JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 58, No. 5 AMERICAN WATER RESOURCES ASSOCIATION October 2022

Featured Collection Introduction: Severe Sustained Drought Revisited: Managing the Colorado River System in Times of Water Shortage 25 Years Later — Part I

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In the 1970s, Water Resources Research institutes and centers from Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming formed the Powell Consortium (in honor of John Wesley Powell) to work on water resource challenges in the Colorado River and Great Basin regions. Collaborative research supported by the Consortium led to a set of studies published more than 25 years ago in a special issue of the *Water Resources Bulletin*, which later became the *Journal of the American Water Resource Association (JAWRA)*. That special issue, "Severe Sustained Drought: Managing the Colorado River System in Times of Water Shortage," brought together expertise from diverse fields: anthropology, dendrochronology, economics, engineering, geography, hydrology, law, and sociology to examine potential economic and environmental impacts of extreme, prolonged drought in the Colorado River Basin.

Historically, surface water availability from the Colorado River Basin has been measured in terms of annual native flows at Lees Ferry, just below Glen Canyon Dam. The Colorado River Compact of 1922 and the 1944 Water Treaty with Mexico allocated 7.5 million acre feet (maf) each to the Upper and Lower Basins and 1.5 maf to Mexico for a total of 16.5 maf (Table 1). At the time of the Sustained Severe Drought (SSD) study, historical measurements placed flows at only 15.2 maf, while tree ring reconstructions over a longer period placed flows at just 13.5 maf (Stockton and Jacoby 1976; Young 1995). Thus at the time of that SSD study, it was recognized that the Colorado River was over-allocated, even absent drought.

Tree-ring research indicated the Basin had, long ago, experienced longer and more severe droughts than any known in modern records; the most severe multi-decade drought occurred in the 1500s. The organizing device for the different studies was a hypothetical multi-decade drought based on, but not identical to, this historically severe drought. The SSD created a Colorado Rearranged Severe Drought scenario by assuming flow reductions were moved to the beginning of the time frame, with declines increasing every year so that annual flows bottomed out in the 16th year (Tarboton 1995). The 16-year average of flows was 9.6 maf. This rearranged scenario served as the basis for SSD analysis.

This special issue considered the questions of, if such a drought began in the 1990s, what would be the impacts on the hydrological system, including operation and management of the federal reservoir systems? What would be the economic and environmental impacts of these hydrologic shocks and how would they be conditioned by existing water laws and institutions? What types of legal and policy responses might be needed to ameliorate negative drought impacts?

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Citation: Frisvold, G.B., L.M. Fernandez, F. Lehner, S.A. McAfee, S. Megdal, E. Payton, J. Schmidt, J. Vano, and C. Woodhouse. 2022. "Featured Collection Introduction: Severe Sustained Drought Revisited: Managing the Colorado River System in Times of Water Shortage 25 Years Later — Part I." *JAWRA Journal of the American Water Resources Association* 58 (5): 597–603. https://doi.org/10.1111/1752-1688.13062.

TABLE 1. Timeline of policies and events affecting Colorado River management.

