Sustainable water deliveries from the Colorado River in a changing climate

Tim P. Barnett[1] and David W. Pierce

Division of Climate, Atmospheric Science, and Physical Oceanography, Scripps Institution of Oceanography, La Jolla, CA 92093-0224

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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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[1]To whom correspondence should be addressed at: Division of Climate, Atmospheric Science, and Physical Oceanography, Mail Stop 0224, Scripps Institution of Oceanography, La Jolla, CA 92093-0224. E-mail: timdotbarnett@ucsd.edu.

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SUSTAINABILITY SCIENCE

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.

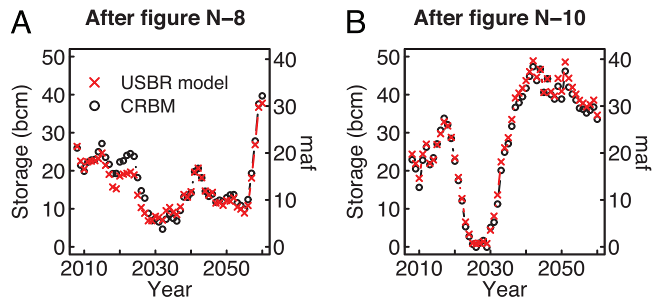

Fig. 1. Model simulations of total active storage in Lakes Mead and Powell for the CRBM model used here (black circles) and the full USBR Colorado River model (red crosses). The 2 inflow sequences and USBR model results (*A*, after figure N-8; *B*, after figure N-10) are taken from ref. 16, appendix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

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 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 shortages as a function of time. In the absence of climate change, shortfalls occur ≈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 shortages. 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.

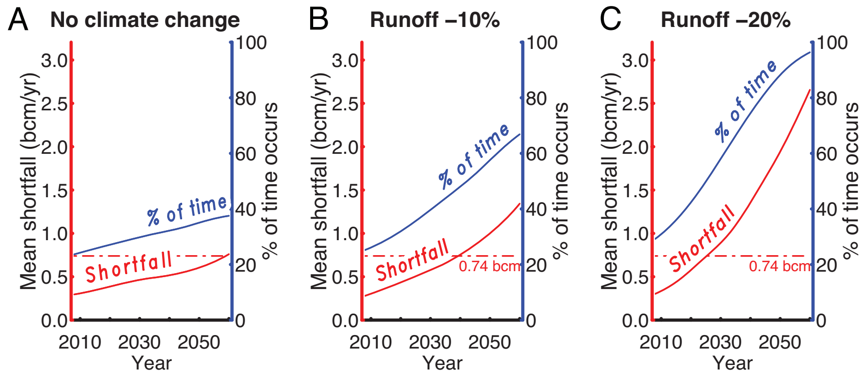

Fig. 2. Probability of experiencing delivery shortages (blue, %), and the mean delivery shortage (red, bcm/yr), for the cases with no climate change (*A*) and a reduction in Colorado River runoff of 10% (*B*) and 20% (*C*). Also shown for comparison is the largest lower-basin delivery cut included in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

shown in Fig. 3*A*. 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. 3*B* 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

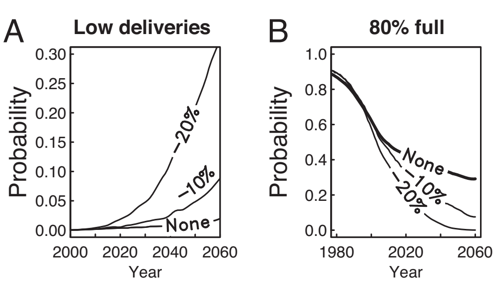

Fig. 3. Probability of delivering <14.5 bcm (11.75 maf) of water in the indicated year (*A*) and probability of the reservoirs being at least 80% full (*B*). Lines show cases with no anthropogenic climate change and with reductions in runoff of 10% and 20% driven by anthropogenic climate change.

