POLICY FORUM

WATER GOVERNANCE

What will it take to stabilize the Colorado River?

A continuation of the current 23-year-long drought will require difficult decisions to prevent further decline

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The Colorado River supplies water to more than 40 million inhabitants in the southwestern United States and northwestern Mexico. A basin-wide water supply crisis is occurring because of decreased watershed runoff caused by a warming climate and legal and water management policies that allow systematic overuse. By the end of 2022, combined storage in Lake Powell and Lake Mead, the two largest reservoirs in the United States, will have declined from 95% full in 2000 to approximately 25% full. If this "Millennium Drought" persists, then stabilizing reservoir levels to avoid severe outcomes will require reducing water use to match diminished runoff. With a process underway to renegotiate interstate and international agreements on consumptive uses of the river, we describe a promising new management approach based on combined storage of both reservoirs, rather than just Lake Mead as currently used, to trigger consumptive use reductions to the Lower Basin and Mexico.

Since 2000, the average annual natural flows (that which would exist without human interventions) into lakes Powell and Mead have been almost 20% below the 20th-century average (*1*, *2*). As a result of these unprecedented low flows and insufficient management adaptations (*3*, *4*), 5-year projections by the US Bureau of Reclamation(Reclamation) suggest that Lake Powell, created by Glen Canyon Dam, has a one in four chance of falling below the minimum elevation necessary to produce hydropower. Storage downstream in Lake Mead, created by Hoover Dam, has a two in five chance of falling to its most severe management condition, which forces large reductions on downstream users (*5*).

Municipalities of Los Angeles, San Diego, Phoenix, Tucson, Las Vegas, Denver, Salt Lake City, Albuquerque, and Tijuana rely heavily on the river for their water supplies. About 70% of the water is used to irrigate nearly 5.7 million acres (2.3 million hectares) of agriculture. The basin is home to 30 recognized Native American Tribes that hold senior legal rights to divert substantially more water than they currently use. Between 2000 and 2021, the average annual energy generation from the two major dams was 7.6 terawatt-hours (TWh)/year, enough to serve 2.5 million people. The river's landscapes and ecosystems provide critical habitat for federally protected species (*6*) and support an extensive recreation-based economy. Today, the entire flow is diverted along its 1400-mile course. In its lower reaches, only 10% of the natural flow reaches Mexico; rarely does the river flow to the Gulf of California (*7*).

CONSTRAINTS OF PAST POLICIES

Management of the river is governed by a set of interstate compacts, court decrees, federal laws, secretarial guidelines, and an international treaty that is collectively referred to as the Law of the River. The cornerstones are the 1922 Colorado River Compact and the 1944 Treaty between the United States and Mexico. The Compact is an agreement among seven Basin States, which divided the watershed into two parts, a lower basin that includes portions of Arizona, Nevada, and California and an upper basin that includes portions of Colorado, New Mexico, Utah, Wyoming, and a small area in Arizona. The Compact apportioned 7.5 million acre-feet (MAF; 1 acre-foot = 1233 m^3) per year of consumptive use to each basin and specified the division between them as Lees Ferry in northern Arizona (*8*, *9*). The Lower Basin was developing rapidly while Upper Basin development lagged; hence, this apportionment sought a degree of future equality among the basins. The Compact also required the Upper Basin not to deplete the river's flow to less than 75 MAF during any 10 consecutive years (the "non-depletion obligation") and required each basin to equally share any obligations to Mexico. The 1944 Treaty established a delivery requirement of at least 1.5 MAF/year.

The distinction between the Upper and Lower Basin created an institutional division that endures today. Lake Mead is often perceived as the water supply for the Lower Basin, and Lake Powell is primarily managed to avoid violation of the non-depletion obligation, even though all stored water effectively flows to the Lower Basin. This division is reinforced by Reclamation's institutional structure and distinct energy marketing arrangements between the two hydropower facilities.

