

Sustainable water deliveries from the Colorado River in a changing climate

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The Colorado River supplies water to 27 million users in 7 states and 2 countries and irrigates over 3 million acres of farmland. Global climate models almost unanimously project that human-induced climate change will reduce runoff in this region by 10–30%. This work explores whether currently scheduled future water deliveries from the Colorado River system are sustainable under different climate-change scenarios. If climate change reduces runoff by 10%, scheduled deliveries will be missed ≈58% of the time by 2050. If runoff reduces 20%, they will be missed ≈88% of the time. The mean shortfall when full deliveries cannot be met increases from ≈0.5–0.7 billion cubic meters per year (bcm/yr) in 2025 to ≈1.2–1.9 bcm/yr by 2050 out of a request of ≈17.3 bcm/yr. Such values are small enough to be manageable. The chance of a year with deliveries <14.5 bcm/yr increases to 21% by midcentury if runoff reduces 20%, but such low deliveries could be largely avoided by reducing scheduled deliveries. These results are computed by using estimates of Colorado River flow from the 20th century, which was unusually wet; if the river reverts to its long-term mean, shortfalls increase another 1–1.5 bcm/yr. With either climate-change or long-term mean flows, currently scheduled future water deliveries from the Colorado River are not sustainable. However, the ability of the system to mitigate droughts can be maintained if the various users of the river find a way to reduce average deliveries.

climate change | global warming | hydrology | sustainability | water resources

The Colorado River system provides water to ≈27 million people in the southwest United States and Mexico. As the population of the region grew rapidly in recent decades, ever more water was supplied from the river to support this growth. Today the water is almost totally subscribed.

During this period of rapid growth, the hydrological cycle in the region began to change (1–3). Snowpack declined in the western mountains, temperatures increased, and many streams gradually shifted their peak flow to earlier in the year. It has been shown, with very high statistical confidence ($P < 0.01$), that a substantial portion of these changes are attributable to human-induced effects on the climate (3–6). Those works also show that at least 2 global climate models, downscaled to the western United States and using anthropogenic forcing, explain these changes quite well.

Those same global climate models indicate that the southwestern United States will become warmer and more arid, especially in the Colorado River drainage basin. Temperature increases of 2–4 °C are projected by 2050. The precipitation forecasts are in less agreement, ranging from essentially no change to reductions of ≈10% (2, 7–10). Despite the range of precipitation results, climate models are strikingly consistent in projecting decreased runoff in the Colorado River Basin (Table 1) (2, 8–12). For example, of 12 global models selected to provide the best simulation of historical runoff compared with observations, 11 showed drying in the Upper Colorado River Basin (12). Statistically based studies show the same result (2, 7, 13). The bottom line is that these changes in the climate will likely reduce the flow of the Colorado River by 10–30%.

In earlier work (14), we explored when these human-induced changes in the Colorado River system might exhaust reservoir storage. As we noted in reference 14, water managers will do everything within their power to avoid this drastic scenario. The reservoirs are operated by the United States Bureau of Reclamation (USBR), which will likely cut deliveries as necessary to maintain Lake Mead's elevation above the water intake for Las Vegas and surrounding communities (305 m above mean sea level). Because Lakes Mead and Powell are man-made, minimum elevations are determined by the USBR, and such protection is entirely achievable. However, simply saying this elevation will be protected does not address what such a constraint would entail in terms of reduced water deliveries, when deliveries would start to be affected, or how large the delivery cuts necessary to maintain this elevation would be.

How climate change is likely to alter Colorado River water deliveries has been addressed by a number of studies (2, 7–10, 15). Those works consistently found that the warmer and drier future conditions from human-induced climate change give a substantial chance of reduced river flow and associated water-delivery shortfalls in the 21st century. Here we extend those studies to estimate multiple time series of probabilities of future Colorado River water deliveries and water-delivery shortages. These results provide quantitative information on the size and timing of future delivery shortfalls and were calculated by using both the scheduled increase in water deliveries and the cuts that will be used under shortage conditions (16). We also examine the impact of different estimates of mean Colorado flow on deliveries and shortages, and illustrate the increasing chance that years will exist when only very low water deliveries are possible. This information, embedded in a realistic probabilistic framework, offers real-life numbers on expected river flow and sustainable water deliveries suitable for planning ways to address the coming water shortages in the Colorado Basin.

