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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.

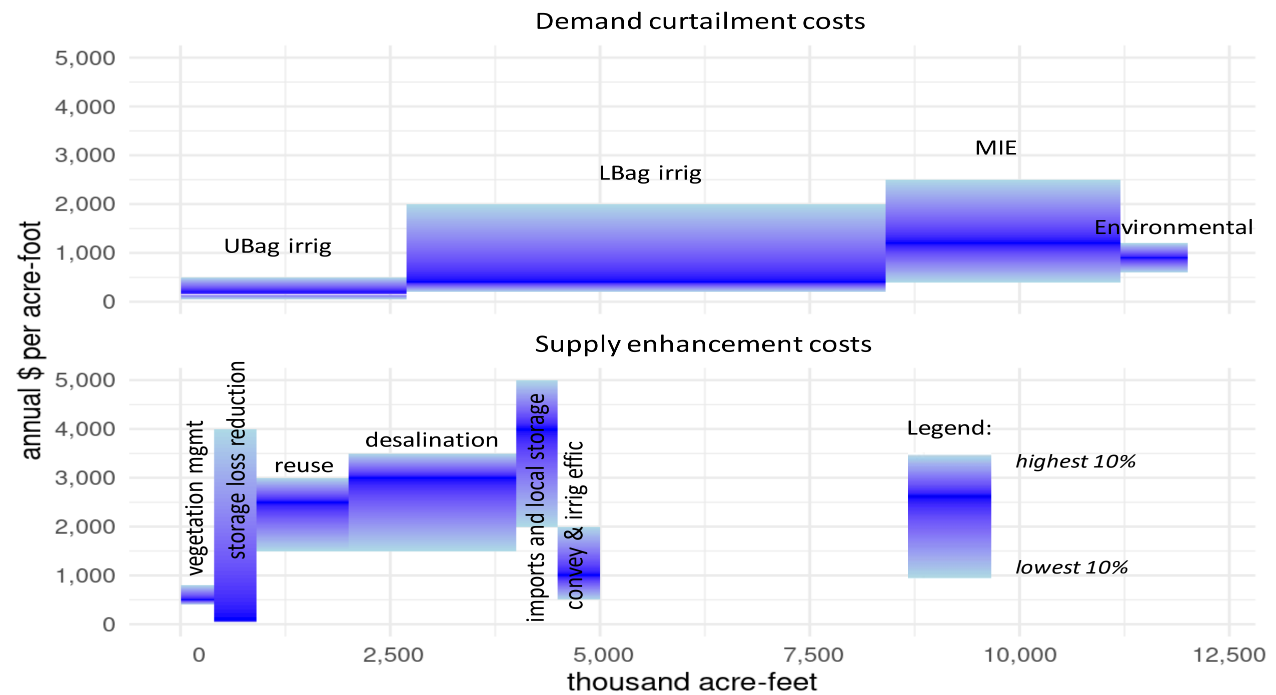
Allocation of the basin's water across state lines was first addressed by the Colorado River Compact of 1922. Since then, a growing body of compacts, court judgements, congressional acts—including agreements on reserved rights of tribal nations, minutes to the 1944 Mexican treaty, and administrative 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.

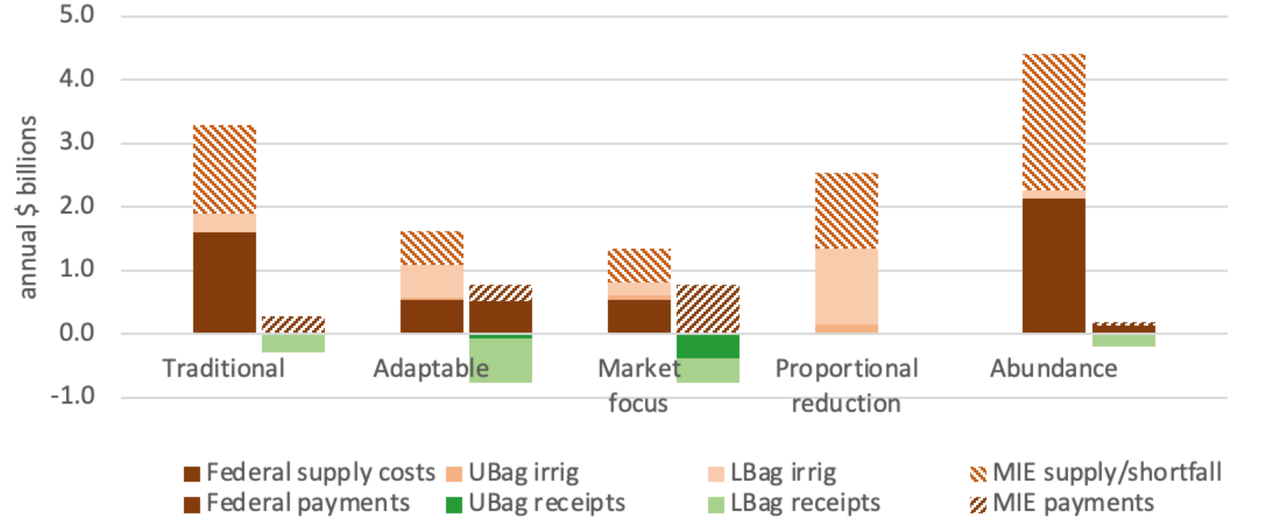
This stylized water budget is the starting point for estimating economic impacts of future stream flow shortfalls under potential changes in climate. Following Booker (2022), flow reductions are expected to result in roughly proportional reductions in total consumptive use, as reservoir evaporation savings 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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