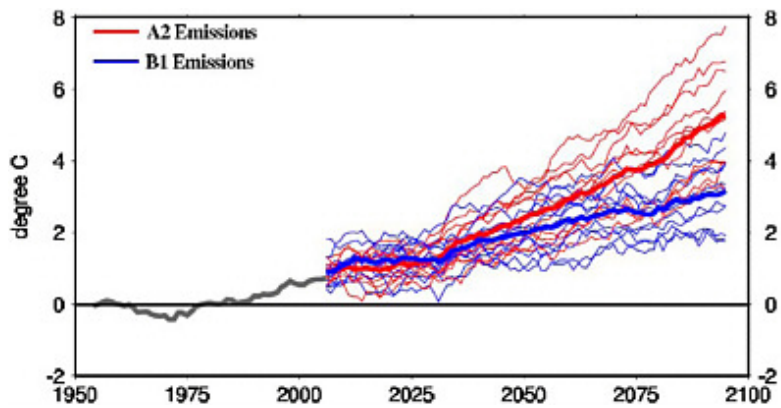

FIGURE 3-4 Nine-year moving average of observed annual air temperature averaged over the Colorado River basin (1950-2001), and projected Colorado River basin annual average air temperature from 11 different climate models, under two different greenhouse gas emission scenarios (2005-2095). Greenhouse gas scenarios were run for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4).
Red (A2) projections are 9-year moving averages based on relatively unconstrained growth in emissions over the next century; solid red line represents a 9-year moving average of A2 projections.
Blue (B1) projections are 9-year moving averages based on a stabilization of global emissions by 2100; solid blue line represents a 9-year moving average of B1 projections.
SOURCE: Gridded observation data from Maurer et al. (2002). IPCC AR4 climate projections from Lawrence Livermore National Laboratory Program for Climate Model Diagnosis and Intercomparison (*http://www-pcmdi.llnl.gov*).

Hydrologic Implications of Warming

These projected temperature increases across the Colorado River region have important direct and indirect implications for hydrology and streamflow, irrespective of precipitation increases or decreases. The likely effects of warmer temperatures across the Colorado River basin for hydrology include the following:

- freezing levels at higher elevations, which means more winter precipitation will fall as rain rather than snow;
- shorter seasons of snow accumulation at a given elevation;
- less snowpack accumulation compared to the present;
- earlier melting of snowpack;
- decreased base flows from groundwater during late summer, and lowered water availability during the important late-summer growing season;
- more runoff and flood peaks during the winter months;
- longer growing seasons;
- reductions in soil moisture availability in summer and increases in the spring and winter;
- increased water demands by plants; and
- greater losses of water to evapotranspiration.

Concerns regarding the implications of future climate changes—especially warming—for Colorado River flows date back to at least the 1970s. Since then, the effects of the listed factors on Colorado River streamflow have been incorporated in different ways by several different hydrologic studies and papers. In a study often acknowledged as the first to evaluate possible impacts of climate change on Colorado River flows, Stockton and Boggess (1979) estimated that a 2°C increase in temperature and a 10 percent decrease in precipitation would result in a decline of upper basin streamflow of about 44 percent. In a 1983 paper, Revelle and Waggoner estimated that a 2°C temperature increase by itself would cause a decrease in mean Colorado River flows by 29 percent. Subsequent studies have used more sophisticated approaches based on hydrologic models that represent the physical processes that relate climate and streamflow, and generally have estimated somewhat less severe impacts on runoff resulting from prospective temperature increases (e.g., Nash, 1991). In the early 1990s, for example, a series of hydroclimate modeling studies indicated that hypothetical temperature increases of 2° and 4°C, and no change in precipitation, would lead to Colorado River streamflow reductions of 4-12, and 9-21 percent, respectively (Nash and Gleick, 1991, 1993).

A 2000 assessment of the potential consequences of climate variability and change on U.S. water resources considered the implications of changes in climate on runoff in the Colorado River basin (Gleick, 2000). Modeling exercises specially conducted for the assessment were based on output from two GCMs; these results included forecast increases of 66-128 percent in upper Colorado River flows (from that report's Table 7). In addition to these specific modeling exercises, the 2000 assessment lists results from several other hydroclimate modeling experiments and professional papers. In contrast to modeling results for the assessment that projected increases in Colorado River runoff, the majority of the results from these other hydroclimate modeling exercises project future decreases in runoff for the upper Colorado River and inflows into Lake Powell (see Table 9 from that report). In its review of these other modeling experiments and papers, the report notes that, "In the arid and semi-arid western United States … [e]ven in the absence of changes in precipitation patterns, higher temperatures resulting from increased greenhouse gas concentrations lead to higher evaporation rates, reductions in streamflow, and increased frequency of droughts." It was also observed that, for climate-runoff projections for several river basins in the semiarid western United States, "[i]n every one of these studies, an increase in temperature and no change in precipitation resulted in decreases in runoff" (Gleick, 2000).

A more recent study of the global consequences of 21st century climate change used average values from 12 different GCMs to project future runoff changes (Milly et al., 2005). Almost all the model runs projected future decreases in runoff over the interior western United States, including the Colorado River region. These decreases are projected to be on the order of 20 percent (Milly et al., 2005). Another study of western North America arrives at similar conclusions: reductions in annual runoff resulting from increasing tempera-

ture and slight decreases in precipitation (by 1-6 percent) may reduce Colorado River inflow to Lake Powell by 14-18 percent over the next half-century (Christensen et al., 2004).

