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Navigating through Whitewater: Understanding the Challenges and Opportunities in the Colorado River Basin

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Many scholars working on the economics and policy of water in the Colorado River Basin benefited from ideas and research findings of works conducted in the Colorado River Basin over the years by Robert A. Young. Bob was a leading water economist, a teacher, a colleague, and a friend who inspired many of us with cutting-edge research dealing with economic aspects of water quantity and quality issues in the Colorado River Basin. This thematic issue on understanding challenges and opportunities in the Colorado River Basin is dedicated to the memory of Bob.

The Colorado River and its tributaries supply water to nearly 40 million people, both within and outside the Colorado River Basin (CRB), and irrigate almost 4 million acres of agricultural land (Crespo et al. 2023a,b). The Colorado River Compact of 1922 and its subsequent agreements and court decrees regulate the allocation and management of the Colorado River water among the seven basin states (Wyoming, Colorado, Utah, Nevada, Arizona, New Mexico, and California), Native American Tribes, and Mexico (U.S. Bureau of Reclamation, 1945).

The water system of the CRB currently faces significant challenges due to climate-change-induced aridification processes, overallocation issues, and proposed developments of new water uses. The U.S. Bureau of Reclamation (USBR) reports that the average flow of the Colorado River in the twenty-first century (12.4 million acre-feet) is so far about 18% lower than the twentieth-century average of 15.2 million acre-feet (USBR, 2021). Some scientists argue that these long-term climate-change-induced changes will continue to deplete flows and fundamentally alter the basin's hydrology, leading to aridification and a "new normal" of reduced runoff and lower river flows (Overpeck and Udall, 2020). These complex issues involve various stakeholders with diverse interests, including agricultural, hydropower, environmental, and municipal sectors.

This thematic issue of *Choices Magazine* highlights the challenges facing the CRB and explores potential solutions from multiple perspectives. The issue consists of seven articles, offering background information on basin-wide policies and regulations as well as analyses

Articles in this Theme:

- **Climate Crisis Is Straining the Colorado River's Complex Policy Architecture**
  Frankel, Z., N. Halberg, M. Nemati, A. Dinar, and D. Crespo
- **Climate and Choice in the Colorado River Basin**
  Booker
- **Economic Impacts of Climate Change on the Agricultural Sector of the Colorado River Basin**
  Crespo, D., N. Mehdi, A. Dinar, Z. Frankel, and N. Halberg
- **Threading the Needle: Upper Colorado River Basin Responses to Reduced Water Supply Availability**
  Asgari, M., and K. Hansen
- **Water Justice Concerns in the Colorado River Basin**
  Colby, B., and Z. Reed-Spitzer
- ***Agricultural Producer Decision-Making around Water Conservation in the Upper Colorado River Basin* "**
  Mooney, D., and K. Hansen
- ***Arizona Policy Responses to Water Shortage: Can They Have an Impact?***
  Frisvold, G

of local policies at the state or regional levels. The articles focus on various sectors, including agriculture, Native American tribes, urban centers, and energy.

Frankel et al. (2024) present an overview of water resources in the CRB, examining current allocation and governance rules while evaluating their impact on effective management. The article provides background information on the various policies and regulations governing the CRB over time. It assesses how these policies and regulations have either created or limited opportunities for effective CRB management moving forward.

Booker (2024) presents future water supply and demand scenarios projected into the year 2100 to evaluate potential policy options. The paper addresses the choices that will confront water users and the institutions governing future allocations, emphasizing the economic consequences of different pathways. The study focuses on anticipated changes in supply and demand and the economic decisions required to adapt to these changes. Five supply-side sectors are considered: streamflow, risk reduction (managed by reservoirs and groundwater), wastewater recycling, brackish water desalination, and water imports. Additionally, five demand-side sectors are examined: irrigation for lower- and higher-valued agriculture, municipal and industrial uses, environmental purposes, and risk reduction (managed by institutions).

Crespo et al. (2024) focus on the impact of climate change on the agricultural sector, the major water user in the CRB. The results indicate that while alfalfa, hay, and cotton are affected by a reduction in water availability due to their large share of the total cultivated area, the impacts on net income at the basin level and within irrigation districts are relatively small compared to the amount of land left fallow. Net income losses from a 10% reduction in water availability are estimated at around $8 million (about 1%), while losses for a 30% reduction are approximately $69 million (or about 5%). However, there is significant heterogeneity across water districts in terms of the level of loss. Under extreme water scarcity, the reduction in water availability results in the fallowing of 606,000 acres of irrigated land, representing 28% of the baseline cropland. In this scenario, crops with higher water intensity and lower economic value are prioritized for fallowing.

Colby and Reed-Spitzer (2024) investigate various water justice issues concerning the tribal nations and acequias in the CRB and their involvement in CRB policies. Their findings reveal that many CRB tribes face ongoing barriers to participating in water transactions and shortage-sharing arrangements. Acequias members hold senior water rights that predate statehood, which are typically integrated into state water rights systems and can be sold or leased. However, individual water sales can weaken the collective strength of acequias. Significant differences exist between tribal nations and acequias regarding water entitlements, access to reliable water supply, representation in policy-making, and community resilience. Both groups have historically been marginalized, although progress has been made in recent decades. Many water justice issues remain unresolved.

Asgari and Hansen (2024) explore the challenges and trade-offs faced by Upper Basin states as they navigate the 1922 Compact to fulfill their obligations to the Lower Basin. Changes in water usage and location are expected under curtailment or demand management programs, with varying impacts on communities depending on the scale and frequency of these policies. The article also discusses patterns of water transfers and exchanges and their implications for rural agricultural communities and ecosystem services. Additionally, Mooney and Hansen (2024) focus on agricultural water conservation programs (AWCPs) proposed to address CRB shortages. They evaluate the potential of AWCPs to conserve water from the perspective of agricultural producers in Colorado’s Upper Basin, examining the technical and economic feasibility of practices such as fallowing, deficit irrigation, and crop switching.

Finally, Frisvold (2024) investigates several policy responses in Arizona, a lower CRB state, to the Colorado River water cutbacks, including (i) water supply augmentation, (ii) subsidies for the adoption of efficient irrigation technologies, and (iii) restricting foreign-owned operations of irrigated cropland. These high-profile responses have captured the attention of water policymakers in the state. This article considers how well these policies can address the state’s water scarcity issues in a cost-effective, timely, or comprehensively.

The CRB plays a major role in the economy and livelihood of a main region of the nation, affecting also indirectly markets of agricultural products outside of the CRB. The fragile structure of the water economy and its present institutions have been challenged by changes in population trends and by climate change-induced water scarcity that will be worsened in the future. The purpose of this thematic issue is to provide the reader with a sample of works that represent the efforts to analyze sectoral and regional consequences of future water scarcity scenarios as well as ideas for possible policy interventions to address water scarcity and other impacts of climate change on the basin. While the sample of works has impressive coverage, it is still not comprehensive in that it excludes important issues such as the impact on and the protection of the environment and the fragility of the energy sector. These and other omitted issues due to space may be addressed in future thematic issues of *Choices Magazine*.

For More Information

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Climate Crisis is Straining the Colorado River's Complex Policy Architecture

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The Policy Architecture of the Colorado River Basin

Conversations about policies on the Colorado River Basin (CRB) invariably lead to criticism of the antiquated nature of the 1922 Colorado River Compact and its overestimate of future water flows. However, the 1922 compact is just one of a suite of water-sharing agreements, court decrees, and treaties that dictate how CRB water is shared among seven states, Mexico, a myriad of sovereign tribes, and the environment. These policies are referred to as the Law of the River.

The CRB states faced a problem in the early 1900s. Southern states, especially California, had begun developing agriculture and wanted infrastructure for flood control and irrigation. The passage of the Reclamation Act and creation of the Bureau of Reclamation in 1902 provided the means by which the infrastructure could be built. However, Congress would not approve any spending until states in the CRB reached an agreement on the division of the CRB's water. Eventually, the 1922 Colorado River Compact was created (Meyers, 1966).

The negotiators of the 1922 compact were concerned with ensuring that each state received enough water to meet their interests (MacDonnell, 2023; Hundley, 2009). Given that states in the CRB's south were developing agricultural systems faster than states in the north were, the northern states feared that southern states would win the right to use most of the water, depriving them of water. This was a legitimate concern because in 1922 the Supreme Court ruled in *Wyoming v. Colorado* that prior appropriation was the method by which interstate streams would be divided (Meyers, 1966).

To get around this, the CRB was divided into two subbasins—an Upper Basin (consisting of Utah, New Mexico, Colorado, and Wyoming) and a Lower Basin (consisting of Nevada, Arizona, and California)—with each subbasin nominally allocated 7.5 million acre-feet (MAF) of water. A separate clause in the 1922 compact granted the Lower Basin the right to use an additional 1 MAF of water beyond the 7.5 MAF they were granted by the previous provision. This was an overpromising of wet water supplies, which only worsened later as the water needs of tribes were recognized and Mexico negotiated a right to a share of the river (MacDonnell, 2023).

Since most of the water in the CRB originates in Upper Basin mountains, Lower Basin states feared that much of the water would be used upstream. Two additional provisions were added that said that the Upper Basin states must not use so much water as to cause the flow of river to fall below 75 MAF over 10 years (an average of 7.5 MAF per year), thereby ensuring water would always make it to the Lower Basin (MacDonnell, 2023). For much of the CRB's history, this provision has been interpreted as constraining the Upper Basin to the amount of water left in the river after 7.5 MAF has been set aside for the Lower Basin (MacDonnell, Getches, and Hugenberg, 1995). As discussed in more detail below, climate change impacts lead some to challenge this interpretation. Another provision ensured that Upper Basin states could not withhold water from the Lower Basin states and that the Lower Basin states could not require the delivery of water that they did not need.

In 1928, the Boulder Canyon Project Act was passed, fulfilling the federal government's promise to provide funding for the Hoover Dam for flood control and hydropower and the All-American Canal for Southern California irrigation. The legislation also delineated how Lower Basin states were to share their 7.5 MAF, with Nevada granted 0.3 MAF, Arizona 2.8 MAF, and California 4.4 MAF.

Arizona did not ratify the 1922 compact for several years. In that time, California secured contracts to more water than they were allotted in the Boulder Canyon Project Act (Meyers, 1966). Fearing that California would win the right to a wealth of water from the yet-to-be-constructed Lake Mead and leave Arizona with little water, Arizona eventually ratified the 1922 compact and sued to settle their water apportionment. The litigation led to a 1964 Supreme Court ruling known as *Arizona v. California*, in which the court established that California could not use more than 4.4 MAF and that tributaries in the Lower Basin (like the Gila River) could be used without counting toward a state's Colorado River allocation (Meyers, 1966).

Before significant diversion altered its flows, the Colorado River entered the Sea of Cortez and supported a vibrant estuary, as documented in *A Sand County Almanac,* where Leopold canoed the river's terminus in Mexico near the Gulf of California (Leopold, 1949). Yet Mexico's claims to the river were not quantified in the 1922 compact. Rather, the 1922 compact framers put in a placeholder provision for a possible future allocation for Mexico. Eventually, a 1944 treaty quantified Mexico's allotment at 1.5 MAF of water.

One other group of water users was largely left out of the 1922 compact: Native American tribes. In 1908, the Supreme Court issued a ruling in *Winters v. United States*, determining that federally recognized tribes with an established reservation had a right to the amount of water that was needed for irrigation and other purposes. These so called "Winters rights" are federally reserved rights that usually hold seniority dates of either time immemorial or of the date that the tribe's reservation was established, often predating the 1922 compact. Generally, tribes hold the most senior rights in the CRB (U.S. Bureau of Reclamation and Ten Tribes Partnership, 2018).

Although this ruling was handed down long before the 1922 compact, tribes were not invited to participate substantively in the 1922 negotiations or for many decades afterward when subsequent water-sharing agreements were crafted. As a result, tribes and their water claims were not part of the river's governing framework, making it difficult for tribes to access the water to which they have been entitled (Robison et al., 2018). If a tribe wishes to turn their promised rights into real water, they have to go through a complex negotiating process, potentially including litigation, to quantify the exact amount of water to which they are entitled. Some tribes have done this, but others have not or have been only partially successful (Guarnio et al., 2021). The 30 tribes in the CRB collectively hold recognized diversionary rights to 3.2 MAF, but 12 tribes have unresolved water right claims to at least 400,000 acre-feet more (Guarnio et al., 2021).

In 1948 the Upper Basin states settled the question of how they should divide their water by opting to split their share on a percentage basis. The 1948 Upper Colorado River Basin Compact granted Colorado the right to 51.75%, Utah 23%, Wyoming 14%, and New Mexico 11.25% of the Upper Basin's available water, after 7.5 MAF were delivered to the Lower Basin. The 1948 compact also outlined a scheme for how Upper Basin states would need to reduce their water use in the event that delivery volumes to the Lower Basin were below the 1922 compact's provision of allowing 75 MAF to flow to the Lower Basin every 10 years. This provision is known as curtailment and is being more frequently discussed in both basins today (Robison, 2016b).

Environmental interests were also ignored in the formation of the Law of the River, meaning that instream flows—water kept in a river for the benefit of the environment—were not considered. Environmental protections of water flows in the CRB came relatively late in its more than 102 year history, and a litany of environmental impacts occurred in that time including inundating aquatic habitat under dams and reservoirs, dewatering of the river's delta, endangerment of native plant and animal species, introduction of invasive species, alterations to the river's natural flow regime, loss of riparian areas, and others.

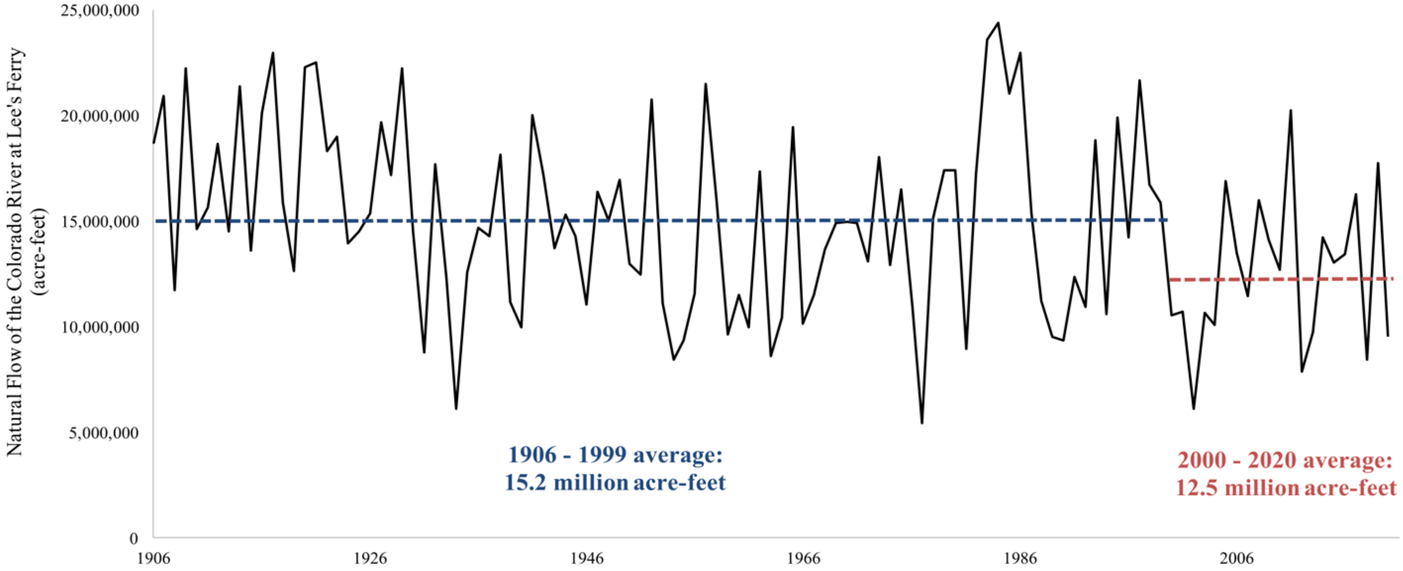
Today, there is still no basin-wide mandate for instream flows, and the majority of water for environmental flows is a result of the Endangered Species Act (ESA), which dedicates small amounts of water to certain areas of the CRB that have been identified as "critical habitat" for endangered species (Shaner, 2004). Most of the ESA activities in the CRB are implemented by four different programs: The Upper Colorado River Endangered Fish Recovery Program, the San Juan River Basin Recovery Implementation Recovery Program, a program run by Grand Canyon National Park, and the Lower Colorado Multi-Species Conservation Program. In addition, when permitting processes take place to build new infrastructure or diversions, or modify existing operations, the Fish and Wildlife Service is generally consulted.

Twentieth-Century Policy Architecture Straining under Twenty-First-Century Global Pressures

The Law of the River was not designed to address the twenty-first-century problem of climate change impacts and economic and population growth. Many of the CRB's policies were devised before scientists began measuring atmospheric concentrations of CO_2, much less forecasting future flows in the CRB (United Nations, 2007). Yet, rapidly developing climate change impacts are affecting farms, cities, tribes, and ecosystems across the CRB, often faster than institutions are capable of addressing (Kenney et al., 2011).

Some seventh-eighths of the water in the Colorado River Basin originates from just one-eighth of the landmass in the headwater mountains of Utah, Colorado, and Wyoming, where snowpacks act as the largest reservoir in the CRB. Snowmelt runoff constitutes the majority of

Figure 1. Natural Flow of the Colorado River, Twentieth Century versus Twenty-First Century



Source: U.S. Bureau of Reclamation (2023b).

water flows in the CRB, which is why rising air temperatures that reduce snowpacks are reducing water flows (Lukas and Payton, 2020). This can be seen by comparing average Colorado River flows from the twentieth century to those in the twenty-first century. As Figure 1 shows, flows in the first quarter of the twenty-first century are roughly 20% lower than they were in the twentieth century, a phenomenon that is in part due to warming temperatures (Udall and Overpeck, 2017; Woodhouse et al., 2016; Milly and Dunne, 2020).

Additional studies have indicated that the CRB is transitioning to a hotter, drier climate in a long-term process called aridification (Overpeck and Udall, 2020), and that the CRB is currently experiencing its worst drought in 1,200 years (Williams, Cook, and Smerdon, 2022).

The rapid pace of flow declines stands in contrast to the glacial pace of decision making in the CRB. With the benefit of hindsight, we are able to see that many of the actions taken in the first quarter of the twenty-first century to address low river flows did not go far enough, requiring states to renegotiate agreements multiple times, as demonstrated by the 2007 Interim Guidelines.

Following a series of low water years in the early 2000s, the federal government spurred the CRB states to create a new agreement to prevent water levels in the country's two largest reservoirs (Lake Powell and Lake Mead) from falling to low levels (Grant, 2008). The 2007 Interim Guidelines required Lower Basin states to reduce water use by set amounts when water levels in Lake Mead fell to certain thresholds. The guidelines last through 2026 (Grant, 2008).

By the early 2010s, it became clear that the 2007 Interim Guidelines did not go far enough to address the ever-worsening conditions in the CRB and additional cuts were needed to ensure that neither Lake Powell nor Lake Mead fell to catastrophically low levels before 2026. The Drought Contingency Plans (DCPs) were enacted in 2019, which bolster the 2007 Interim Guidelines by adding additional water cuts to Lower Basin states. The DCPs also authorized additional actions like releasing emergency water from upstream reservoirs and reducing downstream deliveries from Lake Powell (Stern, Sheikh, and Hite, 2023). Yet, like the original guidelines, the DCPs underestimated just how low river flows would get; a few years later the CRB once again found itself facing a crisis.

In 2022, the Commissioner of the Bureau of Reclamation (USBR) told a congressional committee that the CRB states needed to cut a one-time amount of 2–4 MAF of water to prevent reservoir collapse prior to 2026 (U.S. Congress, 2022). If water levels in Lake Powell approached the minimum hydropower generation levels, downstream water deliveries would be threatened. The testimony sparked a new round of negotiations among the CRB states, which lasted through the winter of 2023. Fortunately, an above-average winter in 2023 provided some breathing room to finalize negotiations. Eventually, the process resulted in another update to the 2007 Interim Guidelines in the form of a supplemental environmental impact statement, in which the Lower Basin states anticipate collectively cutting 0.75 MAF of additional water each year from 2023 to 2026. While these cuts have not been formally allocated among the Lower Basin states, the USBR indicates that Arizona is expected to cut approximately 0.28 MAF, Nevada 0.07 MAF, and California 0.4 MAF per year (U.S. Bureau of Reclamation, 2024a). The USBR finalized this process with a record of decision adopting the above-stated plan (U.S. Bureau of Reclamation, 2024b).

In a similar way, other important tools used by the USBR to manage the Colorado River also lag behind the rapid pace of river flow declines. For instance, the USBR periodically creates a hydrologic determination, or an official estimate of how much water is available for Upper Basin states to share. The last time the USBR created a hydrologic determination was in 2007, based on data exclusively from the twentieth century, before climate change impacts had significantly shrunk river flows (U.S. Bureau of Reclamation, 2007).