1908	*Winters v. United States* Supreme Court decision established priority dates of Indian water rights as the date of reservation formation. Consequently, Indian water rights are generally senior to non-Indian rights and uses from subsequent water projects
1922	Colorado River Compact allocated 7.5 maf each of Colorado River water annually to Upper and Lower Basin states
1928	Boulder Canyon Project Act authorized construction of Boulder (now Hoover) Dam, creating Lake Mead, and the All-American Canal delivering Colorado River water to California's Imperial Valley. To Lower Basin states, allocated 4.4 maf to California, 2.8 maf to Arizona, and 0.3 maf to Nevada, with any surplus divided among them
1933	Hoover Dam completed
1944	United States-Mexico Treaty on Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande. Entrusted the binational International Boundary And Water Commission (IBWC) to address border water and quality problems. Guaranteed 1.5 maf deliveries of Colorado River water to Mexico
1948	Upper Colorado River Basin Compact allocated Colorado River water to Upper Basin states; Colorado (3.855 maf), Utah (1.714 maf), Wyoming (1.043 maf), New Mexico (0.838 maf), and Arizona 50,000 af. Established the Upper Colorado River Commission to coordinate operations and positions of Upper Basin states
1956	Colorado River Storage Project Act of 1956 authorized construction of Glen Canyon, Flaming Gorge, Navajo, Curecanti Dams, and other Upper Basin dams and storage reservoirs
1963	Glen Canyon Dam completed
1963	*Arizona v. California* Supreme Court decision held that the Colorado River Compact addressed only Colorado River mainstem waters and reaffirmed Arizona's right to annual allocation of 2.8 maf of Colorado River water. Established the Secretary of the Interior as the water master for the Lower Basin
1968	Colorado River Basin Project Act authorized the Central Arizona Project to convey Colorado River water to Phoenix, Tucson, and agricultural areas of Central Arizona
1973	IBWC Minute 242 between the U.S. and Mexico established maximum salinity limit of Colorado River water delivered to Mexico
1993	The backbone aqueduct system of the Central Arizona Project (CAP), from Lake Havasu on the Colorado River to its terminus near Tucson, declared substantially complete beginning transfer of Colorado River water to Central Arizona
2003	Under the Quantitative Settlement Agreement (QSA) California agreed to reduce its use of Colorado River water from 5.2 maf to the 4.4 maf required under the Compact. Provision included large-scale, agriculture-to-urban water transfers. California committed to environmental mitigation and restoration of the Salton Sea
2004	Arizona Water Settlements Act included water rights settlements for the Gila River Indian Community (GRIC), and the Tohono O'odham Nation. Roughly half of CAP's annual allotment would be available to Indian tribes in Arizona, at a higher priority than most other uses. It also settled litigation and lowered payment obligations of some non-Indian CAP water users, but in exchanged reduced their access to some CAP supplies after 2030
2007	Colorado River Interim Guidelines for Lower Basin Shortages and the Coordinated Operations for Lake Powell and Lake Mead established tiers of reduced Colorado River allocations to the Lower Basin based on elevations of Lake Mead
2012	IBWC Minute 319 provided water for environmental flows for the Colorado River Delta for restoration and scientific study. This included a one-time Pulse Flow and a smaller Base Flow for environmental restoration, delivered at lower rates over a longer time frame within Mexico
2014	Pilot System Conservation Program undertaken by Reclamation and basin water supply agencies to fund voluntary conservation projects and reductions of water use to maintain water in Lake Mead
2017	IBWC Minute 323 permitted Mexico to store Colorado River water in U.S. reservoirs. Provides for funding and water allocations for Colorado River Delta restoration in Mexico
2019	Drought Contingency Plans finalized. Under the Upper Basin Plan, states agreed to take steps to keep elevations at Lake Powell above the minimum elevation needed to produce hydropower. Under the Lower Basin Plan, states agreed to additional cutbacks in their Colorado River allocations, based on elevations at Lake Mead
2021	Secretary of the Interior declares first-ever Tier 1 shortage for Colorado River operations, requiring a 0.512 maf reduction of Colorado River supplied to Central Arizona in 2022
2022	Bureau of Reclamation calls on Basin States to develop plans to reduce water use to provide an additional 2–4 million acre-feet of water in 2023 to protect critical elevations at Lake Powell and Lake Mead. Reclamation declares a Tier 2a Shortage for the Colorado River for 2023, requiring reductions of annual apportionments of 592,000 acre-feet from Arizona, 25,000 acre-feet from Nevada, and 104,000 acre-feet from Mexico

(continued)

The original SSD project and the publications that arose from it have shaped thought and encouraged multi-disciplinary research on drought and water scarcity in the United States (U.S.) Southwest. To honor the 25th Anniversary of the publication of the original SSD special issue, this *JAWRA* Featured Collection: *Severe Sustained Drought Revisited: Managing the Colorado River System in Times of Water Shortage 25 Years Later* will span two issues of *JAWRA*. It is also the 100th anniversary of the Colorado River Compact of 1922. Table 1 summarizes salient events in the history of Colorado River Management from the Compact to the present. While MacDonnell et al. (1995) provided a legal and institutional history of the set of laws, treaties, regulations, and agreements collectively known as the Law of the River up to the original SSD study, MacDonnell (2021) and Stern and Sheikh (2021) provide a concise update to current times.

As to be expected in future scenario planning, some results of the SSD proved quite prescient. In other cases, the current realities and near-term prospects are quite different from those envisioned in the original SSD study. Kenney et al. (2010) provide more discussion on this point. The main original findings and subsequent events are as follows:

