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COMMENTARY
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Key Points:

- Dam and reservoir management is evolving due to climate change, sedimentation, aging infrastructure, and changing management objectives
- Glen Canyon Dam turns 60 years old amid greater knowledge of balancing dam operations with downstream resource protection and management
- Dam-removal effects are now also better understood and the largest dam removal yet, on the Klamath River, is imminent

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A Watershed Moment for Western U.S. Dams

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Abstract The summer of 2023 is a notable time for water-resource management in the western United States: Glen Canyon Dam, on the Colorado River, turns 60 years old while the largest dam-removal project in history is beginning on the Klamath River. This commentary discusses these events in the context of a changing paradigm for dam and reservoir management in this region. Since the era of large dam building began to wane six decades ago, new challenges have arisen for dam and reservoir management owing to climate change, population increase, reservoir sedimentation, declining safety of aging dams, and more environmentally focused management objectives. Today we also better understand dams' benefits, costs, and environmental impacts, including some that were unforeseen and took decades to become apparent. Where dams have become unsafe, obsolete (e.g., due to excessive reservoir sedimentation), and uneconomical beyond saving, dam removal has become common. The science and practice of dam removal are accelerating rapidly, and some long-term physical and biological response studies are now available. Removal of four hydroelectric dams on the Klamath River will be a larger and more complex project than any previous dam removal. The imminency of this project reflects a very different situation for dam and reservoir management than 60 years ago. Looking forward, dam and reservoir management in the western United States and worldwide will require continued collaboration and innovative thinking to meet a wide range of objectives and to manage water resources sustainably for future generations.

Plain Language Summary The summer of 2023 marks an important moment for water-resource management in the western U.S.: Glen Canyon Dam, one of the last and largest dams built on the Colorado River, turned 60 years old and the largest dam-removal project in history began on the Klamath River. This commentary discusses these events in the context of a changing paradigm for dam and reservoir management. Substantial challenges exist for dam and reservoir management today owing to climate change, reservoirs filling with sediment, aging infrastructure, increasing population and water demands, and environmental compliance. We also better understand dams' benefits, costs, and environmental impacts. Where dams are unsafe, obsolete, and uneconomical beyond saving, dam removal is now common. The science and practice of dam removal are accelerating rapidly, with long-term studies available on physical and biological responses. Removal of four hydroelectric dams on the Klamath River will be a larger, more complex project than any previous dam removal, reflecting a very different situation for dam and reservoir management today than 60 years ago. In the western U.S. and worldwide, dam and reservoir management requires greater collaboration and innovative thinking to meet a wide range of objectives and sustainably manage water resources for future generations.

Summer 2023 marks an important time in the complex story of managing water in the western United States. One of the last and largest major dams built in the region, Glen Canyon Dam on the Colorado River, turns 60 years old this year amid widespread concerns for water management in a changing climate. This summer also marks the start of the largest dam-removal project in history, on the Klamath River in southern Oregon and northern California. We consider each of these events in the context of new understanding of dam and reservoir management, 21st-century water and energy needs, and growing information on river response to dam removals.

A century ago, the era of large-dam construction began in the United States (Figure 1): dams and reservoirs were designed to store water for agriculture, to control floods, and to generate hydroelectricity, allowing communities to flourish in a relatively dry region. The societal, political, and engineering mobilization that ultimately led to large dams left a profound imprint on the western states, chronicled in classic accounts by Powell (1878), Stegner (1953), Reisner (1986), and Worster (1986). As building large dams and water-storage projects became practical, these efforts became symbolic representations of economic development and national pride, particularly as the country climbed out of the Great Depression with large-scale public-works projects. Impacts of western U.S. dams on the environment and Native American land and resources were recognized and decried by