With the benefit of hindsight, we can see that the tools water managers created to manage low river flows—the 2007 Interim Guidelines, the 2019 DCPs, and the hydrologic determination—persistently lagged behind the rapid pace of climate change impacts. This is the result of a number of problems in CRB decision making, including an underestimation of the severity of future flow declines and political complexities posed by the sometimes-opposing agendas of the Upper Basin, Lower Basin, federal government, and other key actors. This has forced negotiators back to the table for lengthy talks to develop ad hoc agreements, focusing states' resources on short term problems rather than long-term plans.

At the end of 2026, the 2007 Interim Guidelines will expire and the CRB will need to implement new long-term plans. The USBR has initiated a National Environmental Policy Act process to permit these new plans, and they hope to release a draft environmental impact statement (DEIS) in December of 2024 (U.S. Bureau of Reclamation, 2023a). This is a similar but separate process from the one described before, which focuses on plans through (but not extending past) 2026. The USBR has asked representatives from the CRB states to agree on and submit one alternative so it can be included in the DEIS. The Upper Basin (Mitchell et al., 2024), Lower Basin (Buschatzke, Entsminger, and Hamby, 2024), and a consortium of conservation groups have all submitted plans to the USBR (National Audubon Society et al., 2024). Both basins plan to continue negotiations until an agreement is reached. These new plans will set the course for the CRB for the next several decades. The USBR and states would be wise to learn from the 2007 Interim Guideline process and create plans for very low river flows to avoid reconvening in a few years to renegotiate the plan again.

The Biggest Challenges Facing the Colorado River in the Future

Failure to plan for a river with much less water is a major problem in the CRB today. Arguably the most important question to ask when considering the CRB's future is how low Colorado River flows are going to get. A series of studies have provided estimates forecasting a 10%–40% decline in river flows from various twentieth-century baselines (Lukas and Payton, 2020). Table 1 ties these projected flow declines to actual water volumes in the Colorado River.

In reviewing these estimates, it is important to keep in mind that average flows in the CRB in the twenty-first century are already roughly 20% lower than they were in the twentieth century. Therefore, estimates that flows will only decline 10%–15% are likely outdated. As two scientists put it, "The emerging reality is that climate change is already depleting Colorado River water supplies at the upper end of the range suggested by previously published projections" (Udall and Overpeck, 2017, pages 2404-2405).

As warming in the CRB continues, average natural Colorado River flows could drop as low as 9–11 MAF, less than the 17.5 MAF allocated in the 1922 compact and the roughly 13.3 MAF of total water used in the CRB (Stern, Sheikh, and Hite, 2023). Attempting to deal with this hydrologic change with existing twentieth-century policies and practices is proving to be problematic.

Take, for example, the classic interpretation of Article III(d) of the 1922 compact. For most of the CRB's history, this provision was interpreted as requiring the Upper Basin to deliver 75 MAF of water every 10 years to the Lower Basin, leaving the Upper Basin the

Table 1. Estimates of Colorado River Flow Declines in the Twenty-First Century

Percent Reduction in the Natural Flow of the Colorado River from Twentieth-Century Average as Measured at Lee Ferry	Corresponding Natural Flow of the Colorado River at Lee Ferry (MAF)
10% decrease	13.7
15% decrease	12.9
20% decrease	12.2
25% decrease	11.4
30% decrease	10.6
35% decrease	9.9
40% decrease	9.1

Source: Lukas and Payton (2020).

"leftovers" and forcing them to bear the burden of reduced flows (Robison, 2016a). CRB scholars have argued that this is an untenable situation, and that interpretation of this provision needs to change to reflect the new hydrologic reality imposed by climate change. A different reading of Article III(d)—one that doesn't impose a delivery obligation on the Upper Basin but requires them to "not deplete" too much water—could relieve some of the climate change burden from the Upper Basin's shoulders (Castle and Fleck, 2019).

Additionally, many tribes in the CRB have been absorbing water shortages de facto since they face barriers that prevent them from developing their full water rights, despite having seniority (Becker et al., 2022). Collectively, tribes in the CRB are currently using a fraction of their reserved rights, which total 3+ MAF. If all these rights were put to use, water use in the CRB would even further outstrip available supply (Guarnio et al., 2021). Many of the CRB's drought responses have succeeded because of tribal nonuse. This cannot be a cornerstone of future plans.

Further, the CRB looks different today than it did in 1922. Las Vegas, for example, has undergone a transformation from small town to booming metropolis, but Nevada is allotted little water from the river. Simultaneously, Utah is allowed three times as much water but has a similar population to Nevada. Is the twentieth-century allocation structure still serving the twenty-first-century CRB, or are more dramatic changes needed?

Old practices and Law of the River interpretations struggle to keep up with twenty-first-century challenges, requiring the reinterpretation of policies or creation of new ones. Fortunately, a new tool can speed the creation and testing of policies to help the CRB address its challenges. Researchers at the University of California Riverside have created a HEM-CRB that can help stakeholders test the impact their policy ideas would have on the hydrology and economy of the CRB and identify previously unseen trade-offs (Crespo et al., 2023). The HEM-CRB is a flexible tool capable of analyzing the performance of existing CRB policies (e.g., voluntary and/or compensated cuts by specific users) and new approaches (e.g., water markets, proportional sharing, social planner allocation). The model can also account for environmental flows, tribal water rights, and other frequently overlooked factors.

While the HEM-CRB does not change the structure of the decision-making process in the CRB—negotiations are largely left to nonelected representatives of the CRB states and residents of those states have little democratic accountability over their representative—it can indirectly influence this process in a few key ways. The HEM-CRB can provide new information to decision makers about the likely impact of proposed policies and changes to the policies that could make them more effective. This could help negotiators further refine their plans, identify previously unseen opportunities, and ultimately craft deals that create more beneficial and durable outcomes for the CRB. Additionally, the HEM-CRB can help stakeholders obtain better information on the effect of various policy proposals, helping them understand how negotiators' proposals will impact them. The HEM-CRB will also create a "sandbox" where stakeholders can create and test their own ideas, expanding the pool of possible solutions.

Although the HEM-CRB might not directly change the structure of the highly insular decision-making structure in the CRB, it can improve transparency by providing excluded stakeholders better information about their representative's proposals. Also, if representatives take advantage of the HEM-CRB's ability to robustly analyze and identify solutions, they will be better equipped to adapt twentieth-century policies to twenty-first-century challenges.

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Climate and Choice in the Colorado River Basin

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Water resources in the Colorado River Basin support over 40 million people (Wheeler et al., 2022) and growing economies across seven U.S. states, dozens of tribal nations, and a Mexican province. Conflict, competition, and co-operation between regions and uses over these limited resources has been the norm for the past century and appears unlikely to diminish, given expectations that basin water supply will decrease (Udall and Overpeck, 2017). This paper addresses choices that will confront water users and the institutions governing future allocations, emphasizing the economic consequences implicit in alternative institutional scenarios under climate change.

The Colorado River arises in the mountains of Colorado and Wyoming, flowing over 1,400 miles before its waters are fully exhausted in remnant delta wetlands at its mouth at the Gulf of California. Along its journey, the river's water is diverted for irrigation, municipal, industrial, and ecological uses. Beyond the withdrawals of the basin's water for human purposes, instream flows support aquatic communities and hydropower at dams throughout the basin. The river's reservoirs total capacity is over four times the river's annual naturalized flow (Rosenberg et al., 2013) and thus provides not only seasonal but also multiyear smoothing of flows. But this storage comes at a cost: Basin reservoirs evaporate nearly as much water as is depleted by current municipal, industrial, and thermal energy (MIE) uses.

The urgency of addressing basin water scarcity sharply increased with the onset of the multidecadal drought that began in 2000 and continues today. There is strong evidence that some fraction of this drought is in fact an early signature of permanently reduced flows expected under climate change (Udall and Overpeck, 2017). And while naturalized basin flows have already averaged over 15% less during this drought than those typical of the historical record starting in 1906, Udall and Overpeck suggest that permanent flow reductions of 20% by mid-century and 40% by the end of this century might reasonably be expected.

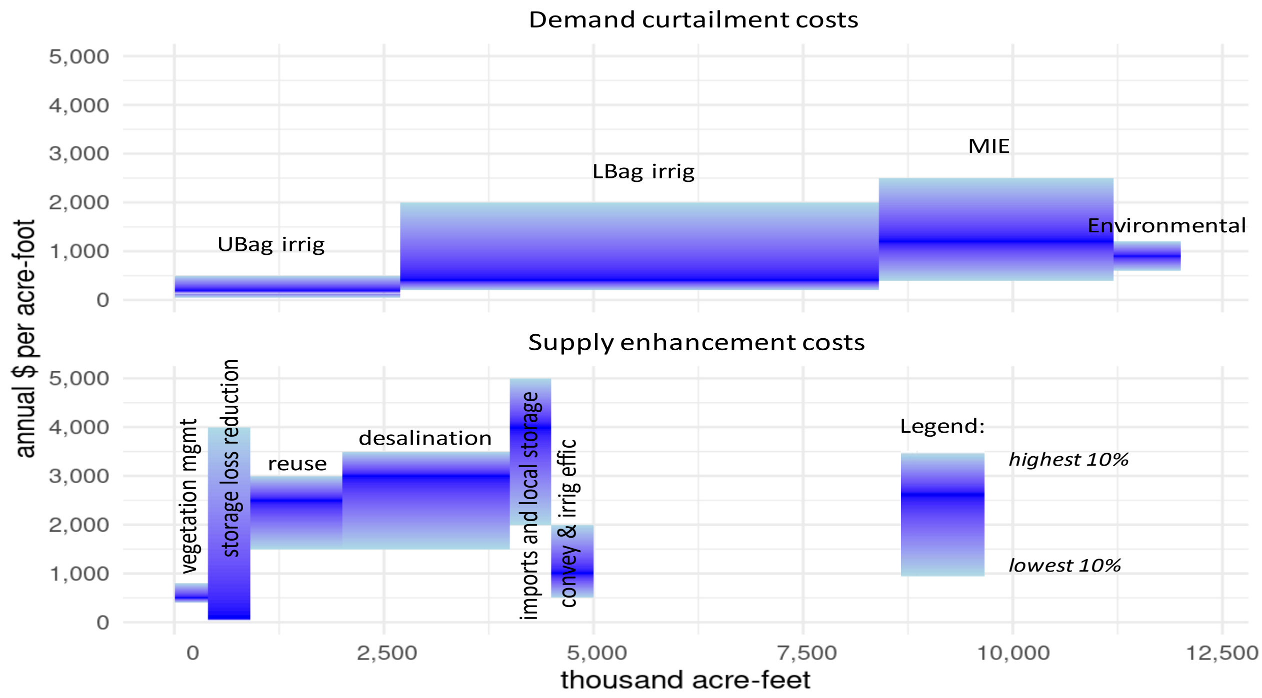
Allocation of the basin's water across state lines was first addressed by the Colorado River Compact of 1922. Since then, a growing body of compacts, court judgements, congressional acts—including agreements on reserved rights of tribal nations, minutes to the 1944 Mexican treaty, and administrative procedures of the U.S. Bureau of Reclamation—have led to what is frequently called the "Law of the River." In addition, court decisions have played an important role, including the 1963 Supreme Court ruling on lower basin (LB) rights between Arizona, California, and Nevada, while also granting considerable discretion to the Secretary of Interior (National Research Council, 1968). The result is a water rights regime with siderails, but also ambiguity.

The Law of the River will likely continue its evolution in response to reduced stream flows, low reservoir elevations, and changing water demands. To inform the policies which will shape the future Law of the River, what follows is the development of several stylized institutional scenarios, focused on the economic consequences of the resulting basin water use patterns on the U.S. side of the border. To begin, a simplified basin water budget is described and then applied to a basin with reduced stream flows. Estimates for the economic value within each of four water use sectors are next presented, and the estimated cost of potential water supply enhancements are added. Both are shown in Figure 1. The remainder of the article introduces five representative institutional and development scenarios under which economic efficiency and distributional impacts of flow reductions are estimated. Details of the five constructed scenarios are provided in Table 1, and estimated outcomes are compared in Figure 2.

Water Budget and Application

The water budget used here starts from consumptive uses reported by the Bureau of Reclamation (2012b) in its study of future basin conditions, drawing largely from and aggregating the typically used Colorado River Accounting and Water Use Report (lower basin states) and the Upper Colorado River Basin Consumptive Uses and Losses report. From this, mainstem U.S. water use

Figure 1. Assumed basin wide sectoral and technology alternatives



under typical historic conditions, excluding evaporative and other losses, is about 12 million acre-feet (MAF). Annual upper basin (UB) irrigated agriculture use is 2.7 MAF, LB irrigated agriculture is 5.7 MAF, and MIE use is 2.8 MAF. Environmental use to support delta flows and Salton Sea inflows from agriculture is the final use sector and depletes 0.8 MAF annually. All water exports from the basin are included above and are assigned to an end use sector. Flows to Mexico are excluded from consideration, as are LB tributary uses on, for example, the Gila River. See Richter et al. (2024) for water accounting including the full hydrologic basin.

This stylized water budget is the starting point for estimating economic impacts of future stream flow shortfalls under potential changes in climate. Following Booker (2022), flow reductions are expected to result in roughly proportional reductions in total consumptive use, as reservoir evaporation savings are roughly proportional to flow reductions. Economic outcomes are thus likely most sensitive simply to the magnitude of the climate related stream flow reduction, economic valuation of water use within the sectors, and differences in the assumed distribution of water use reductions. A more detailed understanding of additional factors, including dynamic effects, conveyance gains and losses, and groundwater influences (Rosenberg et al., 2013) would be possible with a hydroeconomic model (Harou et al., 2009) but is beyond the scope of this article. Quantitative outcomes are estimated here for a 20% stream flow reduction which is assumed to result in a 20% (2.4 MAF) reduction in water use, net of supply enhancements. Climate impacts on stream flows remain uncertain, with a wide range of potential changes to means and variability and timing (Udall and Overpeck, 2017).

Economic Values of Water in Basin Uses

Basin water generates economic and other values through irrigated agriculture, municipal, industrial, and energy purposes and in a range of environmental settings and recreational activities. Figure 1 summarizes economic values in each of the demand sectors defined for this article: UB irrigated agriculture, LB irrigated agriculture, an MIE sector, and an environmental sector. The range of economic values within each sector illustrates economic demand as reported by Gibbons (1986) and discussed by Young and Loomis (2014). For example, some agricultural uses (e.g., specialty crops) typically generate large economic values, in contrast to much lower values in the majority of agricultural uses. The median value across uses within a sector is shown by the darkest shading in the Figure. The highest and lowest values shown are a qualitative representation of values at the 10% and 90% levels of use, respectively. Figure 1 is also constructed to emphasize the large uncertainties in economic value estimation for curtailment of typical consumptive uses.

To estimate economic surplus, net income from crop production is used, defined as crop revenue (if the crop is used on farm, an estimated implicit crop price is used) minus production costs net of water costs. This paper relies primarily on Crespo et al. (2023) to give a range of values representative of crop production in both UB and LB agriculture. Frisvold and Duval (2024) and

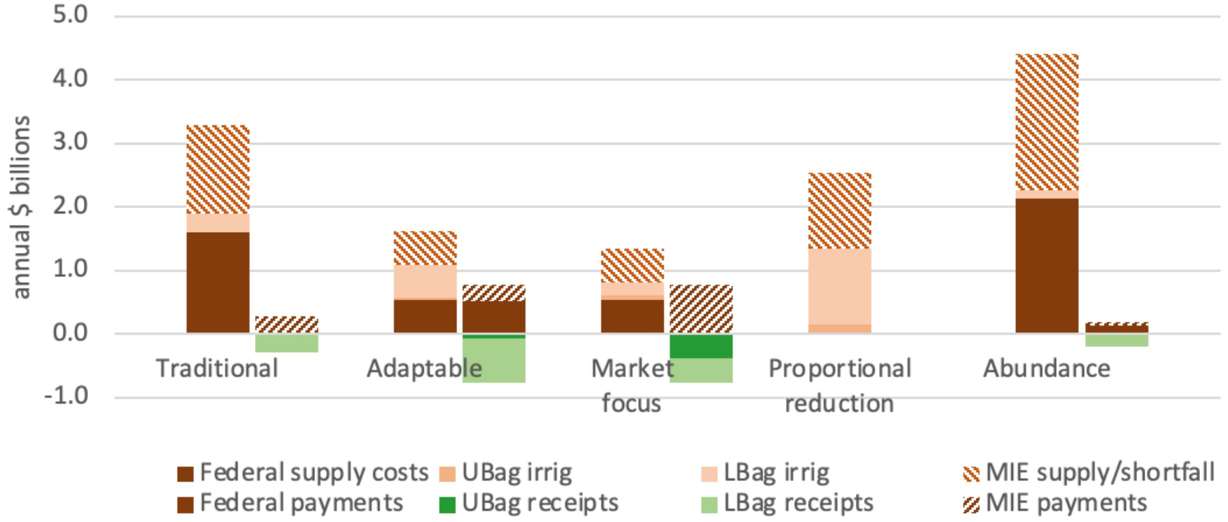


Figure 2. Efficiency and Distributional Impacts of Institutional Scenarios with 20% Streamflow Reduction

Annes (2015) provides similar estimates starting from county data within the basin states. This article uses a median UB agricultural value of $225 per acre foot of consumptive use and subtracts $25 per acre foot to represent the value of forgone hydropower production (Somani et al., 2021) plus increased salinity (U.S. Bureau of Reclamation, Salt Data) negatively impacting downstream water users. Other ecosystem services are not included given uncertainty about the magnitude or direction of impacts.

MIE users in the basin are represented as a single sector. The value of consumptive uses is consistent with figures reported by Porse et al. (2018) and Harou et al. (2010) for southern California. Most important for the stylized model presented here, the range of water value in MIE uses exceeds the marginal value of irrigated agricultural values up to potential reductions much greater than those addressed in all scenarios. MIE uses within (e.g., Las Vegas), exported from the basin (e.g., Denver, Albuquerque, Los Angeles), and withdrawn for use off the mainstem (Phoenix) are included in this sector.

A final sector of environmental benefits of water allocations is defined to capture flows supporting environmental values. These include river flows dedicated to partial restoration of the ecologically diverse Colorado River delta wetlands (Pitt et al., 2000) and flows to limit salinity (Rumsey et al., 2021) and support water levels in the Salton Sea (Ayres et al., 2022).

Costs of Water Supply Enhancements

Actions that increase the ability to provide for the levels of consumptive use shown in Figure 1 are defined here as supply increases. These actions include water efficiency improvements in conveyance facilities, reservoir evaporation loss reductions (e.g., Schmidt et al., 2016), and riparian vegetation evapotranspiration reductions, and production of new fresh water by, for example, desalination or imports from outside the basin. Figure 1 shows that the scale of plausible supply increases is small relative to potential future climate change shortfalls of up to 4.8 MAF per year occurring with a 40% flow reduction.

The result is that basin water consumption will inevitably decline substantially if the largest supply reduction of 40% should occur in the future. The limited potential supply increases from conveyance and irrigation efficiencies ("conservation") used here reflect the difficulty in translating water loss reductions to system-wide consumptive use increases (Ward and Pulido-Velazquez, 2008). For example, further water efficiency gains in the Imperial Irrigation District are assumed to not increase available supplies due to detrimental effects on return flows to the downstream Salton Sea.

Costs of supply enhancements are described by the U.S. Bureau of Reclamation (2012a), Porse et al. (2018), and Cooley and Purisanban (2016) and shown in Figure 1. The alternatives are shown in no particular order because costs are very speculative and it is uncertain what measures are possible or might be pursued in practice; there is little reason to believe that least cost approaches would be chosen first. Median cost estimates, and those at the 10% and 90% level of supply enhancements, are again illustrated.

Scenarios and Institutions

Many combinations of demand and supply changes could occur in the case of large stream flow reductions. To cover widely discussed policy alternatives, five discrete institutional scenarios are developed here. The alternative institutional futures are suggested by the specific legal and demographic factors that have shaped development of the basin and correspond to distinctly differing approaches to addressing future conditions. These include alternative water development and rights regimes, subsidies, opportunities and restrictions on transfers of rights, and resulting water use responses given hydrologic conditions. Scenarios choose between combinations of the predefined supply enhancements and water demands to provide physical balance between hydrologic conditions and basin consumptive uses.

“Scenarios” here are similar to the “portfolios” in the Bureau of Reclamation’s (2012a) Supply and Demand study, and to the use in climate work of “scenarios” or “pathways” to represent uncertainties in emission impacts and alternative economic development futures (Pirani et al., 2024). They are crafted here to illustrate a number of the “multiple, ambiguous, and changing” objectives in choices which must be made in managing the Colorado for the future (National Research Council, 1968).