Colorado River Budget Model (CRBM). We use an updated version of the CRBM, which is a simple water budget model that calculates the net effect of inflows and outflows at a monthly time step. The earlier version (14) attracted a number of criticisms that we have addressed in this revision. In particular, we include the decline in the reservoir evaporation as their surface areas shrink. Also, the “preferred alternative” schedule of delivery cuts adopted by the USBR in 2007 (16) is included in this new model. The deepest delivery cuts specified in this alternative are 0.74 billion cubic meters per year [(bcm/yr); equal

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Table 1. Estimates of future decrease in runoff in the Colorado River basin due to human-induced climate change

Source	Runoff reduction
Nash and Gleick (1991)	12–31% [†]
Nash and Gleick (1993)	8–20%
Christensen et al. (2004)	18%
Milly et al. (2005)	10–25%
Seager et al. (2007)	15–20%
Christensen and Lettenmaier (2007)	6–7%
Hoerling and Eischeid (2007)	45% [‡]
McCabe and Wolock (2007)	8–17%

[†]Authors examined a range of values, quoted numbers are for (+2 °C, no change in precipitation) and (+4 °C, –10% precipitation) in the 2-basin model; see original work for details.

[‡]Estimate under revision.

to 0.6 million acre-feet per year (maf/yr)*]. Climate change is taken as starting in 1985, as indicated by observations of temperature, streamflow, and snowpack over the western United States (4). A 305-m (1,000-ft) elevation of Lake Mead—the level of the Southern Nevada Water Authority intake—is protected even if Lake Powell is depleted and water-delivery cuts deeper than those specified in the preferred alternative become necessary to protect this elevation. At this elevation, the reservoirs are only 8% full if Lake Powell is depleted. Other model details are given in the *SI Text*. All model runs start in 1960, so our results are not affected by the unusually low reservoir conditions in 2008 (see also *SI Text*, section S-2, and Fig. S1).

Fig. 1 compares the new version of CRBM with results from USBR's Colorado River Simulation System (CRSS) model (see ref. 16, appendix N, figures 7–10, and Table S1). The average rms error is 1.85 bcm/yr (1.5 maf/yr), which arises primarily from the neglect of the operations of other reservoirs in the system. Sensitivity tests to the imperfectly known flows and losses in the Colorado system show that the uncertainties could shift our results by ± 5 years. Otherwise our conclusions remain robust to reasonable perturbations in these numbers.

The model improvements noted in the *SI Text* have a variety of effects. Compared with our earlier work (14), the improved models delay the onset of problems by ≈ 4 –10 years when using the same inflow assumptions, depending on the particular scenario. More details are given in the *SI Text*.

Using CRBM allows us to explore the parameter space that affects future deliveries. Additionally, numerous realizations of future river flows can be computed, all consistent with the statistical properties of the historical Colorado River flow but differing in their exact sequence of yearly values. This ability allows future deliveries to be evaluated probabilistically, which is appropriate because the sequence of future flows is not deterministically predictable. The water budget model therefore serves a different purpose than a slower running, but more complete, model of the Colorado River system, such as the USBR's CRSS model. We believe the combination of information from both types of models will provide the best basis for planning the future of this critical resource.

