Using financial contracts to facilitate informal leases within a Western United States water market based on prior appropriation

Harrison Zeff[1], Antonia Hadjimichael[2], Patrick M. Reed[3], and Gregory W. Characklis[1,4]

[1] Center on Financial Risk in Environmental Systems, Gillings School of Global Public Health and UNC Institute for the Environment, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA 27599

[2] Department of Geosciences, College of Earth and Mineral Sciences, Pennsylvania State University, State College, PA, USA 16802

[3] Department of Civil and Environmental Engineering, School of Engineering, Cornell University, Ithaca, NY, USA 14853

[4] Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, University of North Carolina at Chapel Hill, Chapel Hill, NC, USA 27599

*Corresponding author: Harrison Zeff (hbz5000@gmail.com)

Key Points:

- Transaction costs related to regulatory approval are a significant impediment to water market leases in the Western United States.
- Informal leases enable rapid short-term water reallocation during drought while reducing transaction costs.

- The State of Colorado could have accrued $222 million in benefits using informal leases to reallocate water from irrigators to urban users.

Data Availability:

All data and code for this project, including figure generation, are available in a live repository (http://github.com/hbz5000/Adaptive_UCRB

Abstract

The ability to reallocate water to higher-value uses during drought is an increasingly important 'soft-path' tool for managing water resources in an uncertain future. In most of the Western United States, state-level water market institutions that enable reallocation also impose substantial transaction costs on market participants related to regulatory approval and litigation. These transaction costs can be prohibitive for many participants in terms of both costs and lengthy approval periods, limiting transfers and reducing allocation efficiency, particularly during drought crises periods. This manuscript describes a mechanism to reduce transaction costs by adapting an existing form of *informal* leases to facilitate quicker and less expensive transfers among market participants. Instead of navigating the formal approval process to lease a water right, informal leases are financial contracts for conservation that enable more junior holders of *existing* rights to divert water during drought, thereby allowing the formal transfer approval process to be bypassed. The informal leasing approach is tested in the Upper Colorado River Basin (UCRB), where drought and institutional barriers to transfers lead to frequent shortages for urban rights holders along Colorado's Front Range. Informal leases are facilitated via option contracts that include adaptive triggers and that define volumes of additional, compensatory, releases designed to mitigate impacts to instream flows and third parties. Results suggest that more rapid reallocation of water via informal leases could have resulted in up to $222 million in additional benefits for urban rights holders during the historical period 1950 – 2013.

Introduction

Unprecedented water scarcity across the American West (USBR, 2022a; CADWR, 2022; CAP, 2022) has provided water users with a glimpse of the potential challenges posed by a non-stationary hydrologic future (IPCC 2018). The development of reservoir capacity in the United States has plateaued in recent decades (Di Baldassarre et al., 2021) due to the paucity of attractive sites and rising development costs (Graf, 1999), as well as growing resistance to the social and environmental costs of new surface water development (Vorosmarty et al., 2000; AghaKouchak et al., 2015; Veldkamp et al., 2017). Additional groundwater development in many water-stressed regions has similarly slowed as concerns over unsustainable pumping have grown (Konikow, 2015). The inability of new supply development to keep pace with growing demands has motivated a transition towards 'soft-path' water management strategies that emphasize conservation and the reallocation of existing supplies (Gleick, 2003; Pahl-Wostl, 2007; NRC, 2012). Improvements in conservation (e.g., low flow appliances, conservation pricing) have reduced per capita water consumption (Richter et al., 2020), but the institutions that govern water allocation have not evolved at a similar pace, thus driving the need for institutional innovations that can facilitate reallocation, particularly during drought (Howe et al., 1986, Brewer et al., 2007; Hall et al., 2014, Schwabe, 2020).

In the Western US, institutions based on the prior appropriation doctrine allocate scarce water to the longest-tenured rights holders (Wiel, 1911), many of whom consume water in relatively low-value agricultural activities such as the irrigation of hay or alfalfa (Cohen et al., 2013; Cantor et al., 2022). Transferable rights give rise to markets that reallocate water from lower- to higher-valued uses, most often moving water from agricultural to urban activities (Brown, 2006; Hanak and Stryjewski, 2012). The ability to transfer water, either permanently (via rights sales) or temporarily (via rights leases) typically requires a process of regulatory approval that, even when successful, often results in significant delays and expensive fees for legal and technical experts, imposing substantial transaction costs (Carey and Sunding, 2001; Ruml, 2005; Garrick and Aylward, 2012; Garrick et al., 2013). This approval process is primarily designed to reduce impacts to third-parties and/or environmental interests that could arise as a result of changes in the type, place, or timing of diversions that result from a water rights transfer. When considering any changes to the transfer approval process, policymakers must implicitly weigh the potential for these impacts against the transaction costs that the approval process creates (Colby-Saliba, 1987). These transaction costs reduce water market activity and the volume of water transferred, leading to less efficient water allocation patterns, a problem that has become increasingly costly as urban/industrial demands continue to grow and climate change drives more severe and frequent droughts (Maas et al., 2017; Chaudhry and Fairbanks, 2022). Recent research suggests that larger water rights sales typically incur millions of dollars in transaction costs (Womble and Hanemann, 2020b), providing a significant deterrent to reallocation.

When considering a change to a water right's type, place, or time of use, most western states apply some variation of a 'no injury' rule (Thompson et al., 2012; Banks and Nichols, 2015), allowing potentially impacted third parties or those concerned with environmental impacts to oppose a permanent sale or temporary lease before it is approved. The costs of the technical and legal evaluations required to successfully navigate this process comprise a significant fraction of the cost of permanent water right sales (Womble and Hanemann, 2020b), exceeding as much as 20% of the mean price of a permanent sale in many active markets such as Colorado's South Platte basin. Temporary water leases are less expensive, but can have transaction costs that are proportionally greater (relative to the lease price) than those experienced when purchasing rights (CCGA, 2011; Dilling et al., 2019; Basta and Colby, 2010). As a result, transaction costs often comprise an even larger fraction of overall water leasing costs, providing an even greater deterrent to leasing (Hansen et al., 2015). Transaction costs are particularly high for leases in Colorado, making it stand out among water-stressed neighboring states as having a relatively low level of leasing activity (Howitt and Hansen, 2005; Womble and Hanemann, 2020a). More active leasing markets have the potential to generate significant economic benefits (Michelsen and Young, 1993; Rimsaite et al., 2021), particularly during droughts when the losses from inefficient allocation are most acutely felt, suggesting that there is ample motivation for finding new approaches that reduce leasing-related transaction costs. Given the challenges associated with changing existing institutions, however, new approaches that could operate within existing institutions are likely to be more attractive.

Under prior appropriation, short-term leases typically require formal regulatory approval. There are exceptions in certain sub-markets (e.g., within the Colorado-Big Thompson Project), but most water right leases involve *institutional* changes to a right such that it can be exercised in a different manner or at a new location. If a right holder with a newer ("junior priority") right is prevented from diverting during drought, they can either formally lease a *new*, more senior right, or they can instead convince other users in the basin to reduce their own consumption. In the second case, the right holder is able to resume diversions using their *existing* (junior) water rights, informally leasing the water without acquiring formal approval. This form of informal leasing has been used by environmental groups to increase instream flows, but has yet to be adapted for the purpose of transferring water amongst rights holders (Szeptycki et al., 2015; Womble et al., 2022). This study presents an analysis of an alternate form of informal transfer in which financial contracts coordinate conservation activities across multiple right holders to ensure that junior water rights, particularly those dedicated to higher value activities (e.g., urban uses), can continue to be fulfilled during drought using the volumes conserved (i.e., not diverted) by more senior rights holders. This method of *informal* water leasing does not require any changes to the underlying water rights of any parties to the agreement. As a result, transaction costs can be significantly reduced by potentially eliminating the need to engage with the formal approval process. As with formal leasing, the reallocation of water via informal leasing can impact third parties and/or environmental flows, which, if unaddressed, could lead a third party to resort to litigation under the 'no harm' principle established in Western water markets. The approach described here details how these potential impacts can be estimated in advance and managed via the implementation of compensatory releases that augment flow and mitigate concerns over environmental impacts, and provide financial compensation for third parties that may be affected by the informal lease. Leases are facilitated by a novel set of index-based option contracts that can be used to coordinate multi-party conservation, compensatory releases, and financial compensation thereby aligning incentives for cooperation across rights holders and other potentially concerned parties (e.g., environmental groups) in a manner that could significantly reduce transaction costs. These agreements are tailored towards the specific context of water allocation institutions within the state of Colorado, but given that a very similar institutional structure of prior appropriation and related leasing procedures exists across the Western U.S. the results should be more broadly applicable.