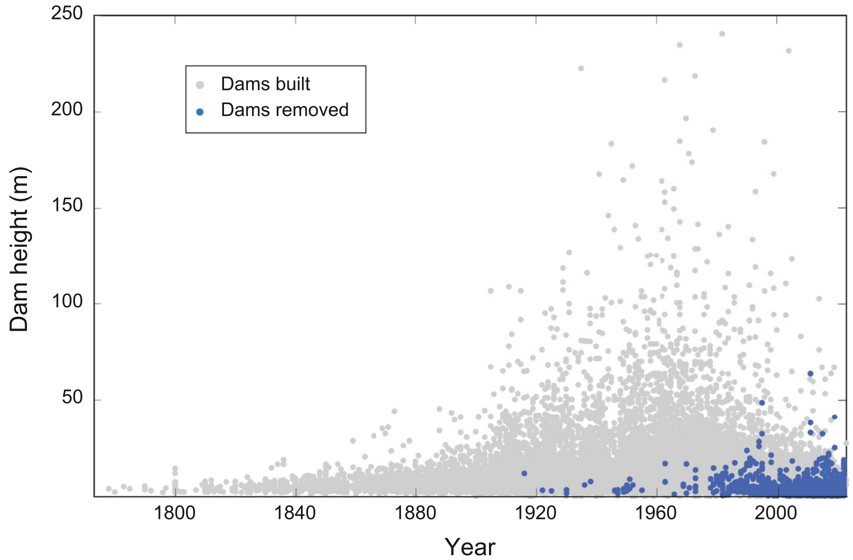

Figure 1. Dams built and dams removed in the United States between 1776 and 2023. Gray points indicate dams constructed, for all dams with available data on height and completion date (National Inventory of Dams, 2023). Blue points show all removed dams for which height and removal year are available (American Rivers, 2023).

some—memorably by environmentalists John Muir and Edward Abbey. Environmentally based objections scuttled plans for several additional large dams, notably Echo Park Dam at the confluence of the Green and Yampa Rivers, Utah, and Marble Canyon Dam on the Colorado River in Grand Canyon National Park, Arizona. But by and large, the first half of the twentieth century saw large-dam construction on nearly every major drainage of the Colorado, Snake and Columbia, Rio Grande, and Sacramento–San Joaquin River watersheds and many other, smaller basins (Figure 1; see also Graf (1999)). Today the National Inventory of Dams (2023) lists nearly 92,000 dams in the United States. Among those, more than 19,700 are "large dams" in the western U.S., which we define as being taller than 8 m (26.3 feet) and with storage capacity greater than 20,000 m^3 (16.2 acre-feet). (The western U.S. is represented in the Inventory using the U.S. Army Corps of Engineers' Northwestern, Southwestern, and South Pacific geographic divisions.) Glen Canyon Dam, one of the largest at 216 m tall, impounds the second-largest reservoir in the United States and was closed in 1963.

Decades later, the population and economy of the western U.S. have indeed expanded tremendously, owing in part to these water projects (the population of the seven Colorado River basin states grew more than 10-fold between 1920 and 2020, U.S. Census Bureau, 2023), but the passage of time has brought new challenges. A warming climate has resulted in shrinking mountain snowpack, a shift in the timing of snowmelt to earlier in the year, and increased water loss to evaporation, particularly during the regional "megadrought" of the past two decades (Pederson et al., 2011; Williams et al., 2020; Woodhouse et al., 2016). Warming temperatures have been the main driver of recent, multidecadal drought in the southwestern U.S., prompting serious concern that recent flow losses will worsen (Udall & Overpeck, 2017; U.S. Global Change Research Program, 2018). The consequences for water resources are daunting and costly. Research abounds on recent hydrologic changes in the western United States, nearly all pointing to future stress to water availability (e.g., Dye et al., 2023; Hidalgo et al., 2009; Schmidt et al., 2023; Wang & Rosenberg, 2023; Xiao et al., 2018; Zamora-Reyes et al., 2022). In April 2023, storage in Lake Powell (the reservoir behind Glen Canyon Dam) dropped below 6.48 billion m^3 (5.26 million acre-feet, or 21% of current capacity; Root & Jones, 2022) for the first time since the reservoir filled in the 1960s (Bureau of Reclamation, 2023a; Schmidt et al., 2023). New, albeit temporary, water-use reductions were codified this year among the seven Colorado River basin states in an effort to ensure sustainability (New York Times, 2023). Projections of future storage volumes in Lake Powell and the next reservoir downstream, Lake Mead, vary by a factor of four depending on consumptive-use scenarios, but continued status-quo use under drought conditions would deplete both reservoirs to the minimum power-generation level in about 30 years (Wheeler et al., 2022). Having synthesized climate impacts on several iconic watersheds, Dettinger et al. (2015) commented, "All told, climate change threatens water resources in the western United States to a degree that is probably unmatched anywhere else in the country." Thus, 60 years after Lake Powell began to fill, much attention is now focused on how the current capacity, design characteristics, and operation strategies for dams and reservoirs can be re-imagined to continue meeting western-U.S. water needs through the 21st century and beyond.

