Decoupling environmental water markets from water law

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Abstract
Environmental water markets have emerged as a tool for restoring flows in rivers across the world. Prior literature suggests that certain legal conditions are necessary for these markets to function. However, we find substantial market activity has occurred without these legal conditions through market and legal data collected in five core U.S. Colorado River basin states (Arizona, Colorado, New Mexico, Utah, and Wyoming) from 2014 to 2020. Ninety-five percent of the 446 water transactions sidestepped formal legal processes to transfer water rights to the environment. We also find that government regulatory and conservation programs, not private-sector investment, have driven most environmental water market activity. Government spending is the dominant funding source, with 90% of the $53 million spent coming from governments and 68% from the U.S. federal government alone. Finally, our analysis finds that current market activity would be insufficient to stave off future curtailment of critical water users under the Colorado River Compact and that $86–89 million annually in new investment is required to do so. In a basin experiencing a historic megadrought, our analysis suggests prioritizing such new investments over legal reform. Global implications are that such flow restoration is possible where legal regimes for environmental water markets do not already exist.

1. Introduction
Across the world, demand for scarce freshwater resources is growing, while climate change is decreasing supply reliability in many areas (Garrick et al 2019, 2020). Consequently, freshwater resources are highly appropriated for human activities (Postel et al 1996, Gleick and Palaniappan 2010). By early estimates, over half of accessible freshwater runoff globally is appropriated for human withdrawals and pollution dilution (Postel et al 1996). The resulting human alteration of natural flow regimes has damaged many of the world’s freshwater ecosystems (Poff et al 2010), with at least 20% of freshwater fish species threatened or extinct (Jackson et al 2001).

Environmental water markets have emerged as a tool to reallocate water from human consumptive uses to address overallocation and restore dewatered ecosystems, with transactions documented in Australia, China, Mexico, Spain, the United States, and other nations (Garrick et al 2020). Proponents argue that water markets offer water conservation and reallocation incentives that are more efficient than direct government regulation and are well-suited for adapting water use to climate change (Squillace 2013). However, development of robust, active water markets for environmental restoration or other purposes has frequently been limited by legal, social, financial, and technical barriers. Legal conditions for water markets have received outsized attention because of the heavily legalized nature of water rights and water transfers.

Two sets of enabling legal conditions are relevant to environmental water markets: (1) those applicable to all water markets and (2) additional legal conditions applicable to the subset of water markets for environmental restoration. Within the first category, scholars have asserted that several legal
conditions must exist to develop a water market. These include a water rights system that legalizes water reallocation, separate ownership of water rights and land, relaxed enforcement of ‘use it or lose it’ provisions under which water rights may be canceled or reduced due to non-use (Endo et al. 2018), well-defined, monitored and enforced water rights, clearly specified limits on total resource extraction, and clear and consistent trading rules (Wheeler et al. 2021). For example, Endo et al. (2018) evaluated the presence of the first three legal conditions globally. They identified 58 regions with those three conditions. Additional legal conditions have been identified specifically for environmental water markets. These include legitimizing environmental uses as valid water rights, enabling trading from existing rights to environmental rights, and public and private financing for environmental water transactions (Gilson and Garrick 2021a). Taken together, these conditions depict environmental water markets whose activity is coupled with legal prerequisites.

A primary purpose of this article is to evaluate whether, as has been widely assumed, legal conditions identified in prior literature are necessary for environmental water markets and what other legal and non-legal factors drive observed variation in market activity. We perform this study in five core U.S. Colorado River basin states. This basin supplies water to around 40 million people and 5.5 million irrigated acres in the U.S. and Mexico (Bureau of Reclamation 2012), is experiencing the worst megadrought in 1200 years (Williams et al. 2022) exacerbated by climate change (Udall and Overpeck 2017), and has been described as the world’s most overallocated river system (Castle et al. 2014). Markets have transferred water between users in these U.S. states for decades, totaling 2772 transactions, $2.06 billion (2010 USD), and 49.4 million acre-feet (AF; 60 909 million cubic meters (MCM)) from 1987 to 2010 (Donohew and Libecap 2010). Most transactions moved water from agricultural to urban use, and environmental water transactions were uncommon until recently. Meanwhile, the Colorado River system is routinely so dewatered that 44 of the basin’s 49 native fish species are endangered, threatened, or extinct (Blinn and Poff 2011).