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. 4*D*). There is a particularly strong effect on the lowest decile of water deliveries. Calculated using the mean paleoclimate flow, a 10%

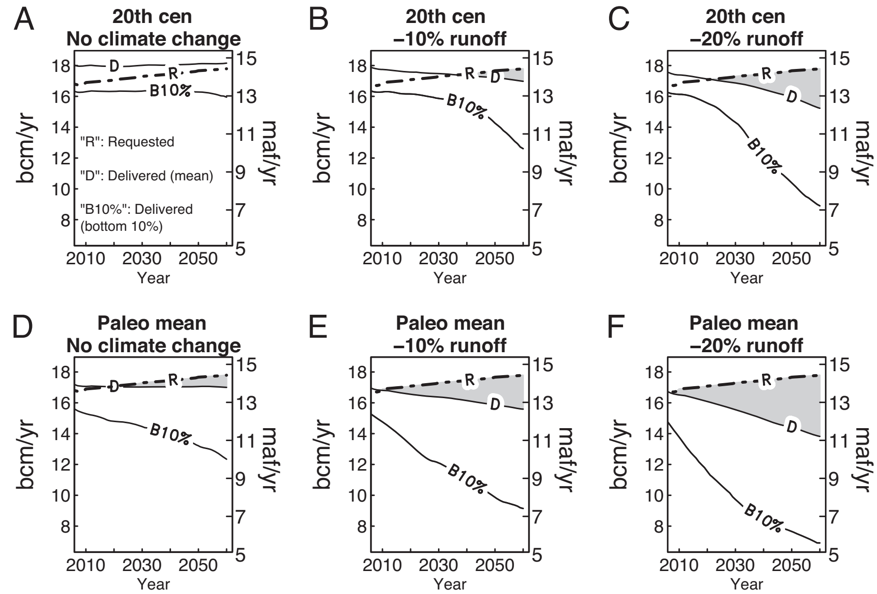

Fig. 4. Mean water deliveries from the Colorado River system under various climate scenarios. Line D shows the mean water delivered across all model realizations and can be thought of as the upper limit of sustainable water deliveries. Line B10% shows mean water delivered during years that fall within 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.

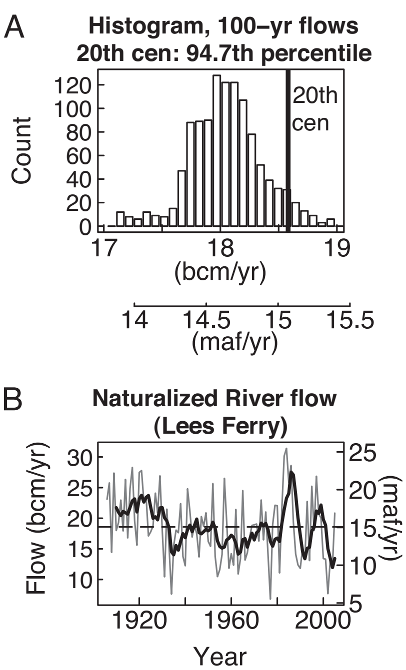

Fig. 5. Historical and Paleoclimate estimates of Colorado River flow. (*A*) Vertical line shows observed (naturalized) mean flow in the Colorado River at Lees Ferry, AZ from 1906–2005 compared with a histogram of the mean flow in all sliding 100-yr segments from a tree-ring-based reconstruction of Colorado 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).

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 overdrafted 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

maf/yr). These numbers represent a reduction of 0–20% relative to current deliveries. Those are potentially substantial shortfalls but are likely manageable through a program of water reuse, conservation, transfers between users, and other measures (15).

The situation becomes more complicated when future deliveries to support population and economic growth in the region are taken into account. The upper basin states have long-standing plans to increase their depletions to support such growth in accord with established agreements on division of the water and as reflected in the USBR delivery schedules used in this work. Although it has been known for many decades that the Colorado River water was originally overallocated and that this problem would have to be addressed eventually, our results show this is no longer a problem for future generations to debate. The problem is at our threshold and appears solvable, at least in the near term. But it needs to be addressed now. The USBR Interim Agreement was a good first step, but neglect of climate-change effects means that it is working from overly optimistic assumptions. Hopefully, information such as that developed here will provide a basis for those managing water resources in the flexible way needed to cope with less water in the future.