Differences among these forecasts of future streamflow can be ascribed to modeling and other methodological differences. Some of these studies (e.g., Milly et al., 2005) are based on output from GCMs with relatively coarse resolution (typically 2-4° latitude-longitude) of the Earth's surface and atmosphere, which cannot resolve details of the relatively small areas from which most of the Colorado River's flow is generated. Aspects of the processes that generate runoff—such as negative feedback between earlier runoff and reduced evaporative demand associated with warmer winter temperatures in headwaters regions—thus are not adequately captured. Differences in GCM results can contribute to differences in hydrologic projections. For example, results in the 2000 U.S. National Assessment (Gleick, 2000) that projected future increases in runoff in the upper Colorado basin were based on the U.K. Hadley Centre model, which tends to simulate large precipitation increases relative to other GCMs. Other GCM-based projections suggest changes in seasonality of precipitation; a parallel climate model (PCM) from the National Center for Atmospheric Research forecasts little change in annual precipitation but shifts some winter precipitation to the summer months. In the Colorado River basin, summer precipitation is on average less efficient in generating runoff (because of higher evaporative losses) than in winter. As a result, runoff changes were amplified from the modest PCM warming projections (Christensen et al., 2004). For these reasons, recent studies have begun to utilize multimodel ensemble approaches and to focus on the ensemble mean, with the range of results used as an index of uncertainty. This approach was used in the Milly et al. (2005) global study and in a recent report of the California Governor's Climate Action Team (California Environmental Protection Agency, 2006). An ensemble-based approach to hydrologic and climate forecasting is becoming more widely applied and accepted.

A 2006 paper employed 11 different climate change models that are being used in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), which is due to be released in 2007 (Christensen and Lettenmaier, 2006). GCM output was used for two global emissions scenarios: an “A2” (relatively unconstrained growth in emissions over the next century) and a “B1” (elimination of global emissions increases by 2100) scenario. Results showed that, in

the ensemble mean, Colorado River discharge at Imperial Dam (naturalized flow) would decrease by up to 11 percent by the end of the century for A2 emissions, and by up to 8 percent for B1 emissions. Over all ensembles, 9 of 11 showed streamflow decreases by the end of the century for A2, and 8 of 11 for B1—roughly the same fraction as in the results from the Milly et al. (2005) paper. In comparison with an earlier paper (Christensen et al., 2004), part of the reason noted for the somewhat smaller streamflow reductions predicted is that most of the IPCC AR4 scenarios show shifts (albeit modest) of summer to winter precipitation, which tend to counteract increased evaporative demand associated with warmer temperatures (Christensen and Lettenmaier, 2006).

There have also been some (but fewer) studies evaluating the implications of streamflow changes on reservoir system performance. A 1993 paper used a U.S. Bureau of Reclamation Colorado River reservoir simulation model with historic streamflows altered according to a range of precipitation and temperature changes (Nash and Gleick, 1993). They assumed an instantaneous temperature (or precipitation) change, so the results in this modeling exercise refer to the eventual equilibrium response. That paper found that a 20 percent reduction in Colorado River natural runoff would result in mean annual reductions in storage of 60-70 percent, reductions in power generation of 60 percent, and an increase in salinity of 15-20 percent at the U.S.-Mexico border (Nash and Gleick, 1993). A 2004 paper concluded that changes of up to 18 percent in runoff could result in somewhat smaller decreases—up to 40 percent—in total basin storage (Christensen et al., 2004). That study's authors noted, within the various climate and hydrologic scenarios they used, that "[r]eleases from Glen Canyon Dam to the Lower Basin (mandated by the Colorado River Compact) were met … only in 59-75% of years for the future climate runs" (Christensen et al., 2004).

Hydroclimatic science experts have used different assumptions in their models and are constantly improving them. Collectively, the body of research on prospective future changes in Colorado River flows points to a future in which warmer conditions across the region are likely to contribute to reductions in snowpack, an earlier peak in spring snowmelt, higher rates of evapotranspiration, reduced late spring and summer flows, and reductions in annual runoff and streamflow. Earlier studies suggested substantial decreases in Colorado River annual flow volumes over the next century; more recent studies

have generally projected more modest declines, with a few modeling exercises suggesting increases. It is worth reiterating that Colorado River hydroclimate sensitivity studies that consider only the impacts of future temperature increases all forecast decreases in runoff. Forecasts show greater variability when considering possible future changes in precipitation. Modeling results across the region show little consensus regarding changes in future precipitation amounts or seasonality.

Any future decreases in Colorado River streamflow, driven primarily by increasing temperatures, would be especially troubling because the quantity of water allocations under the Law of the River already exceeds the amount of mean annual Colorado River flows. This situation will become even more serious if there are sustained decreases in mean Colorado River flows. Results from these numerous hydroclimatic studies are not unanimous, and all projections of future conditions contain some degree of uncertainty. Nevertheless, the body of climate and hydrologic modeling exercises for the Colorado River basin points to a warmer future with reductions in streamflow and runoff.

This discussion has centered on the mainstem Colorado River, dominated by its two huge reservoirs capable of storing several years of flow. There is, however, an important caveat in this discussion regarding tributary flows: climate change implications for streamflow and reservoir management of the many individual upper basin tributaries upstream from Lakes Powell and Mead may vary considerably from those for the mainstem because of seasonal, topographic, legal, and physical infrastructure constraints particular to each specific sub-basin.

INSTRUMENTAL RECORD OF COLORADO RIVER STREAMFLOW

A streamflow gage monitors a river's flow at a given geographic site; analyzed collectively, a network of streamflow gages can provide an integrated account of weather and climate fluctuations and Earth surface processes over a watershed. The two fundamental hydrologic variables recorded at a streamflow gage are stage (depth) and flow (discharge). Stage measures the height of the water surface relative to some arbitrary datum, whereas flow is the total volume of water that flows past a given point in a specified period of time (e.g., cubic meters per second).

Because river discharge is difficult to measure accurately and continuously, easier and simpler river stage measurements are made instead. These measurements are converted to discharge values through the use of *rating curves*. Rating curves show the relation between stage and discharge, and must be calibrated from available simultaneous measurements of both quantities for each particular gage station. These rating curves must be revised occasionally to reflect changes that affect the hydraulics in the vicinity of the gage. These changes can occur because of changes in river cross sections that result from scour or deposition of sediment, changes in stream gradients, other changes in stream channel morphology and bank structure and roughness (such as from floods), changes in land use across a watershed, or transbasin diversions. This is one reason why rocky locations are preferred for gages; they remain relatively stable. Stream gaging methods and instrumentation have improved greatly over time. Nevertheless, because of the practical challenges in measuring river stage and flow accurately over long time periods, and because of the many physical changes that take place across a watershed and that affect stage-discharge relations, some degree of inaccuracy is often contained in stream gage readings.

