

## PERSPECTIVE



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# The Colorado River water crisis: Its origin and the future

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**Edited by:** Kelly Alley, Associate Editor, Wendy Jepson, Co-Editor-in-Chief and Jan Seibert, Co-Editor-in-Chief

**Abstract**

During much of the 21st century, natural runoff in the Colorado River basin has declined, while consumption has remained relatively constant, leading to historically low reservoir storage. Between January 2000 and April 2023, the amount of water stored in Lake Mead and Lake Powell, the two largest reservoirs in the United States, declined by 33.5 million acre feet (41.3 billion cubic meters). As of April 2023, total basin-wide storage was sufficient to support the 21st century average rate of basin-wide consumption for only 15 months. Runoff in spring 2023 is predicted to be large, providing a short-term reprieve. However, it will take four to five additional unusually wet years in succession to refill Lake Powell and Lake Mead if basin-wide water use remains unchanged. Increasing evapotranspiration and dry soils associated with global climate change makes such a scenario unlikely. To stabilize reservoir storage, basin-wide use needs to equal modern runoff. To recover reservoir storage, basin-wide use needs to decline even more. Based on 21st century average runoff, a 13%–20% decline in basin-wide use would allow for stabilization and some reservoir storage recovery. Future policy debate about reservoir operations will inevitably concern whether most, or all, reservoir storage should be in Lake Mead or in Lake Powell. The choice of one or the other will result in significantly different environmental and recreational outcomes for Glen Canyon and the Grand Canyon.

This article is categorized under:

Water and Life > Stresses and Pressures on Ecosystems

Human Water > Water Governance

Science of Water > Water and Environmental Change

**KEYWORDS**

Colorado River, ecosystems, water supply

Eric Kuhn is retired from his position as the General Manager.

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## 1 | INTRODUCTION

The crisis of dwindling water supply in the Colorado River basin (hereafter Basin) dominates today's media whose images and stories include the white “bathtub rings” surrounding Lake Mead and Lake Powell, exposed deltaic sediments at the head of each reservoir, fallowed farm fields, furrowed brows of worried farmers, and finger pointing among Basin state water managers about whose state should take the largest cuts in future water use. Charting a path forward requires understanding how we got to the present situation, identifying plausible options for managing the river in the future, and understanding the environmental consequences of managing the declining future water supply. Here, we describe how the present water crisis arose and some of the environmental consequences of the present water crisis and of future water management policy options.

## 2 | OVERVIEW

The Colorado River has long been known as America's Nile (LaRue, 1916). The river's headwaters are in the Rocky Mountains where most of the river's flow originates (Schmidt, Bruckerhoff, Salehabadi, & Wang, 2022). Administratively, the Basin is divided into three parts: Mexico, the Lower Basin in the United States, and the Upper Basin in the United States (Figure 1). The administrative demarcation between the Lower and Upper Basin, called Lee Ferry, is located approximately 2 mi (3 km) downstream from Lees Ferry in the canyon country of the southern Colorado Plateau.

In most years, no water flows to the Gulf of California, because the entire natural runoff of the Basin is consumed. The Colorado River is managed and operated under the US–Mexico Water Treaty and Minutes to that treaty, several



**FIGURE 1** Map showing the Colorado River basin, outlined in black, and areas served by trans-basin diversions, shown in hachured red. *Source:* Figure adapted from Reclamation (2012).

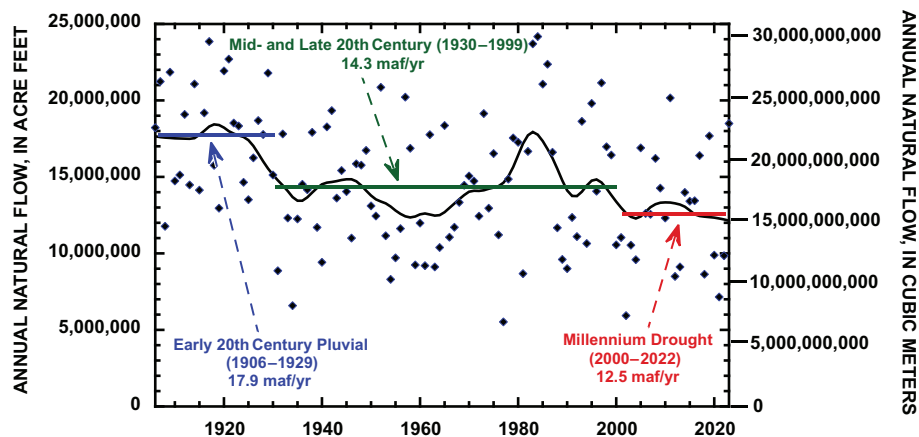
interstate compacts, federal laws, Supreme Court decisions and decrees, water delivery contracts, and regulatory guidelines collectively known as the Law of the River. The Colorado River Compact, that was signed in 1922 and became effective in 1929, is the cornerstone of the Law of the River. Much has been written about the evolution of the Law of the River and of the scientific basis for the allocation agreements that are now in place (Hundley, 1975; Kuhn & Fleck, 2019).

