GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L22708, doi:10.1029/2007GL031764, 2007

Warming may create substantial water supply shortages in the Colorado River basin

Gregory J. McCabe[1] and David M. Wolock[2]

Received 21 August 2007; revised 19 October 2007; accepted 25 October 2007; published 27 November 2007.

[1] The high demand for water, the recent multiyear drought (1999–2007), and projections of global warming have raised questions about the long-term sustainability of water supply in the southwestern United States. In this study, the potential effects of specific levels of atmospheric warming on water-year streamflow in the Colorado River basin are evaluated using a water-balance model, and the results are analyzed within the context of a multi-century tree-ring reconstruction (1490–1998) of streamflow for the basin. The results indicate that if future warming occurs in the basin and is not accompanied by increased precipitation, then the basin is likely to experience periods of water supply shortages more severe than those inferred from the long-term historical tree-ring reconstruction. Furthermore, the modeling results suggest that future warming would increase the likelihood of failure to meet the water allocation requirements of the Colorado River Compact.

Citation: McCabe, G. J., and D. M. Wolock (2007), Warming may create substantial water supply shortages in the Colorado River basin, *Geophys. Res. Lett.*, *34*, L22708, doi:10.1029/2007GL031764.

1. Introduction

[2] The Upper Colorado River basin (UCRB), defined as that part of the basin that is upstream from the streamgage at Lees Ferry, Arizona (Figure 1), generates approximately 90 percent (%) of the total flow of the Colorado River basin and, through the Colorado River Compact of 1922, supplies water and hydropower for much of the southwestern United States (U.S.). The two main reservoirs in the Colorado River basin, Lake Powell (in the upper basin) and Lake Mead (in the lower basin), account for about 85% of the storage capacity of the entire Colorado River basin.

[3] The balance between water supply and demand in the Colorado River basin has become precarious in recent years. The supply of water depends on the allocations prescribed in the Colorado River Compact, the capacity of the basin reservoirs, and the natural flows that supply the reservoirs. The allocations, which were set in 1922, were based on what turned out to be an unusually wet period compared to the remainder of the twentieth (20th) century [*Christensen et al.*, 2004]. Clearly, natural flow variability led to the 1922 allocations being set at high levels that may be difficult to sustain. On the demand side of the equation, population and the accompanying requirements for water have increased substantially since the Compact was written [*Diaz and Anderson*, 1995].

[4] The long-term sustainability of the water-supply system in the Colorado River basin will be affected by the future levels of natural flows that replenish the reservoirs. One approach to defining future expectations of flow is to "reconstruct" historical long-term flow estimates from tree rings [*Woodhouse et al.*, 2006]. This long-term historical context provides an indication of flow conditions that have occurred in the past and may occur in the future. A contrasting approach to predicting future flow conditions in the Colorado River basin is based on climate model simulations. *Christensen and Lettenmaier* [2006], for example, report 8% to 11% reductions in UCRB runoff by the end of the 21st century.

[5] The objective of this study is to evaluate the sensitivity of UCRB water supply to global warming by using a combination of historical flow reconstructions and climate model simulation approaches. In this study, the estimated effects of future global warming on flow and water supply in the UCRB are placed within the context of the long-term reconstructed tree-ring flow record. Also, the effects of global warming are superimposed on the reconstructed flows to get as broad of an assessment as possible of potential future conditions. The study focuses on climate-driven flow and does not address the additional influence of changes in water demand.

2. Methods

[6] Upper Colorado River basin water-year (October through September) natural flow values for the period 1906 through 2004 were obtained from the U.S. Bureau of Reclamation (http://www.usbr.gov/lc/region/g4000/NaturalFlow/current.html). Monthly temperature and precipitation data for the period 1895 through 2004 were obtained from the Precipitation-elevation Regression on Independent Slopes Model (PRISM) dataset (http:www.ocs.orst.edu/prism/). The climate data are provided on a 4-kilometer (km) by 4-km grid and, in this study, were aggregated for each of the 62 U.S. Geological Survey hydrologic cataloging units (HUC8) in the UCRB (Figure 1). Temperature and precipitation data for these units were used as inputs to a monthly time-step water-balance model, which was used to estimate monthly streamflow. Monthly streamflow estimates for all 62 HUC8s were summed by water year (October through September) and aggregated over space to provide a time series of water-year UCRB streamflow.