The U.S. Geological Survey (USGS) is responsible for the national network of streamflow gages. Over the past century, many USGS stream gages have been relocated and/or the datum have changed at least once; in addition, methods of measuring streamflow (or river stage) have also changed over time (LaRue, 1916; USGS, 1954). To assess the accuracy of gage records, the USGS publishes accuracy information in annual Water Resources Data Reports rating the data records (part or whole) as “excellent” (95 percent of the daily discharges are within 5 percent of the true value), “good” (within 10 percent), “fair” (within 15 percent), and “poor” (Fisk et al., 2004). Some early water supply papers documenting data revisions and gage changes also include accuracy information. Estimating and revising data may improve the completeness of streamflow records but the data may be neither highly accurate nor may it represent true system dynamics. The records indicate that data accuracy may be reasonable except when flows are estimated; this is an important point, given that many Colorado River flow records are based on estimates.

Direct measurements taken at streamflow gages along the Colorado River, in conjunction with similar data obtained from tributary streams across the basin, constitute an important part of the Colorado River hydrologic knowledge base. The two earliest sets of streamflow records used in Colorado River Compact negotiations were from the Green River at Green River, Utah, and at Green River, Wyoming. These records began in 1894 and 1895, respectively (Table 3-1 lists select Colorado River basin gages).

The best-known Colorado River stream gage record is from Lees Ferry, Arizona, where the USGS has been operating a gaging station since May 8, 1921 (Topping et al., 2003). Lees Ferry was selected as a gaging site because it was readily accessible by automobile and was strategically located with respect to Colorado River hydrology. Discharge readings at Lees Ferry measure the combined runoff from the upper part of the Colorado River basin, which includes the upper Colorado, Green, and San Juan rivers (Topping et al., 2003). Located near (~1 mile upstream) the mouth of the Paria River, Lees Ferry was also located several miles downstream from a proposed dam site in Glen Canyon favored by the Southern California Edison Company. As explained in Chapter 2, the 1922 Colorado River Compact designated Lees Ferry as the hydrologic dividing point between the upper and lower basins. The record from Lees Ferry is the most prominent measured record of Colorado River flows (Figure 3-5).

Figure 3-5 shows annual, natural Colorado River flows at Lees Ferry for water years (October through the following September) 1906-2006. Also shown are the long-term average flow value for 1906-2006 (red line) and a 5-year moving average flow value (black line, plotted at the end of each 5-year interval). The mean annual flow value in this instrumental record is roughly 15 million acre-feet (red line). The drought of the late 1990s and early 2000s —which began in the fall of 1999 (water year 2000)—clearly stands out within the past century, as it represents the lowest 5-year running average discharge in the instrumental record.

With respect to Figure 3-5 it is important to distinguish between natural flows (as shown in the data in Figure 3-5) and depleted flows. Depleted flows reflect actual measurements of stream flows and re-

TABLE 3-1 Select Colorado River Gages

Station ID	Station Name	Period
9011000	Colorado River near Grand Lake, CO	1904-1986
9019500	Colorado River near Granby, CO	1908-present
9034500	Colorado River at Hot Sulphur Springs, CO	1904-1995

9058000	Colorado River near Kremmling, CO	1904-present
9070500	Colorado River near Dotsero, CO	1940-present
9072500	Colorado River at Glenwood Springs, CO	1899-1966
9085100	Colorado River below Glenwood Springs, CO	1966-present
9095500	Colorado River near Cameo, CO	1933-present
9106000	Colorado River near Palisade, CO	1902-1933
9153000	Colorado River near Fruita, CO	1911-1923
9163500	Colorado River near Colorado-Utah state line	1951-present
9180500	Colorado River near Cisco, UT	1913-present
9188500	Green River at Warren Bridge, near Daniel, WY	1931-present
9191000	Green River near Daniel, WY	1912-1932
9216500	Green River at Green River, WY	1895-1939
9217000	Green River near Green River, WY	1951-present
9315000	Green River at Green River, UT	1894-present
9335000	Colorado River at Hite, UT	1947-1958
9379500	San Juan River near Bluff, UT	1914-present
9379910	Colorado River below Glen Canyon Dam, AZ	1965-present
9380000	Colorado River at Lees Ferry, AZ	1921-present
9402500	Colorado River near Grand Canyon, AZ	1937-present
9421500	Colorado River below Hoover Dam, AZ-NV	1934-present
9423000	Colorado River below Davis Dam, NV-AZ	1905-1907, 1949-present
9424000	Colorado River near Topock, AZ	1917-1982
9429490	Colorado River above Imperial Dam, CA-AZ	1934-present
9429500	Colorado River below Imperial Dam, CA-AZ	1934-present
9521000	Colorado River at Yuma, AZ	1904-1965, 1983
9521100	Colorado River below Yuma Main Canal WW at Yuma, AZ	1963-present
9522000	Colorado River at NIB AB Morelos Dam near	1950-present

Andrade, CA

SOURCE: Harding (2006).