### 3 | THE WATER CRISIS OF THE 21ST CENTURY

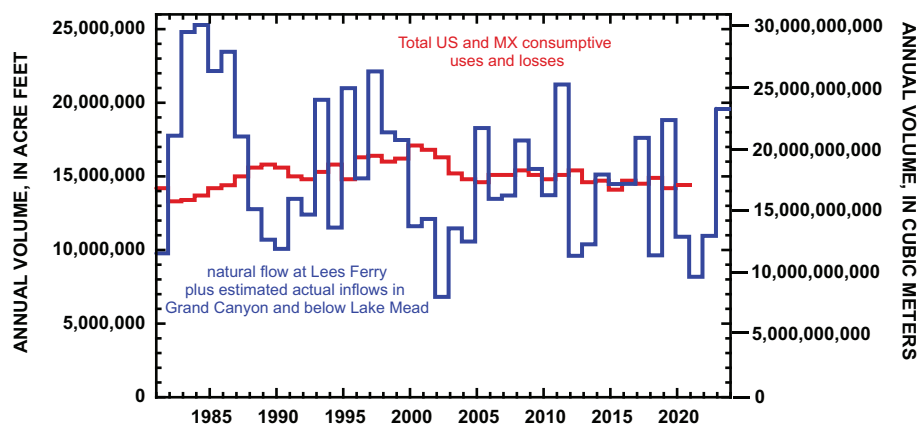
Data concerning available water supply and consumptive uses were assembled from U.S. Geological Survey (USGS) and Bureau of Reclamation (hereafter, Reclamation) sources (see Notes for more details). The water supply available for consumptive use is the sum of the estimated natural flow of the Colorado River at Lees Ferry, the estimated natural flow of the Paria River, and the actual inflow of Lower Basin tributaries, including inflows from springs and spring-fed tributaries in Grand Canyon (Wang & Schmidt, 2020). The Gila River is a large tributary that enters the Colorado River downstream from Imperial Dam near Yuma, and runoff in this tributary is not part of the shared water supply of the Colorado River, based on current interpretation of the Law of the River (Kuhn & Fleck, 2019).

We divided the 117 years of natural flow estimates into three periods: (1) the Early 20th Century Pluvial period when runoff was highest, (2) the Mid and Late 20th Century (1930–1999), and (3) the 21st century, often called the Millennium Drought (K. G. Wheeler et al., 2022). During the Millennium Drought (2000–2023), the average annual natural flow at Lees Ferry was 12.5 million af/yr (15.4 billion m<sup>3</sup>), 13% less than the average annual natural flow between 1930 and 1999 and 30% less than the annual flow between 1906 and 1929 (Figure 2). Inflows to the Colorado River downstream from Lees Ferry are measured as the difference between the annual flow at Lees Ferry (USGS gage 09380000) and the annual flow near Peach Springs (USGS gage 09404200), 225 miles (375 km) downstream. The average increase in flow between these two gages was 0.767 million af/yr (0.946 billion m<sup>3</sup>) between WY2000 and WY2021, the most recent year of available data. Reclamation estimates that 0.338 million af/yr (0.417 billion m<sup>3</sup>) enters the Colorado River between Lake Mead and Imperial Dam, near Yuma (J. Prairie, Chief, Upper Colorado Basin Research and Modeling Group, Reclamation, written commun., 2022). The average annual water supply of the Colorado River at Imperial Dam, based on adding these different sources of water, was 13.6 million af/yr (16.8 billion m<sup>3</sup>) between WY2000 and WY2023.