2. Methods

2.1 Background and Objectives

In Colorado, and most of the Western U.S., drought often leads to a junior right being put "out of priority" (i.e., the right is unfulfilled) in order to maintain the ability of more senior downstream rights holders to divert flows. As an alternative to formally leasing a different, in-priority water right, the owner of the unfulfilled junior right could reacquire the ability to divert water if more senior water rights holders voluntarily reduced their diversions, increasing flow in the river and returning the original junior right to priority (i.e., allowing them to divert). Agreements to coordinate this type of conservation would function as "informal leases" in which water is effectively leased from a more senior to a more junior water rights holder, but via a process that does not require any *institutional* changes to the water rights of either party. Similar types of informal leases in many Western states use conservation agreements to create unprotected flows intended for ecosystem restoration (Szeptycki et al., 2015; Womble et al., 2022). This work generalizes the concept of informal leases by contributing a framework in which informal lease agreements are facilitated through index-based option contracts that compensate third parties for any potential negative impacts, incentivizing cooperation instead of litigation. Hydrologic indices are designed to aid in the coordination of informal leasing relationships that fall into two distinct groups: (a) payments from an out-of-priority (i.e., more junior) buyer to an in-priority (i.e., more senior) seller in exchange for the seller reducing diversions such that the out-of-priority buyer can then increase diversions, and (b) payments from the out-of-priority buyer to other out-of-priority users that are more senior than the buyer but more junior than the seller. The latter group (b) are "intermediate" priority rights holders that are neither buyer nor seller, but act as facilitators who are paid not to exercise their right to divert the additional in-stream flows created by the senior "in-priority" seller. In effect, these facilitators are paid to allow water to remain in-stream as it flows past their diversion location. Given that these additional flows created through conservation by the "seller" would not be available to facilitators unless an informal leasing contract is signed (which would be unlikely unless the facilitators also agree), these intermediate rights holders benefit from informal leases by receiving a payment to effectively "do nothing".

The extra facilitation payment ensures that the additional in-stream water created by the seller's reduced withdrawals can be diverted by the junior right holder (i.e., the buyer) that originally paid for the informal lease. These payments to facilitate informal leases represent transaction costs for the proposed informal leases, and this paper represents a method to quantify those costs into option-based contracts between right holders that can be more predictable and responsive to drought than the legal system. Perhaps more importantly, these payments accrue to regional water market participants as opposed to consultants involved in the legal and technical review processes. The proposed informal leases compensate the potentially impacted third parties in advance, thereby reducing their incentive to claim injury and block the agreement through litigation.

Coordinating these agreements requires a considerable amount of information about right holders, including priorities, seasonal demand patterns, and return flows, as well as hydrologic information regarding the water available to each rights holder over the period of the lease. In the past, acquiring and interpreting such information might have also served as a source of transaction costs, but recent years have seen the emergence of detailed, publicly available (online) databases that can be used to this end, particularly in regions that have embraced water markets as a tool for managing water scarcity. In both Spain and Australia, local governments and authorities collect information on water rights and store it in public, digitally accessible registers (Palomo-Hierro et al., 2021). Public institutions further facilitate markets using centralized clearinghouses (Spain) or federal registers (Australia) that can help potential buyers and sellers discover the timing and location of active markets. Private irrigation infrastructure operators (IIO) in Australia's Murray Darling Basin have also developed online marketplaces in which transfer applications can be submitted and assessed (Loch et al., 2018). The trading platforms operated by the IIOs enable free internal (within the IIO service area) transfers and are the most popular means of conducting water market transactions.

This level of data accessibility and transparency also exists in the state of Colorado, where state agencies have developed a network-based water system model, StateMod (Malers et al., 2001), as part of a broader push to make water rights, demand, and supply data available online via the Colorado Decision Support System (CDSS). StateMod is used by the Colorado Water Conservation Board to evaluate allocation requests and adjudicate conflicts (CWCB & CDWR, 2016). In this work, simulations explore the performance of informal water leases for the Colorado-Big Thompson project (C-BT), a water supply project that primarily serves municipal users that hold relatively junior water rights subject to curtailment during drought. The C-BT uses junior water rights in the Upper Colorado River Basin (UCRB) on the west slope of the continental divide as the source of transbasin water diversions that move water across the continental divide into the more heavily populated Front Range communities (e.g., Boulder, Ft. Collins) on the east slope (Figure 1). Informal leases have the potential to mitigate municipal shortfalls within the C-BT diversion system during drought.

Simulations of water allocations and accounting within the UCRB can be used to evaluate the benefits of increased water reallocation during drought and the transaction required to execute informal leasing contracts in such a way that they do not adversely impact other basin right holders. The latter includes evaluating the potential impacts to third parties and environmental interests that can arise from reallocation via informal leases and mitigating these by including the addition of compensatory water releases as a part of these agreements (effectively allowing some portion of the leased water to remain in-stream). The remainder of the Methods section is organized into three parts, describing (a) the water allocation and accounting simulations within the study area watershed, (b) the institutional context for implementing informal leases, (c) the structure and modelling of informal leases in the UCRB, and (d) the design and pricing of informal leasing option contracts. Although the focus is on this informal leasing test case, the method could be generally applied to an individual right holder in any of the seven Colorado watersheds for which the state has organized detailed water rights/demand/hydrologic data (CDWR, 2022a), as well as to any region in which prior appropriation water rights systems are in place (i.e., the Western U.S.).

2.2 Study Region

The UCRB lies on the western slope of the continental divide, and the portion of the basin that falls within the state of Colorado supports over 900 km^2 (220,000 acres) of irrigated agriculture, primariliy dedicated to relatively low-value activities such as alfalfa and pasture (hay) irrigation (CDWR, 2022). The basin also exports a substantial volume of water eastward across the continental divide to rapidly growing cities along Colorado's Front Range (e.g., Denver, Boulder, Ft. Collins). The exports occur via a series of transbasin diversion tunnels (and related infrastructure), the largest of which is operated by the C-BT project.

Standard prior appropriation rules apply to C-BT water diversions and storage within the UCRB, but once the water enters into the C-BT system along the Front Range, it can be bought and sold by C-BT shareholders (e.g., municipal water suppliers, ditch companies) with little to no regulatory oversight (Mahmoudzadeh-Varzi and Grigg, 2019; Womble and Hanemann 2020b). Water in the C-BT is allocated based on the ownership of homogenous "units" that entitle users to a portion of the annual project yield. Unlike water rights, shortages are shared equally among C-BT units, enabling the units to be traded without impacting the other C-BT shareholders. The C-BT has the right to export up to 0.38 km^3 (310 thousand acre-feet) annually from the UCRB via the Adams Tunnel to Front Range Communities (Figure 1) but only delivers a 'quota' of about 70% of the maximum to shareholders in an average year (Northern Water, 2022a). The quota varies from year-to-year based on a combination of factors, including reservoir storage and snowpack in the UCRB (west slope) and hydrologic conditions along the Front Range (east slope) (Northern Water, 2022b). A total of 310,000 units are made available within the C-BT system, and each unit translates into a long-term average annual delivery of 863 m^3 (0.7 acre-feet). When conditions in the UCRB become very dry, reducing the supply available for export, the C-BT delivery per unit has dropped as low as 616 m^3 (0.5 acre-feet, or roughly 30% below average) (Northern Water 2022a). Many municipalities manage the supply risks associated with shortfalls by purchasing significantly more C-BT units than are necessary to meet their demands during a normal year. Within the relatively frictionless markets for C-BT units, growing urban demands have pushed prices to permanently purchase a single unit to over $60,000, or nearly $\$70/m^3$ ($85,000/acre-foot) of average annual delivery (Bovee, 2020). The high price of C-BT units has made it much more expensive for individual municipalities to permanently maintain the additional units that are only needed during the most severe droughts. The high cost of water motivates the need for developing a more flexible approach for managing drought-related shortfall risks within the C-BT. As proposed here, financial contracts that can facilitate responsive informal leases would enable the C-BT project, which serves mostly high-value urban activities, to quickly augment its supply of water from the UCRB, providing flexibility during times of severe drought.

2.3 *Institutional Use of the Colorado Decision Support System*

Potential lease buyers require detailed data on hydrology, demands, and the priorities of individual right holders to design and coordinate their informal leasing operations. The detail with which StateMod, the water allocation and planning tool developed jointly by the Colorado Water Conservation Board and the Colorado Department of Water Resources, represent individual water rights and demands make them extremely useful for evaluating the potential impacts of future changes to water demands, rights, and/or more complex operations governing storage and conveyance infrastructure within the basin. The model is used to resolve allocation conflicts within the basin and support large-scale planning studies (CWCB, 2010; CWCB, 2012). The CWCB has historically used StateMod to evaluate the impact of institutional changes to water rights and right holder demands and operations (Parsons and Bennett, 2006). Through the development of the CDSS, this data has been made accessible through a number of databases, data visualization tools, and models to support planning and operations (Malers et al., 2001). StateMod is integrated with CDSS databases and contains a detailed spatial representation of water rights, right holder demands, and hydrology in the state's largest watersheds. The StateMod model of the Upper Colorado River Basin (UCRB) contains over 800 diversion nodes, 2000 individual water rights, and the entirety of the basin's 1.8 billion m^3 (1.5 million acre-feet) of reservoir storage capacity that are linked to water rights and current water demands and consumptive uses (Hadjimichael et al., 2023). The model is calibrated with historical natural flows to create a 'baseline' simulation in which water is allocated under historic streamflow conditions according to water right priorities, decreed volumes, and right holder demands. The resulting water allocations represent how the existing infrastructure, demands, and water rights institutions would have managed supplies during historical hydrologic conditions. Inputs to baseline StateMod simulations can be perturbed to test the impact of specific changes to individual water right holders, or to test their sensitivity to changes in hydrologic extremes, water demand, or infrastructure operations (Hadjimichael et al., 2020). This technical capability of this modelling framework aids CWCB in their instream flow acquisition program, which enables the state to purchase, lease, or exchange water for instream flow use (Benson, 2006). In addition, priority dates, historical diversions and hydrologic data are consistent between modeling platform and technical references used to establish or transfer water rights in court (Water Court Committee, 2022). StateMod therefore provides a reliable measure of how the state might evaluate the impact of informal leases on third parties in the basin.