A second objective is to evaluate whether current environmental water markets are sufficient to address the Colorado River’s growing water shortage and, if not, how much new investment is required. These markets include standalone transactions between conservation groups and water users and voluntary transactions performed as part of broader government conservation or regulatory programs. For example, from 2015 to 2018, under the Colorado River Basin System Conservation Pilot Program (SCPP), the U.S. Bureau of Reclamation and municipal water users funded dozens of water transactions. Also, recovery programs that support listed species under the U.S. Endangered Species Act (ESA) have spurred transactions. However, the combination of megadrought and overallocation have raised the probability that Upper Colorado River basin states (Colorado, New Mexico, Utah, and Wyoming) will not deliver 75 million AF (92 511 MCM) every ten years downstream as required by the Colorado River Compact. Failure to deliver would trigger mandatory water use reductions (‘curtailment’) for water users, including major cities, in those states. To proactively reduce the risk of curtailment, in 2019, the U.S. federal government authorized the creation of a demand management program. Under this program, water users would be paid to temporarily and voluntarily consume less water to fill Colorado River reservoirs, including Lake Powell (Castle and Fleck 2019). The Upper Basin states have investigated but have not yet approved a demand management program. As a co-benefit, this program could improve aquatic habitat because its water transactions would leave water instream.

2. Western United States legal context

Environmental water transactions have only existed for several decades in the western U.S. However, the region’s prevailing water rights system, prior appropriation, separates water rights from land and has enabled water rights transfers between human consumptive uses since the 1800s. Although prior appropriation’s trading rules are well-established, they are unclear, inconsistently applied, and generate significant transaction costs and risks (Womble and Hanemann 2020a).

Throughout most of its history, prior appropriation has been hostile to leaving water instream. The system incentivizes water extraction by canceling or reducing water rights for non-use. This ‘use it or lose it’ rule aims to promote off-stream water use and prevent speculative holdings of water rights, though the allowable period of non-use and its enforcement vary by state. The system did not historically recognize the instream environment as a valid use for water rights.

States began to recognize the instream environment as a valid use in the latter half of the 20th century, after the entire flow of many rivers had been claimed (Kendy et al. 2018). Many states have now also authorized transfers of existing water rights to instream use that retain a water right’s original priority (Szeptycki et al. 2015). Nevertheless, the security and clarity of states’ legal authorization for environmental water rights and transfers vary. State laws also frequently place restrictions on environmental water transfers that do not apply to other transfers, like limiting where and when they may be used, whether and how they may be enforced, who may perform them, and their allowable duration. As with all transfers, legal procedures for approving environmental water transfers may be cumbersome, costly,
We recorded transactions inside and outside the Colorado River basin states' laws and policies for environmental water transfers across four dimensions: the (1) clarity of legal authorization, (2) scope of environmental water rights, (3) protection afforded environmental water rights, and (4) process for approving environmental water transfers (Pilz et al. 2017, Szeptycki and Pilz 2017). These four legal conditions, portions of which are anticipated to be necessary for water markets, are absent to varying degrees for U.S. environmental water markets.

3. Methods

We collected a near-comprehensive inventory of recent environmental water transactions in five primary Colorado River basin states to better understand how water law impacts environmental water market activity (by ‘water law,’ we mean a state’s law for allocating water resources with water rights). We used a systematic rubric to assess state laws and policies for environmental water transactions and compared this assessment to market activity. Lastly, we compared current environmental water market activity with Colorado River demand management targets.

3.1. Data collection and analysis: market transactions

Water market development and empirical studies have been impeded by limited public information on transactions (Colby et al. 1993, Garrick et al. 2013). No centralized database captures all water transactions in the Colorado River basin states. Accordingly, we identified and cataloged environmental water transactions from 2014 to 2020 by interviewing staff from non-governmental organizations, government agencies, and water users. We used snowball sampling to identify interviewees, first contacting staff actively involved in conducting or approving environmental water transactions, collecting data on transactions they participated in or knew about, and then asking them to refer us to other market participants. We conducted 39 phone or email interviews. We collected transactions beginning in 2014 to build on a previous study that ended in 2013 (Szeptycki et al. 2015). We also consulted state databases of water rights transfers and public reports, news articles, or websites documenting transactions.