The scenarios used here are informed specifically by the interstate compacts, court decisions, evolving state water laws, local distribution practices, and ad hoc agreements. The latter are illustrated by 2007 and 2019 agreements between LB states to a tiered system of curtailments in response to critical reservoir elevations emerging during the current multidecadal drought (Stern, Sheikh, and Hite, 2023). Recent proposals looking to 2026 and the upcoming expirations of these agreements (U.S. Bureau of Reclamation, 2023) show competing property rights visions from UB and LB states, reflecting differing interpretations of the 1922 Compact itself (Wheeler et al., 2022). To address immediate low elevation levels in basin reservoirs, a 3-year plan to reduce water usage is facilitated by $4 billion in federal funds to purchase curtailments at an annual price of $330–$400 per acre foot prior to 2026 (Stern, Sheikh, and Hite, 2023). This evolution of the Law of the River during the current drought highlights the potential role of water banks (Bernat, Megdal, and Eden, 2020) and demand curtailment Asgari and Hansen, 2024; (Asgari, M., and K. Hansen. 2024. “Threading the Needle: Upper Colorado River Basin Responses to Reduced Water Supply Availability.” Choices 39(4).], Upper Colorado River Commission, 2023) despite legal challenges, to reduce economic impacts through markets (e.g., Booker and Young, 1994; Hanak, Sencan, and Ayres, 2021) or by securing federal funds to support regional interests. The additional question of whether payments for large-scale curtailments can fully target “wet” water use to achieve basin-wide water use reductions is beyond the scope of this article.

The five stylized scenarios developed here are labeled *Traditional, Adaptable, Market focused, Proportional reduction,* and *Abundance*. Each describes a perspective on how basin water use and development *could* be managed for a future under climate change. Details of each are provided in Table 1.

The *Traditional* scenario follows a strict interpretation of the Law of the River in allocating water between basin water users. There is no provision for federally regulated lease payments to reduce water use or voluntary water transfers between states. Limited water transfers within states—and in particular between irrigators and MIE users—are allowed but are not sufficient to eliminate MIE shortfalls. Federal funds cover the majority of water supply enhancement costs, and basin MIE users cover the balance.

The *Adaptable* scenario is an interpretation of the actual current and rapidly evolving institutional conditions. Water transfers occur through within-state MIE purchases and through federally funded programs which transfer water out of consumptive use (curtailment). State allocations implicitly follow the tiered water use reductions negotiated in 2007 and 2019 (Stern, Sheikh, and Hite, 2023) and would not be affected. In total, a combination of supply enhancements and water transfers are at a level sufficient to maintain MIE water use at 100% of the base level.

Table 1. Institutional scenario definitions

	Supply Enhancements		Demand Curtailments			Ag Payments	
Scenario Name	**Shortfall Proportion**	**Federal Cost Share**	**UB Agric**	**LB Agric**	**MIE**	**Federal Cost Share**	**Curtailment Efficiency Cost Methodology**
Traditional	0.4	75%	0	0.5	0.5	0%	mean of values < $400
Adaptable	0.2	50%	0.1	0.9	0	67%	mean of values < $400
Market focus	0.2	50%	0.5	0.5	0	0%	piece-wise linear demand
Proportional reduction	0.1	0%	0.24	0.51	0.25	0%	mean
Abundance	0.8	50%	0.1	0.9	0	67%	mean of values < $400

A *Market focus* scenario adds water rights transfers directly between the MIE and irrigation sectors. The level of transfers is sufficient to exactly eliminate the shortfall to MIE water users and is apportioned between UB and

LB irrigators equally, implying curtailments resulting in water transfers between basins, incompatible with traditional understandings of the Law of the River. There are no federal subsidies: MIE water users pay the full cost of water transfers and modest water supply enhancements.

The *Proportional reduction* scenario is constructed to illustrate proportional sharing of all water shortages, scaled by historic water use. Water transfers are not permitted between any uses in accordance with the principle that water shortages be equally shared. Basin irrigators cover 75% of supply enhancement costs, and MIE users cover 25% of these costs based on the same principle, and their respective water use. Federal funds are not used to address basin water use, as the nonbasin population does not suffer these particular hydrologic stream flow reductions.

An *Abundance* scenario follows the allocations and potential curtailments of the *Adaptable* scenario but emphasizes enhancements to supply. Supply enhancements mitigate 75% of the reduction of modest stream flow decreases and 50% of high stream flow decreases. Federal funds cover half of water supply enhancement costs, and basin MIE users cover the balance.

Implementation of the supply enhancement alternatives and estimates of changes in each demand sector differ with each scenario. Supply alternatives use mean cost estimates across all alternatives given the speculative nature of the alternatives. Costs of water demand shortfalls are valued using the respective sectoral medians (*Traditional*) or at levels consistent with incentivized transfers (*Adaptable* and *Market focused*). Under proportional sharing of shortfalls (*Proportional reduction*), all uses are valued at their mean value. Environmental flows to the delta and Salton Sea are fixed at full levels across all scenarios and are not further discussed.

Results and Discussion

Figure 2 shows direct economic surplus losses from a 20% stream flow reduction, together with payments and receipts for water transfers for each of the five institutional scenarios. Annual surplus losses (i.e., the change in economic surplus compared to no stream flow reduction) are from over $1 billion to over $4 billion. Payments to incentivize consumptive use reductions are as high as $0.7 billion. The greatest economic costs occur under scenarios that attempt to limit consumptive use impacts through supply enhancements. This is the direct result of the high costs of supply enhancement portfolios relative to the value of water in irrigated agriculture. The approaches that include water transfers out of agricultural sectors show the lowest economic costs, though these costs may be underestimated if conveyance losses are substantial.

The magnitude of these impacts should be considered in the context of the primary water supply for nearly 40 million people. The largest economic surplus loss found here is $150 per person, and about half of this might be offset by federal funding sources. This may seem surprisingly low but is consistent with recent findings from California, an overlapping and similarly populated region. Estimates of direct damages from a nearly 50% reduction in surface supplies estimated direct agricultural revenue losses to be $1.8 billion (Howitt et al., 2015). Complicating the comparison, much of the surface water supply reduction was replaced by increased groundwater pumping, albeit at an added cost of $0.6 billion.

The distribution of economic costs and of payments to incentivize transfers varies substantially by scenario. With scenarios which emphasize supply enhancements (Traditional and Abundance), the federal burden for supply costs is about $1 billion annually. The Adaptable scenario has a similar federal burden, but now half of this is a transfer payment to agricultural sectors to incentivize curtailment. The Market focus scenario differs mostly by shifting compensation of agricultural sectors to the MIE sector. A small economic cost reduction results from the assumed broader source regions (i.e., interstate) for curtailments.

Higher levels of climate change induced flow reductions (e.g., to 40%) could in principle also be addressed given the supply enhancements and demand sectors illustrated in Figure 1. But the limited consideration of water scarcity in neighboring regions, and potentially large demand increases under higher temperatures greatly decreases reliability of the cost and value estimates. As a result, no quantitative estimate of economic or distributional impacts is made here. This does not mean, however, that per unit costs of flow reductions would necessarily be substantially greater: If further water supply enhancements are physically impossible beyond those assumed in Figure 1 and substantial proportions of relatively low value agricultural uses are curtailed, it is possible that per unit economic costs could be more or less constant over a large range of water supply reductions.

Five key outcomes are illustrated here:

1. Opportunities for supply enhancement are very costly relative to demand management, and in any case are insufficient to address the stream flow reductions that are likely with climate change. Traditional conservation projects to increase water use efficiency are also unlikely to substantially increase opportunities for increased consumptive use.

2. Consumptive use in irrigated agriculture will inevitably decrease with reductions in hydrologic flows given limited reasonable opportunities for supply enhancement or MIE use reductions.
3. Economic efficiency differences of crop choice are tiny relative to potential costs of shortfalls to MIE users, and small compared to the current regulated price offers for temporary water use reductions.
4. Details of which specific crops or acreage are curtailed are likely less important, from an agricultural household's net income perspective, than the price received for transferred or forgone water use.
5. The distribution of federal versus basin sources to fund voluntary water use reductions in basin agriculture will have large welfare impacts on MIE users. Total federal spending will likely be smaller if focused on buying out water demand rather than developing supply enhancements.

Conclusion

The scenarios presented here were constructed to offer a portrait ranging from traditional water management in the Colorado River Basin to widely discussed potential alternatives. These were applied to two representative levels of basin stream flow reduction under climate change. In total, the alternative scenarios suggest cost effective approaches to mitigating future impacts and insight into distributional consequences. There are large efficiency and equity differences between approaches.

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Economic Impacts of Climate Change on the Agricultural Sector of the Colorado River Basin

Daniel Crespo, Mehdi Nemati, Ariel Dinar, Zachary Frankel, and Nicholas Halberg

JEL Classifications: Q1, Q15, Q18, Q25
Keywords: Climate change, crop production, Colorado River Basin

In the Western United States, including the Colorado River Basin (CRB), climate change is characterized by increased temperature and other climatic variations that include a heightened frequency and severity of droughts (Barnett et al., 2008). Warming in the CRB has led to increased evaporation, reduction in total snowpack, changes in the timing of snowmelt, and a significant decrease in water runoff. These phenomena exemplify the aridification affecting the CRB region (Bass et al., 2023; Overpeck and Udall, 2020). It is crucial to differentiate between droughts and aridification. While drought refers to a temporary period of arid conditions, aridification denotes a transition toward a consistently water-scarce environment over a prolonged period. The risk of experiencing long, intense, and frequent drought periods, including multidecadal drought events, escalates with climate change. Besides aridification and droughts, climate change increases the likelihood of extreme events such as intense heatwaves, short and intense periods of dry and wet conditions, and widespread wildfires (McCoy et al., 2022).

In the CRB, rising temperatures are anticipated to reduce water availability by 6%–30% and increase the persistence of droughts up to 20 times more than historical records (Bedri and Piechota, 2022). Elevated temperatures increase reservoir evaporation and escalate water requirements for irrigation and municipal use due to increased agricultural and outdoor demand in urban areas. The impact of climate change on crop yield is uncertain. Although higher CO_2 concentrations and temperatures could increase crop yields for some crops, they may intensify crop water stress. However, climate change is expected to increase crop production failure chances in some areas of the CRB.

This article assesses the economic impact of reduced water availability for irrigating cropland across irrigation districts in the CRB region within the United States. The agricultural sector is the dominant water user in the Colorado River, with irrigation withdrawals accounting for 85% of the total withdrawal (Maupin et al., 2018; Crespo et al., 2023; Mullane, 2023). Water is used for irrigation of 2.2 million acres across the seven CRB states. To simulate the effects of climate change, we assume reductions of 10%, 20%, and 30% compared to baseline conditions, representing mild, severe, and extreme climate change scenarios, respectively. The analysis determines crop patterns and water allocations by irrigation districts that maximize the net income of crop production.[1] The marginal value of water for each district in the CRB reflects the significant impact that produces the scarcity of water.

The net income of crop production is quantified using a quadratic function in relation to the cropland area. The model incorporates constraints on the availability of water, land, and irrigation technology (flood, sprinkler, or drip). Water requirements for irrigation are set per unit of land and vary according to crop type, irrigation technology, and irrigation district. Crop yields diminish with additional land use, reflecting the fact that the most productive lands are cultivated first and produce the highest net income. The unitary cost of production and the unitary price of crops are constant, and they remain unaffected by changes in production. Further details of the model and parameters are available in Crespo et al. (2023).

Baseline Conditions in the CRB

Under baseline conditions, cropland distribution is the average between 2008 and 2021 of the observed acreage irrigated in the CRB In this study, crop production includes only the irrigation area inside the CRB and the acreage irrigated

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[1] Net income is calculated as revenue minus production costs, including water costs, and excluding land rent.

Table 1. Cropland, Water Applied, Revenue, Cost, and Net Income in the CRB for the Baseline Scenario

	Cropland (1,000 acres)	Water Applied (1,000 acre-feet)	Revenue (million $)	Non-Water Costs (million $)	Water Costs (million $)	Net Income (million $)
Arizona	803	2,996	2,342	1,558	296	489
California	529	1,743	2,125	1,358	190	576
Colorado	469	1,655	900	492	188	220
Nevada	3	7	4	2	1	1
New Mexico	42	130	77	45	12	20
Utah	190	583	319	182	62	75
Wyoming	166	423	211	140	35	35
Basin	2,199	7,539	5,976	3,778	783	1,415

Note: The values include the production from irrigated land within the basin and from irrigated land in Southern California.
Source: Crespo et al. (2023).

by the All-American Canal;[2] otherwise, trans-basin uses of CRB water for agriculture were not considered. The baseline scenario includes 40 irrigation districts in the seven states that maximize the net income from the production of 39 various crops using three distinct irrigation technologies.

Table 1 presents crop acreage, water, revenue, cost, and net income of crop production by state for the baseline scenario. Crop production in California, Arizona, and Colorado captures 90% of the net income of water use by using 85% of the water applied on 80% of the irrigated acres. This shows that the net income per acre and net income per unit of water used is greater in California, Arizona, and Colorado than in Utah, Wyoming, New Mexico, and Nevada. In particular, California generates nearly double the economic value per acre-foot of water relative to other states, and net income per acre shows similar results. Arizona has the second-highest economic net income generated per acre and per unit of water used. In general, the Lower Basin states produce greater net income per unit of water used for agriculture than the Upper Basin states. Crop pattern differences explain the net income differences; trees and vegetables are more profitable than field crops.

Regarding crops grown in the CRB region, alfalfa and hay predominate in the basin's crop patterns, accounting for 66% of the irrigated area. Generally, the crop pattern is heavily focused on four crops: alfalfa, hay, cotton, and wheat. These crops collectively comprise 90% of the irrigated area (as indicated by red points in Figure 1). Although these crops cover a vast area, their net income constitutes approximately 50% of the total net income from agriculture. Detailed results at the irrigation district level are available in Crespo et al. (2023)

Climate Change and Water Allocations

Climate change projections consider different paths of greenhouse gas emissions, called Representative Concentration Pathway (RCP). The RCP 4.5 describes an intermediate scenario, and the RCP 8.5 describes a scenario in which emissions continue to rise. Streamflow is sensitive to variations in precipitation and temperature. Multiple projections of precipitation and temperature under concentration paths conform to the projections of streamflow in the basin. Lukas and Payton (2020) estimate streamflow changes at Lees Ferry for 2041–2070 relative to the 1971–2000 period with the projections of precipitation change and temperature of 64 scenarios of climate change. The majority of the scenarios project reductions of streamflow, and only scenarios with a 5% increase in precipitation compensate for the increase in temperature. However, the likelihood of a scenario in which the streamflow is sustained is low. The sensitivity of the flow to variations in precipitation is measured as the percentage variation of streamflow when precipitation varies. Streamflow varies between 2% and 3% for each variation of precipitations (Udall and Overpeck, 2017). A combination of increased temperatures over 4ºF (2.2ºC) and a reduction in precipitation of between 5% and 15% are associated with a reduction in runoff of over 20%. Other studies estimate the reduction of streamflow at between 6% and 31% (Woodhouse et al., 2021). Climate change projections provide an ensemble of results that range between increments in streamflow to extreme reductions of streamflow. The range of values is based on the consensus of those projections. Reductions in

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[2] The economic net income of CRB water use for agriculture, as reported in this article, is a conservative estimate. We only account for irrigated areas within the CRB's physical boundaries and those irrigated by the All-American Canal. Consequently, this analysis excludes portions of Utah, Wyoming, New Mexico, and Nevada outside the CRB irrigated with CRB water. Water use from the CRB in these areas, regarded as inter-basin transfers, is not included in our study. Additional details of the model can be found in Crespo et al. (2023).

water availability are expressed as average values, misrepresenting droughts and wet periods. Taking into account those scenarios of climate reductions in water availability, this article examines three reductions of water availability due to climate change. Mild, severe, and extreme scenarios of climate change are analyzed by reducing water available in the agricultural sector by 10%, 20%, and 30% with respect to the baseline conditions. Reductions in water availability by 10% and 20% occur in both the RCP 4.5 and RCP 8.5 scenarios, and a reduction in water availability by 30% occurs in the RCP 8.5 scenario (Lukas and Payton, 2020). Fixing reductions in water availability is a simple way to simulate climate change and its impacts, as used in other articles (Baccour, Ward, and Albiac, 2022; Connor et al., 2012). Reductions in water availability are proportional and shared equally among all irrigation districts. Each irrigation district adjusts its crop distribution to maximize net income given the water restrictions. This outcome is equivalent to minimizing net income losses due to water scarcity at the irrigation district level. Crops are fully irrigated, and deficit irrigation is not permitted. The amount of water applied is fixed by the acreage of land, and there is no substitutability between land and water. Because of this, and because the relationship between production factors and net income is quadratic, the response to water scarcity is a reduction in cropland of all crops. The intensity of this reduction is determined by the relative value of each crop compared to the others. Since the baseline conditions represents the maximum, crop area in the baseline represents the maximum extension possible. Other adaptations in water management, such as increasing the availability of advanced irrigation systems, are not allowed in this model since they require assumptions on crop production yields.

Climate change has been occurring since the 1980s; as a result, the current water availability and requirements reflect the emerging effects of climate change. The Colorado Basin has managed to meet water demand during the first quarter of the century due to the water stored in reservoirs. However, given the current conditions of change and water management, it is challenging to imagine that water scarcity conditions can be alleviated with reserves, without a buffer of water that allows for storage.

Climate Change Impacts at the Basin Level

Table 2 shows the net income and cropland at the basin level for the scenarios of reductions in water availability. The results show that the reductions in water availability have a small impact on the total net income in the basin. Indeed, a decrease in water availability by 30% results in an estimated economic loss of $69 million annually, which constitutes about 5% of the net income in the baseline scenario. losses in net income are not directly proportional to the reductions in water. This means that as water scarcity increases, the losses in net income also increase significantly, suggesting that the water system has a certain level of adaptability to water scarcity. Once this threshold is surpassed, however, losses in net income escalate rapidly. This is consistent with the principle of diminishing returns, where the first croplands to be fallowed are those with lower productivity. The result does not include second-order impacts on the economy of the region.

Under extreme water scarcity, the reduction in water availability implies the fallowing of 606,000 acres of irrigated land, which is 28% of the cropland in the baseline (Table 2). Land reduction is lower than the reduction of water availability, indicating that crops intense in water use and lower economic value are fallowed first—the average net income per remaining acre increases by up to 30%.

Cropping Pattern Changes

Figure 1 illustrates several aspects of the crop's representation and the impact of extreme climate change. The red points represent the crop's prevalence under baseline conditions, expressed as the percentage of total basin acreage occupied by the crop. The green triangles depict the impact of extreme climate change on each crop, showing the percentage reduction in irrigated acreage compared to baseline conditions. Last, the blue squares indicate the proportion of the total acreage reduction attributable to the reduction in crop acreage. Each of these elements provides a different perspective

Table 2. Irrigation Cropland and Net Income by Water Availability and Policy Scenarios

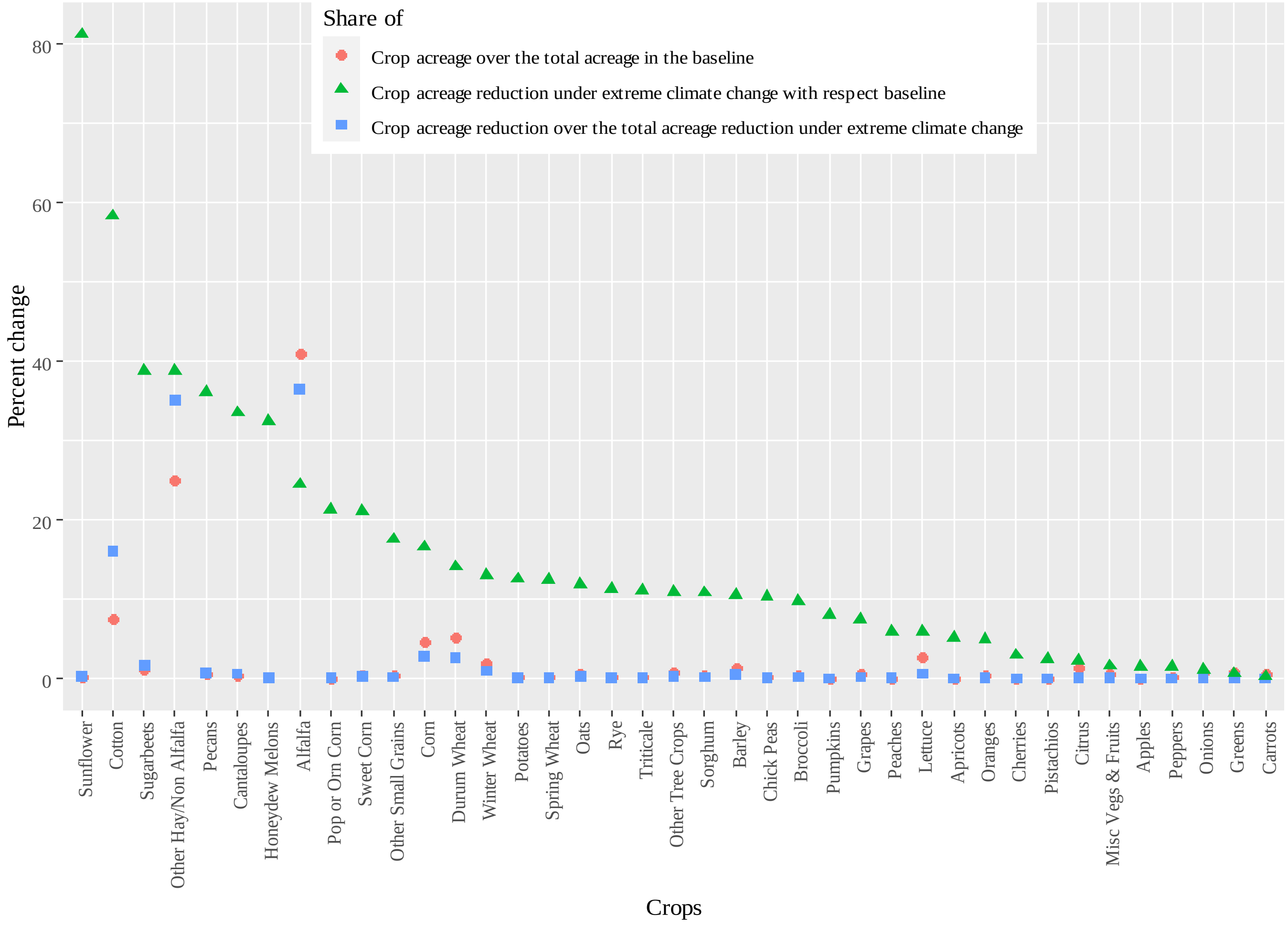
Water availability reduction (%)	Water availability reduction (1,000 acre-feet)	Net income (million $)	Reduction of net income from baseline scenario (million $)	Reduction of net income over baseline (%)	Cropland (1,000 acres)	Reduction of cropland from baseline (1,000 acres)	Reduction of cropland over baseline (%)
Baseline		1,415			2,200		
10	754	1,408	8	1	1,998	202	9
20	1,508	1,385	30	2	1,796	404	18
30	2,262	1,347	69	5	1,594	606	28

on the crop’s role and the effects of climate change. For instance, the sunflower acreage experiences a significant reduction of over 80% compared to the baseline conditions, as indicated by the green triangle in Figure 1. This demonstrates that climate change has a substantial impact on sunflower production. However, the blue square in Figure 1 shows that the proportion of the total acreage reduction attributable to sunflowers is small. This is because, as the red points in Figure 1 indicate, sunflowers occupy a small portion of the total acreage under baseline conditions.