Under the Law of the River, a total of 16.5 MAF/year of the mainstem flow is allocated for consumptive use. The primary metric used to evaluate hydrologic conditions is the natural flow at Lee Ferry. The Compact negotiators optimistically presumed a natural flow at Lee Ferry of 17.5 MAF/year and more than 20 MAF/year basin-wide. Evidence suggests, however, that they eschewed scientifically sound estimates that the available supply was potentially less (*9*). This knowledge was dismissed to help reach an agreement; the basin is increasingly paying the price for this strategy. The 20th-century natural flows at Lees Ferry averaged 15.2 MAF/year, an amount nearly sufficient to meet the Upper Basin's peak use of 4.0 MAF/year, 9.0 MAF/year of normal allocation in the Lower Basin and Mexico, plus 2.4 MAF/year for typical evaporation losses. However, since 2000, the average natural flow dropped to 12.3 MAF/year. To continue meeting demands, storage in lakes Powell and Mead decreased from 46 to 13.8 MAF. If the Millennium Drought continues or inflows decline further, then the only option will be to reduce consumptive uses to match the diminished supply.

THE RACE TO REDUCE DEMANDS

The Lower Basin and Mexico have been fully using their combined 9.0 MAF/year apportionment of the Colorado River. Under forceful federal prompting, the Lower Basin states committed in 2007 to reductions in consumptive uses (known as "shortages") in stages based on Lake Mead levels through "Interim Guidelines." Recognizing that these reductions would be insufficient to slow the drawdown of Lake Mead, a 2019 Drought Contingency Plan (DCP) augmented these commitments. Mexico agreed to reduce uses

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approximately in proportion to US commitments through negotiated implementation agreements to the 1944 Treaty (Minutes).

Collectively, these agreements require the Lower Basin and Mexico to reduce their 9.0 MAF/year usage by 2.7 to 15.2% (0.241 to 1.375 MAF/year), with reductions increasing as Lake Mead's storage declines from 41 to 23% full (10.9 to 6.0 MAF). Reductions in Lower Basin use already occurred in 2020 and 2021 under the DCP. Additional voluntary reductions of 0.5 MAF/year by Lower Basin States and 0.1 MAF/year by Reclamation were recently proposed (*10*).

The Interim Guidelines and Treaty Minutes were triggered for the first time in 2022; thus, the combination of required and newly proposed voluntary Lower Basin and Mexico reductions will be 13.5% of their allocation (1.213 MAF/year). If Lake Mead storage declines to 6.0 MAF (23% of capacity), then the required and voluntary reductions would reach 21.9% (1.975 MAF/year). Citing concerns of hydropower failure, Reclamation's commissioner Touton informed Congress in June that 2 to 4 MAF of reductions below current commitments are needed. She did not specify how these reductions should be made among the states but reiterated the federal authority to act unilaterally if needed. All interstate and international shortage agreements will expire by 2026; a renegotiation process is underway.

THE UPPER BASIN SQUEEZE

In contrast to the Lower Basin and Mexico, the Upper Basin is not using its full 7.5 MAF/year apportionment. Between 2000 and 2020, Upper Basin consumptive uses averaged 3.7 MAF/year plus at least 0.7 MAF/year of reservoir evaporation. There are plans for additional development; the Upper Colorado River Commission (UCRC) ambitiously projects 5.4 MAF/year of Upper Basin uses by 2060, exclusive of reservoir evaporation (*11*). Additional Upper Basin water use threatens to expose the uncertainty around the meaning of the Compact's non-depletion obligation, which in turn could upset basin-wide water delivery expectations.

Under variable year-to-year hydrologic conditions but with unchanging mean flows, the non-depletion obligation is frequently interpreted as a firm requirement for the Upper Basin to deliver a fixed volume downstream. Under declining flows, however, the meaning of a non-depletion obligation becomes unclear. A fixed delivery requirement under declining flows puts the entire burden of climate change on the Upper Basin. A more nuanced view of this obligation—and one that would arguably align with the Compact negotiators' intentions—is that a delivery obligation applies only to intermittent drought risk with no underlying change in mean flows, not the substantively different and much larger risk of permanently reduced flows.

One thing is clear: Additional Upper Basin consumptive uses would decrease inflows to Lake Powell and reduce storage volumes in lakes Powell and Mead. Lower Basin users have indicated that they are unlikely to reduce their uses to stabilize reservoirs only to see new upstream uses nullify these conservation efforts.