[7] The water-balance model uses an accounting procedure to partition water among various components of the hydrologic system [*Wolock and McCabe*, 1999]. Inputs to the model for each hydrologic cataloging unit are monthly

---

[1] U.S. Geological Survey, Denver, Colorado, USA.
[2] U.S. Geological Survey, Lawrence, Kansas, USA.

Published in 2007 by the American Geophysical Union.

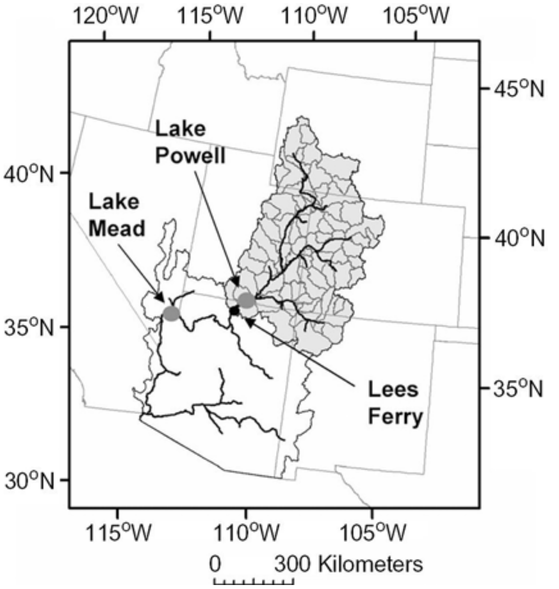

Figure 1. The Upper Colorado River basin (UCRB) is outlined and shaded gray. Hydrologic Unit Code (HUC) 8 regions are shown inside the UCRB outline. The main stem and primary tributaries of the Colorado River are shown in black. The Lower Colorado River basin is outlined, but not shaded.

temperature and precipitation. The water-balance model was calibrated by adjusting several model parameters in order to optimize the agreement between estimated and measured flow for the period 1906–2004. The correlation between time series of measured and post-calibration estimated water-year streamflow for the UCRB is 0.93 ($p < 0.01$). The goodness-of-fit between the water-balance model and measured flow data is indicated by several statistics: the root-mean-squared error equals 14.1% of the mean-annual measured flow; the average bias (estimated – measured) equals 0.7% of the mean-annual measured flow; and the Nash-Sutcliffe statistic [*Nash and Sutcliffe*, 1970] equals 0.76. These goodness-of-fit statistics indicate that the water-balance model reasonably estimates natural streamflow for the UCRB.

[8] The sensitivity of UCRB streamflow to specified changes in temperature is evaluated in this study; only changes in temperature are evaluated because future changes in precipitation are highly uncertain [*Wolock and McCabe*, 1999; *Intergovernmental Panel on Climate Change*, 2007]. Two warming scenarios are used in the study: (1) 0.86 degrees Celsius (°C) (T + 0.86°C), which is the measured trend in UCRB annual temperature during the 20th century, and (2) 2°C (T + 2°C), which represents a warmer scenario that is still within the range projected by climate models [*Christensen et al.*, 2004; *Hoerling and Eischeid*, 2007; *Christensen and Lettenmaier*, 2006]. Each of the warming scenarios was applied as a uniform change in temperature.

[9] In addition to the measured and water-balance estimated values of UCRB water-year flow, a time series of UCRB water-year flow (1490–1998) reconstructed from tree-rings [*Woodhouse et al.*, 2006] was used to provide a reference for long-term streamflow variability in the UCRB. The long-term reconstructed streamflow dataset gives a context for comparison with 20th century streamflow as well as with the estimated effects of warming scenarios.