Those who planned 20th-century water infrastructure in the U.S. West may not have imagined that climate change would shrink inflows and reduce storage volumes, but it was widely known that reservoir sedimentation would be a problem eventually. For a reservoir to be sustainable in the long term, the amount of sediment leaving the reservoir should equal the amount entering. This is achievable only with a commitment to sustainability through annual sediment management (Randle et al., 2021). In the U.S. and worldwide, since around 1990 reservoir storage capacity has decreased due to reservoir sedimentation faster than it has increased due to new dam construction; accounting for population growth, U.S. water storage per capita has dropped by 35% since 1970 (Randle et al., 2021). Maintaining storage capacity requires managing sediment by some combination of reducing sediment yield from upstream, routing sediment-rich flows through or around a reservoir, removing deposited sediment (e.g., by reservoir drawdown and flushing or dredging), or adapting to declining reservoir storage capacity through water conservation or raising the dam height (Kondolf et al., 2014; Morris, 2020). Approaches to sediment management vary by cost and sustainability and were rarely incorporated into the design of western-U.S. water projects in the last century. This inadvertently shifted much of the economic burden of sediment management onto future generations (Anari et al., 2023; Randle et al., 2021). Features of dam design that facilitate sediment flushing, such as sluice gates built low on the dam, are rarely found in large U.S. dams; they are more common in or have been retroactively added to dams in Asia and Europe (Kondolf & Yi, 2022). Original economic studies assumed that severe reservoir sedimentation would occur too far into the future to be relevant and that upstream and downstream sedimentation impacts could be ignored (Anari et al., 2023). Climate change accelerates the rates at which sediment accumulates in reservoirs, however, because increasing wildfire and extreme rain drive greater sediment production in western-U.S. watersheds (East & Sankey, 2020; Sankey et al., 2017). In California, for example, post-fire erosion increased significantly in recent decades, and 57% of post-fire sediment production occurred upstream of reservoirs (Dow et al., 2022). Increasingly, managing water in the West will require attending to frequent, costly sedimentation problems. As a sign of the times, Los Angeles County, California now maintains a public website educating citizens about reservoir-sediment management (https://dpw.lacounty.gov/lacfcd/sediment/).

Older dams also become less safe unless they are well maintained. Dams that have been in place for decades require larger injections of funding to continue operating safely (e.g., Doyle et al., 2008). The National Inventory of Dams currently classifies 25,365 U.S. dams (28% of the nationwide number) as having a “high” or “significant” hazard rating, which relates to the downstream consequence if a dam were ever to fail. More than 40% of U.S. dams in those two hazard categories have no Emergency Action Plan (see also Song et al. (2021)). In the western U.S. climate change increases the hydrologic risk to dams owing to projected increases in extreme rain and flood magnitudes (e.g., Donat et al., 2016; IPCC, 2014; Tohver et al., 2014). Dams were designed for specific flows, and upward shifts in flood regimes (Huang et al., 2020; Lee et al., 2016) mean that the probable maximum floods may be exceeded at some dams. The failure of the main spillway and partial failure of the emergency spillway at California's Oroville Dam in 2017 (Henn et al., 2020) and the complete failures of Edenville and Sanford dams in Michigan during unusually large storm runoffs in 2020 were reminders of the growing need to address the safety of aging dams despite the associated high financial costs (France et al., 2022; Vahedifard et al., 2020). Globally, the September 2023 flood disaster in Libya, where extreme rainfall resulted in the collapse of two storage dams (Washington Post, 2023), underscores the growing risk of aging and inadequately sized infrastructure.

Alongside reservoir sedimentation and safety concerns, today we also have abundant evidence of dams' broader environmental impacts, which are often more widespread both upstream and downstream than originally considered. A dam converts a flowing river into a lake, alters streamflow and limits the natural supply of sediment and nutrients to the downstream river, and fragments habitat, preventing the longitudinal migration of many species. Profound physical and ecological changes follow, some of which were virtually unknown 60 years ago but are widely documented today (Collier et al., 1996; Galay, 1983; Kondolf, 1997; Nilsson & Berggren, 2000; Poff et al., 1997; Schmidt, 2022; Wohl et al., 2015; Zarri et al., 2022). Many large U.S. dams have been in place long enough for the expected effects to be inarguably apparent (e.g., downstream riverbed degradation, riparian vegetation encroachment, depletion of migratory fish runs), and for unanticipated effects to show up.