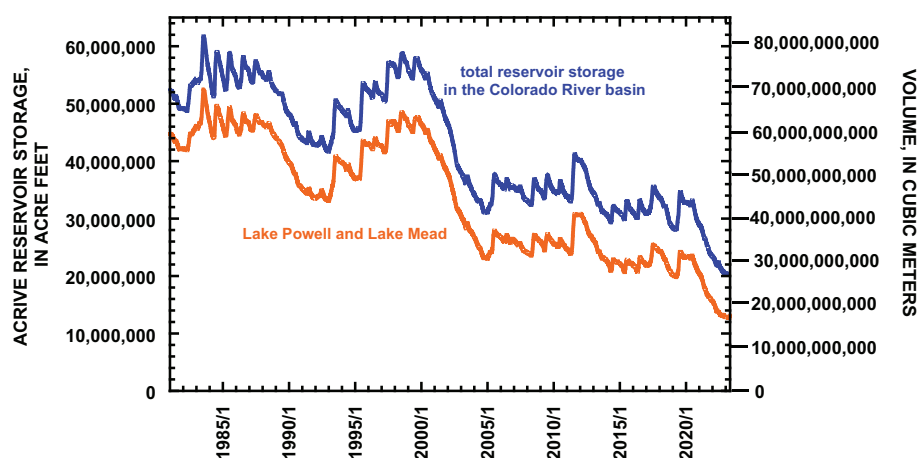
The present water crisis has arisen, because average Basin-wide consumptive uses exceeded the natural supply throughout the 21st century. Between calendar year (CY) 2000 and CY2020 (the most recent available year of Upper Basin data), consumptive uses and losses were 15.1 million af/yr (18.6 billion m<sup>3</sup>), approximately 1.5 million af/yr (1.9 billion m<sup>3</sup>) more than the average supply for the same period (Figure 3). The overuse of water was sustained for more than two decades by significantly draining of reservoir storage, especially from Lake Mead and Lake Powell where more than 80% of the total Basin-wide reservoir storage capacity exists. Between January 2000 and April 2023, the combined



**FIGURE 2** Graph showing annual natural flow of the Colorado River at Lees Ferry, as estimated by Reclamation. Horizontal lines are the average flow for the indicated time periods, and the black line is a smoothing curve based on the locally weighted least squared error method for the nearest 15% of the data set. These data include revised provisional estimates for 2021, 2022, and 2023 released by Reclamation on 17 April 2023. All data are for water years.



**FIGURE 3** Graph showing consumptive use of the Colorado River in the United States and Mexico in relation to the natural supply of water from the Upper Basin, Grand Canyon, and other Lower Basin inflows. Comprehensive Basin-wide consumptive uses and losses data are only available through 2020.



**FIGURE 4** Graph showing active storage in all large reservoirs of the Colorado River basin and of the combined contents of Lake Mead and Lake Powell. *Source:* Data assembled from Bureau of Reclamation (2023, [https://www.usbr.gov/uc/water/hydrodata/reservoir\\_data/site\\_map.html](https://www.usbr.gov/uc/water/hydrodata/reservoir_data/site_map.html)).

contents of Lake Mead and Lake Powell declined by 33.5 million af (41.3 billion  $\text{m}^3$ ) (Figure 4), and those two reservoirs are now 30% of capacity.

Partial draining of Lake Mead and Lake Powell primarily occurred during two episodes. The first episode was between January 2000 and December 2007, when use exceeded supply in every year except 2005 even though Basin-wide use declined from 17.1 million af/yr (21.1 billion  $\text{m}^3$ /yr) to 15.1 million af/yr (18.6 billion  $\text{m}^3$ /yr; Figure 3). Storage in Lake Mead and Lake Powell declined by 22.2 million af (27.4 billion  $\text{m}^3$ ) during this period, because water supply averaged 11.8 million af/yr (14.6 billion  $\text{m}^3$ /yr). During the next 12 years, supply and use were approximately equal, and there was no recovery of reservoir storage (Figure 4). Runoff was very low in WY2020 through WY2022, averaging 9.3 million af/yr (11.5 billion  $\text{m}^3$ /yr), while use remained relatively constant. As a result, Mead and Powell lost an additional 10.7 million af (13.2 billion  $\text{m}^3$ ) between January 2020 and April 2023, taking the system to its present crisis. Reclamation projects that large snowmelt inflow in 2023 will recover approximately 5.6 million acre feet (6.9 billion  $\text{m}^3$ ) of reservoir storage by mid-summer.

#### 4 | WHO USES THE WATER AND WHERE?

In the Upper Basin, most use occurs in the agricultural valleys of western Colorado and southwestern Wyoming, the Uinta Basin and Castle Valley of Utah, and the San Juan River valley of New Mexico (Robison & Schmidt, 2022).