1. The SSD hydrologic model considered a 16-year period with annual flows of 9.6 maf. It predicted that, absent major changes in institutional arrangements, after years of severely reduced runoff, levels at Lake Mead would fall dramatically while Lake Powell and other Upper Basin reservoirs would be emptied. Since 2000, annual flows have averaged 12.3 maf (USBR 2021). As of April 2022, Lake Mead was only 32% full, while Lake Powell was only 24% full (USBR 2022). Levels at other Upper Basin reservoirs have been lowered to keep more water in Lake Powell and to prevent volumes from dropping even further there.
2. Losses of hydropower electricity accounted for the single largest predicted economic loss from drought. Reducing agricultural water allocations in order to maintain hydropower production would reduce total economic losses (at the expense of agriculture). While the situation is less dire for Lake Mead, recent projections from U.S. Bureau of Reclamation (BOR) suggest that Lake Powell has a one in four chance over the next five years of falling below the minimum elevation needed to produce hydropower (Wheeler et al. 2022).
3. After completion of the Central Arizona Project, California would no longer be able to use 1 million acre-feet of water above their Compact allotment. Since 1994, California's consumptive use of Colorado River water has fallen from 5.2 to 4.4 maf.
4. To maintain consumptive uses (to agriculture, industry, and municipalities) water would be allocated away from non-consumptive uses of (hydroelectric power generation, water-based recreation, environmental protection, and salinity control). Since 1994, consumptive use by Lower Basin States has declined by 0.25–0.3 maf, with significant water transfers from agriculture to municipalities. Over roughly the same period, consumptive use in the Upper Basin has increased about 1 maf. Upper Basin use is still below its 7.5 maf allotment under the 1922 Colorado River Compact. There have been recent directives by the U.S. BOR for Basin states to curtail consumptive uses in part to avoid disruption of hydropower generation (Table 1).
5. Some environmental and water quality effects were (a) falling lake water levels would reduce recreation at Lakes Mead and Powell and other system reservoirs, (b) reduced instream flows would threaten some endangered species at some locations, (c) riparian wetlands would be seriously degraded and (d) salinity of drinking and irrigation water would increase (Hardy 1995). Articles in this current issue further explore the implications of the ongoing drought on water-based recreation, fish species, and the health of riparian wetlands.
6. Consumptive uses in the Lower Basin would be largely unaffected, save for those served by the Central Arizona Project (CAP), while the Upper Basin would experience a greater part of overall drought risk. Colorado River supplies to agriculture in Central Arizona (served by CAP) have already been curtailed under the state's Drought Contingency Plan and Shortage Declarations for the river. Recent calls for cutbacks by the BOR will affect other Lower Basin users as well as Upper Basin users.

Some articles in this Featured Collection revisited original analysis of the SSD (e.g., the role and implications of tree-ring research, impacts of drought on water-based recreation). Others explore earlier topics in greater detail (e.g., effects on fish species (Bruckerhoff et al. 2022) and wetlands health (Nagler et al. 2022)). In still other cases, this new Featured Collection addressed issues not explored in the original articles. For example, the terms "climate change" and "global warming" were mentioned only once in all the original articles. Since then, the implications of climate change and the role of Global Climate Models (GCMs) have grown immensely (as the articles by Pierce et al. 2022 and by Booker 2022 attest). Other new articles consider impacts on tribal agriculture and ranching (Drugova et al. 2022) and management of the Salton Sea (Ayres et al. 2022).

This Part I of the Featured Collection contains articles from an array of disciplines. Meko et al. (2022) provide an update of the work that followed the original Colorado River at Lees Ferry reconstruction that was the basis for SSD analyses (Stockton and Jacoby 1976). Although an expanded network of tree-ring data and new statistical approaches for reconstruction model calibration now exist, the late 16th century drought still stands out as the most severe 22-year period in five of eight reconstructions, highlighting the robustness of this period of drought as a SSD scenario (Tarboton 1995). However, recent streamflow reconstructions that extend further back in time highlight sustained periods of drought in the medieval period, unmatched in duration by any drought since. The authors also note that water resource managers have found the updated and lengthened reconstructions of Colorado River flow a useful tool for placing 21st Century droughts in a long-term context.

The article by Pierce et al. evaluates the performance of three generations of global climate models (GCMs) in reproducing the historical mean climate as well as temperature and precipitation variability in the Upper Colorado River Basin, with a special emphasis on dryness. They develop a ranked list of GCM suitability for examining drought in the Basin. They find that, as a group, newer models do a better job at simulating spatial and temporal variability associated with atmospheric circulation patterns. Even as performance on metrics of atmospheric circulation has improved, persistent biases in winter precipitation, including its multiyear variability important for reservoir management, have changed little across model generations. Though the presented model ranking could help practitioners to select models for impact studies, the authors did not find a consistent relationship between model quality and future precipitation change. It thus remains challenging to navigate the very wide range of possible futures projected by GCMs, even as they remain the best available tool for projecting future climate change over broad regions.