Under extreme water restrictions (30% reduction of water availability), 31 of the 39 crops suffered net income losses lower than 5% compared to the baseline scenario. These crops represent a small share of the total cropland area in the basin, less than 10% of the total area of the baseline conditions (red points in Figure 1). Alfalfa, hay, cotton, and wheat accounted for a large share of the basin (red points in Figure 1), and consequently, these crops suffer the impact of water reductions, accounting for 90% (blue squares in Figure 1) of the acreage reduction (545,000 acres). The acreage of alfalfa and hay decreased intensely, given the magnitude of these crops over the total (red points and blue squares in Figure 1). However, other crops with a lower share of the total acreage experienced a relatively large impact, such as sunflower and cotton (green triangles in Figure 1). Under extreme water reduction, alfalfa fallowing is about 25%, and the irrigated area of hay reduces by around 38% with respect to the baseline (green triangle in Figure 1). Despite the significant reduction in acreage of alfalfa and hay, the net income losses from crop production are small, around 6% for alfalfa and 15% for hay, relative to the net income from the baseline scenario.

Cotton acreage accounts for the third largest share, around 7% of the total cropland area in the baseline scenario (red points in Figure 1). Under severe water restrictions, cotton declines heavily in the amount of the irrigated area by 58% (green triangle in Figure 1). These

Figure 1. Percentage of Crop Acreage over the Total in the Baseline Scenario (Red Points), Percentage of Crop Acreage Reduction under Extreme Climate Change with Respect to the Acreage in the Baseline (Green Triangle), and Share of the Crop Reduction over the Total Reduction under Extreme Climate Change Conditions (Blue Square)



reductions in cotton production result in net income losses of 34% compared to the baseline scenario.

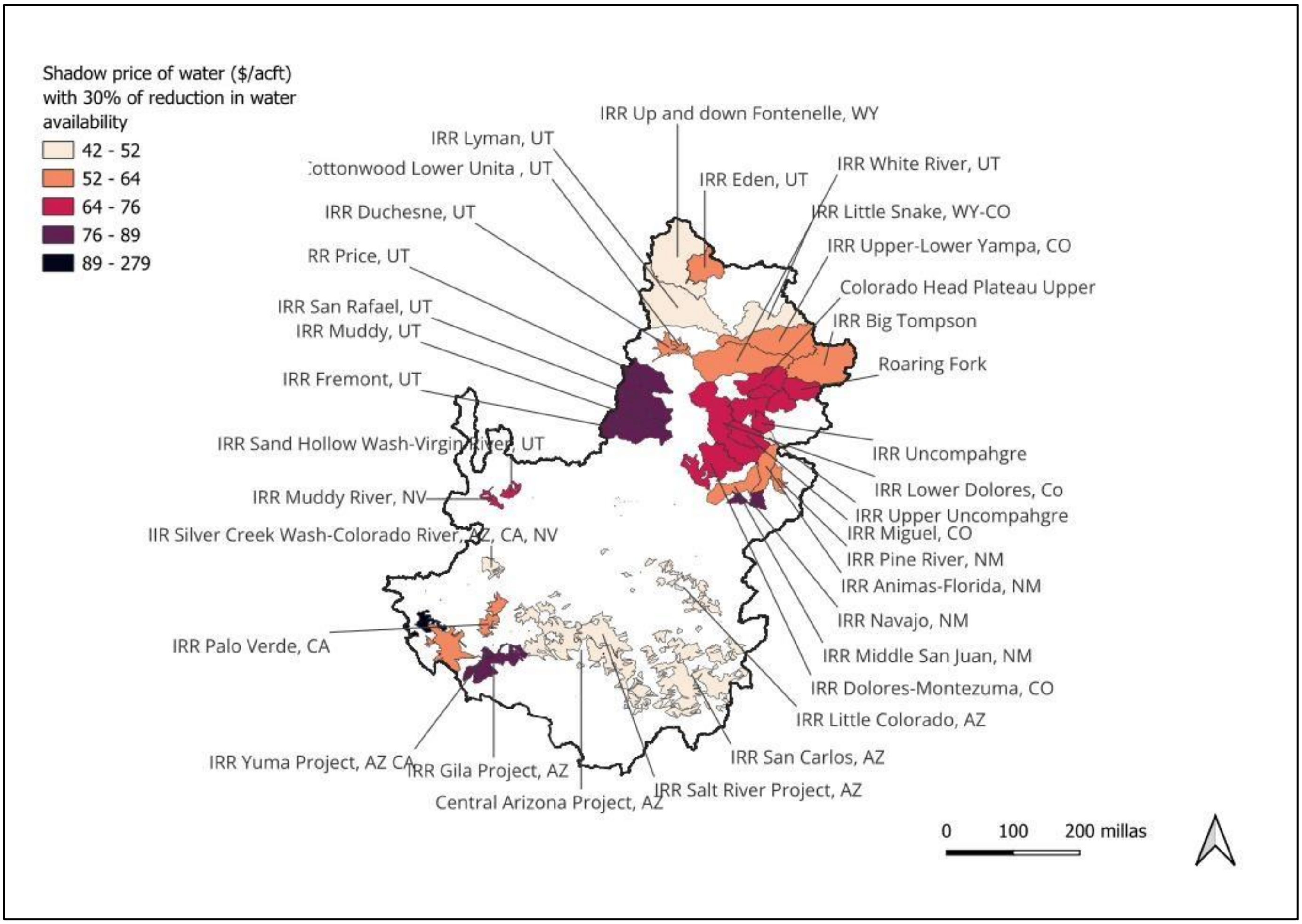
The net income of alfalfa, hay, and cotton crops decrease only slightly when the acreage is reduced significantly. This shows that a large portion of the acreage allocated to those crops is low in productivity, and net income is provided by a smaller portion of area with high productivity. Therefore, reductions in water availability affect irrigated areas with low productivity, and the area with high productivity continues to produce. In consequence, the average net income per acre of those crops increases more than the 50% with respect to the baseline conditions.

Spatial Distribution of the Impacts of Climate Change

Under extreme climate change, net income losses for irrigation districts represent between 1.6% and 8.6% of the net income of the baseline. In relative terms, five irrigation districts maintain net income losses below 5% of the net income of the baseline, which is the average net income losses for the basin. These irrigation districts are Palo Verde (California), Imperial (California), Gila (Arizona), Coachella (California), and Yuma (Arizona), which are able to mitigate the loss of net income because an important share of the net income of these irrigation districts results from the production of trees and vegetables. Adapting to climate change requires maintaining high-value crops with advanced irrigation technology in production and reducing intensely low-value crops such as alfalfa and hay. The irrigation districts highly specialized in field crops have insufficient capacity to change crop patterns and, consequently, to preserve net income.

Figure 2 shows the shadow price of water by irrigation district under extreme climate change, which ranges from $42 per acre-foot to $279 per acre-foot. The shadow price of water indicates the variation in net income for one additional acre-foot of water. The differences in the shadow price between the irrigation districts identify where the water is more valuable and

Figure 2. Shadow Price of Water ($/acre-feet) by Irrigation Districts with 30% Reduction in Water Availability



Note: Shadow price indicates the increment in the net income for one additional unit of water.

the cost of water scarcity. Also, the differences in shadow price show the direction of potential water interchanges.

Summary and Policy Implications

Climate change in the Colorado River Basin is expected to reduce water availability by 30% compared to the last century. The basin is facing water shortages resulting from the imbalance between water demand and supply. Those shortages are expected to increase as climate change imposes a reduction in water availability. This paper examines the impacts of climate change on the agricultural sector in the CRB. The results indicate that alfalfa, hay, and cotton support the reduction of water availability, given the large share of those crops in the total area. However, the impacts on the net income at the basin level, irrigation district, and crops are relatively small compared to the size of fallowed land. The adaptation strategy of irrigation districts to climate change relies on changing the cropping pattern by fallowing low-productivity crops to maintain high economic value, including high-productivity acreage covered by alfalfa and hay. The production of cotton suffers severely from water restrictions, and the impact on the net income for the sector is large.

The results indicate that irrigation districts have the capacity to adapt to water restrictions and maintain net income with the production of crops with high economic value. This result makes us reflect on the current efficiency of water use in the basin.

Declining water inflows and aridification will impose water restrictions that will probably result in permanent reductions of water allocations. The emerging conditions in the basin push for a revision of water management, which may include long-term strategies to face climate change. The results of this article are optimistic since alternative effects of climate change—such as an increase in evapotranspiration, variations of yields, and crop failure—are not considered. In addition, the analysis omits the temporal dimension of drought. This overlooks the fact that climate change increases the probability of experiencing long-lasting and intense drought conditions, thereby ignoring an important source of uncertainty. Risk management is essential to provide robustness to the water system. Therefore, a comprehensive analysis of those aspects of climate change is needed for the CRB.

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Threading the Needle: Upper Colorado River Basin Responses to Reduced Water Supply Availability

Mahdi Asgari and Kristiana Hansen

JEL Classifications: Q25, Q28
Keywords: Colorado River, Curtailment, Demand management, Water conservation

Lakes Mead and Powell, the two largest reservoirs in the Colorado River Basin (CRB) and the entire United States, are at historic low levels due to a 20-year megadrought and steady demand pressures from the Basin's water users. Periodic severe and sustained droughts in the CRB have occurred in the past and will likely continue to occur in the future. Hydrologic models for the basin further project overall decreased annual flows under climate projections of increased temperature and variability in precipitation (Kopytkovskiy, Geza, and McCray, 2015; Salehabadi et al., 2022). Low reservoir levels in Lakes Mead and Powell lead to reduced deliveries to downstream water users and threaten hydropower production.

Low reservoir levels at Lake Powell also have implications for water management in the Upper Colorado River Basin because of how water in the CRB is governed and managed. The interstate compacts, an international treaty with Mexico, and many court rulings, policies, and guidelines governing water allocation in the CRB are collectively called the Law of the River. Two major components of the Law of the River pertain directly to the current water discussions in the Upper Basin.

First is the Colorado River Compact of 1922 (1922 Compact), which apportions 7.5 million acre-feet (MAF) of water to the Lower Division States of Arizona, California, and Nevada and 7.5 MAF of water to the Upper Division States of Colorado, New Mexico, Utah, and Wyoming. The 1922 Compact specifies that the Upper Division States will not cause the flow of the river to be depleted below 7.5 MAF annually, on a 10-year rolling average basis, as measured at Lee Ferry, the dividing line between the Upper and Lower Basins. A portion of Arizona lies within the hydrologic Upper Basin (UB), but Arizona is not an Upper Division State subject to curtailment. For ease of exposition, this article sets aside this technical distinction and refers to just the four states subject to curtailment as the UB states.

The second important element of the Law of the River is the Upper Basin States Compact of 1948, which proportionally allocates water among the UB states. It also establishes that a "curtailment" will occur if flows are depleted below the 7.5 MAF annual rolling average threshold. Under a curtailment, the UB states would be required to turn off their most junior water rights to reduce consumptive water use. In a curtailment, the states would first cut back by the amounts they exceeded their allocation in the previous 10 years. Each state would meet the remainder of the curtailment obligation in proportion to its percentage allocation in the 1948 Compact of post-1922 Compact water rights. Each state would decide how to implement the curtailment within its boundaries (Paige, Hansen, and MacKinnon, 2021). There has not yet been a curtailment, but the current prolonged drought and the resulting drop in elevations at Lakes Powell and Mead have led to concerns that one could occur.

In response, the U.S. Bureau of Reclamation (USBR) and the UB states are exploring the idea of an Upper Basin Demand Management (DM) program. Under a DM program, the UB states would conserve and store water in Lake Powell or one of several other UB reservoirs that have historically been put to beneficial use. This water could be released in future years, as needed, to help the states meet their 1922 Compact obligations, thus reducing—or avoiding altogether—the risk of curtailment. This program is still being studied for technical, policy, and legal feasibility.

Regardless of whether the UB implements a DM program, the threat of curtailment requires that policymakers and water users in the region wrestle with questions about whether and how best to reduce water use. This article identifies some of the challenges and trade-offs that UB states face as they work within the parameters of the 1922 Compact to ensure that they meet their obligations to the Lower Basin (LB). Changes in the amount of water used, and the location of use, are likely to occur under either curtailment or a DM program. The impact of these policy tools on participating and affected communities would differ, depending on the scale and frequency of occurrence. Thus, we also discuss patterns of water transfers and exchanges that are likely to take place as well as their implications for rural agricultural communities and ecosystem service provision. The details of how the UB states meet these challenges—whether through water pricing in urban areas, changes in irrigation technology, or water use efficiency improvements—are beyond the scope of this article.

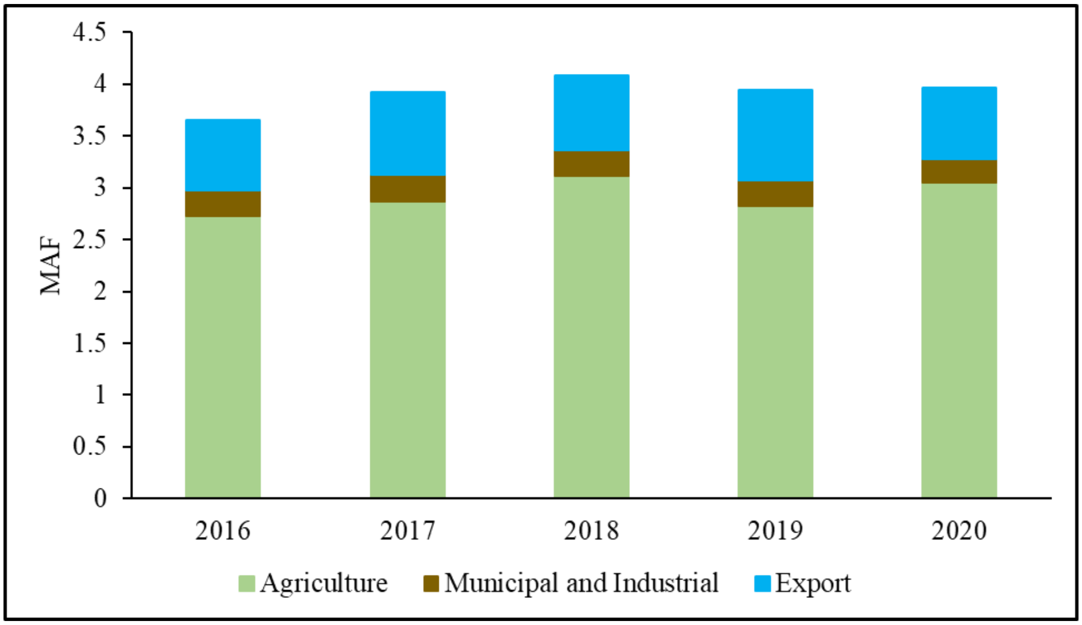
Upper Basin vis-à-vis the Lower Basin

The Colorado River Basin (CRB) has a drainage area of about 242,000 square miles which represents about one-fifteenth of the area of the United States. Less than half of this area, approximately 110,000 square miles, forms the Upper Colorado River Basin (UB) drainage area (USBR, 2022). The UB, with an estimated population of just over 1 million in 2020, is economically different from the Lower Basin (LB), which had an estimated population of more than 8 million that same year (U.S. Census Bureau, 2020).

Both subbasins transfer water to major population centers adjacent to the CRB, though trans-basin diversions in the LB are significantly larger than UB diversions. About 3.6 million people located outside the UB drainage area rely on drinking water from the UB. Most notably, approximately 30% of the water in the UB drainage area is exported to the Front Range of Colorado (which includes Denver) for agricultural and municipal use. By contrast, more than 19 million people located outside the LB drainage area rely on drinking water from the LB. This includes 1.2 MAF exported annually to areas in southern California outside the LB drainage area (MWD, 2024).

Rural economies in the UB rely on agriculture, which has the region’s largest share of water use (see Figure 1). On average, the agricultural land irrigated with water from the Colorado River (including out-of-basin transfers for irrigation) was about 2.16 million acres per year for the 2016–2020 period in the UB (compared to an estimated 3.34 million acres per year in the LB over the same period) (USBR, 2022). The consumptive use of irrigation is more than 62% of the total water used in the UB (USBR, 2022). Agricultural production is less diverse in the UB than in the LB due to its higher elevations and more extreme climate conditions (USDA NASS Reports). Most of the irrigated land is devoted to livestock feed production. Crop sales averaged $131/AF of water consumed in the UB (using 2015 crop revenue data) compared to $814/AF in the LB. Crop sales minus crop-specific input costs averaged $93 in the UB and $485/AF in the LB (Frisvold and Duval, 2024). Agricultural production is thus less profitable in the UB than in the LB.

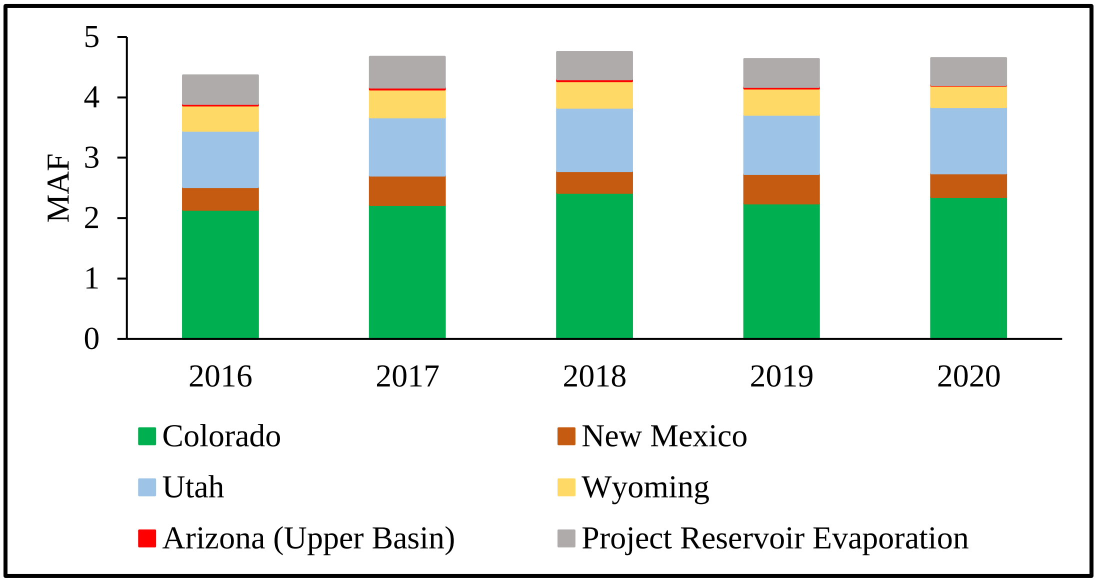
Figure 1. Upper Colorado Basin Estimated Water Use by Type of Use (MAF)



Notes: Agricultural water use includes estimated irrigation consumptive use, stockpond evaporation, and livestock water use. Municipal and industrial water use includes estimated consumptive use of mineral production, thermal electric production, and municipal uses. Exports include transbasin diversions both out of and into the Colorado River System.

Source: Compiled by the authors using U.S. Bureau of Reclamation (2022) report data.

Figure 2. Upper Colorado Basin Estimated Water Use within States (MAF)



Notes: Project reservoir evaporation includes estimated evaporations in reservoirs that participate in the Colorado River Storage Project.