The existing tools and protocols for disseminating water allocation data and modelling the impact of changes to water rights and/or demands could be readily adapted to support the use of informal leases. Geospatial data on water right priorities and points of diversion could be adapted into an identification tool that enables lease buyers to generate comprehensive lists of potential lease sellers and the necessary facilitators to support informal leases. This work uses StateMod to demonstrate a method to translate this data into a series of conservation-based option contracts that simulate the process of informal leases. The integration of CDSS and StateMod into existing water management institutions like CWCB and DWR suggests that these tools could form the basis for a centralized clearinghouse or registrar to facilitate contact between informal leasing parties similar to tools developed in Spain and Australia. Water allocations from baseline

StateMod simulations add context about the hydrologic conditions under which each right holder is allocated water, helping to determine which right holders could be paid to act as lease sellers by conserving water and which right holders need to be paid as facilitators to prevent them from increasing diversions in response to conservation. The CWCB's use of StateMod to evaluate and approve market-based transactions for instream flows provides a blueprint for how potential lease buyers could evaluate the impact of informal leasing contracts on their own water allocations and the potential impacts on other right holders in the relevant basin. These impacts could help to provide transparency to informal leasing contract design, reducing the potential for conflict that could increase transaction costs by requiring formal legal resolution. Here, we demonstrate how publicly available and widely accessible information through CDSS can be used to develop informal leasing scenarios by changing right holder demands in the baseline StateMod simulations.

2.4 *Modelling Informal Leasing Transactions*

The goal of developing an informal leasing program is to enable rapid responses to short-term drought and reduce the cost of leasing. This is accomplished within the context of the prior appropriation-based water rights system through coordinated agreements that compensate senior rights holders engaged in low-value irrigation for reducing their withdrawals (i.e., conservation) with the savings then diverted by a "buyer". So-called 'beneficial use laws', which specify that failure to use a water right can result in its forfeiture (Neuman, 1998), could make some right holders reluctant to enter into a short-term contract for fear of permanently losing their rights. In Colorado, however, water rights are only considered abandoned if there has been a "failure to apply a water right to beneficial use when water has been available for a period of ten years or more" (CDWR, 2022b). The informal leases described here require right holders to conserve/reduce water use for much shorter periods of time, making beneficial use rules a relatively minor concern. It is important to note that informal leasing agreements will often require coordination with rights holders beyond the lease buyers and sellers, who are neither buying nor selling water but are instead paid to 'facilitate' the lease transaction by refraining from diverting the additional water that becomes available when sellers reduce their diversions before the water can be diverted by the buyer (Figure 2).

Given that informal leases rely on conservation as the source of water that is then allowed to flow to the lease buyer, a clear and consistent accounting system is required to determine how much water can be leased from any particular seller(s). Within the model, lease sellers are credited for conservation based on the lesser of either (a) a pre-defined demand schedule or (b) their in-priority water rights, such that:

$$C_{s,t} = \max(D_{m_t}, \textstyle\sum_{r=0}^{n} kp_{r_s,t} * WR_{r_s}) \qquad (1)$$

Where, C = total conservation (m^3/month); s = seller index (1, 2, … n_s); t = monthly timestep index (1, 2, … n_t); D = seller average monthly historical demand pattern (m^3/month); m_t = month of timestep t (1, 2, …, 12); kp = water right in/out-priority coefficient (0, 1); r_s = water right index for seller s (1, 2, … n_r); WR = water right decree (i.e., entitlement, m^3/month).

The diversion reduction resulting from the seller's conservation 'creates' additional in-stream flow that becomes available and can then be diverted by the "buyer". However, some uses of water (e.g., irrigation) are not perfectly efficient, and a portion of the water diversions return to in-stream flow instead of being consumed (for further discussion of the impact of return flows on informal leases see Section 2.4). Additional in-stream flow, and thus the water available to be leased by the buyer, is limited to the consumptive portion of the seller's historical use, such that:

$$L_t = \sum_s (1 - rf_{s,t}) * R_{s,t} \quad (2)$$

where, L = total informal lease volume (m^3/month); rf = return flow fraction for diversions made by lease seller s (-)

Lease facilitators are, like lease buyers, right holders subject to shortfalls during drought conditions, but their rights are more senior than those owned by the lease buyers. When a lease seller with more senior rights (who is not subject to shortfalls under the same drought conditions) engages in conservation for the purpose of an informal lease, the facilitator's interim seniority level gives them the right to divert the additional flow that remains in-stream, putting them in a position to disrupt the informal lease. Thus, to ensure that the facilitator allows the water to pass by their diversion, informal leases include side agreements that pay the facilitators a fee not to divert the additional flow created by the conservation. As the facilitators will have no access to increased flows unless there is an informal lease, and since buyer and seller are not likely to complete an informal lease without the facilitator accepting the fee, the facilitator(s) should be incentivized to accept the fee and allow the lease to proceed. Lease facilitators are paid based on the volume of water rights they own but do not exercise, such that:

$$F_{f,t} = \left(\sum_{r=0}^{n} ks_{r_f,t} * WR_r - DIV_{f,t}\right) \quad (3)$$

where, F = total facilitated demand (m^3/month); f = facilitator index (1, 2, … n_s); t = timestep index (1, 2, … n_t); DIV = right holder diversion (m^3/month); m_t = month of timestep t (1, 2, …, 12); ks = water right coefficient to denote seniority to the lease buyer (0, 1); r_f = water right index for facilitator f (1, 2, … n_r); WR = water right decree (m^3/month)

Exercised together, lease seller and facilitator transactions 'shepherd' water from lease sellers to lease buyers, enabling them to divert water using their existing (but previously out-of-priority) water rights, without making formal changes to the rights themselves, changes that would need to go through the formal regulatory approval process.

The objective of this analysis is to evaluate the tradeoffs associated with informal leases when UCRB supplies are scarce, potentially constraining exports to the urban users along the Front Range. The C-BT holds the right to store up to 0.57 km^3 (465 thousand acre-feet) of UCRB supplies in Lake Granby on the west slope of the Continental Divide, providing some level of stability to the annual volume of exports to the Front Range (East slope). During extended periods of drought, declining supplies in Lake Granby can cause a reduction in the volume of water exported across the Divide through the Adams Tunnel, and thus a reduction in the annual C-BT quota. The informal leases described here are designed as an index-based contract, in which informal leases are triggered when an index crosses a pre-defined threshold. Index-based contracts have been explored as a means of managing water-based risks in many different contexts (Brown and Carriquiry, 2007; Chantarat et al., 2013; Meyer et al., 2016; Hamilton et al., 2020). When there is a high degree of correlation between the index and the risk to the contract buyer, the index-based contract is said to have low 'basis risk'. In this case, the index is constructed such that crossing the index threshold, or "strike", that triggers the transfers is highly correlated with water scarcity for the lease buyer (C-BT). To that end, we construct a "C-BT water supply index" that is tailored to the needs of a specific informal lease purchaser (C-BT), measuring when water stress at their largest storage site, Lake Granby, crosses a specified level. The index is calculated for at a monthly time step (*t*) based on knowledge of reservoir storage, remaining snowpack, and project exports through the Adams Tunnel, such that:

$$CBI_t = S_t + sm_t + D_t \quad (4)$$

Where, CBI_t = C-BT water supply index (m^3); S_t = storage in Lake Granby (m^3); *sm* = remaining snowmelt estimate (m^3); and *D* = year-to-date diversions through the Adams Tunnel

The water supply index described here is specific to the C-BT as a lease buyer, but data is readily available to build a similar index-based trigger for any potential informal lease buyer. Reservoir storage and observed exports can be directly observed from records at Lake Granby and the Adams Tunnel, respectively. Estimated snowmelt over the remainder of the year (another form of storage) is calculated from snowpack observations, obtained from the USDA National Water and Climate Center (USDA-NRCS, 2022). The index estimates snowmelt and assumes a linear relationship between monthly snowpack observations and the remaining cumulative inflow that will make its way into Lake Granby between any given month and the end of September (for more information on index calculations, see Supplement A), such that

$$sm_t = ms_{m_t} * snpk_t + bs_{m_t} \quad (5)$$

where *sm* = USDA snowmelt estimate (m^3); *ms* = linear regression coefficient (m^3/m); *bs* = linear regression constant (m^3); *snpk* = snowpack observation (m); *t* = timestep; m_t = month associated with timestep *t*

Individual regression coefficients (*bs* and *ms*) are estimated for each month, such that the sum of squared errors between the estimates produced in equation (1) and the remaining cumulative inflow into Lake Granby are minimized, according to:

$$\widehat{ms_m}, \widehat{bs_m} = argmin \sum_{y=1950}^{2013} \left(sm_{t_{m,y}} - \sum_{mon=m}^{SEPT} Q_{LG,mon,y} \right)^2 \quad (6)$$

where Q_{LG} = monthly flow into Lake Granby (m^3/month); *m* = month (1, 2, …, 12); *y* = year of the historical record (1950, 1951, …., 2013); $t_{m,y}$ = timestep *t* associated with month *m* and year *y*