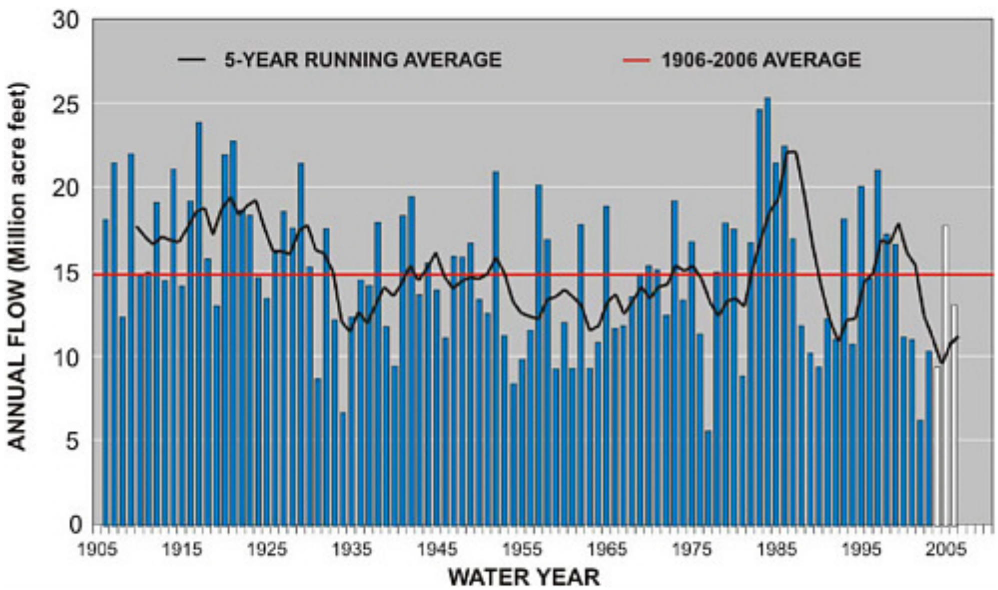

FIGURE 3-5 Natural Colorado River flows at Lees Ferry, AZ, 1906-2006.

NOTE: Black line is 5-year running average and is plotted at the end of 5-year interval. Water years are denoted by the ending year. White bars for 2004-2006 represent preliminary estimates.

SOURCE: Data for 1906-2003 from *http://www.usbr.gov/lc/region/g4000/NaturalFlow/index.html*. Values for 2004-2006 are preliminary estimates from J. Prairie, USBR, personal communication, 2006.

flect the actual amount of water flowing past a gage. These flows are typically depleted from their otherwise natural values as a result of upstream diversions (minus return flows), evaporative losses from reservoirs, bank seepage in reservoirs through porous rock, and other upstream depletions. These depletions can be substantial: for example, estimated annual average evaporation from Lake Powell is on the order of 0.5 million acre-feet, while at Lake Mead it is on the order of roughly 0.8 million acre-feet (USBR, 1977; 1981; 1991; 1998; 2002; 2004). Natural flows, by contrast, are estimates of flows that would have occurred without losses from upstream diversions, reservoir evaporation, and the like. Given the extent of human activity in most rivers across the western United States, records of "natural flows" across the West thus almost always represent estimates and not measured flow values.

The Colorado River, of course, has seen numerous upstream depletions and diversions. Water was diverted from the Colorado's headwaters as early as 1892 (Fradkin, 1984). These early depletions resulted in a roughly 10-15 percent reduction in the natural (undepleted) flow of the Colorado River at Lees Ferry up until 1963, when Lake Powell (which is impounded by Glen Canyon Dam) began filling (Ferrari, 1988). From 1963 through 2003, Lees Ferry flows are assumed to be approximately the sum of the flow volumes of the principal rivers—the Colorado, the Green, and the San Juan—that flow into Lake Powell. Thus, the record in Figure 3-5 represents estimated natural flows and it contains uncertainties related to inaccuracies both in measurements and in estimations of natural flows from various depletions.

Several noteworthy hydrologic periods are reflected in the Lees Ferry gage record. The time period used in Colorado River Compact negotiations—1905-1922—included some particularly wet years. This wet period had important ramifications for the Colorado River Compact and its water obligation and allocation agreements. The Compact framers were interested in the river's mean long-term flow. Data records for over two-thirds of the gages used in the negotiations did not begin until 1905 or later; several very low flow years prior to 1905 thus were not fully reflected at that time (Hundley, 1986). Transcripts of Colorado River Compact negotiations describe occasions when Colorado River Commission representatives expressed concern about potentially overly optimistic estimates of annual flow for the Colorado River, perhaps in recognition of some of the low flows prior to 1905 (*http://wwa.colorado.edu/resources/colorado_river/compact/*). A mean annual flow value for the period of record at Yuma, Arizona, 16.4 million acre-feet, was eventually accepted. As now documented in the gaged record, the 1905-1922 period contained the highest long-term annual flow volume in the 20th century, averaging 16.1 million acre-feet per year at Lees Ferry. Other important hydrologic periods reflected in the Lees Ferry record are drought conditions during the Dust Bowl period of the 1930s, drought in the 1950s and in the 1960s, a pronounced regional drought in 1976-1977, and El Niño conditions in 1983-1984.

When the Colorado River Compact was being negotiated, participants had only two to three decades of stream gage data, and only from a small number of stations. Over time, the Lees Ferry gaged record accumulated more and more years of flow data, and the

BOX 3-1
The Colorado River Stream Gaging Network

Over time the instrumental record of Colorado River flows has been augmented with other hydroclimate data and techniques, such as statistically based models for estimating streamflow. Nevertheless, the U.S. Geological Survey (USGS) system of streamflow gages across the Colorado River basin remains a fundamental component of reliable information on flows of the Colorado and its tributary streams. Despite the value of stream gage data—especially from gages that have been measuring streamflow at a given site for many decades—the level of support for these gages has not always been consistent and has seen periods of decline.

The USGS streamflow gaging network shrank from 1980 through the late 1990s because of constraints in funding from both the USGS and from its many partners who also provide resources for this network. In particular, from 1980 to 2000, the USGS stream gaging network lost about 1,790 stream gages that had at least 30 years of record (*http://water.usgs.gov/nsip/ 2007_budget.html*). Because of congressional concern, in 1999 the USGS developed the National Streamflow Information Program (NSIP), a plan to stabilize and modernize the network and provide a defined "backbone" of high-priority stream gages critical to public safety and long-term water resource assessment. The NSIP calls for federal investments in a core network of stream gages that meet national needs and to modernize and improve the reliability of the network. Congress provided significant new funding—approximately $9 million—to begin the implementation of NSIP in Fiscal Year 2001 (*http://water.usgs.gov/nsip/2007_budget.html*). This infusion of funding temporarily reversed the decline of the network and resulted in an additional ~500 stream gages. The loss of long-record gages declined from an average of about 100 per year in the 1990s to less than 30 in 2001. However, in 2004 and 2005 there were more losses of gages (a net loss of about 150 gages), and over 120 long-record stream gages were discontinued in 2004 (*http://water.usgs.gov/nsip/2007_budget.html*).