Source: Compiled by the authors using U.S. Bureau of Reclamation (2022) report data.

Another key difference between the UB and the LB is their location relative to water storage. The LB is situated below Lakes Powell and Mead, which gives them access to water stored across years. By contrast, the UB is situated above the major storage reservoirs on the CRB. Although there are a few smaller reservoirs in the upper reaches of the CRB, most UB water users are subject to inter- and intra-annual variability in precipitation. The higher risks associated with water supply at the UB reveal the crucial need to conserve water in the region, even though UB states have developed their water resources at levels considerably lower than the 7.5 MAF apportioned to them in the 1922 Compact. Estimates by the USBR for 1988–2018 show about 4.4 MAF of consumptive use in the Upper Basin. More recent reports show an average of 4.6 MAF of consumptive use in the Upper Basin over 2016–2020 (see Figure 2).

These climatic, economic, and geographical characteristics drive the UB response to reductions in water availability in two important ways. First, UB water use can fluctuate significantly each year in response to annual flow due to the lack of upstream storage. For example, in Wyoming, an increase in the irrigation water supplies (measured in summer precipitation and spring snow water equivalent) positively correlates with irrigated agriculture acres for the year (USDA-NRCS and USDA-NASS Reports). In a curtailment, the UB would respond by reducing consumptive use of water rather than by releasing more water from storage simply because upstream storage is limited. In fact, if more stored water was available, it would have already been released to meet its Compact obligation and avoid curtailment.

Second, the lack of upstream storage, though consistent with the focus of the 1922 Compact on nondepletion of flows at Lee Ferry, results in water shortages yearly in the UB. For example, the USBR estimates that in 2020, the agricultural sector in the UB faced a total of 265 thousand acre-feet (KAF) of water shortage: 8.7% of total water use by the agriculture sector that year (USBR, 2022). The fact that the UB experiences shortages every year due to natural variability in flows is a point often made by the UB representatives at regional meetings.

Water User Responses to Reduced Water Availability

Flow reductions and projections of continued dry hydrology mean that the Compact has become binding on total UB consumptive water use; the risk of curtailment is higher in the UB than in the past. All four UB states follow the prior appropriation doctrine for their surface water rights. Under prior appropriation, those with higher seniority in water rights receive their full share of water before a junior rights holder receives any. Each of the four UB states would likely meet a curtailment obligation by regulating off-water rights in reverse priority (starting with the most junior and working backward in time by priority date) until its obligation was met.

Pre-Compact rights holders tend to be agricultural users, while junior water users tend to be from the municipal and industrial sectors, reflecting the historical pattern of development across the western United States. The municipal and industrial sectors would thus be hit hardest by curtailment.

In a curtailment, junior rights holders could respond by increasing water conservation measures. However, many junior water users may find that they cannot manage water reductions through conservation alone. Alternatively, junior water users may opt to acquire additional water from more senior water rights holders. This replacement water would generally come from the agricultural sector, where the marginal economic value of water tends to be relatively low. A junior user could wait until a curtailment occurred and then contract with senior, pre-Compact water rights holders for short-term leases or exchanges during the curtailment. Alternatively, they could execute an option agreement with senior rights holders before a curtailment to transfer water in the future when a curtailment occurs.

Junior water users could also opt to acquire additional water by purchasing senior water rights. All else being equal, municipal and industrial water users needing replacement water might prefer to purchase rather than lease water rights to ensure a long-term firm and lower-risk water supply (Hansen et al., 2015). Leasebacks, in which municipalities purchase agricultural water rights for future growth but lease the water back to agriculture in the meantime, have been implemented along the Front Range of Colorado. However, permanent water rights transfers out of agriculture to junior water users remain relatively rare in the region. A 2020 focus group of municipal and industrial water users in Wyoming expressed only minimal interest in rights transfers, whether due to the challenge of finding sellers willing to part with rights at acceptable prices or political concerns about long-term regional economic impacts (Paige, Hansen, and MacKinnon, 2021).

Permanent transfers would result in a permanent dry-up of agricultural lands, which can significantly impact exporting communities through losses in income, tax receipts, and employment, particularly in specialized and less diverse agricultural economies (Howe and Goemans, 2003). Specialized, marginal agricultural regions (as in Utah and Wyoming) have been shown to experience more severe economic and social impacts from water rights transfers than regions with higher-value agricultural production, and these impacts are more likely to be long-term (Dozier et al., 2017).

Even short-term transfers have implications for the regional economy. In the absence of processing plants and feedlots, reducing irrigated hay acres would reduce a proportionately large percentage of agricultural activity, especially when that leads to reductions in livestock herd size in the region (Hansen et al., 2021; BBC Research & Consulting, 2020). The magnitude of impacts varies depending on the length of the program, the compensation rate, and assumptions about how much compensation is to be recirculated in the local economy.

Transfers—whether permanent or short-term—also have implications for water flows on the landscape. Flood irrigation is the predominant form of irrigation in many high-elevation mountain valleys in the UB. This type of irrigation is less efficient than center pivot or drip irrigation. However, it creates artificial wetlands that provide wildlife habitat for migrating ungulates and bird species. It also generates return flows, which are released in late summer or fall when some creeks might otherwise run dry. This benefits downstream agricultural water users and some fish species. Widespread drying up of irrigated fields could significantly alter return flows and have impacts on ecosystem service provision, groundwater recharge, and downstream water users. However, other fish species and, consequently, recreationists benefit from reductions in consumptive use, through increases in early- and mid-season instream flows. Impacts from change are location-specific and difficult to quantify but significant to water users and recreationists in the region. These impacts on local communities and ecosystems speak to the significant controversy that can result from changes in the timing and location of water use.

Region-Level Responses to Reduced Water Availability

In response to projected shortfalls in water availability and in part to reduce the risk of curtailment, the UB states may implement a Demand Management (DM) program. Under a DM program, water users would be compensated for voluntarily reducing their consumptive water use on a temporary basis. Conceptually, the conserved water would be stored in Lake Powell or other UB reservoirs. The UB could then release water from Lake Powell in dry years when a curtailment would otherwise be announced. This DM program would be a collective response to curtailment risk and allow UB water users to continue historical water use patterns, other than the voluntary and compensated conservation undertaken through the DM program. All four UB states have undergone studies to investigate the feasibility of a DM program (CRCB, 2021; Paige, Hansen, and MacKinnon, 2021).

No UB DM program has been implemented so far. However, the region is undertaking a pilot program, the System Conservation Pilot Program (SCPP), to assess the feasibility of system conservation to increase storage in Lake Powell (UCRC, 2018). During the first four years of the SCPP (2015–2018), 64 projects were supported across the four states. Project types included full- and partial-season fallow, deficit irrigation, alternative cropping in agriculture, and several municipal projects. The cost per acre-foot of water conserved ranged widely from $161 to $670, though by 2018, all projects were compensated at $200/AF. The SCPP resulted in almost 50 KAF in consumptive use reductions during these four years, at a total cost of nearly $8.6 million (UCRC, 2018). The program was revived in 2023 due to concerns during the 2022–2023 winter about low snowpack. In 2023, the SCPP resulted in almost 37.8 KAF in consumptive use reductions, for $15.8 million (UCB System Conservation and Efficiency Program).

One advantage of a DM program over permanent transfers is that its temporary and rotational nature would generate lower regional economic impacts relative to rights transfers. The temporary reductions in water use through a DM program would likely not result in permanent job losses or major shifts in economic activity in the exporting region (Howitt, 1994). Still, concerns about the negative regional economic impacts of a DM program could be addressed prior to its implementation through a mitigation fund.

A DM program also has advantages over curtailment. Curtailment would be mandatory and uncompensated for some less senior water rights holders, whereas water user participation in a DM program would be voluntary and compensated. The compensation received by DM participants would provide an infusion of cash into local communities that would counter some of the negative regional economic impacts associated with reduced water use. Further, a DM program would be proactive, giving water users the opportunity to consider participation on their own timeframe rather than in the rushed moment of a curtailment announcement. However, the concept of a DM program has its own challenges.

The principal among these challenges is funding. The first 4 years of the SCPP (2015–2018) were funded by the USBR and the water utilities serving the cities of Denver, Las Vegas, Los Angeles, and Phoenix. The two most recent SCPP years (2023 and 2024) are funded through the Inflation Reduction Act. However, a long-term source of funds to compensate DM participants has not yet been identified (UCRC, 2018).

Another important challenge for a DM program is the technical details related to implementation. States are working to develop shared metrics and protocols for quantifying and verifying consumptive use reductions. Still of concern is the need to ensure that conserved water is “shepherded” all the way to Lake Powell rather than diverted in transit by other water rights holders. Further, data on how yields and crop consumptive use respond to full and partial reductions of applied water under different soil types and climate conditions is lacking, creating uncertainty for policymakers and water users who want to evaluate the merits of a DM program.

These uncertainties and outstanding questions increase the costs of this proposed new institution. Senior and junior water rights holders have different degrees of exposure to curtailment. Should states invest resources in developing a DM program to protect junior rights holders from curtailment? Whether the benefits of the collective action represented by a DM program outweigh the costs for each state remains to be seen.

In general, whether a DM program (with its compensation provided by an outside funding source and the flexibility provided by banking) is a cost-effective way to shield water users in the region from the disruption of curtailment also depends on the range of curtailment risk that the region faces. If curtailment turns out to be relatively infrequent, the benefit to the region of a DM program would not be worth the expense of establishing one. Alternatively, if curtailment turns out to be more the norm than the exception, a DM program of a size sufficient to substantially reduce curtailment risk would be too expensive. In this latter case, permanent water use reductions would need to be implemented; junior water users affected by curtailment would find themselves needing to either acquire rights or reduce water use to adapt to the new normal.

Though it is possible that some junior rights holders from the municipal and industrial sectors would find ways to reorganize or otherwise adapt to less water available, those who seek to augment supplies would likely lease water from senior agricultural rights holders. So, even in the absence of a DM program, the sector of the economy with reduced water use is likely to be agriculture.

Concluding Remarks

The Colorado River Basin faces many challenges, especially considering projections of climate-induced water supply reductions in the basin. A recent USBR analysis shows that to stabilize elevations at Lakes Powell and Mead over the 2023–2026 period, 0.6 to 4.2 MAF of additional or conserved water is needed annually (Prairie, 2022). Further, the guidelines under which the USBR manages Lakes Powell and Mead will expire in 2026, which, combined with the hydrologic realities of the basin, calls all stakeholders to devise a working plan for the longer term. Continuation of the current management regime is simply not viable. Whether policymakers and stakeholders form a consensus around renegotiating the entire basin management system (unlikely at this point) or modifying effective short-term solutions with bold action plans remains to be seen.

This article has considered just one of these challenges: the UB issue of whether to implement a DM program to reduce curtailment risk. The concept of an Upper Basin Demand Management program has been developed in response to the way that the 1922 Compact distributes water across the Upper and Lower Basins in times of shortage. It is an example of institutional innovation that improves the ability of water managers to address current and projected reductions in water supplies without fundamentally altering the underlying doctrine of prior appropriation. It remains to be seen whether such incremental changes in the tools available to water managers will be sufficient to manage competing demands for water in the basin. Regardless, experience gained by regional water users and policymakers through scoping demand management and implementing a pilot program will help the region understand what flexibilities it has available to address shortfalls in water availability moving forward.

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Water Justice Concerns in the Colorado River Basin

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JEL Classifications: Q25, Q28, Q54
Keywords: Climate change, Hispanic communities, Tribal nations, Water justice

The Colorado River Basin (CRB) and areas served by its waters, includes dozens of indigenous nations and numerous communities and water user organizations rooted in Hispanic culture. Tribal nations and Hispanic communities encounter challenges with access to clean and reliable water and have been marginalized in historic and ongoing water negotiations and policy dialogue. The CRB is experiencing devastating effects linked to a warming planet, including wildfires, extended drought, severe flooding, drying soil, and changing vegetation (Overpeck and Udall, 2020, Payton and Lukas, 2021). This article describes several key water justice issues in the CRB linked to indigenous and Hispanic communities. The concluding sections explore the contributions of tribal nations and Hispanic acequias in creating resilient responses to the basin's water challenges and suggest themes for further research.

The CRB (in this article, we include both the geographic basin and areas receiving imports of CRB water) supports a population of over 40 million, with over 5 million acres of irrigated cropland. The region is home to 30 indigenous tribal nations and to one-third of the entire U.S. Hispanic population (13 million Hispanics) (U.S. Environmental Protection Agency, 2022; U.S. Census Bureau, 2024). The indigenous population residing in CRB is about 2% of the total population. Hispanic nonwhite individuals account for 37% of the population (Reed-Spitzer and Colby, 2024).

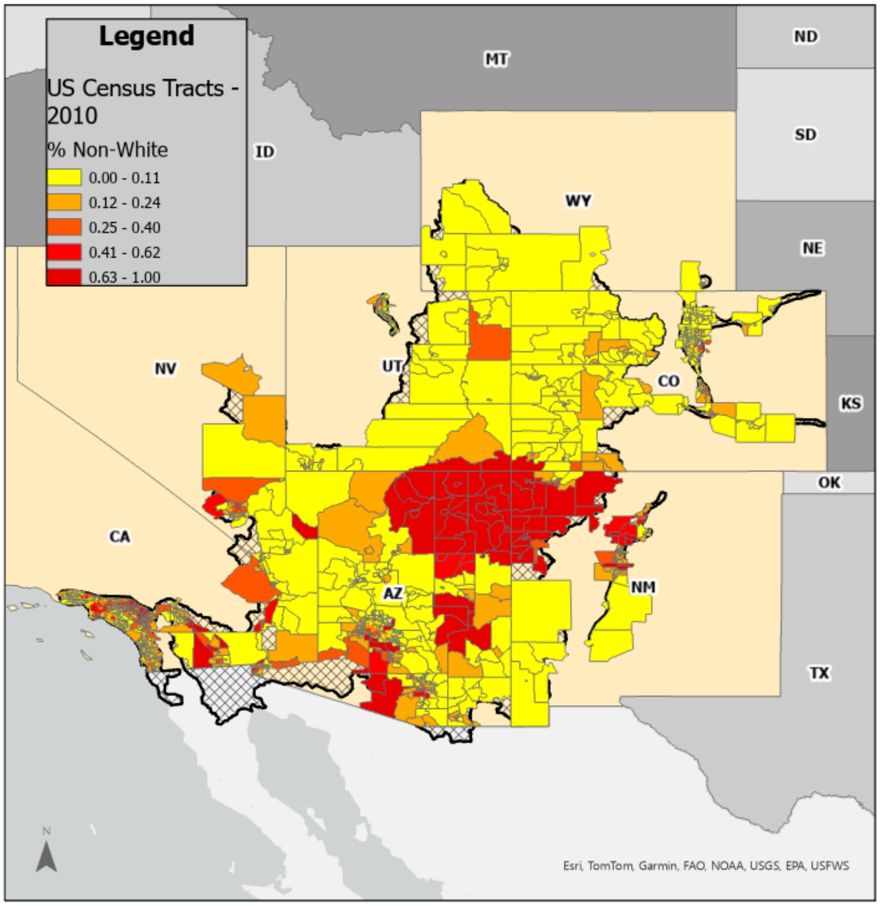
Water justice is a term used worldwide to focus attention on the disproportionate effect of disruptions in regional water supplies on low-income and minority communities, communities already more vulnerable due to existing socio-political and economic inequities (Sultana, 2018). The U.S. federal government has committed to water justice through its environmental justice initiatives. In federal policies, environmental justice is characterized as "fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (U.S. Environmental Protection Agency, 2023). Many empirical studies demonstrate that in the United States, low-income households and people of color have greater exposure to environmental hazards (Banzhaf, Ma, and Timmins, 2019; Chakraborty et al., 2022; Balazs, Morello, and Ray, 2012; Cory and Rahman, 2009; Morata et al., 2022). The 2021 U.S. Justice 40 Initiative establishes a federal policy objective of directing 40% of benefits from federal investments to marginalized or underserved communities, emphasizing water supply, water quality, and wastewater treatment as key components (The White House, n.d.). The Climate and Economic Justice Screening Tool was developed to assist in the implementation of the Justice 40 Initiative (U.S. Environmental Protection Agency, 2022).

This article discusses three aspects of water justice related to Indigenous and Hispanic populations in the CRB: (1) household access to affordable and reliable water, (2) participation and representation in water negotiations and policy processes, and (3) impacts of CRB water policies on low-income and minority communities (including economic, environmental, cultural and resilience impacts). This latter water justice factor encompasses access to resources that support resilience in a changing climate, including public investments in water infrastructure (DataKind, 2023, U.S. Water Alliance, 2023).

The shading in Figure 1 indicates the nonwhite proportion of population (Native American plus black plus nonwhite Hispanic populations, as self-identified in the U.S. Census) in overall population of census tracts in the CRB. (The census tracts in Figure 1 include the geographic CRB as well as areas served by Colorado River water exported from the CRB.)

Table 1 summarizes data on income and education level, stratified by percentage of nonwhites in the census tract population (using the same strata illustrated by shading Figure 1). Note that mean income in the tracts with the smallest percent nonwhite (0%–11%) is about double that of the census tracts with greater than 63% nonwhite. Compared to census tracts with the smallest

Figure 1. Percentage Nonwhite Population in 2019 by U.S. Census Tract



Source: Created by authors based on data from the U.S. Environmental Protection Agency (2022).

percentages of nonwhite residents, the proportion of households with adults having no high school degree is 10 times higher in census tracts with a nonwhite population of higher than 63%.

Table 2 uses the same stratification by percentage of nonwhite population illustrated in Figure 1 to highlight two examples of differential exposure to environmental hazards in the CRB, drawing upon data in the Climate and Economic Justice Screening Tool (U.S. Environmental Protection Agency, 2022). PM 2.5 are fine inhalable particulates posing a significant health threat. Leaking underground storage tanks pose a threat to water quality as toxic materials leak into nearby soils and pollute water. As Table 2 indicates, the prevalence of PM 2.5 and leaking underground storage tanks is notably higher in census tracts with higher proportions of nonwhite populations.

Tribal Nations and Hispanic Acequia Communities in CRB

This article focuses on several water justice issues pertaining to two distinct groups in the CRB: tribal nations and Hispanic acequia communities. While these two minority groups face some challenges in common, they are distinct in many important ways. These groups represent only a subset of populations affected by water justice concerns, and the water justice issues raised are discussed only briefly given the overview nature of the article.

Many tribal reservations and acequia communities are located in rural areas of the CRB, and rural areas face water access issues that differ from major cities. Low-income rural areas in the CRB are characterized by limitations on water supply reliability. Accessing safe, reliable water is a challenge for many rural areas of the CRB. Many small, rural communities lack adequate economic base to support modern water and wastewater services for sparse populations spread out over large areas (U.S. Water Alliance, 2023). Rural areas of the CRB tend to have lower per capita income than urban areas, and many rural census tracts contain high proportions of Native American and Hispanic residents.

The effects of climate change on precipitation, temperature, and water supply reliability are being disproportionately experienced in low-income rural areas, as changing regional hydrology and climate exacerbate long-term disparities and water justice

Table 1. Income and Education by Percentage Nonwhite in Census Tract

% non-white in census tract	Income			no HS degree		
	mean	median	stnd dev.	mean	median	stnd dev.
0 - 0.11	$135,236.68	$125,034.00	$71,349.76	3.1	2.0	3.6
0.12 - 0.24	$114,066.39	$107,999.50	$44,453.31	5.3	4.0	4.3
0.25 - 0.40	$91,588.22	$89,223.50	$29,981.90	9.1	8.0	5.9
0.41 - 0.62	$77,806.73	$75,515.00	$24,468.28	15.8	15.0	7.7
0.63 - 1.00	$62,997.70	$60,988.00	$18,593.21	32.1	31.0	12.5

Source: Data from the U.S. Environmental Protection Agency (2022)

concerns. Historic lack of investment in water-related infrastructure serving low-income and minority populations places these communities at a significant disadvantage. Generally, tribal nations located away from major cities have not benefited from public investment in water storage and delivery infrastructure. Substantial research documents inequitable access to safe drinking water in low-income rural Hispanic communities within the CRB (Balazs, Morello, and Ray, 2012; Pannu et al., 2018; London et al., 2021; Mueller and Gasteyer, 2021; Acquah and Allaire, 2023).
Native American and Hispanic communities each experience disproportionate poverty and marginalization in water decision-making and negotiations. They also each face distinct challenges related to water rights. Tribal nations and some Hispanic communities possess senior water entitlements that make them the target of efforts to acquire access to their water through litigation, political maneuvering and market transactions. There also are important distinctions between the two groups in terms of water entitlements and water justice challenges, noted below.

Tribal Nations

Tribal nations are sovereign governments, enacting their own regulations over reservation water use and water quality. Tribal nations’ entitlements to water resources were recognized by the U.S. Supreme Court in 1908 (Winters v. U.S.), though the process of quantifying those rights and putting them to use for the benefit of tribal communities has been slow and costly. Many CRB native nations have quantified senior water rights, which are more reliable than junior rights held by non-Indian farms, industries, and cities. This superior reliability puts tribes in a unique position in a region struggling with the effects of climate change on water supply and demand.