Because of greater environmental compliance and monitoring requirements, unanticipated effects of dams are coming to light. Returning to Glen Canyon Dam, one example involves archaeological sites lying far above the active floodplain. A recent 50-year synthesis of conditions at 362 archaeological sites downstream of the dam and above the post-dam high water line found that erosion risk has increased at most sites since the 1970s (Sankey et al., 2023). Elevated risk of site erosion from gullying processes (rainfall runoff from hillslopes along the river-corridor margins) results from decreased wind-blown sand supply from sandbars along the river corridor that now lack natural sources of sand from sediment-rich floods. Thus, the modified river conditions from Glen Canyon Dam operations have reduced supplies of sand that cover and protect cultural artifacts and refill gullies (Sankey & Draut, 2014; Sankey et al., 2023). These cascading effects of river regulation on landscapes, ecosystems (Draut, 2012), and irreplaceable cultural resources in Grand Canyon even above the high water line were not foreseen 60 years ago and took longer to become apparent than the more directly impacted declines of fluvial sandbars and native fish (Topping et al., 2000; Van Haverbeke et al., 2013).

Federal, State, Tribal, and local agencies operate many complex restoration projects to try to compensate for dam impacts. These include controlled floods through Grand Canyon (including a controlled spring flood in 2023), gravel augmentation in California's Trinity River (Gaeuman et al., 2017), and fish and wildlife habitat improvement programs on the Columbia and Snake Rivers, to name several examples. Major efforts and funding now go into mitigating direct and indirect environmental effects of dams in the western U.S. The Bonneville Power Administration spends more than half a billion dollars annually working to improve fisheries and other wildlife habitat on the Columbia River (Edmonds, 2020), and the Bureau of Reclamation (2023b) runs multimillion dollar restoration projects in the Sacramento-San Joaquin Delta and Central Valley of California. At some dams, managers are experimenting with different flow-release schedules and strategies to effect a range of environmental objectives (e.g., U.S. Army Corps of Engineers, 2023). All told, protection, mitigation, and enhancement measures typically account for 5%–10% of hydropower projects' Levelized Cost of Energy (LCOE, Oladuso et al., 2021). The effectiveness of these mitigation and restoration efforts varies, but they do not effectively simulate undammed or pre-dam conditions (e.g., Pennock et al., 2021).

When a dam has become unsafe or obsolete beyond rehabilitating, it is now common for dam removal to be considered. Dams become candidates for removal when they can no longer be operated economically, including for reasons of safety, environmental compliance, or major reservoir sedimentation. Around the mid-2000s dam removals in the U.S. began increasing substantially (Figure 1) and to include taller dams storing more sediment (O'Connor et al., 2015). Dams that create reservoir storage for water supply or flood control are not easily replaced, and none of the dams removed so far provided substantial water storage or flood control at the time of removal. The water-storage benefits provided by Lake Powell, for example, would be very hard to replace because Lake Powell provides water storage by which the upper-basin states of Utah, Colorado, Wyoming, and New Mexico can meet their legal water-delivery obligations to the lower-basin states (California, Nevada, Arizona), and Mexico.

Scientists, the public, Tribal members, and practitioners of river restoration tracked early examples of large dam removals with great interest and curiosity. First came Marmot Dam in Oregon in 2007, Milltown Dam in Montana the following year, then Savage Rapids Dam, Oregon, the next year. Each of these dams was over 10 m high and had stood for nearly a century (Bountry et al., 2013; Evans & Wilcox, 2014; Major et al., 2012; Wilcox et al., 2014). Spectacular video footage showed the rapid reservoir drainage as Condit Dam, Washington, was dynamited in 2011. Milltown Dam removal had the added complication of contaminated mining waste that was dredged from the reservoir and disposed of off-site. But these dam removals worked to remove barriers to sediment and fish, and brought measurable physical and ecological restoration to the rivers. Some were concerned about financial costs, lost recreational opportunities, and negative public perceptions, such as the fear that draining a reservoir would leave an ugly, stinking mudflat (Tullos et al., 2016). However, others recognized that dam removal would result in expanded river recreation and river restoration including improved fish runs (Allen et al., 2016; Duda et al., 2021; Reid & Goodman, 2020), not to mention removing the liability of an aging dam.