Although sophisticated techniques are being employed to help augment data gathered from stream flows, the network of gaging stations across the Colorado River basin (especially gages with long-term flow data) provides information that is crucial in describing trends and effects of land use changes, water use changes, and climate changes on the hydrologic system. It thus is important that this gaging network across the basin be maintained and, where possible, expanded.

network of gaging stations also expanded. (That network has not expanded continuously, however, and efforts to add new gaging stations have faced budgetary and other challenges. Box 3-1 discusses the maintenance and value of the USGS streamgaging network.) From the vantage point of the early

21st century, there is now a greater appreciation that the roughly 100 years of flow data within the Lees Ferry gage record represents a relatively small window of time of a system that is known to fluctuate considerably on scales of decades and centuries.

An important question that accompanies the use (exclusively) of the gaged record for river basin planning decisions is how representative the past record is of expected future conditions. To examine the issue of how well the historic, gaged record represents longer-term flow patterns, scientists employ proxy methods. As explained earlier in this report, these proxy data act as stand-ins for instrumental data but cover much longer time spans. As it happens, trees are sensitive to the same climatic elements that cause streamflow to fluctuate, and they live long enough to retain this history within their annual growth rings, in both living and dead trees. The arid climates of the south-western United States and intermountain Rockies fortunately preserve evidence of past precipitation extraordinarily well. The following section discusses the science of dendrochronology and how this field is used to reconstruct past, long-term Colorado River flows.

TREE-RING SCIENCE AND RECONSTRUCTED STREAMFLOW RECORDS

Records of streamflow measured by gages are limited to little more than the last 100 years. Natural recorders of hydrologic conditions can be used to extend estimates of streamflow back in time to lengthen gaged records and provide a longer context for assessing flow characteristics of the 20th and early 21st centuries. Tree rings are the best source of high-resolution, precisely dated proxy records of hydroclimatology over the past several centuries and they have proven useful for reconstructing a range of hydroclimatic variables, including temperature, precipitation, and streamflow (Woodhouse and Meko, 2007). Although the record of past hydroclimatic variability may not be replicated in the future, the extended records are useful for

documenting a broader range of natural variability than provided by the gaged record alone. This section reviews basic concepts underlying tree-ring-based streamflow reconstructions and the uncertainties inherent in them. It includes a comparison of reconstructions of upper Colorado River basin streamflow and discusses the features of the most recent Lees Ferry reconstructions, along with implications for sub-basin flow relationships.

Scientific Basis of Streamflow Reconstructions

Tree-ring reconstructions of past hydrologic conditions are based on the principles of dendrochronology, the science and study of dated tree rings (Fritts, 1976). Dendrochronology allows the dating of tree rings to the exact year of formation by matching ring-width patterns from tree to tree using a technique known as cross dating. This precise dating is critical because annual increments of tree growth are directly calibrated with annual measurement of hydroclimatic variability in the streamflow reconstruction process. Cross dating is possible because trees that are limited in growth primarily by climate will share a similar pattern of ring-width variations with other trees across a climatically homogeneous region.

In the Colorado River basin, coniferous tree species growing at lower elevation and, in particular, stands of trees on well-drained slopes with southern exposures have been shown to be well suited for reconstructions of annual streamflow (Hidalgo et al., 2000; Meko and Graybill, 1995; Michaelsen et al., 1990; Schulman, 1956; Smith and Stockton, 1981; Stockton, 1975; Stockton and Jacoby, 1976; Woodhouse and Lukas, 2006; Woodhouse et al., 2006). These coniferous species include ponderosa pine (*Pinus ponderosa*), pinyon pine (*Pinus edulis*), and Douglas fir (*Pseudotsuga menziesii*). A typical life span for trees within these three species is 300-500 years, and some individuals can live to be over 800 years old. Annual tree growth at these moisture-stressed sites appears to depend on soil moisture in the early part of the growing season (Meko et al., 1995). Climatic conditions that affect spring and early summer soil moisture include antecedent moisture conditions in the prior late summer and fall, and winter snowpack. This set of conditions is also important for surface water flows. Annual (water year) streamflow thus is often highly correlated with the annual tree growth of these moisture-sensitive species (see Meko et al. [1995] and Meko [2005] for more detailed discussions on methods for assessing relationships between annual tree-ring growth and streamflow).

To generate streamflow reconstructions, trees are sampled with an increment borer at collection sites based on the factors described above that affect tree ring growth. Sample replication at individual sites is important, and two cores are collected from each of 15-40 different trees per site. Cores from each site are cross-dated, measured, standardized (e.g., the size/age trend is removed), and combined into tree-ring site chronologies (Cook and Kairiukstis, 1990; Stokes and Smiley, 1968), which are the basis of a streamflow reconstruction. Tree-ring chronologies are calibrated with gage data to develop a reconstruction model. Several statistical approaches, typically based on multiple linear regression, have been employed to develop these models (Loaciga et al. [1993] provide a review of these approaches).

Reconstruction models are evaluated with a suite of statistics that quantifies the variance explained in the gaged record by the reconstruction, and the uncertainty related to the unexplained variance. Reconstructions are validated by testing the model on data not used in the calibration, to ensure that the model is not tuned specifically to the calibration data, but performs well on independent data as well (Cook and Kairiukstis, 1990; Fritts, 1976; Loaciga et al., 1993). The model is applied to the full length of the chronologies to generate an extended record of flow. In applying these models back in time, the assumption is made that the relationship between tree growth and climate in the calibration period also existed in the past, while recognizing that conditions of the past were not necessarily the same as in the instrumental period (Fritts, 1976).