Municipal users are primarily outside of the Basin east of the Continental Divide between Cheyenne and Pueblo, immediately west of the Basin in the Salt Lake and Utah Lake valleys, and in the Rio Grande valley of New Mexico (Figure 1). These users are supplied by trans-basin diversions.

Water users in the Lower Basin and Mexico include Native American and non-Indian irrigation districts along the Lower River and a large part of the former Colorado River delta near Yuma and in the Coachella, Imperial, and Mexicali Valleys. Some of Mexico's allocation of Colorado River water is transferred out of the Basin to Tijuana and Ensenada. Some of California's allocation is transferred out of the Basin to municipal users in Los Angeles, San Diego, and surrounding areas. US metropolitan areas within the Basin that are served by the river include Phoenix, Tucson, and Las Vegas.

Less than half of the total Basin-wide uses are in the Upper Basin (Table 1). The largest water use occurs in California, and this amount was almost as much as the total consumed in the Upper Basin. The primary user of water in the Upper Basin is agriculture; 58% of the total water used in the Upper Basin was by agriculture. The other uses were in reservoir evaporation (20%), trans-basin diversions out of the Basin (17%), and by municipalities and industry (6%) (Robison & Schmidt, 2022).

## 5 | IMPACTS OF RIVER REGULATION, CONSUMPTIVE USES AND THE CURRENT CRISIS ON RIVER ECOSYSTEMS AND RIVER RECREATION IN THE BASIN

Removal of water from the Basin's rivers, the existence of large reservoirs and dams, and modification to the annual, seasonal, and daily patterns of flow have all led to dramatic changes in the aquatic and riparian ecosystems of the Basin (Schmidt, Bruckerhoff, Salehabadi, & Wang, 2022; Schmidt, Bruckerhoff, Wang, & Yackulic, 2022). The degree of ecosystem modification, and the opportunities for ecosystem rehabilitation, differ significantly throughout the Basin. Here,

**TABLE 1** Summary of consumptive uses and losses, 2000–2020.<sup>a</sup>

	Average annual uses or losses, in millions of acre feet per year	Average annual uses or losses, in billions of cubic meters per year
Upper Basin		
Arizona	0.0336	0.0414
Colorado	2.15	2.65
New Mexico	0.405	0.500
Utah	0.900	1.11
Wyoming	0.402	0.496
CRSP evaporation <sup>b</sup>	0.688	0.849
Total	4.58	5.65
Lower Basin		
Arizona	2.69	3.32
California	4.46	5.50
Nevada	0.260	0.321
Reservoir evaporation	0.997	1.23
Evapotranspiration along the Lower River between Davis Dam and Yuma	0.525	0.648
Total	8.93	11.0
Mexico	1.57	1.94
Basin-wide total	15.1	18.6

<sup>a</sup>Consumptive uses are those reported by Reclamation in Colorado River System Consumptive Uses and Losses Reports, Upper Colorado River Basin Consumptive Uses and Losses Reports, and Colorado River Accounting and Water Use (Arizona, California, and Nevada) Reports, all available at <https://www.usbr.gov/uc/envdocs/plans.html> or <https://www.usbr.gov/lc/region/g4000/wtracct.html>. Agricultural consumptive use is calculated by Reclamation as diversions minus return flows (Bruce et al., 2018). Lower Basin uses do not include those in Colorado River tributaries.

<sup>b</sup>Colorado River Storage Project reservoirs, including gross evaporation from Lake Powell.

we briefly summarize the geography of ecosystem modification and the ways in which ecosystem modification intersect with water use and storage decisions, working upriver from the highly modified Colorado River delta.

The constraints on improving ecosystem conditions in the Colorado River delta are formidable, because most of the modern channel is dry. However, a binational collaboration of nongovernment organizations (NGOs), federal and state agencies, and universities have created patches of native vegetation that attract birds and other wildlife. Water is routed to these restoration sites using the existing network of Mexican irrigation canals (Kendy et al., 2017; Pitt et al., 2017). Opportunities to recover additional areas of native riparian vegetation and to reestablish base flows depend on negotiations focused on revising reservoir operating and shortage agreements, including a new Minute of the binational water treaty, and the ability of the NGOs to raise funds to support their on-the-ground restoration work.