The *CBI* values calculated in equation (4) represent a continuous monthly estimate of C-BT supplies stored on the west slope, accounting for expected snowmelt and already-diverted supplies. Historically, the C-BT has cut annual delivery quotas to conserve their supplies during extreme drought conditions, such as during the 2002-03 drought, when quotas were reduced to 50% of full allocation. Informal leases enable the C-BT to replace some or all of this conservation, allowing them to maintain quota levels in the face of extended drought. We simulate this potential drought management decision on behalf of the C-BT by using the *CBI* to 'trigger' informal leases when the index falls below designated threshold (strike) levels. A timeseries of *CBI* values generated from baseline StateMod output is used to identify dry periods when the C-BT could incorporate informal lease purchases into a broader drought management plan. Different thresholds can be employed with the contracts to simulate drought management plans that purchase informal leases with varying frequency and in varying quantities. The advantage of the index is that it captures the dynamic adaptivity of the system's actors contextualized to conditions they are experiencing (i.e., state-aware action rules). Potential lease sellers need to own relatively senior water rights that allow them to divert water (i.e., in-priority water rights) during these periods of water stress. Baseline StateMod simulations are used to identify right holders who make diversions during exceptionally dry periods, as estimated with *CBI* value calculations. Among those right holders with sufficient seniority, lease sellers are selected from those who irrigate low-value crops (e.g., alfalfa, pasture). Low-value irrigation activities often serve as the source for agricultural-to-urban water leasing (Garrick et al., 2019), and given that irrigation of low-value, non-perennial, crops (e.g., hay, alfalfa) account for over 80% of water use in the UCRB, the pool of available lease water is considerable (Figure 3).

Although the UCRB has many non-perennial irrigators with very senior rights and the ability to divert even under the most extreme drought conditions, not all right holders are capable of making exchanges that can be physically delivered to Lake Granby. Informal leases rely on exchanges created by reducing right holder diversions at one location and increasing them at another. When the lease buyer is located directly downstream of a seller, the exchange results in *increased* instream flows in the reach connecting the buyer with the seller. However, the exchange is reversed when lease buyers are located upstream of the lease sellers, resulting in *reduced* instream flow between the buyer and seller, limiting the potential rate of exchange. In-stream flow, calculated in the baseline simulations, provides a constraint on the exchanges in any given monthly timestep. If the attempted rate of exchange exceeds flow at any point between an upstream buyer and a downstream seller, there will be insufficient water to meet the demands of the upstream lease buyer and any senior rights holders in this intervening reach that are not a part of the leasing arrangement. Given those users have seniority over the lease buyer, their diversions take precedence over the informal leases. Environmental flow or reservoir release requirements defined in StateMod, limit exchanges between an upstream buyer and downstream seller to only the portion of that flow greater than the legal minimum flow requirements. The total lease supply available from right holders downstream of any given location is equal to the flow at that location that is greater than the minimum required in-stream flow at any river network node between the lease buyer and the potential lease seller.

$$TL_{j,t} = \min_{n=i:j}(Q_{n,t} - minflow_{n,t}) \quad (7)$$

where TL = total water available (m^3/month) to be leased at node i; n = river network node (1, 2, …, n_i); i = lease buyer node; j = lease seller node Q_t = instream flow (m^3/month); $minflow$ = minimum environmental flow/release requirements (m^3/month); $reach$ = all nodes in the path between the lease buyer (upstream) and any node i

In the UCRB case study, the total volume of informal leases available to urban users in the C-BT is not limited by the quantity of low value irrigation water held by senior rights holders, but rather the downstream flow. In scenarios with multiple lease sellers, each informal lease that is purchased by a lease buyer will reduce the volume of potential lease water available, because exchanges between an upstream buyer and downstream sellers reduce instream flow in the reach between the two. The set of potential lease sellers in each timestep is identified as alfalfa and pasture irrigators with the right to divert water in that timestep, which are then ordered from most junior to most senior. The in-stream flow constraint on informal leases between the buyer (C-BT) and potential downstream lease sellers is calculated using equation (7). After the volume of potential leases from the first seller is calculated, the remaining flow in the reach between the buyer and seller is updated for all nodes k between the buyer at node i and previous seller at node j, such that:

$$TL_{k,t} = \min_{n=i:k}(Q_{n,t} - minflow_{n,t} - L_{j,t}) \qquad (8)$$

where L = total leases purchased from node j (m^3/month), k = node between buyer node i and seller node j *(-)*

This process is repeated, calculating the available leases from the next most junior potential lease seller with updated equation (8) and adding a new lease already purchased term (*L)* after every potential lease seller, until there are no more potential lease sellers with water available to be leased. All potential lease sellers with available water are assumed willing to enter into leasing agreements, although only a fraction of these would be required to participate to satisfy urban demands along the Front Range under essentially all circumstances.

Potential lease sellers are identified at monthly timesteps via simulated values for flow, diversions and storage using the baseline StateMod historical scenario (1950-2013). Here, the C-BT is assumed to purchase the consumptive portion of the water diversion from any rights holder identified as a potential lease seller in a timestep in which dry conditions lead to the specified *CBI* threshold being crossed, as calculated in equation (6). Once the lease sellers are known, any right holder who can act as a lease facilitator must be compensated to prevent them from diverting the leased water newly available instream before it can be diverted by the buyer (C-BT).

This type of exploratory modeling of new institutional structures (Moallemi et al., 2020), such as informal leasing, can provide a contextually rich means of better understanding their impacts. In this case, we explore the effects of informal leasing frequency on the cost of leases, the volume leased and the resulting impacts on third parties and the environment. Alternative candidate leasing strategies can be evaluated by sampling different *CBI* thresholds (i.e., different drought severities) and simulating the resultant volume of leases, costs, and water balance dynamics. The total volume of water available to be leased, and the specific contracts that need to be exercised to lease it, depend on the hydrologic conditions described by the index that triggers informal leases. A four-step, iterative process is used to simulate informal leasing operations that incorporates StateMod (Figure 4). In step 1, a baseline StateMod simulation is conducted to determine right holder allocations under a baseline set on hydrologic and water demand conditions. Output from this baseline simulation is then used in step 2 to calculate *CBI* in each simulation timestep and identify any time periods in which the pre-specified *CBI* threshold has been crossed, triggering informal leases. In step 3, lease sellers and facilitators are identified based on the seniority of their water rights, type of use, and allocations during the *CBI*-triggered informal leasing periods. Finally, in step 4, StateMod demand inputs are adjusted according to the terms of leasing and/or facilitator agreements, and model simulations are subsequently re-evaluated. The new StateMod simulation output is then used to re-calculate *CBI* in step 2, restarting the monthly cycle. Constraints on the volume of water that can be leased from a particular lease seller can change over time based on hydrologic conditions, as described in equations (7) and (8).

The set of right holders who need to be compensated to act as lease facilitators changes over time based on dynamic hydrologic conditions and seasonal demand patterns. Lease facilitators only need to be paid when the facilitator can physically access the additional flow created by the the lease seller's reduced diversions. A lease facilitator can always access the additional water when they are downstream of the lease seller. When they are upstream of the lease seller, their ability to access the extra water created by informal leases can be estimated using a modified version of equation (7), such that:

$$kf_i = \begin{cases} 0 & EX_{i,t} = 0 \\ 1 & EX_{i,t} > 0 \end{cases} \tag{9}$$

and

$$EX_{i,t} = \min_{reach\_i}(Q_t - minflow_t) \tag{10}$$

where kf = facilitator payment coefficient (1 = payment); EX_i = water available to be diverted by lease facilitator at node *i*; and *reach_i* is the collection of river network nodes between node *i* and the lease seller, where the lease seller is downstream of node *i*

After identifying the individual lease sellers and facilitators participating in an informal lease, their demands are changed according to the terms of the agreement. Informal leases are simulated as changes to the baseline StateMod right holder demands. Right holders that are acting as lease sellers must reduce their demands below the level of diversions under the baseline simulation, such that:

$$D^*_{s,t} = DIV_{s,t} - R_{s,t} \tag{11}$$

where, D^* = adjusted lease seller demand after selling informal leases (m^3/month); *s* = lease seller index (1, 2, … n_s); *t* = timestep (1, 2, … n_t); *DIV* = right holder diversion from baseline simulation (m^3/month); *R* = total diversion reduction from leasing agreement (m^3/month)

Likewise, facilitator demands must also be adjusted to complete the informal lease. Although lease facilitators are not subject to any changes in diversions due to informal leases, their water demands can be greater than their observed diversions in the baseline StateMod simulation (because the lease facilitators represent a group of users who are also experiencing shortfalls due to drought). To ensure that their diversions do not increase when more water becomes available, lease facilitator demands must be changed by setting their demands equal to their observed diversions under the baseline StateMod simulation, such that:

$$D_{f,t}^{*} = DIV_{f,t} \tag{12}$$

where, f = facilitator index (1, 2, …, n_f)

Equations (11-12) can be used to update, respectively, lease sellers and lease facilitator demands at each timestep. At any timestep in which lease seller or facilitator demands are changed, the new demands are used to generate a new StateMod simulation, representing an informal leasing scenario. This new StateMod simulation must be executed before the next timestep, because the resulting reallocation of water can result in changes to return flows that lag across multiple timesteps. These changes can impact the availability of water for different users throughout the basin, impacting the informal leasing water balance calculations in equation (7) – (12). Output for a complete (1950-2013) informal leasing simulation are generated iteratively by running a new simulation in each timestep for which informal leases are triggered by the *CBI* threshold. Changes to demands from informal leases in previous timesteps are maintained, creating unique timeseries of demands and diversions that represent an informal leasing scenario. Different thresholds for the *CBI* trigger will generate new informal leasing scenarios, enabling the analysis to evaluate the impact of informal leases under different assumptions of which system conditions warrant the initiation of agreements to mitigate projected drought shortfalls.