Uncertainties in Streamflow Reconstructions

Considering that reconstructions are only estimates of flow, uncertainties in these reconstructions derive from several different sources. The fact that trees are imperfect recorders of hydrologic variability is an inherent source of uncertainty and is reflected in the inability of tree ring-based models to account for 100 percent of the variance in the gaged record (e.g., Brockway and Bradley, 1995). This also makes a direct comparison between reconstructed and gaged values inappropriate unless this uncertainty is considered. The preci-

sion with which tree-growth rings can be used to estimate past flows is quantified by the statistical model generated in the calibration, and a measure of the error in the reconstruction model can be used to describe model confidence intervals. However, this is only one source of uncertainty. Other sources include changes in tree-ring sample numbers over time, which affects the strength of the common (hydroclimatic) signal in the reconstruction (Cook and Kairuikstis, 1990; Wigley et al., 1984). Uncertainties can also derive from the preservation of low-frequency (multidecadal to centennial scale) information in the tree-ring data, which is limited by the lengths of the individual tree-ring series and how these series were standardized to remove the biological growth curve (Cook et al., 1995). There is also some degree of uncertainty because of the quality of the gage record used for the calibration and how that may vary over time. In addition, most reconstructions better replicate dry extremes than wet extremes (Michaelsen, 1987). Reconstructed flows that are higher or lower than the range of values in the gage record often reflect tree-ring variations beyond the range of variations in the calibration period, and may be less reliable than indicated by regression results (Graumlich and Brubaker, 1986; Meko and Graybill, 1995; Meko et al., 1995).

Dendrochronologists have long acknowledged and reported the model error in reconstructions, although error bars have not typically been presented with reconstructions, which would reinforce the probabilistic nature of the reconstruction values. A variety of techniques are used, with some currently under development, to identify and quantify other sources of uncertainty

(Meko et al., 2001; Woodhouse and Meko, 2007). An approach to systematically quantify the amount of error attributed to each of these sources, however, has not yet been developed.

Reconstructions of Colorado River Flows at Lees Ferry, Arizona

As methods for tree-ring-based reconstructions have evolved, the set of streamflow data from the Lees Ferry gage has been a focus of reconstruction studies. Several reconstructions for Lees Ferry flow have been generated, first by Stockton and Jacoby (1976), followed by Michaelsen et al. (1990), Hidalgo et al. (2000), and Woodhouse et al. (2006). Stockton and Jacoby (1976), Michaelsen et al. (1990), and

Hidalgo et al. (2000) used similar networks of tree-ring data, with at least 30 percent of the chronologies shared and with a common end date of 1963. Woodhouse et al. (2006) used a new network of tree-ring data, ending in 1995. All four studies used different gage data for calibration, and Stockton and Jacoby (1976) used two different sources of gage data, illustrating the difference the gage records can make in the final reconstruction. The number of years for calibration also varied from 49 to 90 years. The reconstructions also included some differences in the statistical treatment of the tree-ring data and statistical approaches to the calibration (see Table 3-2).

The resulting reconstructions differ in some respects. Given that these studies employed different data sets, assumptions, and methods, some differences across results are to be expected. All these reconstructions, however, share similar key features with respect to the timing and duration of major wet and dry periods. These reconstructions, as depicted in Table 3-2 and shown in Figure 3-6, support the following points:

1. Long-term Colorado River mean flows calculated over these periods of hundreds of years are significantly lower than both the mean of the Lees Ferry gage record upon which the Colorado River Compact was

based and the full 20th century gage record (Woodhouse et al., 2006).
2. High flow conditions in the early decades of the 20th century were one of the wettest in the entire reconstruction.
3. The longer reconstructed record provides a richer basis from which to assess the range of drought characteristics that have been experienced in the past, revealing that considerably longer droughts have occurred prior to the 20th century.

These three points have important implications for water management decisions for the Colorado River basin and are revisited in the Commentary section at the end of this chapter.

TABLE 3-2 Lees Ferry Reconstructions

Reconstruction	Calibration Years	Source of Gage Data	Chronology Type [c]	Regression Approach [d]	Variance Explained	Reconstruction Years	Long-Term Mean [e] (MAF)
Stockton and Jacoby (1976)	a. 1899-1961 b. 1914-1961 c. 1914-1961 Average of a and b	Hely (1969) Hely (1969) UCRSFIG (1971)	Standard Standard Standard	PCA with lagged predictors	0.75 0.78 0.87	1512-1961 1512-1961 1511-1961 1520-1961	14.15 13.9 13.0 13.4
Michaelsen et al. (1990)	1906-1962	Simulated flows[a]	Residual	Best subsets	0.83	1568-1962	13.8
Hidalgo et al. (2000)	1914-1962	USBR, see Hidlago et al. (2000)	Standard	Alt. PCA with lagged predictors	0.82	1493-1962	13.0
Woodhouse et al. (2006)		USBR[b]					
Lees-A	1906-		Residual	Stepwise	0.81	1490-1997	14.7

Lees-B	1995	Standard	Stepwise	0.84	1490-1998	14.5
Lees-C	1906-	Residual	PCA	0.72	1490-1997	14.6
Lees-D	1995	Standard	PCA	0.77	1490-1998	14.1
	1906-					
	1995					
	1906-					
	1995					

[a] Simulated flows developed from the U. S. Bureau of Reclamation (USBR) Colorado River Simulation System.

[b] J. Prairie, USBR, personal communication, 2004.

[c] Standard chronologies contain low-order autocorrelation related to biological persistence; residual chronologies contain no low order autocorrelation.

[d] Regression approach: PCA is principal components analysis (regression). Best subsets is multiple linear regression, using Mallow's Cp to select best subset. Alternative PCA used an algorithm find the best subset of predictors on which to perform PCA for regression. Stepwise is forward stepwise regression.

[e] Long-term mean based on 1568-1961 except for Michaelsen et al. (1990), which is based on 1568-1962.