We wish to end with a caveat. The effects associated with a reversion of the Colorado River flow to its paleoclimate mean impart a substantial uncertainty into the magnitude and timing of the delivery problems. Beyond some consensus regarding what to use as a realistically conservative (low) mean flow, we need a scheme to predict the river flow at ten- to twenty-year time scales. A combination of global climate models, downscaling, and hydrological models in a proper statistical framework has already been used to demonstrate how such forecasts can be made (9, 10, 23). We suggest it would be prudent to implement operationally such a forecast system for the Colorado Basin as soon as possible.

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Supporting Information

Barnett and Pierce 10.1073/pnas.0812762106

SI Text

S-1. Details of the Colorado River Budget Model (CRBM). ***Side inflows.*** We include side inflows between Glen Canyon and Hoover dams with a mean of 1.06 bcm/yr (0.86 maf/yr) (1). These flows are significantly correlated with the mainstream flow ($r = 0.48$, $P < 0.01$), so CRBM scales side inflows appropriately by using a linear regression model. We assume climate change affects these side inflows in the same way as the main river flow.

Delivery cuts as specified in the USBR 2007 final Environmental Impact Statement (EIS). In our previous work (2), we explored idealized delivery cuts, but did not include the specific "preferred alternative" schedule of delivery cuts adopted in December of 2007 and described in the 2007 final EIS (3). These specific cuts are included here. If the elevation of Lake Mead drops below 328 m [1,075 feet, measured relative to mean sea level (msl)] but is above 320 m (1,050 ft) msl, deliveries will be cut by 0.49 billion cubic meters per year (bcm/yr) [(0.4 million acre-feet per year (maf/yr)]. If the elevation drops below 320 m but is above 312 m (1,025 ft), deliveries will be cut by 0.62 bcm/yr (0.5 maf/yr). And if the elevation drops below 320 m, deliveries will be cut by 0.74 bcm/yr (0.6 maf/yr) (see ref. 3, pp 2–18). For comparison, consider that ≈16.7 bcm/yr (13.55 maf/yr) of water has been delivered to users in recent years, so the USBR cuts are a reduction of about 3–4.5%. The actual amount that deliveries will be cut if Lake Mead elevation drops below 312 m is unknown because the 2007 EIS specifies that a "reconsultation" between USBR and the interested parties will take place if this happens.

Protection of the Southern Nevada Water Authority intake elevation in Lake Mead. The current work estimates deliveries possible when a 305-m (1,000-ft) elevation is protected in Lake Mead, even if Lake Powell has to be drawn down to the dead pool and delivery cuts greater than those specified in the preferred alternative are necessary to achieve this.

Timing of climate change effects. Our previous work rather arbitrarily assumed the climate-change effects on western hydrology began in 2007 (2). However, an analysis of temperatures, snowpack, and stream flow showed that, with $P < 0.05$, western hydrology began to be affected by human-induced climate change in the mid 1980s (4). Accordingly, we take 1985 as the start date of the climate effects. We assume the runoff reduction increases linearly until the full value is reached in 2050.

Reduced evaporation as the reservoir surface area shrinks. As the reservoir levels drop, less surface area is available for evaporative loss. This effect is included in all results, with the evaporation coefficients taken from the USBR (see ref. 3, appendix A). Bank infiltration uses the same parameterization and coefficients as the USBR model.

Increased evaporation in a warmer future world. In the previous work, we assumed evaporation would remain constant as temperatures increased. Based on an estimate of the increase in regional latent heat flux from a number of global climate models, in this work we assume evaporation from the Colorado River Basin will have increased 7% by 2050.

Effect of initial storage. Previously we used the actual reservoir storage values from mid-2007 as an initial condition. Although appropriate, numerous people have asked us what effect the low reservoir conditions at that time had on the water-availability problem, and whether this predisposes the system to problems. Below, we use a range of initial reservoir elevations to demonstrate that the system "forgets" the initial storage conditions on a time scale of a few decades. In any event, our results are with the model started in 1960, so the unusually low current reservoir conditions in 2008 are not included. The results therefore show that the Colorado River delivery problems arise from the systematic effects of human-induced climate change, not from the current low reservoir conditions.