2.5 *Compensatory Releases and Options Contracts*

The coordination of buyer, sellers and facilitators inherent to the 'informal' nature of the leases present several challenges, particularly with respect to the number of counterparties and uncertainties involved with the measurement of return flows. Changes to the magnitude and patterns of return flows (i.e., irrigation water that returns to the stream) associated with water right leases or other transfers can have negative impacts on downstream users. The legal concept of 'no injury' (Thompson et al., 2012; Banks and Nichols, 2015) limits water transfers to only the consumptive portion of historical use, with the remainder required to be left in-stream to ensure the ability of downstream right holders to divert (i.e., they are not injured by the transaction). In order to preserve the concept of no injury within informal leasing agreements, some form of 'compensatory releases' is required to mitigate any changes to return flows (Figure 5). To assess the volume of compensatory releases required, the potential mitigation cost from third-party right holders is estimated by comparing individual diversions in the 'baseline' simulations to diversions during the informal leasing scenarios, removing any water that was explicitly leased by the right holder in a given timestep, such that:

$$MC_{r,t} = DIV_{r,t} - DIV_{r,t}^{*} - R_{r,t} \tag{13}$$

where *MC* = mitigation cost from individual right holder from informal lease (m^3/month); *DIV* = baseline scenario diversions by individual right holder (m^3/month); DIV^* = informal lease scenario diversions by individual right holder (m^3/month); *R* = reduced diversions purchased from lease seller (m^3/month); *r* = index of basin right holders (-), *t* = index of timesteps

Compensatory releases remedy these potential injuries to third party users by requiring lease buyers to purchase an additional volume of water and leave this water in-stream instead of diverting it. The total volume of compensatory releases allows all right holders, excluding lease sellers to mitigate any reduction in water availability as calculated in (13). This volume can be calculated by finding the maximum value, across all basin right holders, of the total mitigation cost from an individual right holder plus the sum of the consumptive portion of the mitigation cost of all right holders upstream of that node, such that:

$$CR_t = \max_r\left[MC_{r,t} + \sum_{n=upstream} MC_{n,t} * cf_n\right] \qquad (14)$$

where *CR* = total compensatory release in timestep *t* (m^3/month); *MC* = total mitigation cost from individual right holder from informal leases (m^3/month); *cf* = consumptive fraction of water use by right holder *n* (-), *r* = index of right holder (-); *upstream* = all right holders upstream of right holder *r* (-); *t* = index of timesteps

The compensatory release volume is calculated conditional on assumptions related to the magnitude and timing of return flows that are built into the simulation modelling. If a downstream right holder thinks the return flows that would result from the conserved water use are higher than what is assumed in the modelling framework, the estimated compensatory release would be too small, potentially resulting in less water available via their right. In this case, the only current recourse available to the right holder is the regulatory system. The formal process regulating water leases is in large part designed to settle conflicts about these assumptions, but the courts have proven to be a prohibitively expensive way to resolve questions of hydrologic uncertainty.

Any effort to develop better functioning water markets in the Western U.S. will by necessity have to provide right holders in a basin with an incentive to avoid resorting to regulatory appeals. These incentives are provided in the form of index-based option contracts, in which the buyer pays an exercise fee to the lease sellers (for their water) and to lease facilitators (for their cooperation). Option contracts typically include an up-front fee (the option ‘price’), used to compensate the seller for any risks from the option that are not captured by the exercise fee. Here, the exercise fee is only meant to insure cooperation, and lease facilitators and other third parties should experience no impacts on their own diversions from the informal lease. Option pricing draws on an extensive theoretical framework developed for various financial applications (Merton, 1998), and here, the up-front option fee provides a way to reimburse third party right holders for the potential losses they may experience as a result of informal leases. The option to lease water during drought provides value to a potential lease buyer, who will likely avoid more costly drought management alternatives. Similarly, the upfront option fee is paid annually, regardless of whether the option is exercised, providing both the sellers and the facilitators with incentives to allow the lease agreement to move forward, particularly as the option also includes compensatory water releases to mitigate both third party and environmental impacts. We can calculate the mitigation needs for each right holder in the basin, based on the mitigation cost calculated in equation (13) and some assumption of the 'uncertainty' in return flow estimation. The potential losses of an individual third-party right holder as result of an informal lease can be considered a linear function of the mitigation cost and the return flow uncertainty, such that:

$$PL_{r,t} = u * MC_{r,t} * MNB_{rf} \quad (15)$$

where *PL* = potential losses of individual right holder (m^3/month); *u* = uncertainty of return flow estimation (%); *MC* = total mitigation cost from individual right holder caused by informal leases (m^3/month); *MNB* = marginal value of water use at right holder *r*; *r* = index of basin right holders (-), *t* = index of timesteps

The marginal value of water use for a right holder depends on the end use of diversions for that right holder. For agricultural right holders, the marginal value is determined by type of crop being irrigated, as a function of the crop's typical price, yield, and water consumption. Municipal and industrial water uses are assumed to have a marginal value of \$0.73/m^3 (\$900/acre-foot), based on the revenue losses municipal water providers in the C-BT service area experience due to conservation (City of Boulder, 2021) and environmental water uses are assumed to have a marginal value of \$0.093/m^3 (\$115/acre-foot), based on the prices paid for short-term water leases with explicit ecological objectives in five Colorado River Basin states (Womble et al., 2022). For more information about calculations of marginal value, see Supplement A.

Annual, up-front option fees for each third-party right holder can be formulated as a function of this distribution of potential losses. In this way, up-front payments to third-party lease facilitators are highest for those who are most likely to be impacted by the informal leases, incentivizing cooperation rather than litigation. These incentivizing payments represent transaction costs for lease buyers and sellers, but the payments are (a) likely to be smaller than the transaction costs associated with the formal system of water leasing and (b) paid to other basin right holders, instead of third-party legal or technical experts, helping to encourage cooperation among stakeholders. For more details about option pricing, see Supplement A.

3. Results

Simulations of the historical period of C-BT operations (1950 – 2013) identified 14 large water rights within the UCRB basin that meet the criteria to act as informal lease sellers.

Of the 33.0 km^2 (8,152 acres) of low-value crops irrigated with these water rights, 32.2 km^2 (7,959 acres) are devoted to grass hay and 0.8 km^2 (192 acres) acres are used for alfalfa, with a consumptive water demand of about 0.021 km^3 (17 thousand acre-feet) each year. For comparison, a typical drought-related shortfall for urban water rights holders in the C-BT, such as the 20% reduction in C-BT quota observed during the 2002-03 drought (NCWCD, 2022), translates to 0.053 m^3 (43 thousand acre-feet). The fraction of water available for informal leases is evaluated in each year in which the *CBI* threshold specified in the informal leasing contract is triggered. Four different scenarios, defined using four different *CBI* thresholds [see equation (4)] are defined to be in line with drought 'stages' that describe the severity of the drought that is needed to trigger each stage. When index values (Figure 6A), cross these threshold values, informal leases are sequentially triggered such that these decisions are state-aware, dynamic operating rules that drive adaptive drought management policy for the C-BT. Lower values of *CBI* signify drier conditions, so Stage 1 is triggered when the *CBI* reaches 0.86 km^3 (700 thousand acre-feet), Stage 2 corresponds to a *CBI* threshold of 0.8 km^3 (650 thousand acre-feet), Stage 3, 0.74 km^3 (600 thousand acre-feet), and Stage 4 to 0.68 km^3 (550 thousand acre-feet). These four thresholds trigger leases at different frequencies during the simulation period (Table 1). In Stage 4, the C-BT waits until extreme drought conditions ($CBI < 0.68$ km^3) before initiating informal lease purchases. This focuses lease purchases on the driest periods in which they are most needed (Figure 6B), but it also means that in some multi-year droughts the overall impact of leasing is reduced relative to what it could be because leases are initiated later or end earlier. In the leasing scenario when purchases begin during Stage 1 drought conditions, many of the leases are purchased during droughts that are short or mild, increasing the chances that the C-BT will not need those supplies to ensure urban reliability. Figure 6B shows the annual volume of water acquired by the C-BT via informal leases (after accounting for any required compensatory releases) during each stage of drought. The scenarios are defined by the drought stage at which informal lease purchases *begin*, so while the Stage 4 scenario only triggers informal leases after Stage 4 has been reached, the Stage 1 scenario considers all informal leases purchased in Stages 1 through 4. The total volume of additional flow created via informal leasing ranges between 12.3 and 39.0 million m^3 (10 and 30 thousand acre-feet) and compensatory releases vary significantly with hydrologic conditions from year to year. After accounting for compensatory releases, leases totaled between 12.3 and 18.5 million m^3 (10 and 15 thousand acre-feet). Compensatory releases are a larger percentage of the informally leased water in drier years such as 1978 and 2002.