Table 2. PM 2.5 and Leaking Underground Storage Tanks (UST) by Percentage Nonwhite in Census Tract

Percentage nonwhite **in census tract**	**PM 2.5**			**Leaking UST**		
	mean	median	stnd dev.	mean	median	stnd dev.
0–0.11	8.29	7.82	2.18	1.71	0.79	2.62
0.12–0.24	8.90	8.47	2.37	2.61	1.63	3.24
0.25–0.40	9.18	8.69	2.56	3.25	2.20	3.70
0.41–0.62	9.62	9.34	2.54	3.72	2.71	3.84
0.63–1.00	10.79	12.06	2.66	4.80	3.49	4.73

Source: Based on data from the U.S. Environmental Protection Agency (2022).

Since tribal water rights are senior in priority, recognition and development of tribal rights threatens the reliability of supplies for other water users. This threat provides the impetus for negotiating tribal water settlements, legally binding agreements negotiated among tribal nations, federal agencies, states, water districts, and other water users. These agreements aim to reduce conflict by specifying water allocations and providing assured water supplies and are now an important component of water institutions in the CRB (Deol and Colby, 2018). Over four dozen tribal water rights settlements have occurred in the western United States, with Arizona and New Mexico settlements accounting for a large share of these. Each of the other five CRB states has a few tribal water settlements and/or tribal water entitlements formalized through litigation and court decrees (U.S. Department of the Interior, 2023).

Settlements provide many potential benefits (Colby and Reed-Spitzer, 2024). They can address inadequate access to water for tribal communities and often fund water infrastructure to serve tribal farms and communities and to address broader regional water challenges. Some settlements include provisions that expedite environmental restoration, contributing to cultural and recreational values.

Water settlements are costly in both water and financial commitments. The U.S. government—along with states, cities and other water users—incurs notable financial obligations. Commitments of water can be large. The quantities of water for tribes in settlements vary across the CRB. The Gila River Indian Community settlement affirmed a water supply of 650,000 acre-feet per year for the tribal nation, a mix of local surface water and Central Arizona Project water (Lewis, 2005). Some settlements involve only a few thousand acre-feet per year for tribes but provide key economic development components. Examples include agreements made with the Yavapai Prescott Tribe in Arizona and the Shivwits Band of Paiute Indian Tribe in Utah (Colby and Young, 2018). Some settlements and court rulings restrict nontribal water groundwater users located near a reservation to protect groundwater underneath tribal lands (Colby and Young, 2018).

The role of Native American tribal nations in the CRB continues to evolve. A number of tribes serve as negotiators and co-implementers of agreements that address regional water challenges while also quantifying tribal water rights (Deol and Colby, 2018, Young, Colby and Thompson, 2018, Ten Tribes Partnership, 2023). Four states and six tribal nations are engaging in their first formal talks to establish a process for jointly negotiating Colorado River water issues. Each of the six tribes hold established senior water rights in the CRB, formalized through negotiated settlements and/or court decrees (Smith, 2022)

Acequia Water Users

Spanish colonists arrived in the CRB in the 1500s, bringing the Acequia irrigation system governance to parts of New Mexico, Colorado, and Arizona. Acequias continues to manage and deliver water in portions of the CRB (Brown and Ingram, 1987; Wescoat, Headington, and Theobold, 2007). The term acequia refers both to the physical water delivery system and to the governance of that system. While Hispanic communities are prominent in the CRB in many ways beyond acequias, the acequia focus was selected as particularly relevant for Hispanic water justice challenges. Acequia associations are still active in some portions of the CRB. The acequia systems operating in parts of New Mexico and Colorado involve farms that are smaller in size and that rely more heavily on off-farm income, compared to other farms in the region (Tory, 2021, Hicks and Pena, 2003). Most are located in areas remote from cities.

The acequias trace their water use back many centuries; water rights within acequias typically are held by landowner members of the acequia and are integrated into state water rights systems (Raheem et al., 2015, Rosenberg et al., 2020). This differs notably from tribal nations, whose water entitlements were recognized by the U.S. Supreme Court early but have required protracted and costly litigation and negotiations to become formalized water rights available for use on reservations.

Water Justice and Senior Tribal and Acequia Water Rights

Tribal nations and members of acequia associations often hold senior water rights, superior in reliability during times of shortage. While senior entitlements are an important asset and source of bargaining power, the question has arisen: What constitutes a voluntary transaction when the parties have highly disparate access to capital, political power and legal, economic, hydrologic, and other expertise? The United Nations developed guidelines related to this question, scrutinizing the role of coercion in natural resource transactions (United Nations, 2007). United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) principles are applied later in this article to tribal nations and Hispanic community engagement in water transactions to lease or sell their water. One key advantage of water markets is voluntary participation by those offering water for sale or lease. A water justice perspective invites more nuanced consideration of what constitutes a “voluntary transaction.”

Water Justice, CRB Tribal Nations, and Hispanic Acequia Communities

This section discusses three components of water justice, as applied to two different minority population in the CRB: tribal nations and acequias communities. A disclaimer at the outset: This article refers to tribal nations generically given the brief length of this piece. However, tribal nations in the CRB differ from one another in culture, language, ways of livelihood, current status of water entitlements, and perspectives on water justice. Some tribal nations have senior water entitlements quantified decades ago in key court decisions and reliable water supplies for on-reservation use and for leasing. Other tribal nations are still struggling for formalization and implementation of water rights.

Access to Affordable and Reliable Water

Tribal Nations. While affordable and reliable water is a foundational component of water justice, basic potable indoor water is absent for many Native American households in the CRB. Native American households in the United States are 19 times more likely to lack indoor plumbing than white households. In CRB census tracts that include Native American reservations, complete indoor plumbing is available to 96% of households. Contrast this with 99.5% of all CRB households having complete indoor plumbing. (U.S. Census Bureau, 2024). In some tribal reservation areas of the CRB, a significant proportion of tribal households lack potable water and must rely on hauled water (Conroy-Ben and Richard, 2018; Teodoro, Heider, and Spitzer, 2018, Deitz and Meehan, 2019).

Hispanic Communities. Safe drinking water access is a concern in many Hispanic communities. There exists a strong correlation between higher proportion of Hispanic residents and higher exposure to contaminants in drinking water and higher lack of access to indoor plumbing (Acquah and Allaire, 2023; Balazs, Morello, and Ray, 2012; London et al., 2021; Mueller and Gasteyer, 2021; Pannu et al., 2018). Regarding reliability, water rights of acequia members generally are senior in their region and integrated into their state’s water right management. Consequently, these rights tend to provide a reliable water entitlement even during drought.

Representation in Water Negotiations and Policy Processes

Tribal Nations. There has been progress in recent decades in tribal representation in CRB water decision-making, stimulated by severe drought and recognition that senior tribal water entitlements can help ameliorate losses in supply reliability for cities and commercial agriculture. Twenty CRB tribes formulated a joint statement of tribal consensus articulating what the Basin Tribes expect from the United States in ongoing federal-state-tribal negotiations to identify new operating guidelines for the CRB (Water and Tribes Initiative, 2024). Among other provisions, these include ensuring that tribes can use their water rights in CRB conservation programs, leasing water off reservations for multiple purposes and creating compensated forbearance agreements. The document also calls for a permanent, formalized structure for tribal participation all Colorado River policy and governance and federal consultation with tribal governments on a basis comparable to state governments (Water and Tribes Initiative, 2024).

Specific CRB tribal nations that hold formalized senior entitlements have been playing a prominent role in CRB water negotiations (Colby and Young, 2018; Young, Colby and Thompson, 2018). For the nearly two dozen completed and ongoing tribal water settlement negotiations in the CRB, tribal signatories are central not only in crafting settlement provisions but in the multiyear settlement implementation process. In 2024, tribes with senior rights in the Upper CRB are meeting with states and other water users to craft Upper Basin responses to ongoing basin-wide negotiations (Smith, 2022).

Tribal nations are lead participants in negotiations involving sales or leases of tribal water. There are many long-term leases (up to 99 years) of tribal water in the basin, often negotiated in the course of a water settlement (Colby and Young, 2018). UNDRIP issues related to coercion continue to be relevant to water transactions involving tribes, given poverty and limited access to other revenue sources beyond water leasing. However, tribes with quantified senior rights now have strong bargaining power in this water-scarce era (Water and Tribes Initiative, 2019).

Hispanic Acequia Communities. While acequias are communally managed ditch systems, the water rights are held by individual acequia members as state water rights and their seniority typically predates statehood. Acequia associations represent groups of acequias in policy dialogue in New Mexico and southern Colorado (HECHO, 2023, Hicks and Pena, 2003). The individual ownership of rights leads to concern over the erosion of acequia associations when valuable senior rights are acquired by outside interests and water is transferred away for use elsewhere (Raheem et al., 2015, Hicks and Pena, 2003). The challenge with acequia associations and individual members selling off water rights differs markedly from the challenge that Indigenous nations face in barriers to leasing or selling water entitlements held by the tribal nation. The UNDRIP guidelines to address potential coercion in natural resource transactions are relevant to both tribal water and acequia water, due to financial, technical, and political power imbalances among the negotiating parties.

Impacts on Community Resilience

The third component of water justice discussed in this article is resilience in the face of climate change effects on water, a key concern for tribal nations and for acequia water users. These groups historically have not been primary beneficiaries of public infrastructure projects that can boost resilience in the face of shifting supplies. Today, however, some USDA programs allocate funds specifically for Native American and Hispanic farmers, and other federal programs provide funding targeted for Native American and Hispanic communities (U.S. Environmental Protection Agency, 2023). Newly strengthened federal environmental justice initiatives may provide another source of funding (USDA Office of Tribal Relations, 2022, U.S. Environmental Protection Agency, 2023).

Tribal Nations. Tribal nations are negatively impacted by slow recognition of their water rights and lack of inclusion in basin decision processes (Sanchez, Leonard, and Edwards, 2023. The 2023 U.S. Supreme Court decision involving federal trust obligations for Navajo Nation water is another in decades of examples of failure to consider the impacts on tribal communities of key water policy decisions (Fletcher, 2023).

Tribal nations have historically experienced much lower access to resources for resilience in a changing climate. The benefits of decades of investments in water infrastructure largely have been directed to major cities and largescale commercial agriculture, with little emphasis on tribal nations. This lack of modern infrastructure results in tribal communities being disproportionately exposed to variability in water supplies (DataKind, 2023). The CRB tribal nations that have negotiated water settlements typically have received resources that improve their water supply reliability, along with funding for other tribal water needs and economic development (U.S. Department of the Interior, 2023).

Hispanic Acequia Communities. CRB water policies affect rural Hispanic communities through economic, environmental, and cultural impacts. The ability of acequias to demand mitigation of negative impacts rests upon legal tools they can draw upon (such as the Endangered Species Act or Clean Water Act), media attention, and cultivation of more powerful allies (Raheem et al., 2015, Hicks and Pena, 2003). Over time, recent U.S. social justice policies and commitments to expend federal monies to address water needs of disadvantaged populations may prove to useful to rural Hispanic communities (U.S. Environmental Protection Agency, 2023).

Tribal and Acequia Contributions to Regional Resilience in CRB

This section of the article highlights ways in which tribal and acequia water management practices and policies contribute to resilience in the CRB. These contributions bolster the case for addressing water justice concerns to support diverse approaches to meeting the challenges of a changing climate and regional hydrology. Minority water user communities with different approaches to addressing shortages can provide an institutional diversity valuable for informing ongoing evolution in larger CRB policy processes and responses to the challenges facing the region.

Recent research highlights New Mexico acequia contribution to improved seasonal water flow, even though acequia farms account for a small portion of the state’s irrigated cropland. Acequia ditch systems, often unlined, divert water from rivers and spread it across irrigated lands. This provides broad spatial distribution of groundwater recharge and alters the seasonality of return flows to streams in ways favorable to downstream cities, farms, and riparian ecosystems (Rosenberg et al., 2020, Gunda, Turner, and Tidwell, 2018). These hydrologic functions provided by acequias are important to regional water resilience during long-term drought. (Rosenberg et al., 2020, Gunda, Turner, and Tidwell, 2018).

Acequias differ from Western state approaches to cutting back water users during times of shortage. All acequia members are cut back proportionally relative to their individual baseline entitlements. This differs from the “first in time, first in right” approach common among the seven CRB states, in which junior water users are completely curtailed before senior right holders are cut back (Raheem et al., 2015). Equal proportional sharing of shortage is thought by some observers to facilitate a more co-operative approach to addressing shortages and may provide an informative contrast in creating new paradigms for the CRB (Gunda, Turner, and Tidwell, 2018, Kummu et al., 2016).

Tribal water settlements in the CRB contain resilience features valuable to both tribal and non-Indian water users and communities (Young, Colby and Thompson, 2018). Many settlements provide for trading of public project water, surface water, groundwater, and treated effluent between tribal nations and non-Indian water users. Several Phoenix-area cities lease tribal Central Arizona Project water for 99 years. Some Arizona settlements restrict pumping water from wells located near the tribal reservation by nontribal farms and towns to protect groundwater underlying tribal lands. These buffer zones benefit not only groundwater users but also streams and wetlands that rely on maintaining the groundwater table.

Tribal nations have provided innovations later adopted more widely in the CRB. The Navajo Indian Irrigation Project agreements, negotiated in the 1960s, provided a new approach for sharing shortages affecting New Mexico’s San Juan-Chama Project and the Navajo Indian Irrigation Project. The 2004 Arizona Water Settlements Act created an innovative water banking system to store millions of acre-feet in aquifers underlying the Gila River Indian Community and contributed to broader regional acceptance and use of groundwater banking (Gila River Water Storage, 2013, Woods, 2017),

In settling litigation, the Quechan Tribe and Metropolitan Water District (MWD) of Southern California agreed in

2005 to a Forbearance Agreement under which the tribe limits the use of its water entitlement in return for MWD payments (Morisset, 2015). This allows the tribe to earn lease revenues without the expense of building storage and conveyance facilities to withhold their water. Tribes face obstacles to leasing their water given lack of incentive for other water users to pay tribes for tribal water already being used without payment. The Quechan Tribe-MWD agreement indicates that motivated parties can find a way, although forbearance agreements are still rare.

Tribes play an ongoing role in the Colorado River Basin System Conservation Program, initiated in 2014 by the Bureau of Reclamation and major municipal water interests to address shortage. Funding for “system conservation” supply reliability projects comes from multiple federal, municipal, and foundation sources. “System water” is stored in Lake Mead to avert shortage declarations and their cascading negative consequences. Several tribes with reservation lands located in Arizona contribute “system water” in return for payment (American Indian Policy Institute, 2019).

To summarize, acequias’ water management practices and innovations in tribal water settlements add to the resilience of the CRB in diverse ways. These include various forms of water leasing, shortage sharing, aquifer banking, dispute resolution approaches, and new types of groundwater pumping restrictions to protect both the environment and other water users. Focusing on water justice for minority water user communities enhances overall CRB resilience by supporting the diverse communities that contribute innovative approaches to shortage sharing and other forms of resilience.

Summary and Avenues for Future Research

This article has focused upon several water justice issues related to CRB tribal nations and acequias. Tribal nations have distinct legal status as sovereign governments, with a legacy of court rulings supporting senior water entitlements that bolster tribal bargaining power in regional negotiations. However, for many CRB tribes, impediments remain for tribal participation in water transactions and shortage sharing arrangements. Members of acequias possess senior rights predating statehood, rights that typically are integrated into state water right systems and can readily be sold or leased. However, sales of water by individual members can weaken the collective strength of the acequia.

Important differences exist between tribal nations and acequias in terms of water entitlements, access to reliable water, representation in policy-making, and consideration of community resilience. Both groups have historically been marginalized, but some improvements have been noted in recent decades, with many water justice issues remaining to be fully addressed.

Water justice is a promising arena for future research. The Climate and Economic Justice Screening Tool used in this article is an example of the types of data becoming available at finer spatial scales to identify disproportionate exposure to hazards (flooding, water contamination) and disproportionate access to amenities (parks and natural green space). The tool was developed to assist in the implementation of the U.S. Justice 40 Initiative (U.S. Environmental Protection Agency, 2022).

Over the next few years, further data will become available to analyze spatial specificity in water justice concerns and impacts on rural indigenous and Hispanic communities. Researchers also will be able to analyze whether 40% of federal resources indeeed have been directed to reduce disparities faced by marginalized communities in the CRB since the adoption of the U.S. Justice 40 Initative in 2021.

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Agricultural Producer Decision Making around Water Conservation in the Upper Colorado River Basin

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Water conservation is a pressing issue, especially in the Colorado River Basin, and agricultural water conservation programs (AWCPs) have been proposed as part of the policy response. If implemented, these programs would seek to achieve voluntary and temporary reductions in the amount of Colorado River water consumed by irrigated crops. By participating in AWCPs, producers would receive compensation for conserved consumptive use (CU) (i.e., a reduction in crop water use compared to a historical baseline), which would be stored in downstream reservoirs for other users. The producers would be compensated based on the amount of water conserved, the location, and the practice implemented. This compensation would enable them to receive financial benefits while contributing to preserving the Colorado River Basin. The reallocation of water to AWCPs would not risk abandonment of water rights if the conserved CU is temporarily enrolled in a state or federally approved program.

In this article, we examine the potential for AWCPs to conserve water in the Colorado River Basin from the decision-making perspective of agricultural producers in the Upper Basin states of Colorado, New Mexico, Utah, and Wyoming. Specifically, we consider the technical versus the economic potential of AWCPs, characterize agriculture in the Upper Basin, and discuss three candidate practices: fallowing, deficit irrigation, and crop switching. We then review factors influencing willingness to participate based on recent experience with the System Conservation Pilot Program (SCPP). Currently, no overarching AWCP coordinated by the Upper Basin states exists. However, they are exploring its feasibility to help meet their obligations to Lower Basin states under the Colorado River Compact. Although AWCPs exist in other regions outside the Colorado River, they have many differing designs. Therefore, understanding the Upper Basin context, producer decision making, and implications for future policy is essential.

Upper Basin Context

The Colorado River is divided into Upper and Lower Basins. The 1922 Colorado River Compact requires Upper Basin states not to deplete river flows to the Lower Basin below a threshold of 75 million acre-feet (MAF) over 10 years. This compact obligation has always been met, but Upper Basin states are investigating a demand management (DM) program that would allow them to store water that could be released during future droughts to reduce the risk of mandatory future curtailment (CRCB, 2021). The program would compensate participants in affected sectors (municipal, industrial, agriculture, etc.) who voluntarily implement temporary measures to reduce CU. It would also represent a more measured and planned response to water shortages than the improvised water transfers that might arise when a curtailment is called. The conserved CU would be held in a downstream reservoir through a storage agreement that was approved in 2019. A DM program, if approved, may include an AWCP as a subcomponent specifically related to river depletions from irrigated agriculture. Other DM subcomponents would focus on other sectors (municipal, industrial, etc.) and are beyond the scope of this study.

Water scarcity in the river system is partly driven by a prolonged drought and shrinking snowpack. Low water threatens agricultural, municipal, and industrial water deliveries, hydropower generation, recreation and habitat, and river ecology. Producers in the Upper Basin, primarily farmers and ranchers, own and manage a large share of the water rights (Richter et al., 2024). They put this water to beneficial use by producing food, feed, fiber, energy, and other products. One approach to meeting gaps in basin-wide water supply and demand in the past was permanent water transfers away from agriculture. However, preserving some irrigated agriculture is recognized as important because of its role in farm viability and local economies. The loss of irrigated land can impact rural communities by decreasing land values, diminishing economic activity, degrading amenities, and disrupting a sense of place (Holm, 2022).

Producers in the Upper Basin often pursue multiple objectives, but maintaining a profitable farm or ranch business is a top priority. They also aim to achieve secondary objectives, such as quality of life, environmental stewardship, and risk management. However, ensuring profitability, solvency, and liquidity is crucial for their long-term survival. The cropping systems, production technologies, and management practices they choose reflect how they seek to achieve these objectives. While many producers want to contribute to water conservation efforts, they may be limited by technical, financial, and other factors. Understanding this perspective helps differentiate the technical and economic potential of AWCPs as distinct concepts.

Technical and Economic Potential of AWCPs

Technical Potential

Technical potential refers to the maximum reduction in river depletions that can be achieved through agricultural practices for conserved CU, given the physical (climate, topography, etc.) and legal (beneficial use, return flows, etc.) constraints governing irrigation practices. It provides a theoretical upper bound on how much AWCPs could contribute to balancing future water supply and demand. For example, from 2016 to 2018, the Colorado River provided water to an average of 1.53 million acres of irrigated land in the Upper Basin each year (U.S. Bureau of Reclamation, 2022). Some water is also exported to irrigated lands outside the Upper Basin. Recent estimates put the total annual crop CU on these combined irrigated lands at 3.1 MAF. By comparison, the projected long-term water imbalance in both basins is 3.2 MAF per year by 2060 (U.S. Bureau of Reclamation, 2012). The goal of an Upper Basin AWCP would not be to solve this long-term imbalance. However, the comparison demonstrates that an AWCP alone is insufficient to address overall water scarcity issues.