[10] The effects of the warming scenarios (0.86 and 2°C) on UCRB streamflow were evaluated in two ways. The first approach was to directly apply the warming scenarios to 20th century climate data. The monthly temperature data for the period 1901–2000 were raised uniformly (not ramped) by the specified changes in temperature, and the water-balance model was run with the modified climate inputs.

[11] The second approach was to apply the warming scenarios to the driest century of reconstructed streamflow in the tree-ring record. This can be viewed as a worst-case scenario, in which a "naturally" very dry period is modified consistent with the 0.86 and 2°C warming scenarios. It is not possible to directly apply the warming scenarios to tree-ring reconstructed climate data because such climate data for the UCRB do not exist. Instead, the reconstructed streamflow values for the driest century in the tree-ring record (1573–1672) were adjusted by average percentage changes in estimated streamflow caused by the warming scenarios applied to 20th century data. For example, the 0.86°C warming scenario applied directly to 20th century climate caused an 8% decrease in streamflow (see next section), so the reconstructed streamflow values were decreased by 8% to represent a 0.86°C warming.

[12] A simple flow/surplus water-supply model was developed to examine the effects of specified changes in temperature on the likelihood of UCRB flow to meet the minimum flow requirements of the Colorado Compact. The flow/surplus water-supply model uses water-year UCRB flow as input, and a critical threshold (17866 mcm) of annual flow. This critical value was developed from a mass balance analysis of the inflows and depletions (evaporation and consumptive use) of both the Upper and Lower Colorado basins (Eric Kuhn, Colorado Water Conservation District, personal communication, 2005). If naturalized UCRB water-year flow is greater than this specified threshold, then the critical flow value is met; flow in excess of the critical flow value is accumulated as surplus water that can be used in subsequent years to augment water-year UCRB flow. The surplus is permitted to accumulate to a total of 41938 million cubic meters (mcm), which is the current reservoir capacity of the UCRB; surplus in excess of this reservoir capacity passes through the river system as excess streamflow. When naturalized water-year UCRB flow is less than the critical flow value, water is extracted from the accumulated surplus (i.e., from the reservoirs) to reach the critical flow value. If available accumulated surplus is not sufficient to reach the critical threshold, then the critical threshold is not met and the system has failed. This accounting-type model permits a simple examination of the effects of specified climate changes on the likelihood of meeting, or failing to meet, the minimum flow requirements of the Colorado Compact. For each simulation, the initial reservoir storage was set to 41938 mcm.

[13] The flow/surplus water-supply model was evaluated by comparing estimated storage in Lake Powell with measured storage data obtained from the U.S. Bureau of Reclamation (http://www.usbr.gov/uc/crsp/GetSiteInfo). The period 1985 to 2000 was chosen for the comparison

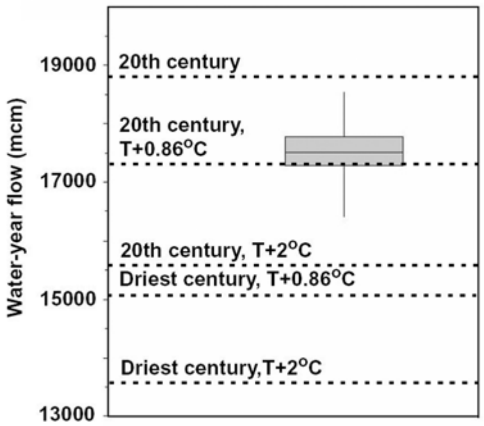

Figure 2. Boxplot of mean water-year flow (in millions of cubic meters (mcm)) for the Upper Colorado River basin (UCRB) for 100-year moving periods during 1490–1998 (determined using tree-ring reconstructed water-year flows). Also indicated are mean water-year UCRB flows for the 20th century (1901–2000, based on water-balance estimates), 0.86 degrees Celsius (°C) and 2°C warmings (labeled as T + 0.86°C and T + 2°C respectively) applied to the 20th century water-balance estimates, and 0.86°C and 2°C warmings applied to the driest century (1573–1672) from the tree-ring reconstructed flow time series.