Much of the 600 miles (1000 km) between Yuma and Hoover Dam has been converted to reservoirs or has been channelized and leveed; other parts of the channel are incised below the former bed elevation (Borland & Miller, 1960; Schmidt, Bruckerhoff, Salehabadi, & Wang, 2022). Reservoir releases from Lake Mead are set to meet the needs of downstream water users and have completely changed the natural flow regime. Environmental mitigation in this part of the river is conducted by the Lower Colorado River Multi-Species Conservation Program, a program that includes representatives from federal and state agencies, NGOs, and tribal governments and is focused on the creation of new habitat for threatened or endangered species. Because most of the floodplain is disconnected from the modern river, patches of natural riparian habitat are primarily maintained by pumping (Rubin et al., 2019), and changes in the flow regime caused by reservoir reoperations are unlikely to affect water availability for these pumping schemes.

Whereas environmental conditions between Yuma and Hoover Dam are mostly decoupled from reservoir operations, the future of the Grand Canyon ecosystem is tightly linked with decisions regarding reservoir operations and water use. In the context of the Law of the River, flow through Grand Canyon represents the delivery of water from the Upper Basin to the Lower Basin. In the context of environmental conditions in Grand Canyon, the magnitude of annual volumes as well as the amount of water stored in both reservoirs are significant drivers of ecosystem conditions.

When water storage in Lake Powell is less than 4.0 million af (4.93 billion m<sup>3</sup>) (16% of capacity), the elevation of the reservoir is too low to safely withdraw water through the penstocks into the turbines of the power plant. The capacity of the turbines is approximately 31,000 ft<sup>3</sup>/s (approximately 880 m<sup>3</sup>/s). If water cannot be withdrawn through the penstocks, the only way to release water is through the river outlets whose maximum capacity is between 5000 and 15,000 ft<sup>3</sup> (140 and 420 m<sup>3</sup>/s), depending on reservoir elevation. When reservoir storage drops below the elevation of the river outlets, no water can be released downstream (i.e., dead pool). As the total annual release decreases, it will be more difficult to provide sufficient base flows that ensure safe river navigation by large, motorized rafts through Grand Canyon's rapids. Low water storage in Lake Powell also jeopardizes implementation of controlled floods (administratively called High Flow Experiments) (Bruckerhoff et al., 2022). If reservoir releases are steady without hydropeaking or controlled floods, vegetation encroachment onto sand bars used as campsites is likely (Sankey et al., 2015).

Ecosystem impacts also will be caused by changes in the temperature of the released water (Dibble et al., 2021). Until 2000, releases from Lake Powell ranged between 8 and 12°C, because the penstock intakes were more than 100 ft (30 m) below the surface of the thermally stratified reservoir (Vernieu et al., 2005). Native species that relied primarily on the mainstem Colorado River for spawning and rearing, or that needed to migrate to distant spawning or nursery habitats, were extirpated. Native fish that persisted in the cool mainstem water relied on warmer tributaries for spawning and rearing. Nonnative rainbow trout were introduced to provide a recreational fishing experience in the Glen Canyon Dam tailwater where water temperature was the coolest.

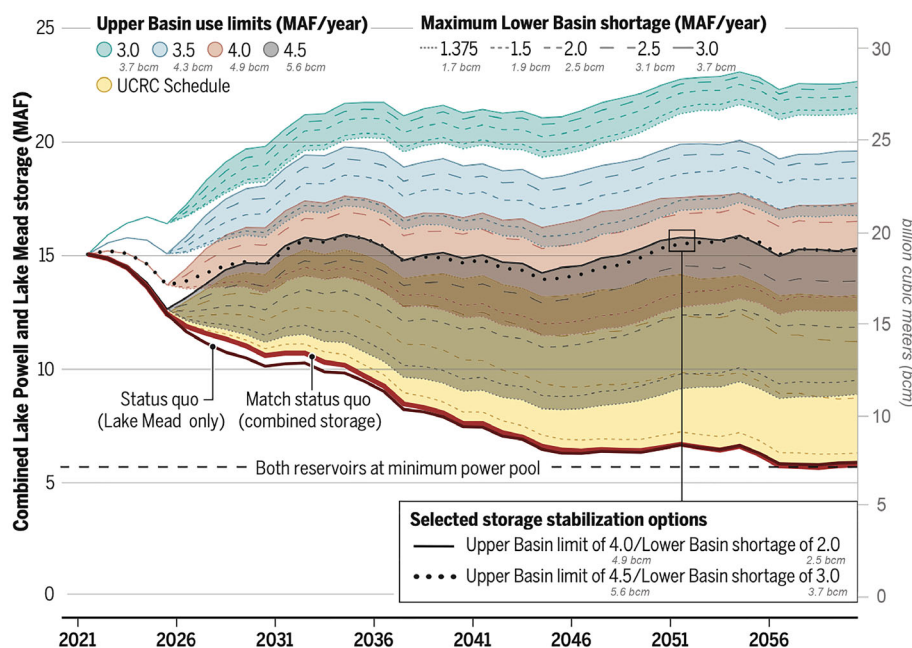
During the extended drawdown of Lake Powell during the Millennium Drought, reservoir release temperatures increased, because water was drawn closer to the reservoir's surface. Until 2020, these increases in temperature were modest and had only minimal impacts to the tailwater rainbow trout fishery. Warming of the released water as it moves downstream was sufficient to allow native fish populations in western Grand Canyon to increase greatly (van Haverbeke et al., 2017). In 2021, reservoir release temperatures increased dramatically, peaking at 21.4°C in the tailwater in September 2022, more than 4°C warmer than any recorded water temperature in the previous 50 years. These warm temperatures threaten the viability of the recreational rainbow trout fishery (Korman et al., 2022). Lowered reservoir levels also increased the rate at which warm-water invasive fish species that were never part of the post-dam Grand Canyon fish community were passed from Lake Powell into the river and created sufficiently warm temperatures for these species to reproduce. These species include smallmouth bass, which is considered the greatest threat to native fish in the Upper Basin and was observed reproducing in the tailwater of Lake Powell for the first time in 2022 (National Park Service, unpublished data). Persistent low reservoir storage will result in warm releases from Lake Powell that are likely to permanently shift the aquatic ecosystem of the Grand Canyon away from the fish community typical of the past 50 years.