The lease sellers currently irrigate enough grass pasture and alfalfa hay that they are able to provide a sufficient volume of conservation, and the value of water in these activities appears to be quite low. Based on crop yields, prices, and estimated seasonal water requirements (Table 2) taken from crop enterprise budgets developed by the Colorado State University Agricultural Extension (CSU, 2022; Schneekloth and Andales, 2017), we estimate the marginal value of irrigating grass hay in the UCRB at \$0.19/m^3 (\$231/acre-feet) and of irrigating alfalfa at \$0.133/m^3 (\$164/acre-feet). Considering the most recent purchase prices for a permanent share of the C-BT have been close to \$70/m^3 (or \$4.5/m^3 per year assuming the up-front purchase is financed for 30 years at 5% interest) (Bovee, 2020), there is ample opportunity for mutually beneficial trade between lease sellers in the UCRB and the C-BT system. After accounting for compensatory releases, the average annual lease estimated during the simulation period (Figure 6B) represents roughly 5% of the full, 0.38 km^3 (310 thousand acre-feet) C-BT allocation (or 7% of the average historical delivery, 220 thousand acre-feet). Although this volume may not be sufficient to enable the C-BT to manage long or extreme droughts with informal leases alone, they provide an important supplement to conservation via C-BT quota reductions, which have historically reduced water consumption by about 20% of the full C-BT allocation (e.g., reduction in quota from an average of 70% to 50%). The ability to reallocate water at this scale generates significant benefits to municipal water utilities who rely on the C-BT for their water supplies, who would otherwise be forced to implement conservation measures on their own municipal customers. Figure 6C shows the annual benefits of agricultural-municipal water reallocation enabled by informal leases, estimated by comparing the marginal value of municipal water ($0.73/m^3, equal to municipal lost revenue from conservation) to the marginal value of irrigation on the part of lease sellers ($0.18/m^3 for grass hay irrigators and $0.133/m^3 for alfalfa). Using a weighted average of the marginal value of irrigators, the benefits of increased water reallocation from UCRB irrigators to the C-BT is equal to $0.55/ m^3. When informal leases are purchased only during Stage 4 drought, this translates into $45 million in total reallocation benefits, equal to an average of $7.2 million per year in which informal leases are triggered. When informal leases are triggered by Stage 3 drought conditions, the total net benefits are equal to $93 million, or an average of $8.5 million per year in each of the 11 years where informal leases are purchased. The total net benefits increase to a total of $158 million ($8.3 million annual average) and $222 million ($7.9 million annual average) when informal leases are triggered by Stage 2 and Stage 1 drought conditions, respectively. Whenever leasing options are exercised, facilitator options are also exercised to ensure that the water can be diverted by the lease buyer (C-BT). The number of facilitator options varies based on the hydrologic conditions encountered at the time of the lease, the seniority of the lease buyer and sellers, and in some cases their relative geographic locations. The fees paid to lease facilitators are set in advance as part of the terms of the informal leasing contract, but the quantity of unmet demand that must be 'facilitated' can change, and as a result the transaction costs vary through time. When more facilitator options are exercised to obtain the same volume of leasing options, the transaction costs (per unit of volume leased) will increase, even as they typically stay far below those shown to be incurred in the formal leasing process (cite Womble and Hanemann)..

This process can be illustrated by observing the spatial dynamics of lease facilitators through increasingly severe droughts (Figure 7). Informal leases purchased during Stage 1 drought (Figure 7A) require relatively few lease facilitators, with relatively small unmet demands (which we will call 'facilitated' demand). The lease facilitators are concentrated towards the bottom of the basin, in tributaries of the main river channel. These facilitators cannot directly access the additional water created by the lease sellers' conservation, but their diversions are restricted by more senior rights associated with the Grand Valley Project (GVP), which diverts from the main river channel near the Utah border (see Figure 1). If more water is made available on the main channel, the GVP will be able to divert that water, enabling restrictions to be lifted on some of these right holders. Given that the lease facilitators' rights are more senior than those owned by the C-BT, their shortages will be lifted first, unless they are paid to not act on the additional water that has been made available. The lease facilitators allow water to flow past their diversion structures on the tributaries, into the main river channel where it can be diverted by the GVP. This water will fulfill the GVP's water rights, allowing the C-BT to divert their leased water at Lake Granby without its access being curtailed to meet the demands of a more senior right holder. The total number of lease facilitators and volume of facilitated demand increases during Stage 2 (Figure 7B) and Stage 3 (Figure 7C) drought conditions. Less water in the main river channel results in GVP propagating shortages for a larger number of more junior right holders in order to fill their right, and less water in the tributaries means these shortages impact a broader array of more senior right holders.

As expected, more extreme Stage 4 drought conditions yield higher magnitude shortfalls for an increased number of water right holders throughout the UCRB. In the previous drought stages, the GVP forced shortfalls onto other right holders to ensure their ability to divert, but in 2002 they reached the limits of that ability and experienced shortages themselves. These shortages were exacerbated by extreme dry conditions further upstream in the basin, where the Shoshone Power Plant (Figure 1) is located. The Shoshone Power Plant water rights are even more senior than those of the GVP, but because those water rights are not used consumptively, the cooling water used at the power plant is later made available to users further downstream. When there is enough water to meet the full Shoshone water right, the GVP can essentially free-ride on a portion of the water delivered to Shoshone. The extreme drought observed in 2002 caused shortages at Shoshone, and these shortages were essentially ‘transmitted’ downstream to the GVP and other downstream junior right holders. This amplifies the total number of right holders who must act as lease facilitators, increasing the facilitator exercise fees, and thus the transaction costs, to the C-BT during very dry conditions.

Lease sellers use their water rights for low-value irrigation, and a significant portion of the diversions applied to crops returns to the river as ‘return flow’. The magnitude of this return flow is heavily influenced by the method of irrigation (e.g., drip, sprinkler, flood). Inefficient irrigation methods such as flood irrigation are common in the UCRB, particularly among low-value irrigators. Under normal conditions, these return flows can be subsequently diverted by downstream right holders. However, this flow does not always return to the stream immediately, meaning that changes to diversions can impact water availability at a later point in time. When informal leases reallocate irrigation diversions to the lease buyer (C-BT) to be exported out of the basin, the return flows are eliminated, impacting downstream right holders. These impacts create mitigation costs for the informal leases, and must be addressed via compensatory releases.

We compare right holder diversions in the StateMod baseline simulation to the diversions made in informal leasing scenarios to determine the mitigation cost at every diversion structure. Junior right holders are first to be impacted by reduced flows, and in the UCRB many of the most junior rights represent environmental (instream) flows and were acquired by the CWCB since 1973 (CWCB, 2022). These water rights are non-consumptive, meant to preserve a minimum flow within a stream. As a result of their lack of seniority, reductions in return flows require compensatory releases to maintain flow at the baseline (without informal leases) conditions, as shown in Figure 8. In each of the 1995, 1982, and 2013 simulation years (representing a Stage 1, 2, and 3 drought condition), reduced return flows as a result of informal leases create shortfalls at one or more of a series of environmental flow rights downstream of Lake Granby.

The impact on these environmental rights grows in years with drier hydrologic conditions. During the Stage 4 drought experienced under 2002 flow conditions, a much broader range of water rights holders are vulnerable to shortfalls as a result of informal leases in the absence of compensatory releases, including a downstream reservoir and the water rights for Shoshone Power Plant (Figure 8D). In the baseline StateMod simulation (e.g., water allocation simulations using current right holder demands, storage and conveyance infrastructure operating rules, and historical hydrologic conditions), 2002 was an extremely dry year, causing shortfalls to occur even for senior water rights like Shoshone Power Plant. Senior right holders like Shoshone (Figure 8D, silver) can force junior users to stop diverting to prevent its own shortfalls, but when conditions are very dry, agricultural conservation in the summer growing season can cause reduced return flows in the late fall, after reservoirs have stopped filling. Senior water rights can prevent reservoirs in the UCRB, like Lake Granby, from filling given its junior rights but cannot force it to release previously stored water, consequently the delayed reduction in return flow can cause shortages even for senior right holders. Here, we calculate the volume of compensatory releases required to mitigate the uncompensated losses from junior and senior right holders alike.

In years that include the type of Stage 4 drought conditions observed in 2002 (Figure 8D), compensatory releases from Lake Granby prevent cascading changes associated with interrelated operations at the basin's largest reservoirs. Green Mountain Reservoir (Figure 8D, red) is another UCRB reservoir operated by the C-BT, and while water stored there cannot be directly exported to the C-BT service area on the Front Range, the C-BT makes supplementary releases from Green Mountain to preserve additional water for export in Lake Granby. Under the current operational rules, Green Mountain Reservoir responds to a reduction in return flows caused by informal leases by making compensatory releases of its own. The changes at Green Mountain also induce operational changes at Dillon Reservoir, upstream of Green Mountain Reservoir, causing shortages in some of the environmental flow rights upstream of Green Mountain (Figure 8D). To avoid creating impacts from operational changes at other basin reservoirs, we specify that any compensatory releases due to informal leases originate at the point of lease (e.g., Lake Granby) and are not included in any existing exchange operations in the basin.