We captured environmental water transactions that met a broad definition from recent scientific literature: ‘agreements by which water users commit to change their water use to protect or restore environmental flows or other freshwater ecosystems in exchange for compensation, investment, or regulatory relief. Such transactions include, but are not limited to, forbearance agreements, dry-year options, deficit irrigation, water conservation agreements, crop substitution, split-season leases, infrastructure construction or reoperation, groundwater recharge and storage, use of alternative water sources, and traditional water right sales and leases’ (Kendy et al. 2018). We included donations.

We use several measures of market activity: the volume of water acquired, water acquisition costs, and number of transactions. Because diversionary versus consumptive use volumes from the same water transaction can differ substantially, with significant environmental implications—reduced diversions frequently only boost flows between a point of diversion and return flow, while reduced consumption can boost flows far downstream—we report both values where available.6 We recorded transactions inside and outside of the Colorado River basin to better understand how state law impacts activity.

3.2. Data collection and analysis: water law

The Colorado River basin states vary significantly in how their laws and policies enable environmental water transactions, providing an ideal region for comparative analysis. We applied a rubric to systematically compare state laws and assess their robustness for environmental water transactions. That rubric was based on the presence or absence of specified legal mechanisms for environmental transactions, administrative burden of state review of such transactions, formality and permanence of legal recognition of such transfers, and successful uptake, among other factors. The rubric was validated by scoring Oregon, widely recognized as having robust laws and activity for environmental water markets (Szeptycki and Pilz 2017). The results were also based on extensive review of each state’s law and interviews with practitioners about how law was applied. Expert practitioners reviewed the metrics and results.

The Colorado River states’ laws and policies were scored on four elements (table 1). The rubric provides up to 40 points for each element, with a total maximum score of 160. During our study period (2014–2020), little change occurred in states’ scores (supplementary materials part 9 available online at stacks.iop.org/ERL/17/065007/mmedia).

4. Results and discussion

4.1. Market overview

During the 2014–2020 study period, we recorded 446 environmental water transactions, translating to $52.9 million in spending to acquire at least 616 570 AF (761 MCM) of diversions and 418 361 AF...
Table 1. Rubric for comparing state law and policy for environmental water transfers (Szeptycki and Příz 2017).

| Element of state law and policy | Enabling conditions |
|---------------------------------|---------------------|
| Clarity of legal authorization  | Environmental water rights may be established through transfers of existing water rights. Non-transaction mechanisms exist to protect environmental flows, like appropriation of new junior environmental water rights. Projects that support environmental flows may receive exemption or protection from forfeiture, abandonment, or diminishment. |
| Scope of environmental water rights | Environmental instream use has equal legal recognition as a beneficial use as out-of-stream uses. A state regulatory agency has environmental flows as an explicit part of its mission. A state agency has dedicated funding and/or staff for an environmental flow program. |
| Protection of environmental water rights | Other water rights can be curtailed to ensure higher-priority environmental water rights are satisfied. New water users and existing groundwater users cannot diminish water supply for environmental water rights. |
| Process for approving environmental water transfers | Processes for permanent or long-term transfers, leases, and reallocation of conserved water are evaluated according to the degree to which law contains procedures specifically for instream flow transfers, whether the approval process is judicial, administrative, or expedited, and the amount of experience using the process. |

Figure 1. Environmental water market activity in the Colorado River basin states (A) over time; and (B) by transaction characteristics. Several plots in (B) exclude very small categories; see figure S1 for complete plots. 'PDSI' in (A) is the Palmer Drought Severity Index. 'M&I' in (B) is for municipal and industrial use.

(516 MCM) of consumptive use. Less than half of market activity occurred physically within the Colorado River basin (49.7% of diversions, 32.9% of consumpion, 45.7% of spending, and 59.4% of transactions). Market activity varied by year, with the most transactions, most water acquired, and the second-most money spent in 2018, the worst drought year (figure 1(A)). Of the 446 transactions, 429 were temporary and primarily short-term, costing $41.2 million for at least 527,294 AF (650 MCM) of diversions and 396,480 AF (489 MCM) of consumption (figure 1(B)). Most of the transactions by number (314), spending ($33.8 million), and diversions (350,816 AF; 433 MCM) were acquired from agricultural irrigation users, while most consumptive use came from municipal and industrial users (253,715 AF; 313 MCM).