Impact of Climate Change on Deliveries. Our main purpose is to investigate the effect of climate change on deliveries of water from the Colorado River when protecting a 305-m elevation of Lake Mead, the elevation of the lowest water intake for Southern Nevada. Is it likely that scheduled deliveries can be met in the

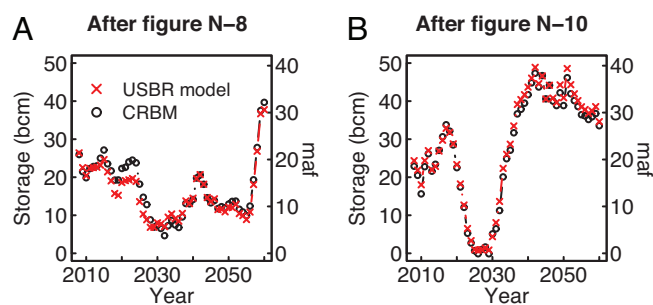


Fig. 1. Model simulations of total active storage in Lakes Mead and Powell for the CRBM model used here (black circles) and the full USBR Colorado River model (red crosses). The 2 inflow sequences and USBR model results (A, after figure N-8; B, after figure N-10) are taken from ref. 16, appendix N, figures 7–10 with elevations converted to total active storage.

future, and, if not, what are the shortfalls likely to be and when will they occur?

In this section, we assume that 20th-century naturalized Colorado River flow at Lees Ferry, AZ is representative of future values in the absence of climate change. Because measurements started in 1906 and we take the beginning of climate-change effects to be 1985, we use the mean value from 1906–1984—18.86 bcm/yr (15.30 maf/yr)—as our estimate of Colorado River flow unaffected by climate change. Paleoclimate research suggests this is an overestimate; the effects of using a mean flow consistent with the tree-ring record are significant and are examined below.

We ran the water budget model 100 years into the future, and the water available each year was compared with scheduled deliveries (see ref. 16, appendix C). This process was repeated for 10,000 independent realizations of Colorado River flow. As befits our water budget approach, we compare the total water available to the total demand without regard to how the complex legal rights to the water determine where shortages occur.

Fig. 2 shows the probability of experiencing delivery shortfalls as a function of time. In the absence of climate change, shortfalls occur $\approx 40\%$ of the time by midcentury and their magnitude remains modest. However, both the likelihood and size of shortfalls increase rapidly as increasing scheduled deliveries and climate change begin to affect the system. With a 10% reduction in Colorado River runoff, full deliveries are no longer the norm by 2040. With a 20% runoff reduction, delivery shortfalls of >1 bcm/yr (0.81 maf/yr) become more common than full deliveries by 2043. By 2060, shortfalls are experienced 70–95% of the time; the mean annual delivery shortfall is 1.3 bcm/yr (1 maf/yr) if runoff reduces 10% and 2.6 bcm/yr (2 maf/yr) if runoff reduces 20%. These values are ≈ 1.5 - to 3-times the maximum lower basin delivery cut explicitly included in the preferred alternative plan.

Mean shortfalls, also discussed in earlier work (2, 7–10), do not tell the whole story. The large number of realizations in CRBM and its statistical framework allowed us to look at extremes in expected shortfalls. The results show that if absolute protection of the 305-m elevation in Lake Mead is desired, delivery cuts of >2.5 bcm/yr (2 maf/yr) are sometimes required under climate-change scenarios. We note that a USBR simulation driven by a flow with 20% reduced mean, which would be unremarkable if climate changes reduce runoff 20%, was unable to protect the 305-m elevation of Lake Mead even with cuts up to 4.1 bcm/yr (3.3 maf/yr) (see ref. 16, p. N-18).

Low-flow years when protection of the Lake Mead elevation requires delivery of less than, say, 14.5 bcm (11.75 maf) from a request of ≈ 17.3 bcm (14 maf) would require substantial accommodation by the users. The fraction of time cuts of this magnitude is required to protect the 305-m, elevation and is

*We additionally supply values in the units used in all the USBR documents pertaining to the reservoirs. 1 bcm = 0.81 maf.