Although some senior right holders can be impacted by informal leases in the driest years, junior environmental water rights account for 75-85% of the third-party shortfalls caused by informal leases (Figure 9). A large proportion of the impacted water rights are non-consumptive, consequently compensatory releases can mitigate shortfalls experienced by multiple right holders in series. Average compensatory releases in each of the informal leasing scenarios (in which informal leases are triggered by *CBI* Stage 1-4 drought conditions) are illustrated in Figure 9. Compensatory releases are highest as a percentage of the total leases when informal leases are purchased during Stage 4 drought conditions. Return flows make up a larger portion of the overall flow when conditions are drier, particularly in the late fall, and as a result changes to those return flows cause larger, potentially cascading impacts on downstream right holders.

Calculations of impact to other basin right holders, and the associated compensatory releases, rely on assumptions about the magnitude and timing of lease seller return flows. Lease facilitators and other third-party right holders may be reluctant to sign into the agreement if they are unsure about the approach used to calculate compensatory releases. If the return flows assumed by the informal leasing agreement are lower than the observed (actual) return flows, estimated compensatory releases will be too small and third-party right holders could be impacted. We evaluate total option payments assuming 2.5, 5, and 10% under-estimation of the compensatory releases needed to mitigate lost return flows (for more information about option pricing, see Supplement A). The total transaction costs associated with informal leases is equal to the sum of the annual up-front option payments plus the lease facilitator exercise fees (Figure 10). For each component of transaction costs, we used the total payment made over the 64-year simulation period and divided it by the total volume of informal leases purchased (after accounting for compensatory releases) as a way to calculate a consistent 'transaction cost' between fees that are paid annually as opposed to only when exercised. Comparing the transaction costs of informal leases with previous estimates of transaction costs in the legal record is non-trivial. It requires being explicit in the assumptions used when specifying the lease facilitator fee and the uncertainty associated with return flows.It is difficult to determine an exact lease facilitator exercise fee, because the facilitator is not being paid to reduce diversions. As a result, a marginal value-based technique is not appropriate, given that a facilitator is largely paid not to do something (divert), and that the facilitator is very unlikely to have the opportunity to do unless the facilitator agrees to accept the fee (i.e. no informal lease will take place). The facilitator therefore has two alternatives, either allow the transaction to proceed and receive a payment, or block the transaction and receive no payment. Facilitators may be willing to hold out for higher prices knowing that the lease buyers alternative is a significantly more expensive formal lease, but there is an incentive to find a price that will be acceptable to the lease buyer, otherwise the lease facilitator will lose out on the opportunity to receive any payment at all (as well as the opportunity for other potential lease facilitators, who according to Figure 9 may be members of the same community). As a benchmark value for estimating the facilitator fee, we use two recent transactions made by the CWCB to lease water from the Ute Water Conservancy for $0.0058/m^3 ($7.20/acre-foot) in 2019 (CWCB, 2019) and $0.016/m^3 ($20/acre-foot) in 2022 (CWCB, 2022). Lease facilitator exercise fees are evaluated at volumetric prices between $0.004-0.016/m^3 ($5-20/ acre-foot). The price accepted for the delivery of physical water, even in a year when the seller (e.g., Ute Water Conservancy) may have significant excess supplies, serves as a high-end estimate for the price paid to 'facilitate' an informal lease by taking no action. Ranges for uncertainty in return flow assumptions were chosen so that the high end of both estimates (e.g., 10% uncertainty in return flows, $20/acre-foot facilitator fees) resulted in transaction costs that are in line with the lower bound of prior estimates of transaction costs within the formal leasing system (Womble and Hanemann, 2020b; Dilling et al., 2019).

Figure 10 illustrates that the total transaction costs associated with informal leases are highest when leases are purchased during drier (e.g., Stage 4) conditions. When leases are purchased most frequently, beginning during Stage 1 and 2 conditions, the combination of up-front payments representing a 5% uncertainty in return flows and $5/acre-foot facilitator exercise fees translates to $0.036/m^3 and $0.035/m^3 ($46/acre-foot and $43/acre-foot), respectively. When lease purchases are restricted to only include Stage 3 and above drought conditions, the average transaction costs increase to $0.041/m^3 ($49/acre-foot). When leases are only purchased during the driest (Stage 4) drought conditions, the average transaction costs increase further to $0.049/m^3 ($60/acre-foot). If lease facilitators and third parties demand higher price levels as a conditions of joining these agreements, transaction costs increase closer to the cost of formal leases. If we assume a facilitator exercise fee of $20/acre-foot and an up-front option fee that represents a 20% uncertainty in return flows, then total transaction costs increase to $0.17/m^3 ($215/acre-foot) during Stage 4 drought conditions, $0.16/m^3 ($196/acre-foot) when leases are triggered by Stage 3 conditions, and \$0.137/ m^3 and \$0.142/ m^3, (\$171/acre-foot and \$184/acre-foot) in Stage 2 and 1 conditions, respectively. This set of assumptions (facilitator exercise fees of \$20/acre-foot and up-front option payments assuming 10% uncertainty in return flows) represents the price level for contracts at which informal leases become cost-neutral with the lower bound of previous estimates of transaction costs for formal water rights leases in this region, which fall in the range of \$0.16/m^3 - \$0.29/ m^3 (\$200 - \$360/acre-foot) (Womble and Hanemann, 2020b; Dilling et al., 2019).

As a result, the overall cost of leases represents between a 43% reduction (minimum informal lease cost estimate, Stage 1 leases), and 15% reduction (maximum informal lease cost estimate, Stage 4 leases) in the overall cost of leasing water compared to formal leases. Although these represent reasonable estimates for the range of potential informal lease costs, the actual prices paid for informal leases if they were to be implemented would be the result of negotiations between lease buyers (e.g., the C-BT), sellers, facilitators, and other basin right holders. Buyers have an incentive to push for lower exercise prices and option fees, while the sellers, facilitators, and other right holders have an incentive to push up prices. An analysis of this negotiation process is beyond the scope of this paper, but a key benefit of the informal process is the potential for compromise to share the benefits between right holders in the basin. Under formal leases, between \$0.16/m^3 - \$0.29/ m^3 (\$200 - \$360/acre-foot) is paid to non-basin participants, including lawyers, technical experts, and court fees (cite Womble again). Under a regime of informal leases, these transaction costs would accrue to lease sellers, facilitators, and other right holders (in the form of facilitator fees and up-front option payments) and the lease buyers (in the form of reduced transaction costs). Unlike the formal legal system, informal leases present basin stakeholders with the opportunity to negotiate to find a solution that meets everyone's needs, increasing the opportunity for basinwide benefits to be realized through reallocation.

Discussion

The ability to informally lease water has the potential to generate significant benefits relative to formally leasing water rights. Most importantly, this analysis suggests that informal leases have the potential to accomplish more rapid (as a result of not going through the regulatory approval process) short-term water reallocation with significantly lower transaction costs. This finding is, however, subject to several assumptions about the size of facilitator exercise fees and the up-front payments that would be needed to convince parties to join the agreement. Unlike the formal leasing process, a substantial portion of the transaction costs associated with informal leases are distributed to right holders within the basin, as opposed to being distributed amongst various actors in the regulatory approval process (e.g., attorneys). In the formal leasing process, there is no mechanism for potentially affected third parties to realize any benefit from the transaction.

Up-front, annual option fees paid to all potentially affected third parties provide an economic incentive for cooperation. Structuring the lease facilitator contracts as option contracts creates a mechanism for valuing and compensating third parties for their uncertainty about the actual changes in return flows stemming from informal leasing activity. If there is a greater amount of disagreement about the potential changes to return flows, prices could be calculated with higher estimates of return flow uncertainty, pushing the estimated facilitator option payments up. This flexibility to increase option payments could help to resolve conflict over return flows with lower costs than the formal lease approval process. Lease facilitators and other third parties who stand to receive payments have an incentive to try and extract as large of a payment(s) as possible from this process. Knowing that lease purchasers have no other alternative to the formal legal leasing process, they could push up the fees and contract costs to approach the transaction costs associated with the formal legal system. However, if the lease buyer (C-BT) chooses not to go through with the purchase, then the lease facilitators and third parties lose out on the opportunity to receive a payout for doing nothing. As a result, all parties have an incentive to move towards a deal, a characteristic that is not shared with leases made via the formal legal system, where all benefits are captured only by the two transacting parties (and agents engaged in the approval process). In addition, many of the lease facilitators and/or third parties who might participate in informal lease agreements represent right holders who are subject to relatively frequent shortfalls due to drought. Any facilitator exercise fees will be paid to a right holder experiencing some level of shortage from ongoing drought, and thereby mitigate the facilitator's drought-related losses. Likewise, up-front option payments, which go primarily towards the owners of environmental flow rights, could be a useful source of funds to acquire additional leases and/or permanent rights that could be applied towards instream flows or another form of environmental restoration.