Our data show that environmental water markets in these states include diverse transaction types. Of the 446 transactions, 311 had an explicit ecological objective, costing $42.3 million for 558,975 AF (689 MCM) of diversions and 360,784 AF (445 MCM) of consumption. The remaining 135 transactions were experimental demand management or system conservation projects that included environmental benefits, costing $10.6 million for 57,595 AF (71.0 MCM).
of diversions and 57,576 AF (71.0 MCM) of consumptive use. Transactions involving infrastructure improvements, like headgate upgrades, ditch lining, or sprinkler installations to improve water-use efficiency, constituted 42 transactions for $2.45 million, 163,972 AF (202 MCM) of diversions, and 6986 AF (8.62 MCM) of consumption. The 446 transactions also include 20 crop switching transactions ($0.535 million, 3768 AF (4.65 MCM) diversions, 2839 AF (3.50 MCM) consumption) and nine voluntary groundwater mitigation transactions ($11,906, 225 AF (0.278 MCM) diversions, 87.0 AF (0.107 MCM) consumption).

The water source and legal status of water rights for transactions also varied. Natural flow surface water supplied 264 transactions for $16.1 million, 265,827 AF (328 MCM) of diversions, and 88,376 AF (109 MCM) of consumption; surface water reservoir storage supplied 139 transactions for $20.2 million, providing 271,152 AF (334 MCM) of diversions and consumption; and groundwater supplied 21 transactions for $15.8 million, providing 76,601 AF (94.5 MCM) of diversions and 56,602 AF (69.8 MCM) of consumption. The legal status of water acquired also varied, with prominent water right types implicated in transactions including appropriative water rights (260 transactions, $34.2 million, 449,130 AF (554 MCM) diversions, 252,824 AF (312 MCM) consumption), federal project water (99 transactions, $13.7 million, 144,815 AF (179 MCM) diversions and consumption), and tribal reserved water rights (23 transactions, $8.25 million, 74,665 AF (92.1 MCM) diversions and consumption). We compared unit costs in table S7.

4.2. Comparing water markets with water law

Total environmental water market activity measured by spending, volume of water, and number of transactions shows little relation to states’ legal favorability as scored with the rubric (figure 2). The rubric shows Colorado with the most favorable legal environment for environmental water transactions, followed by New Mexico, Utah, Wyoming, and Arizona (figure 2(A)). However, the two states with the least favorable legal environments for environmental water transfers, Arizona and Wyoming, experienced substantial market activity. Arizona had the worst-scored legal environment but had the second-most spending ($12.2 million) and diversionary water (184,222 AF, 227 MCM) acquired, with 85 transactions. Similarly, Wyoming had the third-most money spent ($8.90 million) and water transacted (94,252 AF (116 MCM) of diversions, 89,752 AF (111 MCM) of consumption), exceeding Colorado, which had the most favorable legal environment. New Mexico had the second-best legal environment and the most environmental water market activity. With the third-most favorable legal environment, Utah had the least activity. Consistent with these findings, ordinary least squares (OLS) regression models showed little effect of the four elements of state law or the state’s total legal score on total spending, water acquired, or number of transactions (tables S1–S6).

The substantial transaction activity in states with less favorable legal environments is remarkable because those states lack some legal conditions that scholars have assumed are necessary for water markets. For instream flow water rights transfers, Arizona law and policy do not satisfy any of the three legal conditions from Endo et al. (2018) in some circumstances: they do not fully separate water rights from land and geographically limit where instream transfers may occur, only allowing transfers where the state owns neighboring riparian land. Arizona law also restricts reallocation of water rights by only allowing the state, not private parties, to own or lease water rights transferred to instream flows. As of 2020, Arizona also offered no exemption from ‘use it or lose it’, meaning that water users who do not exercise their water right for five years risk losing it. Water rights also remain
poorly defined in much of Arizona due to unfin-
ished decades-long court adjudications (Perramond
2020). Wyoming law is similarly restrictive because it
only allows donations of environmental rights—not
purchases—which impedes Endo et al (2018)’s most
important factor, law allowing water rights reallo-
cation. Also, Wyoming law does not authorize temporary
transfers of water rights to instream flows, does not clarify whether instream flow water rights may be
legally enforced against downstream diverters, only
allows the state, not private parties, to own such water
rights, and offers no ‘use it or lose it’ exemption.