At the field level, the maximum technical reduction in CU corresponds to the amount of water crops consume, not the amount diverted from the river nor the amount applied as irrigation. Reduced diversions or irrigation at one location makes more water available to downstream users but may not reduce total river depletions. A fraction of the water applied eventually returns to the river through deep percolation or runoff and becomes available to downstream users, potentially resulting in the same total crop CU. Distinguishing between field-level practices that improve efficiency (fraction of water consumed by the crop rather than lost to percolation or runoff) and those that conserve CU is essential. To conserve CU at the field level, one of the following criteria must hold: reduce irrigated area (e.g., fallowing), reduce actual crop water use to below potential crop water use (e.g., deficit irrigation), reduce potential crop water use (e.g., crop switching), or reduce evaporation from the soil surface (e.g., drip irrigation, conservation tillage) (DiNatale et al., 2011). Improving efficiency alone may not conserve crop CU. Technologies and practices that improve efficiency can also improve water distribution within a field such that, for instance, previously under-irrigated areas see an increase in CU. Practices that increase efficiency but do not necessarily conserve CU include conversion from flood to sprinkler irrigation, land leveling, furrow diking, contour farming, and reduced tillage.

Economic Potential

The economic potential of AWCPs is the maximum reduction in river depletions from conserved crop CU that can be achieved while accounting for constraints on profitability and financial feasibility. Profitability is important for ensuring the financial sustainability of farms and ranches and building equity. It implies that compensation for conserved CU should offset increases in operating expenses, decreases in production, and other risks and opportunity costs associated with AWCP participation. The economic potential is less than the technical potential but more accurately reflects the actual conserved CU that can be practically achieved.

The economic potential can be described by the share of the technical potential that is achievable at a given level of compensation for conserved CU. Breakeven conditions can help assess the economic potential. They explain the combination of compensation for conserved CU and changes in crop or management practices that make participation profitable. In most cases, they can be found using partial budgeting. Lower breakeven values imply that a given practice is profitable for more producers, profitable on a larger share of irrigated area for a given producer, or some combination. Setting compensation at appropriate amounts will ensure participation is financially feasible, which is a necessary but not sufficient condition for participation.

The simple breakeven is appropriate for practices that modify an existing crop enterprise (e.g., deficit irrigation). It is met when compensation for conserved CU is equal to the increase in direct costs associated with implementing the practice plus the expected forgone revenue from decreased production (Cabot et al., 2022). Comparative breakevens are useful when changing enterprises (e.g., crop switching) (Mooney and Kelly, 2023). They are met when compensation for conserved CU just equals the difference in expected net returns between cropping options. Breakevens can also account for risk effects, like increased yield or price variability, using methods that account for risk preferences (e.g., stochastic budgeting, stochastic dominance) (Mooney et al., 2022). Calculating breakevens for producers who depend on forage as a feed input will be more complex than for crop producers who do not manage a livestock enterprise.

Table 1. Crop Mix in the Upper Colorado River Basin, 2018

Category	Farms[a]	Acres	% of Total Irrigated Acres
Pasture, irrigated	6,703	570,461	38.7%
Hay, alfalfa (alfalfa hay, other alfalfa mixtures)	7,082	430,590	29.2%
Hay, other	3,185	364,806	24.8%
Corn (grain, seed, sweet)	261	37,840	2.6%
Sorghum & small grains	206	15,145	1.0%
Orchards	783	3,726	0.3%
Nursery	294	3,230	0.2%
All other crops[b]	916	46,522	3.2%
Total	13,125	1,472,320	

Source: Adapted from the USDA Farm and Ranch Irrigation Survey (USDA, 2019a)

[a] Some farms grow crops from more than one category.

[b] Includes wheat, beans, vegetables, tomatoes, lettuce, potatoes, berries, and all other crops not specified.

Agriculture in the Upper Basin

Agriculture in the Upper Basin is shaped by climate, agronomy, and economic factors (Pritchett, 2011). The region has a short growing season due to higher elevations and colder temperatures, which limits irrigated production to summer months. As of 2018, the Upper Basin had 1.47 million acres of irrigated land, which included diversions off the Colorado River, its tributaries, and, to a smaller extent, groundwater (USDA, 2019a). Grass pasture accounted for 39% of this land area, alfalfa and alfalfa mixtures for 29%, and other hay for 25% of the irrigated crop mix in 2018 (Table 1). Together, these forages covered over 90% of the irrigated area and accounted for most crop water use. Irrigated farms and ranches totaled over 13,000 operations in 2018 (USDA, 2019b). Those operations were diversified, with over 75% receiving income from nonirrigated crops or livestock in addition to irrigated crops.

Forage crops are a primary focus of conservation efforts, but only partly due to their physical abundance. Agronomic attributes also make them attractive for conserving CU (Udall and Peterson, 2017a). Alfalfa is a perennial legume that can be harvested or grazed several times per year. It and other hay crops are relatively easy to grow, drought tolerant, and require few external inputs. Some varieties go dormant when irrigation is removed, making them good candidates for limited irrigation. Grasses also go dormant but have shallower roots and cannot access deep soil moisture. Less data on the conserved CU potential of grass pastures for grazing are available compared to alfalfa, but research is ongoing (Cabot et al., 2022).

Despite this technical potential, not all land will be available to AWCPs for economic reasons. Livestock enterprises (cattle, equine, sheep, goat, dairy) represent the main agricultural economic activity in the Upper Basin and irrigated lands provide feed inputs. Census estimates put the Upper Basin inventory at over 1 million head (USDA, 2019b). Livestock producers in AWCPs would face reduced forage production and need to increase supply (rent new pasture, purchase hay, etc.), decrease demand (wean early, retain fewer yearlings, reduce herd size), or some combination. Nevertheless, opportunities for livestock producers to feasibly participate in AWCPs can arise. For example, participation could be tied to replacement cycles for livestock when forage demands are less. Labor availability, cattle prices, or strategic goals may change, causing some to exit livestock production. In this case, they could sell forage to livestock producers. Prospective participants may also face hay price, cattle price, and interest rate variability, and incorporating a risk premium when quantifying participation costs is important.

Elevation also plays a key role in Upper Basin agriculture (Table 2). Irrigated forage at higher elevations is unlikely to change because it is relatively well suited to the aridity, wind, short growing seasons, and dramatic temperature changes that characterize the region. Grain and high-value crops like vegetables and orchards do not grow well at higher elevations but represent a larger share of irrigated land at lower elevations.

Agricultural Practices for Conserved Consumptive Use

Producers will consider multiple factors when selecting practices for conserved CU. However, the amount of conserved CU attributed to a practice is key because it determines the compensation payable to them and the amount of water made available to others.

Fallowing

Fallowing is the practice of leaving land unplanted and terminating irrigation for the entire growing season. This technique has been widely studied within the Colorado

Table 2. Consumptive Use in the Upper Colorado River Basin by Crop Type and Elevation (acre-feet per year), 2018

	Elevation Band (feet above sea level)							
Crop	Under 5,000	5,001 -6,000	6,001 -7,000	7,001 -8,000	8,001 -9,000	9,001- 10,000	Above 10,000	Total
Grass pasture	54,639	217,508	400,738	249,087	133,525	13,905	359	1,069,761
Alfalfa	55,269	48,119	66,177	8,550	634			178,749
Corn grain	15,694	23,232	540	7				39,473
Other grain	7,207	15,723	8,335	1,795	769			33,829
Orchards	5,235	4,683	1,798	7				11,723
Dry beans	223	6,517	4,863	58				11,661
Other crops	2,572	1,373	1,737	1,676	1,233	507		9,098
Vegetables	1,172	300						1,472
Total	142,011	317,455	484,188	261,180	136,161	14,412	359	1,355,766

[a] The consumptive use estimates shown reflect the supply-limited values in the report.

Source: Adapted from the Colorado River Water Bank Water Supply study (Colorado River District, 2012).

River Basin (Udall and Peterson, 2017b). Options for perennial crops are limited, but it may be possible after terminating alfalfa, for example, and before planting the subsequent crop. Eliminating all vegetative growth conserves the most CU; however, fallow also entails additional management actions. Producers must control weeds, dust, salinity, and soil erosion, typically at their own cost. Terminating irrigation on upper-elevation hay meadows is possible, but conserved CU will be lower than other crops because some plant growth still occurs and yield impacts in subsequent years are unknown, creating uncertainty (Hansen et al., 2021).

Fallowing is more easily incorporated into annual cropping systems, where planting occurs yearly. Compensation for conserved CU from incorporating fallow into a rotation spread over multiple fields could provide a steady alternative revenue stream. Fallowing is easy to verify but estimating conserved CU is more complex. Assumptions need to be made about the CU that would have occurred, had the field not been fallowed. One approach is to use a fixed per acre CU savings relative to a reference crop appropriate to the region. Another is to measure historical crop CU on the fallowed field as a baseline for conserved CU calculations.

Deficit Irrigation

Deficit irrigation is the practice of applying less irrigation water than necessary to meet crop water needs. Typically, standard irrigation schedules aim to satisfy a field’s full evapotranspiration potential, but planned deficit irrigation intentionally induces water stress. It can be pursued with any crop but is well suited to alfalfa because of its dormancy. Regulated deficit irrigation applies less water than needed during plant growth stages that are more tolerant to water stress. This strategy is better suited to annual crops like corn and small grains than vegetable crops, where yield and quality are more sensitive to water stress. Orchard crops can also be sensitive to water stress, or producers already intentionally limit irrigation at some stages to improve quality and are unlikely to yield significant additional conserved CU.

Split-season irrigation involves completely stopping irrigation for part of the year. In an AWCP, irrigation diversions could occur as normal early on—for example, during the first two cuts of alfalfa—and then cease entirely, allowing more water to remain in the river. Deficit irrigation would provide less compensation on a per area basis because, unlike fallow, some crop CU still occurs. Applying less water than needed, however, results in lower average crop yields and higher expected yield variability. A risk premium on top of the comparative breakeven value is likely needed to ensure economic feasibility of deficit irrigation practices.

Crop Switching

Crop switching is the practice of replacing a high CU crop with one with lower potential water consumption. At high elevations, differences in CU between forge crops are often small, decreasing crop-switching advantages (Udall and Peterson, 2017c). More opportunities arise at lower elevations where annual crops are more common. The conserved CU potential of early-maturing crops (e.g., winter peas) are being explored. In this case, the CU of the new crop needs to be compared to a historical baseline to determine the level of conserved CU. Promoting new crops, however, could require the development of supporting market channels and infrastructure. Shifts in production could impact market prices for crops or inputs, including labor. Declines in forage production could lead to rising prices, encourage more production, and increase the compensation needed to induce AWCP participation.

Table 3. System Conservation Pilot Program (SCPP) Project Summary

Year	Applications	Implemented	Estimated CCU (acre-feet)	Total Cost ($)
Round 1 (2015–2018)				
2015	15	10	3,227	$0.89 million
2016	32	20	7,475	$1.49 million
2017	46	15	11,408	$2.17 million
2018	30	19	25,097	$3.97 million
Round 2 (2023–present)				
2023	123	64	37,800	$15.80 million
2024	Program currently underway			

Source: Adapted from UCRC (2018) and U.S. Bureau of Reclamation (2023).

System Conservation Pilot Program (SCPP)

Currently, no DM program exists in the Upper Basin, but the feasibility is being investigated. Ongoing pilot projects are helping inform this process. The System Conservation Pilot Program (SCPP) explores producer implementation of agricultural practices for conserved CU. It is jointly implemented by the Upper Basin states through the Upper Colorado River Commission. The SCPP monitors implementation, measures potential conserved CU, and compensates participants. Potential conserved crop CU is the difference between a historical CU at the field level and actual crop CU in the year of participation. In 2023, historical CU was based on remotely sensed data for a field minus effective precipitation.

The SCPP completed two rounds of pilot projects. From 2015 to 2018, the first round consisted of 64 projects completed across Upper Basin states (Table 3) (UCRC, 2018). They included full-season fallow (16 projects), split-season deficit irrigation (34 projects), combined crop switching and deficit irrigation (6 projects), combined full-season fallow and split-season deficit irrigation (6 projects), and municipal conservation (2 projects). Together, they produced 47,207 acre-feet in potential conserved CU at a cost of $8.05 million. Producers made offers to participate based on their implementation costs. Actual payments ranged from $79 to 330 per acre-foot of conserved CU.

The second round began in 2023 and funded an additional 64 on-farm projects for $15.8 million with a potential water savings of 37,800 acre-feet (Table 3) (U.S. Bureau of Reclamation, 2023). The total potential conserved CU was equivalent to 80% of the total conserved CU achieved throughout all 4 years of the first round but at a higher total and per acre-foot cost for conserved CU, even if inflation were to be taken into account.

Insights from the SCPP on Willingness to Participate

The SCPP experience offers valuable insight into Upper Basin producer willingness to participate in AWCPs. One original intention of the SCPP was to determine whether Upper Basin water users would be willing to forgo water use in exchange for payment at any price; the answer was a resounding yes. Lessons learned in the 2023 SCPP (and incorporated into the 2024 SCPP) were an earlier application date (to better align with farm enterprise planning), more transparent pricing (compensation changed to a fixed schedule based on state and practice type, see Table 4), more stakeholder outreach, and a preference for projects incorporating drought resiliency. One lesson learned (and reflected in the high prices in Table 4) is that the opportunity costs of forgone water use are higher than had been anticipated by many in the region, largely due to producer concerns regarding yield impacts and risks to the livestock enterprise associated with reduced hay production.

Findings from the literature reinforce these insights from the SCPP. According to technology adoption and diffusion principles, producer decisions are also influenced by social factors such as relative benefits, compatibility with current practices, and learnability (Pannell et al., 2006). These social factors can be significant. Therefore, even when conditions for technical and economic feasibility are met, producer willingness to participate in AWCPs is expected to vary geographically and temporally. A stakeholder engagement process conducted in the Upper Basin (and whose participants included SCPP participants) broadly supports this notion, particularly highlighting how the significant heterogeneity in operational characteristics and irrigation rights across producers affects willingness to participate (Paige, Hansen, and MacKinnon, 2021). Greater engagement could be expected from those with the land base, financial capital, and managerial capacity to manage the yield and livestock feed effects of reduced CU and increased risk. Hay farmers without livestock, absentee landowners, and nonoperator owners may be more likely to participate because they will be less concerned about potential spillover costs and risks to

Table 4. SCPP Payments for Potential Conserved Consumptive Use, 2024

State	Compensation ($ per acre-foot conserved CU)[a]
Colorado	$509
New Mexico	$300
Utah	$506
Wyoming	$492

[a]Permitted practices for conserved CU in the 2024 SCPP are full season fallow, split season irrigation, and crop switching.
Source: Adapted from UCRC (2024).

their livestock enterprise. Larger operators or operators with off-farm income may also be able to better withstand the increased risks associated with participation.

Raising awareness and providing education on AWCPs and associated compensation are essential for facilitating participation and ensuring that voluntary AWCPs contribute to equitable conservation of CU in the river system (Paige, Hansen, and MacKinnon, 2021; Bennett et al., 2023). Intermediating organizations and information pathways also appear important to producers' voluntary participation decisions. AWCPs offer a unique potential for experimentation and collaboration. Providing Upper Basin producers with information through trusted sources is important (Hansen et al., 2021a,b; Bennett et al., 2023). Most 2015–2018 SCPP projects were facilitated by local nongovernmental organizations (NGOs) that were familiar to and trusted by participants (UCRC, 2018). Identifying practices that are commercially viable in addition to policy appropriate will also improve reception (Mooney et al., 2023). It is also essential to include input from producer organizations, irrigation organizations, and civic groups that support producers and are critical to their ability to participate (Colorado River District, 2021). Risk management tools like insurance for new crops, limited irrigation, or long-term contracts could be available alongside AWCPs.

Summary and Conclusions

Water scarcity in the Colorado River system will continue to be of national importance. AWCPs that compensate producers to voluntarily conserve CU are one policy option being considered to manage this considerable challenge. What takeaways from this article can help inform future policy? Producer willingness to participate will be influenced by technical, economic, and social factors. The technical and economic potential to conserve CU in the Upper Basin for storage in downstream reservoirs exists, but the savings achieved will depend on the compensation offered, general economic conditions, and producer interest. A primary focus of water conservation efforts will be on irrigated alfalfa, other grass hay, and pasture. Practices for conserved CU will include temporary fallowing, deficit irrigation, and crop switching.

Compensation for conserved CU should provide expected benefits that exceed the value of forgone returns and compensate for risk and other considerations that could hinder feasibility. Diffusion patterns for the candidate practices will likely mirror other agricultural conservation practices, with some early innovators eager to experiment with new options and others content to wait and learn about the technical and economic feasibility before committing. Future studies could further explore the role of intermediating institutions like irrigation organizations in producer participation decisions and evaluate the feasibility and cost-effectiveness of alternative accounting and verification programs to measure and track conserved CU.

Overall, AWCPs could be useful in narrowing short-term gaps in water supply and demand in the Colorado River Basin by allowing a portion of agricultural CU to be temporarily sent downstream to other users. However, they will be ineffective at addressing deeper issues that increase expected future gaps in supply and demand. Fixing these issues will require a breadth of long-term measures that slow or limit growth in water demand across sectors. Finally, economics is about the allocation of scarce resources. The considerations provided here can help policy makers weigh the private and public merits of AWCPs relative to alternative options like municipal and industrial conservation or supply augmentation.

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Arizona Policy Responses to Water Shortage: Can They Have an Impact?

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As drought persists in the Colorado River Basin, demand continues to draw down reservoir levels. In 2019, seven Basin States (Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) and the U.S. Bureau of Reclamation (USBR) signed Drought Contingency Plans (DCP) setting guidelines to spread shortfalls across Basin water users. Since that signing, Arizona has faced increasingly stringent cutbacks of Colorado River water, with deliveries falling by 0.7 million acre-feet (MAF) from 2019 to 2023 (USBR, 2019a, 2023a). In May 2023, the Lower Colorado River Basin States (Arizona, California, and Nevada) submitted a plan to the USBR to conserve 1.5 MAF of Colorado River water by the end of 2024 and 3 MAF cumulatively by the end of 2026 (CRBSR, 2023). USBR has accepted this plan as their preferred water management alternative for the basin (USBR, 2023b). The Boulder Canyon Project Act allocates 4.4 MAF to California, 2.8 MAF to Arizona, and 0.3 MAF to Nevada, for a total Lower Basin allocation of 7.5 MAF.

Growers in Central Arizona (who hold the most junior water rights in the basin) have responded to reduced Colorado River deliveries by fallowing cropland. Acreage receiving crop insurance payments for failure of irrigation supply in Pinal and Maricopa Counties averaged fewer than 17,000 acres in 2016–2021 (Figure 1). Acreage receiving payments jumped to 41,278 acres in 2022 and 58,617 acres in 2023. These counties had 404,515 acres of harvested cropland in 2022 (USDA, 2024c).

The Colorado River water cutbacks have triggered policy responses by Arizona state entities related to (i) water supply augmentation, (ii) subsidies for the adoption of efficient irrigation technologies, and (iii) restricting foreign-owned operation of irrigated cropland. These high-profile responses have captured the attention of water policymakers in the state. This article considers how well these policies can address the state's water scarcity issues in a cost-effective, timely, or comprehensive way.

With reductions in Colorado River deliveries, Arizona will be increasingly dependent on groundwater. Since the 1980s, the state has maintained two different groundwater management regimes. In metropolitan counties, there are irrigated acreage limitations, monitoring and reporting requirements for agricultural groundwater use, and pumping regulations. In rural counties, agricultural groundwater use is largely unregulated. Rapid depletion of some rural aquifers has spurred competing legislative proposals for rural groundwater management. Some elements of groundwater management proposals show promise in economic efficiency terms, by, for example, emphasizing use of cost–benefit analysis and on allotments that are tradable across time and between users. Yet, achieving a policy consensus on how to move forward remains elusive.

Water Supply Augmentation

In 2021, the Arizona State Legislature passed nonbinding legislation requesting a congressional feasibility study of a pipeline project to send Mississippi River floodwater to supply Arizona. The USBR (2012) had earlier reviewed water importation schemes to supply the Colorado River Basin. One proposal, which would have shipped water from the Mississippi River, was estimated to cost $2,400 (2012 nominal) per acre-foot and would take 30 years for regulatory approvals and construction.