The article by Booker notes that the original SSD study suggested the Colorado Basin had surprising levels of resilience in the face of sustained drought but also notes that the SSD analysis did not address the potential impacts of climate change. Booker's piece thus introduces an economic model of water use under climate change and formally considers the effects of projected reductions in streamflows on levels and management of the two large reservoirs (Lakes Powell and Mead). Different reservoir operation rules are compared with the primary benefits considered being better water allocation across time. Factors such as the effects of reservoir levels on recreation benefits are not included in the analysis.

The climate scenarios suggest that streamflows will continue to decline as climate warms and that future reservoir levels will remain substantially reduced throughout this century. Model results suggest that assumptions about the severity of streamflow reductions have a much greater impact on future economic losses than do operation rules. While different operating rules have significant impacts on elevations and intertemporal storage, these rules have limited scope for reducing economic losses from declines in streamflows. Booker concludes that policies to reallocate Colorado River water across time have a quite limited role in mitigating the effects of climate change. He notes that the last 25 years have seen significant institutional innovations in the allocation of water between users. His results suggest an additional institutional change to reallocate Colorado River water *across* uses will be critical for such mitigation.

Duval et al. (2022) estimate the effects of lower reservoir water levels on visits to Lake Mead and Glen Canyon (Lake Powell) National Recreation Areas. This updates and extends earlier SSD work on lake recreation by Booker (1995) and Booker and Colby (1995). The current article estimates the effects of changing lake elevations on total recreational and overnight visits. The authors find that closures of access points (such as boat launches and marinas) are a more robust predictor of declining visits than simple elevation measures. They next estimate how declining lake levels affect recreation benefits as well as visitor spending and related economic activity. Rather than estimate benefits, they employ benefit transfer methods (Loomis 2015), obtaining per-visit benefit estimates of water-based recreation from other Southwestern sites. Surprisingly, results specific to Lake Powell are now quite old, from 1997 (Douglas and Johnson 2004). Booker and Colby's (1995) estimates for Lake Mead are derived from studies conducted in the 1980s. More recent regional water-based recreation benefits are somewhat higher (adjusted for inflation) than those used by Booker and Colby and most lie in a relatively narrow range of $67–$75 per trip. Yet, updates of direct estimates of recreation benefits at Lakes Mead and Powell are long overdue.

While the U.S. BOR's *Interim Guidelines* (USBR 2007) discussed qualitatively the implications of falling water levels for recreation, it did not quantify their economic consequences. Duval et al.'s analysis map changes in visits (from changing elevations) to changes in visitor spending, recreationist user benefits, and regional economic indicators such as value added (equivalent to GDP) and employment. Basin States and the federal government are adopting various policies to maintain elevations at Lakes Mead and Powell. Recreation benefit and other economic values reported in this article could inform future benefit–cost or economic impact analyses of Colorado River water management policies.

The SSD study discussed tribal water rights issues, but the only economic effects of drought on tribes considered were estimation of impacts to agriculture of the Colorado River Indian Tribes. Here Drugova et al. consider the effects of drought on Southwestern tribal agriculture, focusing on cattle and hay production of the Navajo, Tohono O'odham, and Uintah and Ouray Nations as well as on other reservations combined in Arizona, Nevada, and New Mexico, respectively. They considered, via regression analysis, both the effects of drought in the current year, using the annual Palmer Drought Severity Index as well as measures of consecutive years of drier or wetter conditions. These results were then used to estimate broader impacts using a supply-driven social accounting matrix (SAM) approach, relying on the IMPLAN modeling platform and data. The results suggest drought lowers both cattle inventories and hay yields, but the effects on cattle inventories were much larger. The estimated direct economic effects of drought on hay sales averaged only 4% of effects on cattle sales. The authors used county-level data for analysis. Then, they adjusted estimates based on tribal shares of county agricultural activity. A fruitful area of future research would be to base analysis on reservation-specific data, both for the regression analysis of drought impacts and for the development of SAM multipliers. The USDA Census of Agriculture conducts separate surveys for American Indian Reservations, but does so only every five years. Thus, additional primary data collection may be necessary. The results suggest large and highly variable multiplier effects across reservations. More fine-tuned data may be better able to capture economic leakages off-reservation to surrounding counties and adjust multiplier effects accordingly. Zipcode-specific IMPLAN data may be useful for such an approach.

Baker et al. (2022) describe an evaluation system to address a long-standing source of uncertainty and error in U.S. BOR reservoir elevation projections. Reclamation issues an operating plan each year based on the probability of storage at Lakes Powell and Mead falling within certain operational elevation tiers. With shortage or surplus declarations hinging on whether reservoir storage is expected to be above or below a particular elevation on a certain date, the skill of the mid- to long-term inflow forecast is key. At the time of the original SSD issue, mid- to long-term streamflow forecasts were based primarily on snow surveys and historical climate statistics. The science of inflow forecasting has advanced since that time, and its application is underway. Baker et al. describe an approach they have developed at Reclamation to test inflow forecast methods and evaluate their utility for accurately forecasting reservoir elevations. Their paper describes a testbed system, the various forecast methods subject to testing, and the skill of the methods at predicting monthly reservoir elevations as far as two years out.