Arizona and Wyoming are not the only states
where supposedly necessary legal conditions are
restricted or absent. During our study period, Utah
law allowed certain private and nonprofit fishing
groups to temporarily lease water rights instream,
but only where it would conserve habitat for three
native trout species. Utah law also only allows the
state to lease or buy instream flow water rights with
funds specifically appropriated by the state legis-
lature, which can be difficult to secure. New Mex-
ico, which had the most market activity, lacks explicit
legal authorization for instream transfers because this
authorization exists in a legal opinion written by the
state’s attorney general rather than in statute or reg-
ulation. Even Colorado, with the most favorable legal
environment of these states, limits when and where
instream flow leases may occur and does not allow
private parties to own instream flow water rights.

So why have restrictive state law and policy not
precluded substantial environmental water mar-
ket activity? The answer is that less formal water
transactions—those that sidestep states’ legal pro-
cesses for formally transferring water rights to
instream use—have dominated the environmental
water market in all five states (figure 2(B)). Very
few transactions—just 4.71%—involve formal water
rights transfers.

There are distinct implications of avoiding formal
transfers from diversionary water users and reservoir
storage. First, informal transactions with diversion-
ary water users generally pay them to leave water
instream. However, they do not complete a state’s
process to transfer water rights instream. These trans-
actions include forbearance (non-diversion) agree-
ments and irrigation infrastructure improvements.
Unlike formal transfers, which legally protect water
left instream from other water users, these informal
transactions frequently provide no such legal protec-
tion. If other water users divert flows acquired via an
informal transaction, that transaction would restore
less flow than a comparable formal transfer. There-
fore, buyers might accept greater non-water transac-
tion costs for formal transfers where there is greater
risk that other water users will divert restored flows. In
a logistic regression we found some evidence for this,
finding that informal transactions were more prob-
able in regions facing less severe drought (table 2).
Furthermore, absent a ‘use it or lose it’ exemption,
informal transactions may also place water rights at
risk of being lost or reduced. Colorado was the only
state that used such an exemption to protect water
rights enrolled in informal transactions from ‘use it
or lose it’ during our study period. However, trans-
actions were shorter than the forfeiture or abandon-
ment period in other states. Overall, 93% of trans-
actions (287 of 307) that involved diversionary water
users did not formally transfer water rights.

A second way to sidestep formal transfers involves
leasing water from storage reservoirs already author-
zied to release water for environmental use. Of the
139 transactions that only acquired water in stor-
age, all but one (99.3%) did not formally transfer
Figure 3. Government regulatory or conservation programs, not private-sector investment, primarily (A) motivated and (B) financed environmental water markets in Colorado River basin states.

water rights, and our logistic regression found formal transfers were less probable for storage transactions (table 2). Also, storage transactions sometimes offer the benefit of a formal transfer—namely, that released water is protected against diversion by downstream users. These advantages help explain why 44.0% of diversions and 64.8% of consumption in our data are storage transactions.

Overall, when market activity only considers formal instream flow transfers, a relationship between state law and activity emerges (figure 2(B)). The two states with the least favorable law, Arizona and Wyoming, had no formal transfers to instream flows. New Mexico still has the most water transferred through formal transfers. Among states reporting formal instream flow transfers, Colorado has the least water from formal transfers despite having the highest-scored state law and policy. Our logistic regression also found that formal transfers were more probable with higher total legal scores (table 2).

4.3. Government versus private-sector involvement

Environmental water markets represent a voluntary, more flexible approach than direct regulation to achieve environmental protection. However, our data show that government funding and regulatory programs are driving most environmental water market activity in Colorado River basin states—and that these programs help explain the divergence between state-level transaction activity and the favorability of state law and policy.

Water mandates supporting listed species under the ESA and interstate compact compliance have created demand (requiring water instream) and provided funding for transactions. These transactions avoid the contentious and difficult process of mandating water use reductions to protect flows and meet other legal requirements. All 24 of our OLS regressions found that ESA transaction programs were a highly significant driver of more spending, water acquisition, and transactions (tables S1–S6).