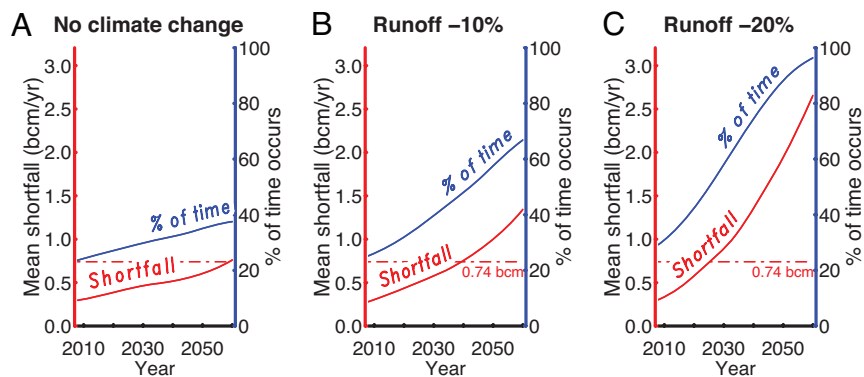


Fig. 2. Probability of experiencing delivery shortages (blue, %), and the mean delivery shortage (red, bcm/yr), for the cases with no climate change (A) and a reduction in Colorado River runoff of 10% (B) and 20% (C). Also shown for comparison is the largest lower-basin delivery cut included in the USBR's preferred alternative of reservoir operations, 0.74 bcm/yr, or 0.6 maf/yr (dashed line).

shown in Fig. 3A. There is a negligible chance of such substantial delivery shortages if there is no climate change. With 10% and 20% reductions in runoff, this chance increases to 5% and 21%, respectively, by the middle of this century.

The temporal autocorrelation of the Colorado River flow and intermittent nature of the El Niño/Southern Oscillation cycle gives rise to a dynamic where water is plentiful during infrequent heavy-precipitation years and the Colorado's reservoirs fill. Then the levels slowly decline during subsequent dry years. Fig. 3B shows the chance that the reservoirs are at least 80% full. Although this situation was quite likely in the 1980s ($P > 0.8$), it becomes less likely in the future (even without climate change) as increasing deliveries cause the lake elevations to be systematically lowered. With climate change included, the probability of having the reservoirs 80% full falls sharply between 2000 and 2030, with a $<10\%$ chance after 2030 if the runoff is reduced by 20%. Intermittent wet years are unable to replenish the reservoirs given climate change and planned future water deliveries.

Sustainable Future Deliveries. Our results indicate that currently scheduled future deliveries are unlikely to be consistently met if the climate changes as projected. Just how much water can the Colorado River sustainably deliver in the face of climate-induced flow reductions? This question does not seem to have been addressed by previous workers.

In Fig. 4, the line marked "D" is the mean water delivered across all model realizations and can be thought of as an upper limit for sustainable water deliveries from the Colorado River. The line marked "B10%" shows the mean of the bottom 10% of deliveries. Also shown, for comparison, are requests for delivery, indicated by the line marked "R." With any climate change that

tends toward dryness, the sustainable amount of water the river can provide decreases with time, and the shortfall during low-delivery years becomes more severe.

Using assumed 20th-century flows (Fig. 4 A–C), a 10% reduction in runoff caused by human-induced climate change means that requested deliveries exceed sustainable deliveries by 2040. With a 20% reduction in runoff, these shortfalls happen by 2025.

The bottom decile of deliveries has a mean of 14.2 bcm/yr (11.5 maf/yr) by 2050 for a 10% decrease in runoff. With a 20% decrease in runoff, the bottom decile mean is 10.4 bcm/yr (8.4 maf/yr) by 2050. In other words, the greatest effects of climate change will most likely be seen at the delivery extremes, not at the mean.

The occurrence of low-delivery years is partly a consequence of attempting to deliver more water from the Colorado River than it can sustainably supply. Doing so means the reservoirs spend more time in a depleted state, which decreases the buffering ability of the system to maintain deliveries in low-precipitation years. Reducing requested deliveries to be in line with what the river can sustain increases the amount of water delivered in the bottom decile of years because the reservoirs are then maintained at consistently higher elevations. For example, when scheduled depletions are linearly reduced from the current value in 2008 to 14.8 bcm/yr (12 maf/yr) in 2060, the average amount delivered in the bottom decile stays above 12.3 bcm/yr (10 maf/yr) even if runoff declines 20%.