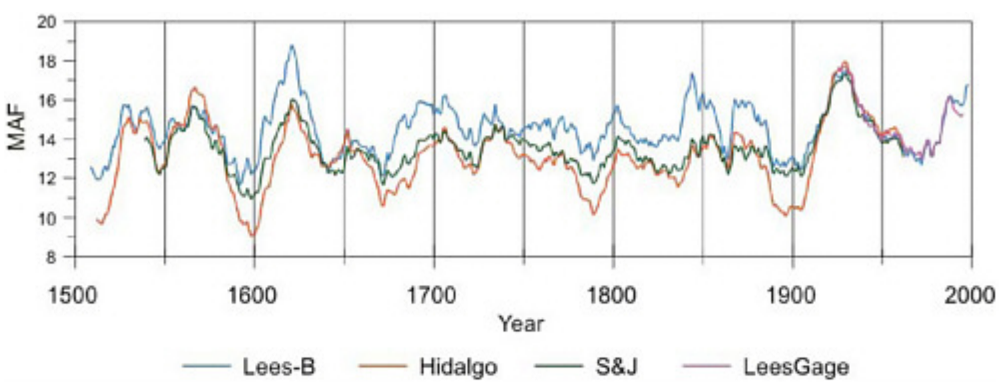

FIGURE 3-6 Colorado River annual streamflow reconstructions, Lees Ferry, AZ (smoothed with a 20-year running mean). NOTE: Year plotted is the last year in the 20-year mean. SOURCE: Lees-B (standard chronologies, stepwise regression) from Woodhouse et al. (2006); Hidalgo et al. (2000); S&J from Stockton and Jacoby (1976; average of two models); Lees Gage is gage record, 1906-1995, J. Prairie, USBR, personal communi-

cation, 2004.

Differences among the Reconstructions

The most obvious difference among the reconstructions is the long-term mean, a measure with implications for long-term water allocation decisions. The reconstructions based on the calibration periods that end in 1961 or 1962 generally have lower long-term means than more recent reconstructions with a calibration period that ends in 1995 (Table 3-2). A second noticeable difference is the magnitude of the high and low flow periods, which vary between all reconstructions to some degree.

Some differences in the Lees Ferry reconstructions may be attributed to the tree-ring and gage data, including the length of the calibration period. Differences may also result from choices made in statistical methods when processing tree-ring data, which can affect the characteristics of the chronology and, in turn, affect the reconstruction (see Meko et al. [1995] and Woodhouse and Meko [2007] for details on the treatment of tree-ring data). In the Lees Ferry reconstructions, Stockton and Jacoby (1976) and Hidalgo et al. (2000) used chronologies that retained the biological persistence (standard chronologies), which is the tendency for a tree's growth in one year to be associated with growth in a following year due to biological processes. In contrast, Michaelsen et al. (1990) used chronologies in which this biological persistence was statistically removed. Woodhouse et al. (2006) tested models using both types of chronologies. Different results may also arise from the statistical approach used in the calibration process and can stem from the inclusion of "lagged predictors" (tree-ring chronologies lagged forward and backward several years relative to the gage record) and details of regression methods used (see Woodhouse et al. [2006] for more information on statistical methods used in dendrochronology research).

The sensitivity of the resulting reconstructions to some of these statistical treatments and approaches has been tested for Lees Ferry (Woodhouse et al., 2006). Results from this study indicate that different types of chronologies (standard versus residual) can have an influence on the skill of the reconstruction in replicating some of the time-series characteristics of the gage record, and persistence of low flows may be heightened with standard chronologies (Woodhouse et al., 2006). The use of different modeling approaches in model calibration was not an obvious source of differences. In addition, the length of the calibration period did not appear to be critical, as calibrating a model on a shorter time period (1914-1961 versus 19061995) resulted in a similar reconstruction (Woodhouse et al., 2006).

In summary, differences among Lees Ferry reconstructions can likely be attributed to several factors. There are some indications that periods of persistent low flows may be accentuated using standard chronologies and/or lagged predictors, but the sources of the differences in long-term mean are not yet clear. Additional studies will be needed to more accurately assess the impact of the different sets of chronologies and gage records on the final reconstructions. As to which reconstruction might be the most accurate or "best," reconstructions with the longest calibration period are statistically more robust (i.e., exhibiting similar results when tested with different models), particularly considering that the recently recalibrated gage record from 1906-1995 is assumed to be the most accurately estimated natural flow data. Within the set of reconstructions calibrated on the longest period, however, there is no clearly superior solution, with each reconstruction containing strengths and weaknesses (e.g., match in persistence in the gage record, over/underestimation of decadal-scale low flows; Woodhouse et al., 2006).

Analyzing Reconstructed Colorado River Flow

The extended record of streamflow provided by the tree-ring reconstructions is useful for assessing the characteristics of the gage record in a long-term context and for examining low-frequency (multidecadal-scale) behavior of flow, which is not possible with the shorter gage record. Questions relevant to drought and management in the upper Colorado River basin that can be addressed are:

1. How does the drought of the early 2000s compare to other past droughts of similar duration?
2. Have longer periods of drought occurred? and
3. What is the character of decadal-scale variability over time compared to the 20th century?

When early 2000 drought conditions are assessed as a 5-year (2000-2004) mean value, the reconstruction indicates one period—1844-1848—with a lower mean value, but several additional periods with a fairly high probability of being lower as well (Woodhouse et al., 2006). The Lees Ferry gage record contains no periods of below median flow that lasted more than 5 consecutive years. In the Lees Ferry tree-ring-based reconstruction, however, longer periods of below-median flow have occurred, including periods of up to 10 and 11 years. The reconstruction also reflects the nonstationarity—or changes in the values of decadal-scale means—of flow over decadal time scales (Figure 3-6).

Colorado River Sub-Basin Relationships and Circulation

In addition to the record of upper Colorado River flow at Lees Ferry, reconstructions can provide information about long-term hydroclimatic variability within Colorado River sub-basins. Along with Lees Ferry, flow records at gages on major tributaries of the upper Colorado River—the Green River, the San Juan River, and Colorado River mainstem (i.e., before it joins the Green and San Juan rivers, which was historically known as the Grand River)—have been reconstructed (Woodhouse et al., 2006). A comparison of reconstructions for these tributaries suggests that major multiyear droughts and multidecadal dry periods impact the entire basin, although the relative

magnitude may vary spatially. Similarly, research that examined reconstructions of several tributaries of the lower Colorado River basin in Arizona—in the Salt and Verde River basins—found droughts (and wet events) in the upper Colorado and Salt-Verde River basins to be concurrent more often than not (Hirschboeck and Meko, 2005). Details of the primary mechanisms that influence upper Colorado River basin climate and hydrology at multidecadal time scales are not yet clear. Studies of extended periods of streamflow, however, considered along with other high-resolution climate reconstructions, have the potential to increase scientific understanding of the links between ocean/atmosphere circulation and Colorado River basin water supply.