The article by Smith et al. (2022) deals with decision-making under Deep Uncertainty — a condition where stakeholders and decision makers cannot determine or agree on the probabilities of future events or their objectives and priorities. Further, outcomes of decisions are unpredictable. Given the diversity of stakeholders and objectives, combined with uncertainties about the length and depth of drought in the West, and future water demands, Colorado River management indeed represents a case of Deep Uncertainty. Smith et al. discuss applications of Decision Making under Deep Uncertainty (DMDU), a branch of decision science, to Colorado Basin management. They note that many risks are assumption-driven risks and that the value of lowering specific individual risks depends (often fragilely) on the accuracy of those assumptions. In contrast, DMDU asks which uncertain future conditions cause vulnerabilities, where should management build in robustness, and what information is needed to adapt to future conditions. The article provides examples DMDU applications to BOR analysis and scenario development to improve decision making.

Bruckerhoff et al. examine how different scenarios for consumptive water use and operation rules for Lakes Powell and Mead affect ecosystem management. They consider implications for three different factors: water temperature which affects viability of native and non-native fish species, creation of barriers to fish movement, and the capacity to design flows (short-term reservoir releases, including controlled floods) for ecological restoration. Consumptive use scenarios include a reduction in Upper Basin use to 3 maf/year, (from about 3.66 maf/year), an increase to 4 maf/year and to 5 maf/year. Outcomes when water storage in Lake Powell is prioritized are compared with those when storage in Lake Mead is prioritized. The authors assume that hydrologic conditions of the ongoing Millennium Drought continue into the future.

Based on simulation results, the authors suggest that the only way to avoid Lakes Powell and Mead being fragmented from the inflowing Colorado River is to significantly reduce consumptive water use in the entire Basin and increase storage in the two reservoirs. They also find that the capacity to implement design flows for environmental restoration will be severely hampered in several scenarios. Different operational choices affect water temperatures, which causes certain tradeoffs. Cooler temperatures favor native fish species, while warmer temperatures favor non-native ones. Scenarios of low runoff and persistently low reservoir levels contribute to warmer temperatures, favoring non-native fish species over native ones. This suggests changes in the composition of regional fish populations.

The original SSD studies did not consider the impacts of drought on Mexico in any detail. Commitments by the U.S. to deliver specified quantities under maximum salinity limits were treated as constraints on operation of the system in the U.S. But, economic or environmental implications of drought within Mexico were not assessed. Over the past 25 years the governments of Mexico and the U.S., as well as environmental organizations on both sides of the border have devoted increasing attention to the health of the Colorado River Delta ecosystem (which reaches from the border to the Sea of Cortez). Surface water diversions at the border, groundwater losses, land clearing, and fire have all contributed to reductions in vegetation in the Delta. Through the International Boundary and Water Commission (IBWC), the U.S. and Mexico implement binational agreements, known as Minutes. In 2012, the U.S. and Mexico approved IBWC Minute 319, which provided water for environmental flows for the Colorado River Delta for restoration and scientific study (Table 1). This included a one-time Pulse Flow and a smaller Base Flow for environmental restoration, delivered at lower rates over a longer time frame within Mexico. Then, in 2017, IBWC Minute 323 was approved, which provided for funding and water allocations for Colorado River Delta restoration in Mexico.

The article by Nagler et al. assesses the effects of drought on the Colorado River Delta ecosystem and the effects of restoration activities. The 2014 Pulse Flow revitalized Delta riparian vegetation, but this effect was short-lived (1–2 years). The Nagler et al. study measures the effectiveness of smaller surface flows, directed agricultural return flows, and directed water to the prepared restoration sites in raising vegetation greenness (measured by the two-band Enhanced Vegetation Index [EVI2] and water use as measured by evapotranspiration [ET]). The article discusses how earlier research contributed to implementation of these successful strategies. While shortly after the Pulse Flow, EVI2 and ET began to fall again in unrestored reaches of the Delta, both grew in restored reaches. Further, restoration was effective at mitigating negative effects of drought. Though encouraging, restoration benefits to habitats and native plant health were primarily confined to the restoration sites themselves. Because the restoration areas were relatively small, there has yet to be appreciable spillover benefits to non-adjacent areas. This research can inform decisions about future water allocations for future Delta restoration efforts and improve water-delivery strategies.

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