Other government water conservation programs have also provided funding, notably the SCPP. When totaled across all five states, we found that government involvement prompted the vast majority of environmental water market activity, including transactions for ESA-listed species (56.4% of diversions, 78.1% of consumption), interstate compacts (23.8% of diversions, 30.0% of consumption), the SCPP (8.79% of diversions, 12.9% of consumption), and other government intervention, either as a funder, seller, or buyer (17.3% of diversions, 8.11% of consumption) (figure 3(A)). Purely private transactions accounted for just 17.5% of diversions and <1% of consumption.

Government spending is also the dominant funding source for transactions, with 90.4% ($47.9 million) coming from federal, state, or local governments and 67.5% ($35.7 million) from the U.S. federal government alone. In these transactions, the government does not always directly buy water. Instead, it frequently provides transaction funding to nonprofit conservation organizations. Similarly, for private transaction funding, although no private individuals, foundations, or corporations directly bought water for environmental purposes, they have funded nonprofit conservation organizations to do so (figure 3(B)). Corporate sustainability programs and philanthropic foundations provided the most financing among private funders. Corporations supplied 5.82% of total financing ($3.08 million). Despite recent analysis showing foundations contributed an annual average of $30.8 million from 2013 to 2019 to broader Colorado River conservation initiatives (Gilson and Garrick 2021b), we found that just $1.15 million in foundation funding from 2014 to 2020 directly financed water acquisition costs for environmental water transactions (2.18% of market spending). Stated differently, foundations’ average annual spending on Colorado River conservation initiatives spread over our seven-year study period totals $216 million, a value 4.07 times spending in
Figure 4. Significant variation exists in acquired water and spending, both within and across states. Regions with some of the most water acquired and money spent are those with endangered species recovery programs and downstream interstate compact requirements. Subbasins are HUC-6 watersheds subdivided by state. ‘Critical habitat’ is habitat needed to support recovery of ESA-listed species.

the entire environmental water market in these five states or 8.92 times spending within the Colorado River basin.

At a river basin scale, the impacts of the ESA and interstate compacts on environmental water markets become particularly apparent (figure 4). The top four subbasins by consumption and spending and four of the top five by diversions have seen substantial transactions to benefit federally listed fish. The top subbasin by consumptive water and spending, the Middle Rio Grande River basin in New Mexico, has also experienced substantial transactions for interstate compact purposes. However, ESA or compact mandates are not required for an active environmental water market, as evidenced by the Verde River basin in Arizona, which restored the most diversions of any basin without any transactions for ESA or compact purposes.

Although government spending and programs dominate the overall environmental water market, this is not true in every subbasin (figure 5). While public spending is over two-thirds of spending in 12 subbasins, it is less than one-third of spending in the remaining nine subbasins. No subbasins have environmental water markets that are evenly publicly and privately financed (between one-third and two-thirds of public spending). The reasons for this discrepancy are unclear, but this result signals that in specific basins, government spending may induce a ‘crowding out effect’ that discourages private investment (Bergstrom et al. 1986, Albers et al. 2008), or similarly, that private funders may be targeting locations with little public funding (Winfree et al. 2006). Some scholars have envisioned that water markets might overcome the market failure of public goods such as streamflow by galvanizing private-sector investment (Anderson and Leal 1991). However, in aggregate, environmental markets have been driven by governments using public dollars to pay for a public good, although there are localized subbasins where private investment dominates.

4.4. Market expansion required to address megadrought and overallocation

Finally, we compared current water markets with targets for demand management in the Colorado River basin. Under the Colorado River Compact, Upper Colorado River basin states have lower legal priority than downstream states, and thus are increasingly vulnerable to legal mandates to curtail water use to meet compact requirements as supplies diminish due to megadrought. This makes water use reductions through voluntary demand management a potential proactive alternative to curtailment. Because of this arrangement, we focused this analysis on this Upper Basin region (figure 6).