because Lake Powell did not finish filling until the early 1980s. The estimated storage values for the entire UCRB were multiplied by 0.79 to approximate Lake Powell storage. (Storage in Lake Powell represents approximately 79% of the total reservoir storage capacity of the UCRB.) The correlation between the estimated and measured storage values is 0.93, the bias is 7.8% of the mean measured storage and the root-mean-squared error is 16.8% of mean measured storage. Despite the simplicity of the flow/surplus model and the simple adjustment of the UCRB total storage estimates to represent Lake Powell storage, the agreement between the measured and estimated storage values is reasonable.

3. Results and Discussion

[14] The reconstructed tree-ring streamflow values were aggregated with a 100-year moving average to generate a frequency distribution of 100-year average water-year flow values for the period 1490–1998 (Figure 2). This distribution of 100-year average values is represented in the box plot, where the box is bounded by the lower (25th percentile) and upper quartile (75th percentile) values, the line through the box indicates the median (50th percentile) value, and the vertical lines extending out from the box terminate at the minimum and maximum values. The minimum 100-year average value (the driest century: 1573–1672) was 16406 mcm and the maximum 100-year average value (the wettest century: 1899–1998) was 18541 mcm. The lower quartile, median, and upper quartile values were 17283, 17503, and 17777 mcm, respectively.

[15] The 20th century (1901–2000) average water-year flow estimated by the water-balance model was 18799 mcm. (The 20th century average flow is shown in Figure 2 as a horizontal dashed line.) This value is slightly higher than the maximum 100-year period in the tree-ring reconstruction (18541 mcm: 1899–1998). This difference in the average flow values reflects the small bias between the tree-ring record and the water-balance estimates for this mostly overlapping period.

[16] When the 20th century temperature record is uniformly increased by 0.86°C, the mean water-year flow estimated by the water-balance model is reduced to 17291 mcm, a reduction of 8% (Figure 2). The horizontal dashed line in Figure 2, indicating the T + 0.86°C mean water-year flow, coincides with the lower quartile line of the tree-ring reconstruction distribution. In other words, within the context of the 500-year tree-ring reconstruction, a uniform increase of 0.86°C changes the 20th century water-year average from the wettest in the tree-ring record to the lower quartile value.

[17] A 2° C warming imposed on the 20th century temperature record reduced the water-balance model estimates from 18799 to 15627 mcm, a reduction of 17% (Figure 2). Relative to the distribution of 100-year average flow values based on the tree-ring reconstruction, the T + 2°C scenario caused the average water-year flow to decrease to an unprecedented level. This result is consistent with the findings of *Christensen et al.* [2004], who reported a 17% decrease in UCRB flow for a 2.4°C warming combined with a 3% decrease in precipitation. In a more recent study, *Christensen and Lettenmaier* [2006] applied changes in temperature and precipitation from 11 climate models and reported 8% to 11% decreases in UCRB runoff by the end