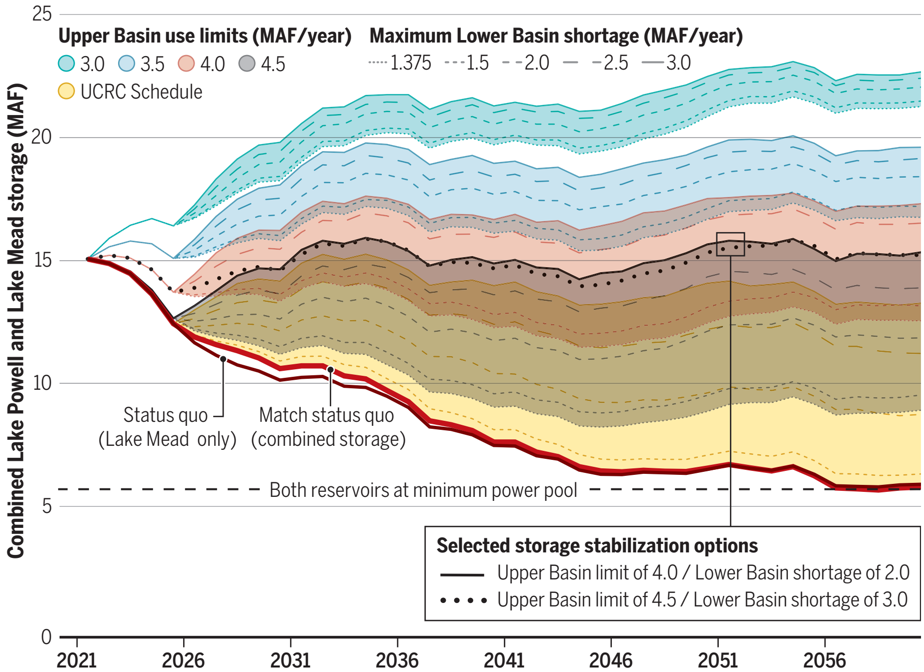
The Upper Basin emphasizes water use equality between the basins as envisioned in the Compact, yet 100 years later, that has not occurred. Economic and equity considerations also exist. The Lower Basin irrigates less than half the area irrigated by the Upper Basin, yet its agricultural sales are more than three times that of the Upper Basin (*13*). Because the loss of an established resource is arguably more harmful than never having developed one, proposed large new uses are being questioned, and existing uses are facing unprecedented reductions.

Given many possible solutions, our research identified combinations of Upper Basin consumptive use limitations and Lower Basin reductions to maintain reservoir storage levels if the Millennium Drought continues (*14*). If these measures allow the current storage levels to be maintained, then we consider the system to be stabilized under these specific, but highly relevant, runoff conditions. Although the focus of our study is a scenario of continued drought, the insights and approaches can be adapted to plan for other future scenarios.

We used Reclamation's Colorado River Simulation System (CRSS) (*15*), which has been used for all major basin-wide analyses and decisions on the Colorado for the past 20 years and will be used in forthcoming

Average combined storage assuming drought conditions continue

Average end-of-year combined Lake Powell and Lake Mead storage is shown, assuming hydrologic conditions of the Millennium Drought continue. Results show combined reservoir contents using a range of Upper Basin consumptive use limits (colored ribbons) along with a range of Lower Basin maximum consumptive use reductions (line styles) triggered when the combined storage falls below 15 million acre-feet (MAF). The status quo lines use the 2016 Upper Colorado River Commission (UCRC) projections and existing elevation-based shortage triggers. All water use and shortage values are annual volumes (MAF/year).



WHAT MUST BE DONE?

Considering alarming warming trends and the past 23 years of drought, water managers must face the possibility that recent conditions will persist or worsen. Tree ring studies indicate that longer past droughts have occurred (*12*). Up to half of the recent flow decline has been attributed to Upper Basin warming, and additional declines are likely with continued climate trends (*1*, *2*). Under these conditions and with reservoirs nearly depleted, simple mass balance dictates that consumptive uses must be reduced. But to what extent and how should reductions be allocated?

The Upper Basin emphasizes water use equality between the basins as envisioned in

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renegotiations. To represent future hydrologic conditions, we developed 100 possible scenarios by randomly resampling natural flows that occurred from 2000 to 2018 (*12*). Mean annual flow at Lee Ferry during this period was 12.4 MAF/year, and our resampling method maintained the annual variability (see supplementary materials).