Impact of Paleoclimate Flows on Sustainable Deliveries. We have used 20th-century flows in obtaining the results shown above. However, tree-ring reconstructions of Lees Ferry flow show this was a wet period with unusually high flows in the Colorado River (17–21). Of the 10 reconstructions we examined, 9 show the 20th century as being the wettest of the last 500–1,200 years with the exception showing it as the second wettest over the same timeframe (Fig. 5) (see also *SI Text*, section S-3, and Fig. S2). The bottom line is that using 20th-century flows for evaluating the Colorado River's ability to meet future deliveries is neither a conservative assumption nor one supported by paleoclimate evidence.

Sustainable deliveries that are possible from the system using the average of the 10 paleoclimate flow estimates, 17.38 bcm/yr (14.08 maf/yr), are shown in Fig. 4 D–F. A reversion to average climate conditions indicated by the tree-ring records would reduce sustainable deliveries to near the value being requested today, even without anthropogenic climate change (Fig. 4D). There is a particularly strong effect on the lowest decile of water deliveries. Calculated using the mean paleoclimate flow, a 10%

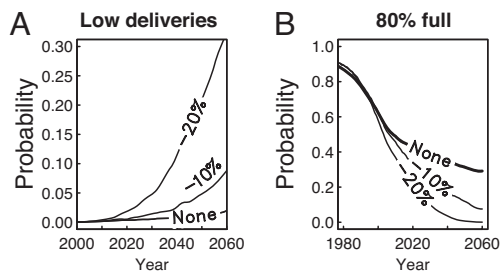


Fig. 3. Probability of delivering <14.5 bcm (11.75 maf) of water in the indicated year (A) and probability of the reservoirs being at least 80% full (B). Lines show cases with no anthropogenic climate change and with reductions in runoff of 10% and 20% driven by anthropogenic climate change.

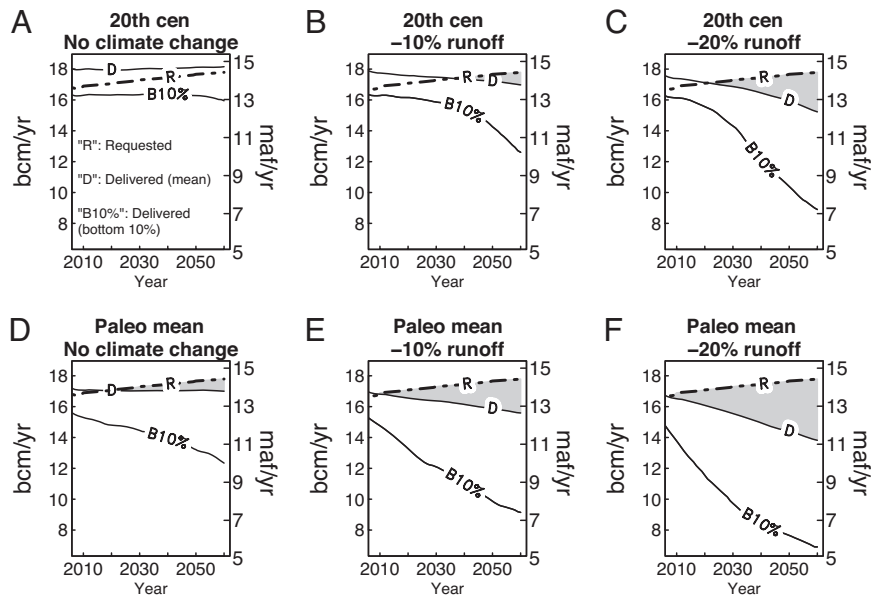


Fig. 4. Mean water deliveries from the Colorado River system under various climate scenarios. Line D shows the mean water delivered across all model realizations and can be thought of as the upper limit of sustainable water deliveries. Line B10% shows mean water delivered during years that fall within the bottom 10% of deliveries. For comparison, line R shows requests for scheduled deliveries. (A–C) Computations with 20th-century values of Colorado River flow. (D–F) Computations using an assumed Colorado River flow of 17.38 bcm/yr (14.08 maf/yr) at Lees Ferry, AZ, the mean of estimates from 10 different tree-ring reconstructions. Wherever the D line drops below the R line (shaded regions), requests for water are exceeding sustainable deliveries.