Gains and losses below Hoover Dam. Intervening inflow between the Hoover and Imperial dams is taken at 0.45 maf/yr (1). Losses due to evaporation and Phreatophyte evapotranspiration in this reach are 0.93 (± 0.10 maf/yr) during the 10-year period for which Lower Colorado River Accounting System reports are available (5). We use a value of 0.88 maf/yr, which minimizes rms errors of the CRBM model with respect to the USBR (3) simulations (Fig. 1). Lower basin unmeasured returns (i.e., returns to the Colorado River through the groundwater system) are taken from the "decree reports" to be 0.245 maf/yr (6).

Other aspects of the model are as described in ref. 2. Future water deliveries are taken from USBR schedules (see ref. 3, table C-1). Deliveries are planned to increase by ≈1.11 bcm/yr (0.9 maf/yr) to 17.75 bcm/yr (14.4 maf/yr) over the next 50 years, with the increases going to the upper basin states. We calculate deficiencies relative to this scheduled increase in future deliveries. We generate synthetic time series of Colorado River flow using a fractional Gaussian noise model (7–11) tuned to match the observed flow (see ref. 2, appendix A for details). Table S1 shows that the statistics of our synthetic flows match well with these observations. Yearly mainstream flows are not allowed to drop below 2.86 bcm/yr (2.32 maf/yr), the minimum value found in a recent, long tree-ring reconstruction (12); this limit is hit <0.1% of the time. Upper basin depletions are reduced if insufficient natural flow exists to physically make the deliveries and upper basin reservoirs are assumed to buffer 5% of the variability of inflow to Lake Powell using parameterizations taken from the Colorado River Open Source Simulator (CROSS) model (13).

The model improvements have a variety of effects, with some leading to an earlier onset of problems and others to a later onset. Overall, they delay the onset of problems compared with our earlier work (2) but otherwise leave the conclusions unchanged. For example, let the assumed reduction in runoff due to anthropogenic climate change be 20%. Using an assumed net inflow of −1.2 bcm/yr (−1 maf/yr) based on the 1.6 bcm/yr water loss from Lake Mead that has been ongoing since 1999 (14) and allowing the storage to be exhausted, the previous version had a 50% chance of running dry by 2021 (see ref. 2, figure 8). The new model has a 50% chance of reaching its 305-m protection elevation (8% storage) by 2025 using the same net inflow assumption. When driven by an assumed mean 20th-century Lees Ferry naturalized flow of 18.58 bcm/yr (15.07 maf/yr) and either no delivery cuts or idealized 10% cuts, the previous version had a 50% chance of exhausting storage by 2028 or 2035, respectively (see ref. 2, figure 9). The new version, driven by the same assumed flow using the specific preferred alternative delivery cuts (which average about 8.2% over the 21st century), has a 50% chance of reaching its protected elevation (8% storage) by 2042.

S-2. Influence of Initial Conditions. Lakes Mead and Powell are, as of this writing, about half full. What influence does this relatively low initial condition have on our results? We can make a rough estimate by using a residence time argument, i.e., how long a typical water parcel remains in the system. For times shorter than the residence time, the initial conditions determine the behavior of the system. For times much longer than the residence time, the initial conditions are "forgotten," and only water deliveries, climate change, and reservoir operations are important.

The Colorado River system has a storage capacity of ≈4-times the current yearly inflows, so we take our mean residence time to be ≈4 years. (The actual residence time will vary with the net inflow and current storage.) If we take ≈3 residence times as a time scale after which the initial conditions are largely forgotten, it would suggest that the initial conditions become largely irrelevant after ≈12 years. In other words, this estimate suggests that changes before about 2020 are affected by the current low initial reservoir conditions but results in later decades are influenced little by current conditions.

In addition to this estimate, we can run the water budget model with different initial conditions to get a more accurate view. This is illustrated in Fig. S1 using 2 different starting dates, 1960 and 2007, and a 20% reduction in river flow due to human-induced climate change. When the system is started in 1960, the initial conditions are forgotten by 1970. When the system is started in 2007, the initial conditions make an appreciable difference until about 2030 but have little effect thereafter. For example, if the reservoir is initialized with very little storage in 2007 (Fig. S1, yellow curve), the fact that sustainable deliveries exceed requested deliveries until about 2015 (Fig. 4*C*) means that excess water is available to fill the reservoir rapidly during this period. The future evolution of this case then approaches, and eventually becomes indistinguishable from, cases initialized with greater storage. In summary, the systematic water delivery problems we find in coming decades do not arise simply because of the unusually low reservoir conditions of 2008. The problems would still arise if the reservoirs currently held more water. In any event, the estimates in this work start in 1960 and so are not directly affected by the low reservoir conditions of 2008.