Upstream from Lake Powell, each of the three headwater branches retains a relatively natural flow regime with a distinct spring snowmelt flood, but the modern flow of the San Juan River is much less than conditions in the mid-20th century (Schmidt, Bruckerhoff, Salehabadi, & Wang, 2022). Measured flow in the 21st century (WY2001–WY2022) of the Colorado River near Cisco (USGS gage 09185000) and of the Green River at Green River (USGS gage 09315000) was 74% and 84%, respectively, of the mean annual flow of the mid-20th century (1930–1949). In contrast, modern flow of the San Juan River near Bluff (USGS gage 09379500) was only 51% of the mean annual flow of the mid-20th century. The flow of some tributaries in the Upper Basin has been greatly decreased by trans-basin diversions or large diversions to support irrigated agriculture. These streams include small tributaries to the upper Colorado River (e.g., St. Louis and Ranch Creeks whose flow is 60% of mid-20th century averages), the Dolores River (39% of mid-20th century flow), Duchesne River (46% of mid-20th century flow), and San Rafael River (52% of mid-20th century flow). These streams have significantly narrowed (Fortney, 2015; Gaeuman et al., 2005), and aquatic habit has been degraded, adversely affecting native fish populations (Pennock et al., 2022).

## 6 | THE FUTURE

The Colorado River cannot provide a sustainable water supply unless consumptive use is reduced to match the declining supply. Additionally, recovery of reservoir storage, such as will occur this spring, would provide security when a string of dry years inevitably occurs again. Despite large inflow predicted from the substantial 2022–2023 Rocky Mountain snowpack, Lake Powell and Lake Mead will not refill in 1 year, because the reservoirs have been drawn down so far. Reclamation predicts that the 2023 inflow will be 14.2 million af (17.5 billion m<sup>3</sup>), greater than annual inflow in any year since 2011. An additional 4–5 years of similar inflows will be needed to refill Lake Powell and Lake Mead, assuming Basin-wide consumptive uses remain as they were between 2016 and 2020. Such a string of high runoff years is highly unlikely.

Although it is easy to articulate the general principal that use must match supply, it is more difficult to precisely define the magnitude of the needed reduction. K. Wheeler et al. (2021) and K. G. Wheeler et al. (2022) explored the implications of persistent low Basin runoff under different scenarios of reduced use. Reservoir storage can be stabilized if Basin-wide consumptive use is reduced to match runoff, and greater reduction in use will result in greater average



**FIGURE 5** Graph showing average end-of-year combined Lake Powell and Lake Mead storage, 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 af. The status quo lines use the 2016 Upper Colorado River Commission projections and existing elevation-based shortage triggers. All water use and shortage values are annual volumes, in million af/yr. Source: Figure from K. G. Wheeler et al. (2022).

carry-over storage in Lake Mead and Lake Powell (Figure 5). Assuming persistence of conditions like those of the past 20 years, use would have to be reduced by 1.5 million af/yr (2 billion m<sup>3</sup>/yr) to match supply, but an additional 1 million af/yr (1 billion m<sup>3</sup>/yr) of reduction would be needed to recover lost reservoir storage. Thus, to stabilize the reservoirs, Basin-wide use would have to be reduced to 12–13 million af/yr (15–16 billion m<sup>3</sup>/yr), 13–20% less than the average during the 21st century. Reduction in Basin-wide use by 2–3 million af/yr (3–4 billion m<sup>3</sup>/yr) is equivalent to eliminating the combined consumptive use of Colorado and Utah or the total use of California.