reduction in runoff gives a bottom decile mean of ≈ 10 bcm/yr (8 maf/yr) by 2050. The bottom decile mean drops to 8 bcm/yr (6.5 maf/yr) if anthropogenic forcing reduces runoff by 20%, less than

half of the water used today (Fig. S3). As before, reducing scheduled deliveries would increase these numbers and the resiliency of the system.

Discussion and Conclusions

We find that either protecting a 305-m (1,000-ft) elevation in Lake Mead in the face of human-induced climate change or the Colorado River flow reverting back to the lower mean value indicated by tree-ring data, or both, makes it increasingly unlikely that currently scheduled future deliveries can be sustained. In fact, attempting to meet scheduled deliveries increases the number of years where the only deliveries possible are < 14.5 bcm/yr (11.75 maf/yr) of the requested ≈ 17.3 bcm/yr (14 maf/yr).

The difficult situation described above could be ameliorated by aiming for more realistic deliveries that are lower than those currently scheduled. We have shown that lower delivery requests would reduce the likelihood of having years in which the only option available is to deliver < 14.5 bcm/yr of water (assuming the 305-m elevation of Lake Mead is protected).

In any event, currently scheduled water deliveries from the Colorado system are not sustainable in the future if anthropogenic climate change reduces runoff even by as little as 10%. If Colorado River flow reverts to the long-term mean suggested by tree-ring studies, currently scheduled deliveries cannot be met even in the absence of runoff reductions due to anthropogenic climate change.

This work adds to and strengthens our previous results (14) as well as those from other workers (2, 7–10). The Colorado River faces scheduled increases in water delivery combined with the likelihood of reduced runoff caused by climate change in a system conceived during and calibrated to one of the wettest centuries in the last 1,200 years. Lake Mead has been overdrifted by an average of 1.6 bcm/yr (1.3 maf/yr) since 1999 (22). Colorado River delivery shortfalls could become systematic if current delivery schedules are followed and river management guidelines are unchanged.

Our results suggest long-term sustainable deliveries from the Colorado River are likely in the range of 14–17 bcm/yr (11–13.5

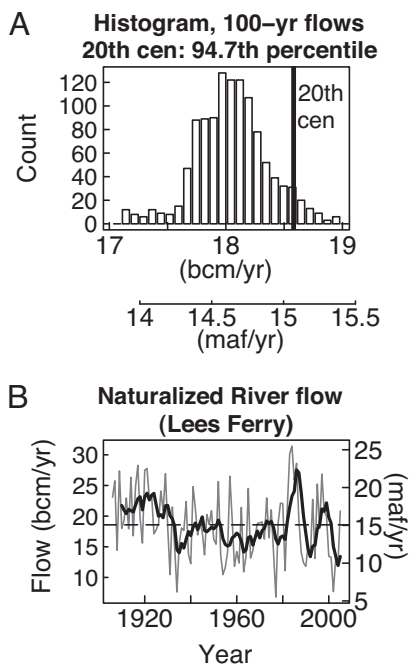


Fig. 5. Historical and Paleoclimate estimates of Colorado River flow. (A) Vertical line shows observed (naturalized) mean flow in the Colorado River at Lees Ferry, AZ from 1906–2005 compared with a histogram of the mean flow in all sliding 100-yr segments from a tree-ring-based reconstruction of Colorado River flow (21). (B) Time series of naturalized mean annual flow in the Colorado River at Lees Ferry, AZ, along with the 5-year running mean (heavy line) and mean over the period 1906–2005 (18.6 bcm/yr or 15.07 maf/yr) (dashed line).