In the decade after Marmot Dam came down, additional dam removals accrued and added valuable findings to support synthesis studies. These have now addressed rivers' physical and biological response (Bellmore et al., 2019; Foley, Bellmore, et al., 2017; Foley, Magilligan, et al., 2017; Pess et al., 2014), whether common management concerns about dam removal were borne out (Tullos et al., 2016), and how well the scientific literature of dam removal aligned with the geography of its practice (Bellmore et al., 2016). Conceptual and quantitative models of dam-removal response are far more advanced now than 10 years ago (Bellmore et al., 2019; Collins et al., 2017; East et al., 2018). The growing knowledge base has showed that geomorphic responses to dam removal are typically rapid and don't necessarily last long, with the largest changes evident in the first 1–2 years. Ecosystems see short-term negative impacts over a similar time scale but thereafter recover substantially, usually to a better condition than the river's dammed state. Specific outcomes vary from watershed to watershed; as Foley, Bellmore, et al. (2017) noted, response trajectories depend on how and where dams are removed and on overall watershed conditions. Overall, the post-dam-removal river will not be identical to the original, pre-dam river, in part because human land use and invasive species may have changed the watershed while the dam existed.

The science and practice of dam removal continue to accelerate rapidly. American Rivers (2023) reports that at least 2,025 U.S. dams have been removed since 1912, with the great majority (1,530) since 2000 (Figure 1). Of the removed dams whose height is known, 89% were small dams, less than 8 m tall, but some taller dams have come down now too (Figure 1, American Rivers, 2023). New and valuable findings have emerged from dam removals just in the past 4–5 years. A decade of observations on the Elwha River in Washington state showed that even a very large sediment release can pass through the river system relatively quickly, at least in a relatively steep river and wet region. After removal of two aging hydropower dams with no fish passage, 32-m-high Elwha Dam and 64-m-high Glines Canyon Dam, the Elwha River naturally eroded decades' worth of sediment (20 million tons), sending 90% of it to the river mouth within the first 5 years (Randle et al., 2015; Ritchie et al., 2018). The sediment pulse caused changes to the river morphology that were mostly short-lived (East et al., 2018), although the elevated riverbed and flow stage caused collateral damage to some riverside infrastructure through increased river migration. Persistent new sediment deposition along the river-mouth delta and shoreline reversed decades of coastal erosion (Stevens et al., 2023; Warrick et al., 2019). The most expensive mitigation component of the Elwha River dam-removal project was to address water-quality impacts from releasing decades of trapped sediment. Downstream water users had become accustomed to artificially clear water releases from the dams and municipal, industrial, and fish hatchery facilities had to be upgraded to address the newly restored sediment loads. Eight native species of anadromous fish have now returned to the upper Elwha River above the former reservoirs (Duda et al., 2021). This much-anticipated sign of fish recovery carries great weight for the Lower Elwha Klallam Tribe given their close cultural ties to the salmon runs. A fishing moratorium intended to let fish abundance increase further is now beginning to ease (Washington Department of Fish and Wildlife, 2023).

Letting a huge sediment pulse down the Elwha River was an intentional part of watershed restoration there, but we have also learned that large dam removals can be managed so as *not* to create an Elwha-scale response. During the removal of 32-m-high San Clemente Dam from California's Carmel River in 2015, two-thirds of the reservoir sediment was sequestered in place to avoid downstream channel aggradation that could have increased flood risk (Harrison et al., 2018). When a 40-year flood tested that approach the following winter, the modest geomorphic changes downstream of the dam site were attributable just to flooding caused by major rain events, not to effects of sediment from the former reservoir (East et al., 2023). Eight years later the downstream river still has not seen undesired impacts from the dam removal. Additionally, we've learned that a large, unsafe dam exposed to exceptional sedimentation can be removed in a hurry if need be. The third-largest dam removal in the U.S., that of 41-m-high Cucharas #5 Dam in Colorado, was carried out on an emergency basis in 2018 when, more than 30 years after the dam was deemed structurally unsound, a wildfire in the upstream watershed escalated concerns that post-fire flooding and sedimentation could further compromise dam safety. The State of Colorado took ownership of the dam and removed it within a few months, leaving the newly stabilized sides of the dam partly in place to slow and limit the downstream sediment release (Perry et al., 2020).

The rapid, recent increase in knowledge of river response to dam removal now supports detailed decision tools, too. A new database was released this year that facilitates estimating dam-removal costs (Duda, Johnson, et al., 2023). This and an accompanying predictive model (Duda, Jumani, et al., 2023) allow resource managers to evaluate specific situations of dam structure, watershed geography, sediment management and mitigation requirements, and various anticipated post-removal management actions in their assessments of dam removal. Investigations of sediment response to dam removal also have provided valuable insights as to how reservoir storage capacity could be sustainably managed. For example, a new reservoir sedimentation and economics model has been developed to evaluate the economics of sustaining reservoir storage capacity (Randle et al., 2023).