S-3. Tree Ring Reconstructions of Colorado River Flow. We used data from 10 different tree-ring reconstructions generated by 4 different authors (12, 15–17) of Colorado River flow at Lees Ferry over the last 500–1,200 years. We extended reconstructions that ended before 1999 using observed USBR Lees Ferry flows from the flow gauges. Nine of the reconstructions show that the mean flow over the period 1900–1999 was the highest 100-year mean in their respective study periods, and one showed it being the second highest (Fig. S2).

We also compared the values measured over the period 1905–2005 (18.58 bcm/yr, or 15.07 maf/yr) to the histogram of 100-year means computed in sliding 100-year windows through the reconstructed time series. The percentile of the observed 20th-century flow in the histogram of 100-yr means from the reconstructions is indicated in the subtitles of Fig. S2.

These studies show that in the future we are likely to find less water flowing down the river; the average of the means in the reconstructions is 17.38 bcm/yr (14.08 maf/yr). Note that this is a result associated with natural climate variability only and has nothing to do with human-induced changes. However, it shows that expecting the 20th-century mean flow to be maintained in the future is unrealistic even without consideration of climate change.

The effect of using the average of the tree-ring estimated mean flows on the probability of having a delivery shortfall, and the mean delivery shortfall when one occurs, is shown in Fig. S3. This is constructed exactly as in Fig. 2 but uses a mean Colorado River flow of 17.38 bcm/yr (14.08 maf/yr).

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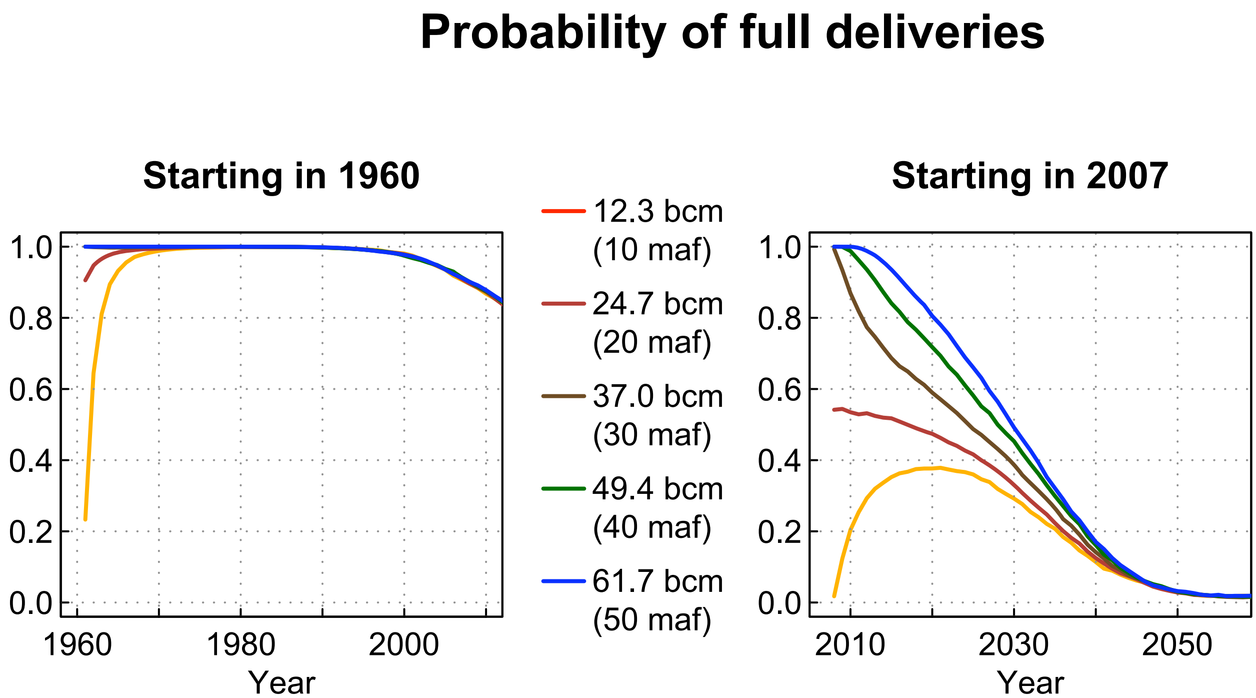