In May 2023, the Lower Basin states proposed to temporarily reduce their consumptive use by 1 million af/yr (1.2 billion m<sup>3</sup>) through 2026, and this reduction will be subsidized by \$1 billion of funds made available from the Inflation Reduction Act of 2022. There is widespread hope that a consensus among the Basin states can be reached regarding permanent cuts taken within the U.S. but it is uncertain whether Mexico will absorb shortages greater than those already agreed to in Minute 323 of the binational water treaty. The 2022–2023 snowpack may provide short term relief and time for negotiations among states, however, the water crisis will not ease until Basin-wide use drops to match average modern runoff—that is, until the Basin begins to use water at a rate similar to its provision.

The fixed allocations for each state dictated by the Law of the River rely on the assumption that the water supply available to be distributed has a long-term average that is unchanging. The assumption of stationary runoff conditions is no longer applicable, and climate scientists project additional decline in runoff of 1–3 million af/yr (1.2–3.7 billion m<sup>3</sup>/yr) by 2050 as the climate warms (Udall & Overpeck, 2017). Negotiations about how to allocate a declining supply while assuming that each state is to receive the same fixed allocation that it received in the past is untenable. Kuhn and Jacobs (2022) argued that allocations among the Basin states should be on a proportional basis. Such a policy change would be a significant departure from the present Law of the River, but we see no alternative to a new paradigm for water allocation.

Because agriculture uses the most water in the Basin, water use can only be significantly reduced if there are large reductions in agricultural use. To date, reductions in use have primarily been achieved by market transactions involving improvements in irrigation efficiency and transfers to urban uses, such as has occurred in California. Consideration might also be given to identifying which irrigated crops in which regions provide the highest economic return or are most important to meeting national food needs. Alfalfa and pasture grasses, used as livestock feed, are the primary crop in much of the Basin, and use of large amounts of water for this purpose has been questioned (Richter et al., 2020).

Municipal water use will almost certainly need to be reduced, and the greatest opportunities to reduce municipal use are likely to be in mid-sized urban areas. Richter (2022) demonstrated that total water use by the largest cities served by Colorado River, including Los Angeles, San Diego, Orange County, Las Vegas, Phoenix, and Denver, has significantly declined due to large decreases in per capita use. However, there are significant opportunities to reduce water use in mid-size urban areas whose population is between 100,000 and 1,000,000. Total water use by these communities increased due to large population growth and insignificant reductions in per capita water use during the last two decades.

The magnitude of the needed reductions in use will inevitably inspire consideration of how to augment water supply, such as by recycling gray water or desalination of ocean water. Both strategies are employed in coastal California and are being considered in other cities, but these technologies are not available at a scale necessary to support irrigated agriculture and are energy intensive. Proposals were made in the past to divert the Yukon, Columbia, Missouri, or Mississippi Rivers to the Colorado River Basin, but the costs of such projects are generally viewed as prohibitive.

The likelihood that the combined storage in Lake Mead and Lake Powell will rarely exceed 50% of capacity (K. G. Wheeler et al., 2022) suggests a need to evaluate the environmental and hydropower trade-offs associated with policy alternatives that emphasize storage of water in Lake Powell or in Lake Mead. Although Lake Powell is in the Upper Basin and Lake Mead in the Lower Basin, there are no significant uses in the 400 miles (670 km) of the Grand Canyon separating the two reservoirs. For purposes of water management, it does not matter whether water is stored in Lake Powell or in Lake Mead. Maintaining less storage in Lake Powell and emphasizing storage in Lake Mead would allow the pre-dam landscape of Glen Canyon to recover from 50 years of inundation. Emphasizing storage in Lake Powell would allow continued hydropower production at Glen Canyon Dam, allow periodic release of designer flows to augment sandbars and the aquatic food base in Grand Canyon, and result in a return to cooler reservoir releases that might stabilize the existing Grand Canyon fish community. However, emphasizing storage in Lake Powell would re-inundate valued portions of Glen Canyon that have recently been exposed.