Thus, we now have ways to manage the end-of-life, decommissioning phase for large or small dams in situations where dam removal is the preferred option. This brings us to the second major event of summer 2023: the start of dam removal on the Klamath River. The first of four hydroelectric dams slated for removal began to be removed in July 2023, with the other three to follow in 2024. Undamming the lower Klamath River, a project considerably more complex than any previous dam removal, will allow migratory salmon runs throughout this river reach for the first time in a century (Klamath River Renewal Corporation, 2023). It is widely hoped that dam removal will improve the condition of this third-largest salmon run on the west coast of the continental U.S. (after the Columbia and Sacramento-San Joaquin Rivers). This will not be a full watershed restoration, however: additional dams remain upstream of the four being removed, to maintain agricultural water supply. But removing Iron Gate (53 m high), Copco 1 (40 m), Copco 2 (9 m), and John C. Boyle (21 m) Dams will open the longest mainstem river reach (370 km) and largest watershed area (31,000 km^2) yet among dam-removal projects worldwide. Aiding salmon by restoring migratory fish access to mainstem and tributary habitats, as well as improving water quality and temperature by removing four reservoirs, is of great importance to the Yurok, Karuk, Hoopa Valley, and Klamath Tribes who have lived in this watershed for millennia.

As with any restoration effort, the effectiveness of the Klamath River dam removals will be modulated by consequences of other land uses in the watershed and climate change. A major fire in the Klamath River basin in 2022 led to poor water quality and killed innumerable fish (New York Times, 2022), and the watershed is also recovering from 20th-century logging and mining practices that were less environmentally sensitive than today's. But the fact that these dam removals are imminent points to the evolution in river management over the past 60 years.

What will future river management look like, in the western U.S. and globally? The proliferation of dams has affected most rivers worldwide and is one of humanity's largest environmental impacts (e.g., J. P. M. Syvitski et al., 2005; J. Syvitski et al., 2022). The era of building large dams continues in some regions, notably South America and Asia, where hydropower is being relied upon for a future of lower carbon emissions. Climate change is driving ever more urgent reevaluation of water and energy resources and how to manage them, not just in the western U.S. but in most regions worldwide (Forrest et al., 2018; Mehran et al., 2017; Yao et al., 2023). In some settings, this will lead inevitably to building large new dams while shoring up older ones and going to great lengths to manage reservoir sediment. Balancing water use against environmental values involves difficult decisions, including how to manage intra-basin water transfer and storage—such as between Lake Powell and Lake Mead, other reservoirs on the Colorado River, and its delta in the Gulf of California (Bruckerhoff et al., 2022; Wheeler et al., 2022). Managing significant amounts of sediment requires watershed-scale appraisal of the problems and possible solutions. Dams built in high mountain regions will face exacerbated risks from glacial lake outburst floods and mass-wasting events as the climate warms (Shugar et al., 2021; Taylor et al., 2023). As in the western U.S., other arid and semi-arid regions will face challenges of maintaining water-storage capacity for winter floods while ensuring sufficient reservoir water supply for summer demand in a warming climate. Just as the impacts and consequences of western-U.S. dams were not fully appreciated 60 years ago, it is likely that some future consequences of dams remain to be seen, especially as dams are built in new geographic and ecological settings. At the same time, interest in removing obsolete and unsafe dams is growing internationally (e.g., Habel et al., 2020). For those dams that must remain in place, and that will continue to help address the shifting supply and demand of water use globally, we know more than ever before about how to manage dam operations and reservoir sediment in environmentally conscious ways (Shelley et al., 2021). The 60th anniversary of Glen Canyon Dam and the start of large dam removals on the Klamath River remind us that technological achievements and concepts of progress evolve greatly over timespans of a few generations. The malleability of water-management approaches, recognition that paradigms sometimes change, and the need for greater collaboration and innovative thinking will be essential to addressing the serious challenges of managing water for future generations.

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Data Availability Statement

No new data were generated for this commentary. The data that appear in Figure 1 on dam construction can be accessed from the National Inventory of Dams (2023) and the data on dam removals can be accessed from American Rivers (2023).

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