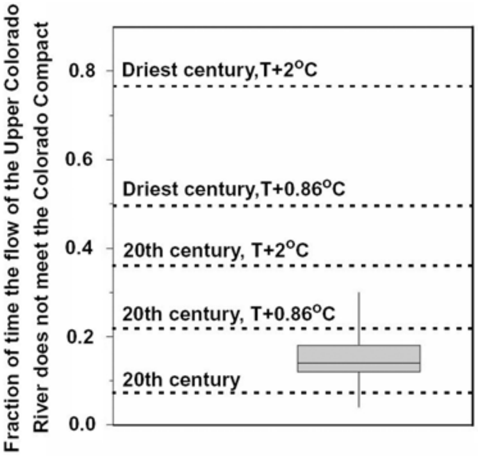

Figure 3. Boxplot of the fraction of time the water-year flow of the Upper Colorado River basin does not meet the flow requirements of the Colorado Compact for 100-year moving periods during 1490–1998 (determined using a simple reservoir model and tree-ring reconstructed water-year flows). Also indicated is the fraction of time the UCRB water-year flow does not meet the Colorado Compact for the 20th century (1901–2000, based on water-balance estimates), 0.86 degrees Celsius (°C) and 2°C warmings (labeled as T + 0.86°C and T + 2°C respectively) applied to the 20th century water-balance estimates, and 0.86°C and 2°C warmings applied to the driest century (1573–1672) from the tree-ring reconstructed flow time series.

Table 1. Fraction of the Time the Water-Year Flow of the Upper Colorado River Basin Fails to Meet the Flow Requirements of the Colorado Compact for Various Climate Scenarios and for Current and Unlimited Reservoir Storage Capacity

Scenario	Current Reservoir Storage	Unlimited Reservoir Storage
20th century	0.07	0.00
20th century, T + 0.86°C	0.22	0.15
20th century, T + 2°C	0.37	0.37
Driest century	0.30	0.12
Driest century, T + 0.86°C	0.50	0.49
Driest century, T + 2°C	0.77	0.77

of the 21st century. *Hoerling and Eischeid* [2007] examined 42 climate simulations for the UCRB and reported average decreases in UCRB flow of 25% by 2030, and 45% by 2060.

[18] The two levels of warming also were applied to the driest century (1573–1672). For these scenarios, the average percentage changes in streamflow, based on the 20th century results, were applied to the water-year flows for the period 1573–1672. An 8% reduction in flow was used to approximate the 0.86°C increase in temperature and a 17% decrease in flow represented the effects of a 2°C warming. When the 0.86°C warming (8% reduction in flow) was applied to the driest century, mean water-year flow decreased to 15094 mcm (Figure 2). The 2°C warming (17% reduction in flow) caused the driest century mean water-year flow to be reduced to 13617 mcm. These average streamflow levels are much lower than any 100-year average flow values in the tree-ring reconstructed record.

[19] The flow/surplus water-supply model was used to estimate the fraction of time the flow of the UCRB fails to meet the Colorado Compact (the failure rate). Using moving 100-year periods of tree-ring reconstructed water-year flow, a frequency distribution of failure rate was computed for the period 1490–1998 (Figure 3). The minimum, lower quartile, median, upper quartile, and maximum failure rate values were 0.04, 0.12, 0.14, 0.18, and 0.30, respectively. Notably, the 100-year period with the highest failure rate did not correspond with the 100-year period with the lowest mean-annual flow. The specific temporal sequence of flows has a substantial effect on the failure rate [*Jain et al.*, 2002]. For example, 20 consecutive dry years followed by 20 consecutive wet years would have a higher failure rate than 40 consecutive moderate years.

[20] When the 20th century temperature record was uniformly increased by 0.86°C, the failure rate increased to 0.22; this value is within the higher quartile of failure rates based on the tree-ring reconstructed record (Figure 3). A 2°C warming imposed on the 20th century temperature record increased the failure rate to 0.37, a level which exceeds any 100-year period in the reconstructed record. These failure rates for a 0.86°C and 2°C warming applied to the 20th century record are similar to the range of changes in failure rates reported by *Christensen et al.* [2004] and *Christensen and Lettenmaier* [2006] for future climate projections. Increases of 0.86°C and 2°C in temperature applied to the driest century resulted in failure rates of 0.50 and 0.77, respectively, which far exceed any 100-year period in the reconstructed record.