In 2022, the Arizona State Legislature passed SB 1710, authorizing $1 billion over 3 years for water augmentation projects, earmarking 75% of funds for projects to import water from outside the state with the rest for in-state augmentation. Arizona's Water Infrastructure Finance Authority (WIFA) was designated to approve projects. To date, WIFA's focus has been a desalination plant at Mexico's Gulf of Baja with a pipeline to ship the water to Arizona. Black and Veatch (2020) examined projects that would import water from Baja to

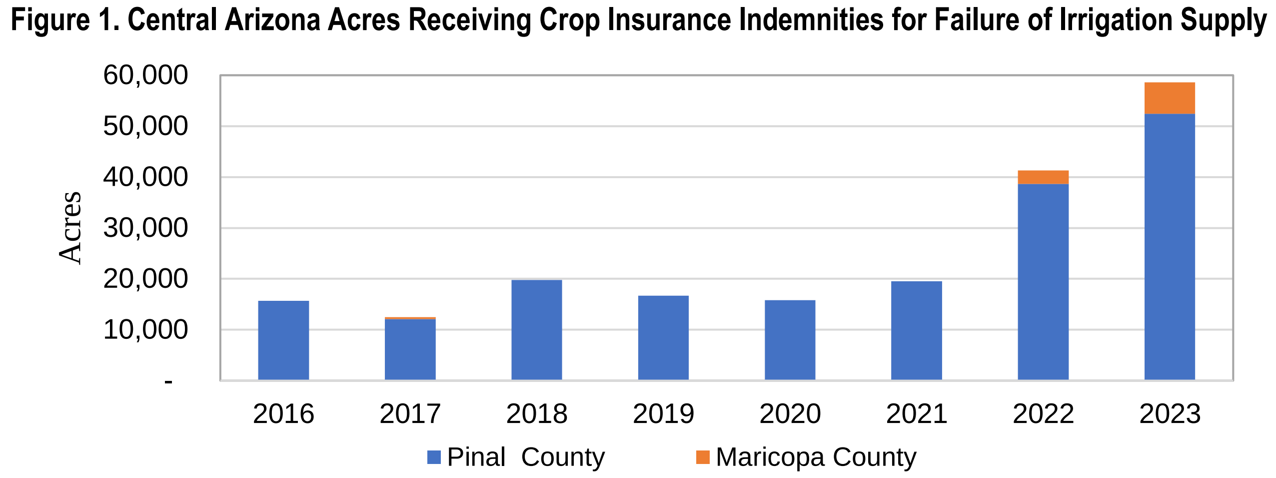

Figure 1. Central Arizona Acres Receiving Crop Insurance Indemnities for Failure of Irrigation Supply
Source: USDA (2024a).

Arizona. Comparing different technology options that could deliver 200,000 AF of water annually, they estimated costs between $2,050 and $2,280 per acre-foot. WIFA considered a subsequent plan by the Israeli firm IDE costing $2,500/AF (Mumme and Lyde, 2023). The USBR (2012) estimated that a Gulf of Baja desalination project would require 20 years for feasibility studies, permitting, and implementation. To date, no large-scale water importation projects have been approved. WIFA received only half of its first-year funding of $333 million. In the newly approved state budget, Governor Hobbs and the state legislature agreed not to provide WIFA with its authorized allocation of $333 million for water supply augmentation in FY 2025 (Sanchez 2024).

Four smaller brackish groundwater desalination projects have been proposed throughout the state. Combined, these could provide 126,000 AF/year and cost $600–$1,200 per acre-foot (2017 nominal) (Kyle Center, 2024). Proposed in 2017, these projects have yet to be developed. None have been funded, and none have been formally proposed to WIFA.

Subsidies for Improving Irrigation Efficiency

Improving irrigation efficiency is seen by many as a key component of Western water conservation. This is shown by federal funding for improved efficiency through the USDA EQIP program, USBR projects, and new programs under the Inflation Reduction Act (IRA) (USBR, 2021; Stern, Sheikh, and Hite, 2023; USDA, 2024b). Improved irrigation efficiency has also received financial or technical support from the North American Development Bank and from environmental groups such as Environmental Defense and The Nature Conservancy (NADBank, 2004; Carter, Seelke, and Shedd, 2015; The Nature Conservancy, 2018; USBR, 2021).

Arizona instituted two programs in 2022 to subsidize adoption of more efficient irrigation technology: the Water Conservation Grant Fund (WCGF) (WIFA, 2023) and the Water Irrigation Efficiency Program (WIEP) (University of Arizona, 2024). The WCGF, administered by WIFA, was established via $200 million from the federal American Rescue Plan Act. Funds must be obligated by June 2024 and spent by December 2026. At least one-third of funds must address Colorado River water shortages, while another third must encourage groundwater replenishment. The program has spent $113 million to date (WIFA, 2023). While agricultural system upgrades (reducing conveyance losses and switches from flood to pressurized irrigation) account for 22% of funding, they are credited with achieving 93% of the program's water savings. WIFA claims savings from one-time system upgrades of 2.6–3.9 MAF over 50 years. The reported cost is an astonishingly low $6–$10 per acre-foot conserved. Ironically, WIFA is arguing publicly with Governor Hobbs about insufficient funds for importation projects (Podolak, 2024) that would cost $2,500/AF, while simultaneously claiming to achieve water savings at a cost of $6–$10 per acre-foot via irrigation efficiency improvements (WIFA, 2023).

The WIEP provided an initial $30 million in state funding. The program, administered by Arizona Cooperative Extension, pays growers $1,500 per acre up to $1 million per farm to switch from flood to drip or sprinkler irrigation. WIEP has distributed $23.1 million of $30 million to date with legislative plans to spend $15.2 million in the coming year. The program requires matching funds, with farmers paying $16 million. WIEP reports water savings to date of 38,000 AF with a public program cost of $631 / AF (Orr, 2024). Savings over the next three years are estimated to exceed 109,000 AF.

It has been an article of faith among many water conservation advocates that improving irrigation efficiency will conserve water. Yet, a large body of scientific evidence shows that improving efficiency, by itself, often does not conserve water, and, in most cases, actually increases water consumption (Huffaker and Whittlesey, 2003; Golden and Peterson, 2006; Jensen, 2007; Upendram and Peterson, 2007; Ward and Pulido-Velazquez, 2008; Lecina et al., 2010; Contor and Taylor, 2013; Gómez and Pérez-Blanco, 2014; Pfeiffer and Lin, 2014; Scheierling and Treguer, 2016; Grafton et al., 2018; Sears et al., 2018; Persons and Morris, 2019; Pérez-Blanco, Hrast-Essenfelder, and Perry, 2020; Pérez-Blanco et al., 2021). Summarizing the findings of 230 studies, Pérez-Blanco et al. (2021, p. 1) stated, “A zombie idea is one that has been repeatedly refuted by analysis and evidence, and should have died, but clings to life… The perception that investments in modern irrigation systems automatically save water constitutes a zombie idea.”

What accounts for this disconnect between policy preference and scientific evidence? One reason is that water is not like other inputs. Withdrawn water, not taken up by the crop, can flow back to rivers or aquifers. This residual water can then be available to others. Irrigation efficiency measures the share of applied water consumed by the crop. Improving efficiency, by definition, reduces the share of unused water that could go back to rivers or aquifers. At the field level, improved efficiency means that the irrigator does not need to withdraw as much water to get the same level of output. At a system level, improving efficiency can reduce water available to others. A number of studies provide figures illustrating this process (Huffaker and Whittlesey, 2003; Jensen, 2007; Scheierling and Treguer, 2016). The effect depends on whether water leaving fields is recoverable or “lost to the system” (Jensen, 2007). If return flows cannot be recovered, then increased consumptive use from increased efficiency does not reduce water availability to others. How common are such cases? Not very. In their comprehensive review, Pérez-Blanco, Hrast-Essenfelder, and Perry (2020) found this occurring in just 7% of cases. They also found that improved efficiency increased water consumption in 70% of cases and consumption did not change or results were ambiguous in 19% of cases.

Pérez-Blanco, Hrast-Essenfelder, and Perry (2020) found reduced water consumption following improved efficiency in 11% of their case studies. But in every one of these, improved efficiency was combined with institutional constraints (such as charges or quotas) being imposed. Here, the institutional constraints are what achieved reductions in consumptive use. Improved efficiency can make constraints less costly to irrigators. Increased irrigation efficiency, by itself, may not conserve water. But it could be combined with institutional constraints to make those constraints less economically onerous and more politically feasible.

A problem with both WIFA’s WCGF and the WIEP is that they measure water conservation based on potential reductions in withdrawals, not reductions in water consumption. Their “water savings” are the estimated reductions in withdrawals required to maintain production at a constant level. There are two problems here: First, withdrawals are not the same as consumption. Improved efficiency can lower withdrawals without lowering consumption; Huffaker and Whittlesey (2003), Jensen (2007), and Scheierling and Treguer (2016) provide graphical examples. Second, why would irrigators necessarily maintain their output at a constant level? Improved efficiency reduces the effective price of water (Caswell and Zilberman, 1986). Why would output remain fixed with a reduction in an input cost? Irrigators have incentives for “water deepening” (Scheierling and Treguer, 2016). If they have rights to withdraw a certain volume of water, they can keep that volume constant but apply water to more acres, increasing output, profits, and consumptive use.

Might there be cases where these programs can achieve true system-level water conservation? Two come to mind. First, as Pérez-Blanco et al. (2021) have found, programs that combine improved irrigation efficiency with institutional constraints have successfully reduced water consumption. The WIEP allows for payments to irrigators to “piggyback” on federal conservation agreements under the Inflation Reduction Act. For example, Arizona irrigators can receive federal payments for not taking water deliveries and keeping water in Lake Mead. Combining subsidies for efficient irrigation systems with required curtailments could be both economically attractive and actually conserve water.

Second, if water tables are low enough, then return flows may not reach the water table and be usable by others. In such cases, improved efficiency can reduce groundwater depletion (Peterson and Ding, 2005). Do such cases exist in Arizona? Perhaps. They are unlikely along the Colorado River mainstem, where the water table is extremely shallow. However, Clemmens et al. (2000, p. 96) argued that in one Central Arizona irrigation district, “It is unclear whether… water actually reaches the groundwater (transit times are on the order of decades) … All water delivered is assumed lost to the system.” Arizona Department of Water Resources (ADWR) planning models assume that, because of slow seepage and deep water tables, it can take 10–20 years in some subbasins for percolating water to be usable (ADWR, 2009, 2020). So, flows are nonrecoverable in the short run but not in the longer run.

The default assumption among state programs is that improving irrigation efficiency will necessarily conserve water. While such cases are uncommon, they might exist in some of Arizona’s groundwater subbasins. If the state programs (i) assessed whether areas targeted for efficiency improvements had hydrological features favoring conservation and (ii) measured water savings correctly in terms of changes in water consumption instead of potential reductions in withdrawals, holding production constant, then they would be more likely to achieve true system-wide water conservation.

Restricting Foreign-Owned Company Operation of Irrigated Cropland

Fondomonte, a subsidiary of a Saudi Arabian-based corporation, has been leasing Arizona State Trust Lands since 2014, growing alfalfa for export to Saudi Arabia. Fondomonte held four leases totaling 3,520 acres in Butler Valley and a 3,088-acre lease in the Ranegras Plain Basin, both in La Paz County. This made Fondomonte the second largest lessee of Arizona State Trust agricultural lands. The Butler Valley leases became contentious for several reasons. Fondomonte's pumping was leading to rapid groundwater depletion. There were objections to a foreign-held company "exporting" the water through alfalfa exports. The area was seen as a future source of water for the Phoenix metro area. Fondomonte was not required to report its groundwater use nor pay fees for groundwater pumped (although Fondomonte paid the energy costs for pumping). Finally, Fondomonte's lease rate was below market rates for similar cropland.

In reality, Fondomonte's lease arrangements were no different than other State Trust Land lessees. An Arizona Auditor General report determined that lease rates paid by Fondomonte were below market rates, but this was also true for other State Trust Land agricultural leases (Perry, 2024). While the State Land Department has authority to charge lessees fees for groundwater pumping, it does not do so for any lessees (Perry, 2024). Agricultural water users outside the state's regulated Active Management Areas (AMAs) or Irrigation Non-Expansion Areas (INAs), in general, are not required to report their groundwater use.

In 2022, the federal Domestic Water Protection Act was introduced, calling for a 300% excise tax "on the sale and export of any water-intensive crop by any foreign company or foreign government in areas experiencing prolonged drought." In 2023, Arizona Attorney General Kris Mayes and Governor Hobbs announced that the Butler Valley leases would not be renewed. Fondomonte accounted for virtually all of the groundwater use in Butler Valley. These leases accounted for 18% of Arizona's alfalfa exports but 2% of total alfalfa production. The lease cancellations are a solution to a localized groundwater problem, but they do not address broader issues of groundwater depletion in the state.

Groundwater Management

Since passage of the state's Groundwater Management Act in 1980, there have been two distinct groundwater management regimes in Arizona. In more urban counties with 80% of the population, five AMAs (Prescott, Phoenix, Pinal, Tucson, and Santa Cruz) were established along with two INAs (ADWR, 2024d; McGreal and Eden, 2021). Both AMAs and INAs require reporting of groundwater use and limit expansion of irrigated acreage. Outside the AMAs and INAs, in rural areas, groundwater is largely unregulated. These unregulated areas account for 47% of Arizona's entire groundwater pumping capacity (James, 2020). These two areas—inside versus outside the AMAs/INAs—differ in the paths of their water use and groundwater supplies and face distinct groundwater management challenges.

In the AMAs, irrigated acreage cannot expand beyond 1970 levels. However, this period was the historic peak of agricultural acreage and so is not a binding constraint (Frisvold, Wilson, and Needham, 2010). Wells pumping more than 35 gallons per minute (nonexempt wells) must use approved measuring devices and report their annual groundwater withdrawals to the ADWR. New real estate developments must demonstrate that they have 100 years of assured water supplies. INAs do not have this restriction but do limit the expansion of irrigated acreage. Those with nonexempt wells must also monitor and report groundwater use if irrigating 10 or more contiguous acres.

In the Phoenix, Pinal, and Tucson AMAs, many irrigators are served by the Central Arizona Project (CAP), which delivers Colorado River water. Irrigators have been given incentives to use CAP water in lieu of groundwater. Managed aquifer recharge (MAR) projects were also implemented, storing unused portions of Arizona's CAP allocations underground (Megdal, Dillon, and Seasholes, 2014; Scanlon et al., 2016). The MAR projects have raised water tables in Central Arizona at rates that are among the fastest in the world (Jasechko et al., 2024). The combination of substituting CAP water for groundwater and the MARs has significantly bolstered groundwater supplies in the Phoenix and Tucson AMAs.

Moving forward, as Arizona's CAP allocations are curtailed, there will be less water available for MAR. But this could also make these facilities more valuable. The city of Tucson in 2003 entered into a water-sharing agreement with the cities of Scottsdale, Peoria, and Gilbert, which will store some of their CAP water at Tucson's Southern Avra Valley Storage and Recovery Project facility when supplies are more plentiful and withdraw them under shortages. The cities make use of Tucson's storage infrastructure and will pay Tucson $75/AF of water stored (City of Tucson, 2023).

Prior to the construction of the CAP, Central Arizona faced substantial groundwater overdraft problems. Many irrigators plan to switch back to groundwater pumping in response to reduced CAP supplies. It remains to be seen whether this leads to a return of rapid groundwater depletion.

Groundwater depletion has been more rapid in certain rural areas outside the AMAs and INAs. Over the past

20 years, the Gila Bend Aquifer had the third-fastest rate of depletion among all aquifers in the United States (Jasechko et al., 2024). Depletion has also been rapid in the Willcox–Douglas Basin (Jasechko et al., 2024). Rural residents throughout the state have had to deepen or drill new wells to continue accessing groundwater.

Concerns over groundwater have spawned state and local responses. Locally, voters approved the establishment of an INA in Hualapai Valley (ADWR 2024b) and the conversion of the Douglas INA to an AMA (Federico, 2022; ADWR, 2024a). In the Willcox area, voters rejected a referendum to create an AMA (Federico, 2022). Governor Hobbs has discussed the possibility of having the ADWR establish an AMA in the Gila Bend area (Davis, 2024). Attorney General Mayes is also exploring the use of lawsuits under Arizona nuisance laws to limit groundwater use where local landowners have documented damages from depletion (Loomis, 2024).

Alternative bills for rural groundwater management have been introduced in the state legislature. Senate Bill SB 1221 (Arizona Senate, 2024), favored by agricultural interest groups, passed out of the Senate but is not supported by the governor. House Bill HB 2857 (Arizona House of Representatives, 2024) has yet to be passed out of committee. These bills have some similarities but also major differences in approaches. SB 1221 requires that cost-benefit analyses be conducted for management areas limiting groundwater use. Both bills allow groundwater use certificates that are transferable between users. SB 1221 allows rights to be transferable across time so that withdrawals can be deferred but “banked” for later use. While HB 2857 requires the use of water ADWR-approved metering devices, SB 1221 prohibits metering requirements. Under SB 1221, plans cannot be implemented without the unanimous vote of a local council. Under HB 2857, if the local council does not develop a management plan within 2 years, then the ADWR director can implement one. SB 1221 also sets an upper limit on groundwater use reductions.

A 2022 state statute requires the ADWR to issue Supply and Demand Reports (SDRs) for the state’s 51 groundwater basins, beginning in 2023 and issuing at least six basin reports per year. The ADWR completed seven SDRs in 2023 (ADWR, 2024e). Five basins had agricultural water use: Douglas AMA, McMullen Valley, Harquahala INA, Willcox Basin, and Butler Valley (ADWR, 2024f). Fondomonte’s canceled leases account for virtually all of Butler Valley’s agricultural water use. We focus on the remaining basins (Table 1).

The ADWR estimated annual groundwater withdrawals (demand), recharge (including incidental recharge from farms), and net impacts on groundwater depletion and supplies. Available water storage was measured as “groundwater reasonably accessible at the average depth of the wells in the basin.” Groundwater below average well depth in the Willcox Basin was reported as a negative value. To access this water, “well owners will have to deepen wells or drill new wells at a significant financial cost” (ADWR, 2024f). In the Willcox Basin, the cumulative drawdown of groundwater from supplies below accessible levels from 2023 to 2049 is 4.6 million AF (ADWR, 2024f).

The ADWR examined groundwater depletion paths under various scenarios (ADWR, 2024c,f). A status quo scenario was based on water use and practices as of 2022. A technology scenario assumed cotton and alfalfa acres using flood irrigation would switch to gravity micro-irrigation, reducing water demand 33%. Improvements to sprinkler and center pivot systems would reduce water withdrawals by 5%. A 2% annual growth rate in adoption was assumed. The ADWR assumed that electricity power plants would switch to dry or hybrid cooling. A conservation scenario assumed allotment-based quantity restrictions resembling the program in the ADWR’s 5th Management Plans.

While improved irrigation technology lowers agricultural water demand (Table 1), it also reduces incidental recharge of aquifers, which reduces groundwater supplies (ADWR, 2024f). By 2049, improved technology reduced annual overdraft by less than 1.5% in the Harquahala Valley and Willcox Basin, while it minutely increased overdraft in the McMullen Valley and Douglas AMAs. By 2049, improved technology had a minimal positive impact on available groundwater in one basin and minimal negative impacts in the other three. The allotment-based Conservation scenario significantly increased groundwater available in storage in two of the basins but had a negligible effect in the other two. For these basins, the ADWR’s simulations are consistent with the findings of Pérez-Blanco, Hrast-Essenfelder, and Perry (2020) that, under most actually observed hydrological settings, improved irrigation efficiency does not contribute significantly to basin-wide water conservation.

Conclusions

If one assesses Arizona’s highest-profile policies to address water scarcity, water augmentation comes up short in terms of cost-effectiveness and timeliness, while irrigation restrictions on foreign firms fail to have large state-wide impacts. State programs to conserve water via improved irrigation efficiency will more likely succeed if they are combined with institutional constraints (or incentives), measure water conservation properly (which they currently do not), and determine whether hydrological conditions favor conservation beforehand (which they currently do not). Competing legislative bills for rural groundwater management have stalled. These groundwater management proposals have, however, encouraging elements from an economist’s perspective. These proposal elements include quantity limits that are transferable across users, over time, or both, and an emphasis on cost-benefit analyses.

Table 1. Projected Groundwater Demand, Supply, and Depletion by 2049 in Selected Arizona Basins under Status Quo, Technology, and Conservation Scenarios

	Douglas	McMullen	Harquahala	Willcox
Agricultural demand				
Status quo	60,975	53,168	131,224	190,140
Technology	59,373	52,987	116,673	185,297
Conservation	58,907	51,330	121,017	189,885
Total demand				
Status quo	67,984	53,658	135,696	214,060
Technology	66,381	53,478	118,381	207,048
Conservation	65,383	51,755	125,482	212,904
Supply				
Status quo	19,722	9,128	40,794	66,760
Technology	17,999	8,933	24,838	61,554
Conservation	19,689	10,915	33,304	67,572
Balance (total demand – supply)				
Status quo	-48,262	-44,530	-94,902	-147,300
Technology	-48,382	-44,545	-93,543	-145,494
Conservation	-45,694	-40,873	-92,183	-145,332
Percentage difference in groundwater overdraft from status quo				
Technology	0.2%	0.03%	-1.4%	-1.2%
Conservation	-5%	-8%	-3%	-1%
Water available in storage				
Status quo	6,451,700	116,200	2,235,900	-4,608,800
Technology	6,450,000	116,000	2,245,600	-4,582,500
Conservation	6,516,600	214,600	3,309,400	-4,559,000
Percentage difference in water available in storage from status quo				
Technology	-0.03%	-0.2%	0.4%	-0.6%
Conservation	1.0%	84.7%	48.0%	-1.1%

Note: The technology scenario assumes diffusion over time of improved irrigation systems and water-efficiency improvements in power generation. The conservation scenario assumes allotment-based water conservation

Source: ADWR (2024f).

For More Information

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