Fig. S1. Influence of different initial reservoir storage levels (colored lines) on the probability of being able to supply full deliveries, assuming a 20% decline in runoff due to human-induced climate change.

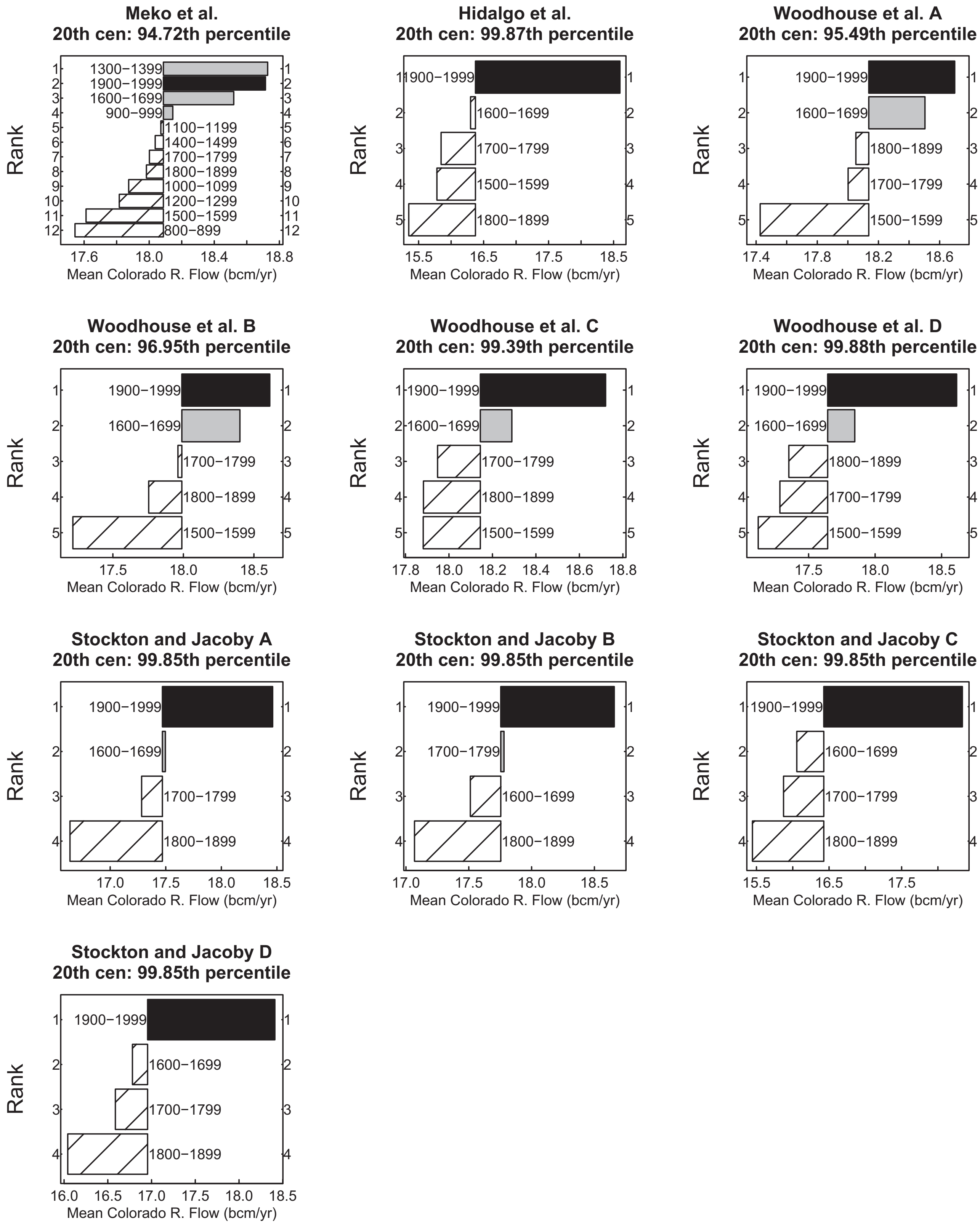

Fig. S2. Rank of Colorado River flow at Lees Ferry, AZ over the period 1900–1999 (black bars) in 10 different tree-ring-based reconstructions of the flow. Bars for each reconstruction are shown relative to their own overall means, which differ between reconstructions. The headings show the percentile of the observed 20th-century flow in the histogram of 100-year means taken in sliding 100-year windows through each reconstructed flow time series.

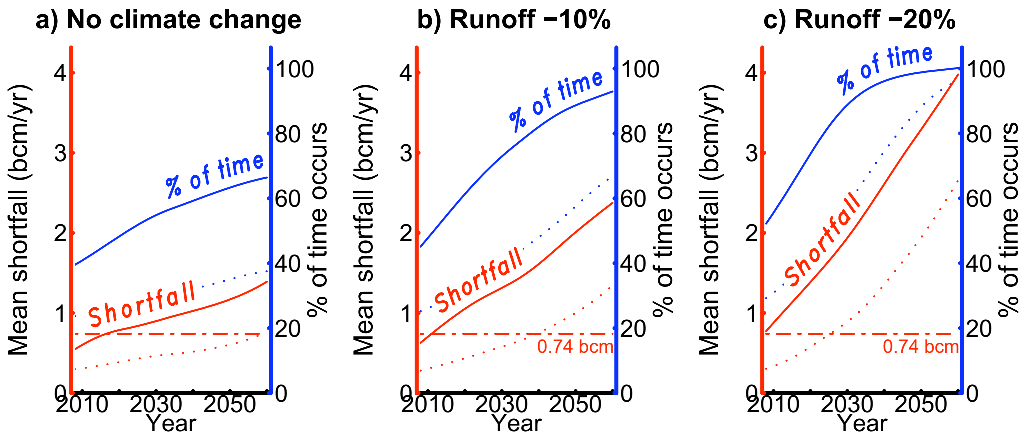

Fig. S3. Probability of experiencing delivery shortages as shown in Fig. 2, but solid lines are calculated using the mean Colorado River flow inferred from tree rings (17.38 bcm/yr, or 14.08 maf/yr) instead of the mean flow observed over the period 1906–1984 (18.86 bcm/yr, or 15.30 maf/yr). Also shown, for comparison, are the original values from Fig. 2 (dotted lines). Note that the *y* axis of this plot differs from that used in Fig. 2.

Table S1. Statistics of Colorado River flow (measured at Lees Ferry, AZ) from various sources

Source	Mean (bcm/yr)	Standard deviation (bcm/yr)	Skewness	Lag-1 autocorrelation	Min (bcm/yr)	Max (bcm/yr)
Observations, 1906–2005	18.58 (17.49, 19.67)	5.46 (4.82, 6.04)*	0.16 (−0.16, 0.47)*	0.26	6.79	31.40
fGn simulation	18.58†	5.46†	0.00 (−0.61, 0.61)	0.24 (−0.05, 0.51)	6.12 (1.42, 9.43)	31.07 (27.68, 35.82)
Meko, et al.	18.06 (17.83, 18.30)	4.34	−0.18	0.32	2.86	29.97

Observations are from the USBR, using numbers current as of 8/16/2008. Numbers in parenthesis show the 95% confidence interval (CI) about the mean estimated value. For the fractional Gaussian noise (fGn) simulation, the CI is calculated from the values found in the 10,000 century-long realizations. Statistics for Meko, et al. are derived from Meko DM, et al. (2007) Medieval drought in the upper Colorado River basin. *Geophys Res Lett*, 10.1029/2007GL029988.

*CI estimated by a bootstrap test.

†Value is set by a fit to observations.