COMMENTARY

A steady warming trend of about 2°F has been under way over the past three decades across the Colorado River basin. Results from several different climate modeling experiments indicate that future temperatures will continue to rise across the Colorado River basin. Projections of annual precipitation changes from these same models exhibit a range of results, most of them approximately centering around present values. The models project a tendency for increases in winter precipitation of about the same magnitude as decreases in summer precipitation. Higher temperatures will cause higher evaporative losses from snowpack, surface reservoirs, irrigated land, and land cover surfaces across the river basin. Hydrologic modeling studies of future Colorado River runoff exhibit a variety of results, and such forecasts always reflect some degree of uncertainty. Collectively, however, these studies indicate that future Colorado River streamflow will decrease with increasing future temperatures.

The 20th century saw a trend of increasing mean temperatures across the Colorado River basin that has continued into the early 21st century. There is no evidence that this warming trend will dissipate in the coming decades; many different climate model projections point to a warmer future for the Colorado River region.

Modeling results show less consensus regarding future trends in precipitation. Several hydroclimatic studies project that significant decreases in runoff and streamflow will accompany increasing temperatures. Other studies, however, suggest increas-

ing future flows, highlighting the uncertainty attached to future runoff and streamflow projections. Based on analysis of many recent climate model simulations, the preponderance of scientific evidence suggests that warmer future temperatures will reduce future Colorado River streamflow and water supplies. Reduced streamflow would also contribute to increasing severity, frequency, and duration of future droughts.

In the context of multidecadal and multicentury hydroclimatic patterns across the Colorado River region, the Lees Ferry gaged record represents a chronologically limited sliver of information. Paleoclimate-based reconstructions of Colorado River streamflow have become of great interest to water managers across the region because, instead of 100 years of Colorado River flows, the reconstructions provide estimates of hundreds of years of flows. The first tree-ring-based reconstruction was developed in the 1970s and has been followed by several other studies using similar tree-ring data. Although the various reconstructions are not perfectly congruent, this is not unexpected given that the reconstructions were independently developed by scientists using different data sets and relying upon differing assumptions and statistical methods. Nonetheless, the reconstructions exhibit broad agreement in several important respects: they replicate similar past wet and dry periods; they suggest that the Colorado River's long-term mean annual flow is less—ranging from 13 to 14.7 million acre-feet—than 15 million acre-feet (the mean annual value based on the Lees Ferry gaged record); they show that the 1905-1920 period was one of the wettest periods in the past several centuries; and, they indicate multiple drought periods that were more persistent and severe than droughts reflected in the gaged record. Past climates may not necessarily be replicated in the future but reconstructions of past flows provide information that, when used in concert with projections of future climate, can offer valuable guidance to aid future water resources planning.

Although much remains to be learned about the drivers of hydroclimatic variability in the basin—particularly those that operate at multidecadal and longer time scales—the scientific foundation underlying contemporary understanding of Colorado River streamflow patterns has evolved markedly during the past 50 years. Whereas in the mid-1950s that foundation relied almost solely upon gaged flow records, today it consists of a more sophisticated understanding and modeling of the global climate system, better temperature data from

the Colorado River region and across the world, paleoclimate studies and streamflow reconstructions, and a longer record of gaged river flows. Assessed collectively, this body of knowledge invalidates any assumption that Colorado River flows vary around an annual mean value that is static and unchanging.

For many years, scientific understanding of Colorado River flows was based primarily on gaged streamflow records that covered several decades. Recent studies based on tree-ring data, covering hundreds of years, have transformed the paradigm governing understanding of the river's long-term behavior and mean flows. These studies affirm year-to-year variations in the gaged records. They also demonstrate that the river's mean annual flow—over multidecadal and centennial time scales, as shown in multiple and independent reconstructions of Colorado River flows—is itself subject to fluctuations. Given both natural and human-induced climate changes, fluctuations in Colorado River mean flows over long-range time scales are likely to continue into the future. The paleoclimate record reveals several past periods in which Colorado River flows were considerably lower than flows reflected in the Lees Ferry gaged record, and that were considerably lower than flows assumed in the 1922 Colorado River Compact allocations.

Multicentury, tree-ring-based reconstructions of Colorado River flow indicate that extended drought episodes are a recurrent and integral feature of the basin's climate. Moreover, the range of natural variability present in the streamflow reconstructions reveals greater hydrologic variability than that reflected in the gaged record, particularly with regard to drought. These reconstructions, along with temperature trends and projections for the region, suggest that future droughts will recur and that they may exceed the severity of droughts of historical experience, such as

the drought of the late 1990s and early 2000s.

Data from the gaging station at Lees Ferry, Arizona, represent the best-known Colorado River measured flow record. As flow data accumulated over time at Lees Ferry, it became clear that 1905-1920—the period upon which Colorado River allocations were ascribed—was significantly wetter than average. It has also become evident that the river's average annual flow is considerably less than the approximately 16.4 million acre-feet figure used by Colorado River Compact negotiators. For many years the 20th century gage record of Colorado River flows represented the best understanding of the river's year-to-year hydrologic variability. Despite the value of data from these gage records—especially from sites that have accumulated data for several decades—support for the USGS system of stream gages has not always been steady and has seen some past periods of decline. Today, science-based knowledge of the river's flows and the basin's climate systems has become more sophisticated. Nevertheless, the gage record of river flows will remain an important source of information for scientists and water resources planners.

Measured values of streamflow of the Colorado River and its tributaries provide essential information for sound water management decisions. Loss of continuity in this gaged record would greatly diminish the overall value of the existing flow data set, and once such data are lost they cannot be regained. The executive and legislative branches of the U.S. federal government should cooperate to ensure that resources are available for the USGS to maintain the Colorado River basin gaging system and, where possible, expand it.

The National Academies of Sciences, Engineering, and Medicine
500 Fifth St., NW | Washington, DC 20001