We estimated moderate and aggressive demand management targets using an approach recently adopted by a key stakeholder group (Water Bank Work Group 2020). Moderate demand management was authorized by federal law in 2019 and consists of filling a 500,000 AF (617 MCM) storage account. Aggressive demand management would fill a 2 million AF (2467 MCM) account, corresponding to the amount that stakeholders found is required to stave off or significantly delay curtailment. Each target
Watersheds in Colorado River basin states include predominantly publicly or privately funded areas, but none that are evenly publicly and privately funded.

Significant market expansion in (A) the volume of consumptive use acquired and (B) investment are required to achieve moderate and aggressive demand management targets to address Colorado River overallocation. 'CO' is Colorado, 'UT' is Utah, 'NM' is New Mexico, and 'WY' is Wyoming.

Our results show that current environmental water markets within the Upper Colorado River basin fall far short of the demand management targets (figure 6(A)). To meet the moderate target, the annual consumptive volume marketed would need to increase to be 5.94 times the average current market volume and spending.
(+83 162 AF, +103 MCM) and 1.82 times the maximum current market (+45 100 AF, +55.6 MCM). To meet the aggressive target, the annual consumptive volume marketed would need to be 23.8 times the average (+383 162 AF, +473 MCM) and 7.29 times the maximum (+345 100 AF, +426 MCM). Colorado’s market would require the most expansion, followed by Utah, New Mexico, and then Wyoming. Wyoming’s maximum annual volume marketed already exceeded its moderate target.

Acquiring this water would require significant new investment (figure 6(B)). Assuming each state’s average unit consumptive water price remains the same for transactions representative of those envisioned for demand management (temporary, compensated transactions within the Colorado River basin, excluding those exclusively from storage), meeting the moderate target requires $21.0 million more annually than the average current market and $17.6 million more than the maximum current market. Meeting the aggressive target requires $89.1 million more annually than the average and $85.7 million more than the maximum. These costs are only for water and exclude administrative costs and any economic mitigation.

5. Conclusion

Our results have global and regional implications. First, we found substantial environmental water market activity in U.S. states lacking legal conditions previously considered essential for water markets. Informal environmental water transactions have effectively decoupled market activity from water law by sidestepping formal legal processes to transfer water rights to the environment. Informal transactions like those in Colorado River basin states could theoretically occur anywhere in the world without waiting for policy reform: buyers can simply pay water users to leave water in rivers. Of course, informal transactions present additional risk—they generally do not protect water left instream against diversion by other water users, and our transaction data do not capture how far acquired water remained instream. Prior research in the U.S. Columbia River basin suggested that heavy use of informal transactions represents an early stage in environmental water market development and that more developed markets rely less on them (Garrick and Aylward 2012). However, our data show that even in states like Colorado with well-developed legal frameworks for environmental water transactions, buyers still conducted far more informal than formal transactions. A key reason for this is that informal transactions incur lower non-water transaction costs than formal transactions (Womble and Hanemann 2020b).

Consistent with findings in other countries (de Stefano and Llamas 2012, Wheeler et al 2013), we found that environmental water markets in Colorado River basin states have largely been driven by government programs and funding—not the private sector. Private investment has predominantly financed some localized basins, but overall, government has played a significant role in stimulating demand for environmental water transactions with the ESA and interstate compacts and has funded >90% of transaction spending. For ESA transactions, water markets have not been so much an alternative to regulation as a market-based mechanism for achieving regulatory objectives akin to wetland mitigation banking, water quality trading, fishing catch shares, air quality emissions trading, and some carbon markets. Therefore, in environmental water markets driven by the ESA, careful attention should be paid to shortcomings—particularly those driven by political pressure—of other market-based regulatory policies (Leonard et al 2019).

Finally, our findings show that significant new water market activity and funding are required for water markets to address the growing risk that major Upper Basin water users will be curtailed under the Colorado River Compact due to megadrought and overallocation. We found that existing environmental water markets pale in comparison to aggressive demand management targets that could realistically stave off curtailment and that $85.7–89.1 million annually in new spending would be required to meet that target. Although significant public controversy has centered on private-sector investment in Colorado River demand management, our results suggest that most new funding would come from the U.S. government. This market expansion would also require unprecedented participation from water users. While the existing market arguably shows that where funding exists, sufficient pools of irrigators and other water users will participate in transactions, it remains to be seen whether there will be enough sellers to supply this expansion.

Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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