Another option for reservoir management is to entirely abandon reservoir storage in Lake Powell by drilling river-level diversion tunnels around Glen Canyon Dam. Diversion tunnels could be designed with emergency valves that could be closed in the unlikely event that large runoff filled Lake Mead and storage in Lake Powell was needed. Such

an action would restore a natural stream flow and sediment regime to the Grand Canyon and might benefit some pre-dam elements of the Colorado River ecosystem. This management option would also lead to increases in water temperature and changes in the fish community, including elimination of the nonnative, tailwater trout fishery. Such a strategy would increase turbidity and favor some nonnative fish species like carp and channel catfish over other nonnative fish species such as smallmouth bass. Carp and channel catfish coexisted with native fish species in the Grand Canyon for decades prior to construction of Glen Canyon Dam (Mueller & Marsh, 2002) and may represent a lesser threat to the continued persistence of native fish species than do smallmouth bass.

Most of the Upper Basin's river ecosystems are maintained by stream flow destined for the Lower Basin. It is unlikely that Upper Basin water use will significantly increase (K. Wheeler et al., 2021), and Upper Basin ecosystems are likely to be relatively unaffected by impending renegotiations about Basin-wide water allocations. The few Upper Basin tributaries that are significantly dewatered by agricultural or trans-basin diversions could be rehabilitated by dedicating environmental flows to them.

## 7 | CONCLUSIONS

The Colorado River water-supply crisis is real and on-going. Although the root cause of the problem is declining runoff in a warming climate, the proximate cause is society's inability to adaptively respond to declining runoff that has been occurring for more than 20 years. There is no longer an opportunity to sustain overconsumption by drawing down reservoir storage, because the reservoirs are nearly empty, and large runoff in 2023 will not eliminate shortage conditions. If Basin-wide long-term average water consumption is reduced by 13%-20%, reservoir storage could be maintained and potentially increased, providing the buffer against interannual variability in water supply that has supported economic and population growth in the Basin. Over longer time scales, water-supply allocations will likely need to continue to be adaptive and responsive to changes in runoff under future climate change. It is likely that average storage in Lake Mead and Lake Powell will only be 50% of capacity, and decisions about which reservoir to preferentially assign storage will have profound ecosystem impacts on Grand Canyon and portions of Glen Canyon. Rehabilitation of dewatered ecosystems in the Colorado River Delta and in some Upper Basin tributaries will require continued commitment among users to protect existing environmental flows and to acquire additional water for the environment of an overallocated system.

## NOTES

Data used to calculate natural available supply and consumptive uses and losses include annual average flow at gaging stations reported by the USGS, estimates of natural flow made by Reclamation (<https://www.usbr.gov/lc/region/g4000/NaturalFlow/provisional.html>), consumptive uses reported by Reclamation in reports applicable to the Upper Basin (<https://www.usbr.gov/uc/DocLibrary/reports.html>) or to the Lower Basin and Mexico (<https://www.usbr.gov/lc/region/g4000/wtracct.html>), and internal Reclamation spreadsheets that revise some published records (J. Prairie, written commun., 2022). Water is also “lost” as reservoir evaporation and in evapotranspiration by riparian vegetation. Reclamation estimates evaporative losses from all reservoirs ([https://www.usbr.gov/uc/water/hydrodata/reservoir\\_data/site\\_map.html](https://www.usbr.gov/uc/water/hydrodata/reservoir_data/site_map.html)) and estimates evapotranspiration losses downstream from Hoover Dam (J. Prairie, written commun., 2022). Natural flow is the estimated river flow in the absence of any human activity. Data concerning calendar year annual consumptive uses and losses were added together to estimate the total basin-wide uses of water between 1981 and 2020, which is the most recent year that comprehensive data are available.

## AUTHOR CONTRIBUTIONS

**John C. Schmidt:** Conceptualization (lead); formal analysis (lead); funding acquisition (lead); writing – original draft (lead). **Charles B. Yackulic:** Conceptualization (supporting); formal analysis (supporting); writing – original draft (supporting). **Eric Kuhn:** Conceptualization (supporting); writing – original draft (supporting).

## FUNDING INFORMATION

None of the authors received specific funding to write this paper.

## CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

## DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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**How to cite this article:** Schmidt, J. C., Yackulic, C. B., & Kuhn, E. (2023). The Colorado River water crisis: Its origin and the future. *WIREs Water*, e1672. <https://doi.org/10.1002/wat2.1672>