The first management strategy we assessed is what would happen if current consumptive use reduction commitments by the Lower Basin and Mexico remain in place and uses in the Upper Basin increase as projected by the UCRC. This status quo scenario assumes continued drought conditions but otherwise uses all existing assumptions and logic in CRSS, including current obligatory and voluntary consumptive use reduction measures. Following Reclamation's previous studies, this scenario also assumes that the Upper Basin non-depletion obligation in the 1922 Compact is not invoked. Meeting this obligation would require the Upper Basin to curtail uses, a legally disputed issue owing to differing interpretations of when this obligation is triggered and to what extent Upper Basin uses must be curtailed. This issue is unlikely to be resolved in a time frame conducive to managing further drought. The result of the status quo scenario is sharply declining combined storage of lakes Mead and Powell (see the figure), which falls to levels that further threaten hydropower production and increases risk of disruptions to downstream water deliveries.

To evaluate the magnitude of potential policy changes to stabilize the system, we conducted a two-dimensional sensitivity analysis that mapped out a range of greater reductions in existing consumptive use by the Lower Basin and Mexico when reservoir storage diminishes, combined with a range of future Upper Basin uses. Our proposal deviated from current management practice in which Lower Basin shortages are based only on elevations of Lake Mead, a policy that reflects the institutional divisions between the Upper and Lower Basin. We instead used the combined storage of the two reservoirs to trigger consumptive use reductions to the Lower Basin and Mexico. Our approach acknowledges the hydrologic reality that water stored in both reservoirs is consumed almost exclusively in the Lower Basin and Mexico. Furthermore, the current operational policies that govern the storage balance between the reservoirs are likely to evolve in the forthcoming negotiations. We also assumed that the non-depletion obligation is not invoked if the Upper Basin limits future depletions. This removes the longstanding ambiguity over the meaning of the non-depletion obligation in exchange for defined Upper Basin use limits, providing both basins with less risk and more certainty.

To implement our approach, different combined storage trigger thresholds were iterated with varying Lower Basin and Mexico shortage volumes until a reasonable match with the status quo was discovered (see the figure). We then incrementally increased the consumptive use reductions to the Lower Basin and Mexico whenever the combined reservoir storage falls below 15 MAF. Reclamation's well-established CRSS model is thoroughly documented (*15*), and our adaptations are described in preceding work (*14*) and the supplemental materials.

If the Millennium Drought persists, then the combined storage under the status quo will decrease to 6 MAF (12% of total Mead and Powell storage) before it stabilizes. At this volume, either Glen Canyon Dam or Hoover Dam would stop generating hydropower. These impacts show reservoir contents averaged across conditions since 2000; exceptionally dry years such as 2020 and 2021 will have an even greater impact.

Current reservoir storage levels could, however, be stabilized if consumptive uses decrease under different scenarios (see fig. S1). If the Upper Basin commits to limit water uses to 4.5 MAF/year (60% of their 7.5 MAF/year allocation, approximately 0.8 MAF/year higher than recent use), then the Lower Basin and Mexico must commit to more than doubling their current maximum reductions in existing use to 3.0 MAF/year (see the figure and fig. S1). In this scenario, the Lower Basin and Mexico receive 66.7% of their allocation, nearly matching the Upper Basin percentage. If the Upper Basin limits their depletions to 4.0 MAF/year (53.3% of their allocation, 0.3 MAF/year higher than recent use), then the Lower Basin and Mexico would need to decrease uses by approximately 2.0 MAF/year to stabilize the reservoirs (see the figure and fig. S1), assuring 77.8% of their allocation. This is close to recently proposed maximum Lower Basin and Mexico commitments to reduce existing use, which would not be invoked until Lake Mead declines further by 3 MAF. Delaying these reductions until then would result in greater loss of storage and stabilization occurring at lower levels than shown in the figure.

Water management models such as CRSS are only one part of the difficult work needed to achieve real-world solutions. Resolving complex water supply problems in large transboundary basins also requires deep understanding of the social and economic implications of any proposed policies, along with political barriers to adoption. Such work is iterative and slow, adding to the difficulties and pressures faced by decision makers.

Our results show that although current policies are inadequate to stabilize the Colorado River if the Millennium Drought continues, various consumptive use strategies can stabilize the system. However, these measures must be applied swiftly. Although these concessions by both basins may seem unthinkable at present, they will be necessary if recent conditions persist. ■

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SUPPLEMENTARY MATERIALS

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