[21] Reservoir storage was set to a specific level (41938 mcm) in the flow/surplus water-supply model used in this study. This assumption begs the question of whether or not increased reservoir storage could mitigate the effects of the estimated decreases in streamflow. To address this issue, an additional set of analyses was performed in which the reservoir storage capacity was assumed to be unlimited. All streamflow in excess of the required annual threshold (17866 mcm) was permitted to accumulate as surplus and then be available to augment flows during dry years. Results of these analyses (Table 1) show that unlimited reservoir storage caused a decrease in failure rates for the 20th century climate, 20th century climate with a 0.86°C warming, and the driest century (tree-ring reconstruction) scenarios. Unlimited reservoir storage did not, however, reduce the failure rate for the 20th century climate with a 2°C warming scenario or for the scenarios that were generated using flows from the driest century and included a 0.86°C or 2°C warming. For this latter set of scenarios, the estimated flow values are so low that little excess water is available in any year and, therefore, surplus accumulations are not sufficient to accumulate to levels that exceed the current reservoir storage capacity. This result would imply that for the 20th century climate 2°C scenario, increasing the reservoir storage capacity of the Colorado River basin likely would not reduce the fraction of time that the flow of the UCRB fails to meet the Colorado Compact. This result is consistent with findings of *Christensen and Lettenmaier* [2006] who reported that, due to the large storage to inflow ratio of the Colorado River basin, neither increases in reservoir capacity nor changes in operating polices are likely to mitigate stresses imposed by adverse climate change.

4. Summary

[22] These analyses provide a perspective on the possible future of water resources in the Colorado River basin given global warming, within the context of possible climate scenarios based on tree-ring reconstructions. These analyses focused on a warming in the basin and did not consider changes in precipitation, changes in evaporative water losses from reservoirs, or changes in consumptive water use associated with population increases. In addition, the analyses did not consider separately the depletions and obligations to meet the Colorado Compact of the Upper and Lower basins. Additional model development is needed to address these issues.

[23] The results of these sensitivity experiments indicate that given current consumptive water use in the UCRB, 1°C to 2°C increases in temperature, assuming no offsetting increases in precipitation, would create increased water-supply problems in the basin. Continued increases in consumptive water use will likely exacerbate and accelerate the problems associated with possible warming.

[24] **Acknowledgments.** We thank Steve Gray (University of Wyoming) and Eric Kuhn (Colorado River Water Conservation District) for helpful comments and advice.

References

Christensen, N., and D. P. Lettenmaier (2006), A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River basin, *Hydrol. Earth Syst. Sci. Discuss.*, *3*, 3737–3770.

Christensen, N. S., A. W. Wood, N. Voisin, D. Lettenmaier, and R. N. Palmer (2004), The effects of climate change on the hydrology and water resources of the Colorado River basin, *Clim. Change*, *62*, 337–363.

Diaz, H. F., and C. A. Anderson (1995), Precipitation trends and water consumption related to population in the southwestern United States: A reassessment, *Water Resour. Res.*, *31*, 713–720.

Hoerling, M., and J. Eischeid (2007), Past peak water in the Southwest, *Southwest Hydrol.*, *6*, 18.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate*, 996 pp., Cambridge Univ. Press, New York.

Jain, S., C. A. Woodhouse, and M. P. Hoerling (2002), Multidecadal streamflow regimes in the interior western United States: Implications for the vulnerability of water resources, *Geophys. Res. Lett.*, *29*(21), 2036, doi:10.1029/2001GL014278.

Nash, J. E., and J. V. Sutcliffe (1970), River flow forecasting through conceptual models, I: A discussion of principles, *J. Hydrol.*, *10*, 282–290.

Wolock, D. M., and G. J. McCabe (1999), Effects of potential climatic change on annual runoff in the conterminous United States, *J. Am. Water Resour. Assoc.*, *35*, 1341–1350.

Woodhouse, C. A., S. T. Gray, and D. M. Meko (2006), Updated streamflow reconstructions for the Upper Colorado River Basin, *Water Resour. Res.*, *42*, W05415, doi:10.1029/2005WR004455.

G. J. McCabe, U.S. Geological Survey, Denver Federal Center, MS 412, Denver, CO 80225, USA. (gmccabe@usgs.gov)

D. M. Wolock, U.S. Geological Survey, 4821 Quail Crest Place, Lawrence, KS 66049, USA.