Although the simulation of informal leasing operations described here applies to a specific region, a similar arrangement could be developed elsewhere, as other regions in the Western U.S. have similar rules of prior appropriation that govern water allocation and similar activities competing for water (i.e. low-value irrigation, high-value urban uses). In fact, other regions may offer an even more favorable context for informal leases than the study region considered here, which is particularly complex. Geography and existing operational agreements limit the right holders who can act as lease sellers to the C-BT, but senior right holders can disrupt this process (by making a claim on the additional water) from nearly anywhere along the mainstem Colorado River (and, under certain hydrologic conditions, from the tributaries).The C-BT example was selected to demonstrate how informal leases are capable of overcoming the challenges associated with water reallocation in an institutionally complex basin. In addition to demonstrating the viability of informal leases as a lower-cost method of water reallocation, results here also suggest other contexts in which informal leases might be able to scale beyond the case study presented here. In particular, informal leases could be particularly effective for users that (a) are downstream of large quantities of low-value irrigation and (b) possess reservoir or other types of storage in which informal leases purchased in more mild drought years (when transaction costs are lowest) can be stored and consumed by the lease buyer in later years when conditions are drier.

Complications related to the location and capacity of storage in the UCRB limit the volume of informal leasing, however, users further downstream within the Colorado River Basin have access to significant volumes of unused storage capacity that would enable them to purchase informal leases in a wet year, when they are less expensive, and store them for use during drier conditions. In particular, Lake Powell and Lake Mead, which together have nearly 61 km^3 (50 million acre-feet) of storage capacity, lie downstream on the Colorado River. These two reservoirs provide water to a significant portion of the Western United States, including Las Vegas, Phoenix, and Southern California, and recently have been subjected to an unprecedented drawdown. Even though these reservoirs possess no water rights within the State of Colorado, any water that is not used within the UCRB flows into them naturally, with relatively few intervening water users. Municipal water providers who store water in these reservoirs could effectively purchase informal leases within the UCRB as if they were the lowest-priority water right in the basin, and informal leases could act to 'shepherd' water towards the outlet of the basin. The number of lease facilitators who would need to be paid in a dry year increases when the water needs to be shepherded, in effect, to the lowest-priority right, but in wetter years the overall number of lease facilitators would be lower. Municipal users in Nevada, Arizona, and California could pay for conservation within the UCRB when conditions are very wet, allowing informal lease purchases when the number of lease facilitators who need to be paid to shepherd the water to Lake Powell is at its lowest. In addition, Lake Powell and Mead are downstream of a number of other Western Colorado watersheds, including the Yampa, White, Dolores, and San Juan, making informal leases originating from any of these basins available to water users there. The U.S. Bureau of Reclamation, which controls operations and makes deliveries to contractors from Lake Powell and Lake Mead, has recently offered up to $400/acre-foot in conservation incentives to water users in the Lower Basin (California, Arizona, Nevada), but have not extended these incentives to users in the Upper Basin (USBR, 2022b). In the long-term, it is conceivable that informal leases could provide mechanism to extend these purchases to users in Colorado while providing the institutional means to send these purchases into the large downstream reservoirs.

Conclusions

Unprecedented drought in the Western U.S. has highlighted the need for institutional innovations that are capable of efficiently reallocating water use in response to changing conditions. Prior appropriation rules that govern reallocation across much of this region involve costly regulatory processes which hinder water reallocation via established water markets, particularly for short-term leases. This work is designed to offer a new alternative to formally approved leases of water rights, and to test their performance under a range of conditions. Results suggest that informal leases could reduce the transaction costs associated with short-term water reallocation, potentially increasing resilience during drought more rapidly and at lower cost. The informal leases proposed here reduce transaction costs through a novel framework in which index-based option contracts provide up-front, annual payments to any right holders that may be negatively impacted by reallocation, with larger payments going towards users who are more at risk of being impacted. By compensating all actors in the system for the individual risks that arise from a given change, the overall cost of that change could potentially decrease because legal transaction costs decrease when institutional incentives align. While there are certain to be a number of additional steps required in order to fully vet this concept with market participants and other stakeholders, results indicate that the potential for improvement would justify additional investigation.

Climate models and development patterns both point towards a future in which droughts are more common and extreme in the Western United States. Reallocation of supplies from low-value agriculture towards municipal, industrial, and environmental uses via leasing is one option to reduce the costs of persistent, recurring drought events. This work presents an example of the joint management of institutional and environmental risk through leasing contracts that are designed to be responsive to changing environmental conditions while also addressing institutional constraints. The framework put forward here aligns the incentives of institutional actors (e.g., water right holders) in such a way that the institutional constraints are overcome as environmental risks grow. Solutions that engage with the complex interactions between institutional and environmental risks are much more likely to be capable of managing major changes to climate and society.

Figures and Tables

Table 1: Informal leasing scenarios, with corresponding trigger thresholds and frequency of leasing patterns during the simulated period (1950-2013).

Scenario Name	*CBI* threshold (km^3)	Frequency of leasing (% of years)	Total net benefits of informal leases ($MM)
Stage 1	0.86	43	222
Stage 2	0.8	30	158
Stage 3	0.74	17	93
Stage 4	0.68	9	45

Table 2: Informal leasing scenarios, with corresponding trigger thresholds and frequency of leasing patterns during the simulated period (1950-2013).

Component	Grass Hay	Alfalfa Hay
Price ($/kg)	0.26	0.26
Marginal cost ($\$/m^2$)	0.06	0.09
Yield (kg/ m^2)	0.63	0.83
Water Requirements (m/year)	0.53	0.91
Marginal value of water use ($\$/m^3$)	0.06	0.04
Total irrigated area, UCRB lease sellers (km^2)	32.2	0.8

Table 3: Components of formal and informal leasing prices

	Lease Base Price $\$/m^3$ ($/acre-foot)	Informal lease facilitator fee $\$/m^3$ ($/acre-foot)	Informal lease option fee $\$/m^3$ ($/acre-foot)	Formal lease legal costs $\$/m^3$ ($/acre-foot)	Total leasing costs, informal $\$/m^3$ ($/acre-foot)	Total leasing costs, formal $\$/m^3$ ($/acre-foot)
Stage 1	0.13-0.19 (164-231)	0.02 – 0.08 (25 - 99)	0.02-0.07 (21 – 85)	0.16-0.29 (200-360)	0.17-0.34 (210-415)	0.30-0.48 (364-591)
Stage 2	0.13-0.19 (164-231)	0.02 – 0.08 (24 – 96)	0.02 – 0.06 (19 – 75)	0.16-0.29 (200-360)	0.17-0.33 (207-402)	0.30-0.48 (364-591)
Stage 3	0.13-0.19 (164-231)	0.02 – 0.09 (27 – 108)	0.02-0.07 (22 – 88)	0.16-0.29 (200-360)	0.17 – 0.35 (213-427)	0.30-0.48 (364-591)
Stage 4	0.13-0.19 (164-231)	0.03 – 0.12 (35 – 142)	0.02-0.08 (25-102)	0.16-0.29 (200-360)	0.18–0.39 (224-475)	0.30-0.48 (364-591)

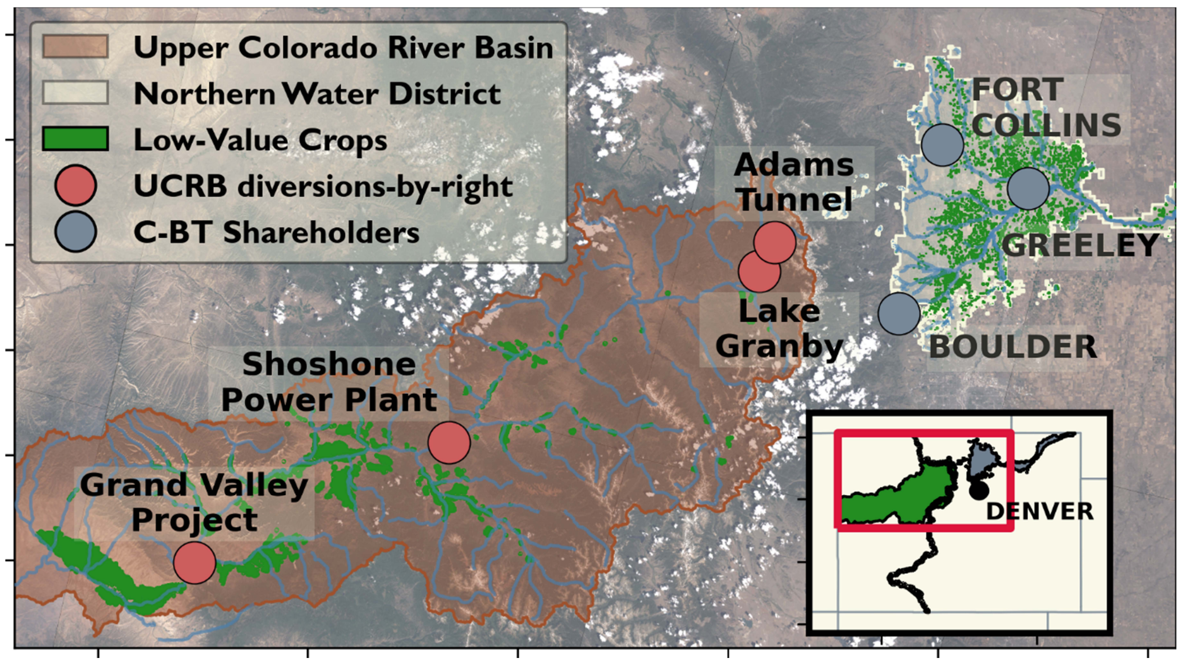
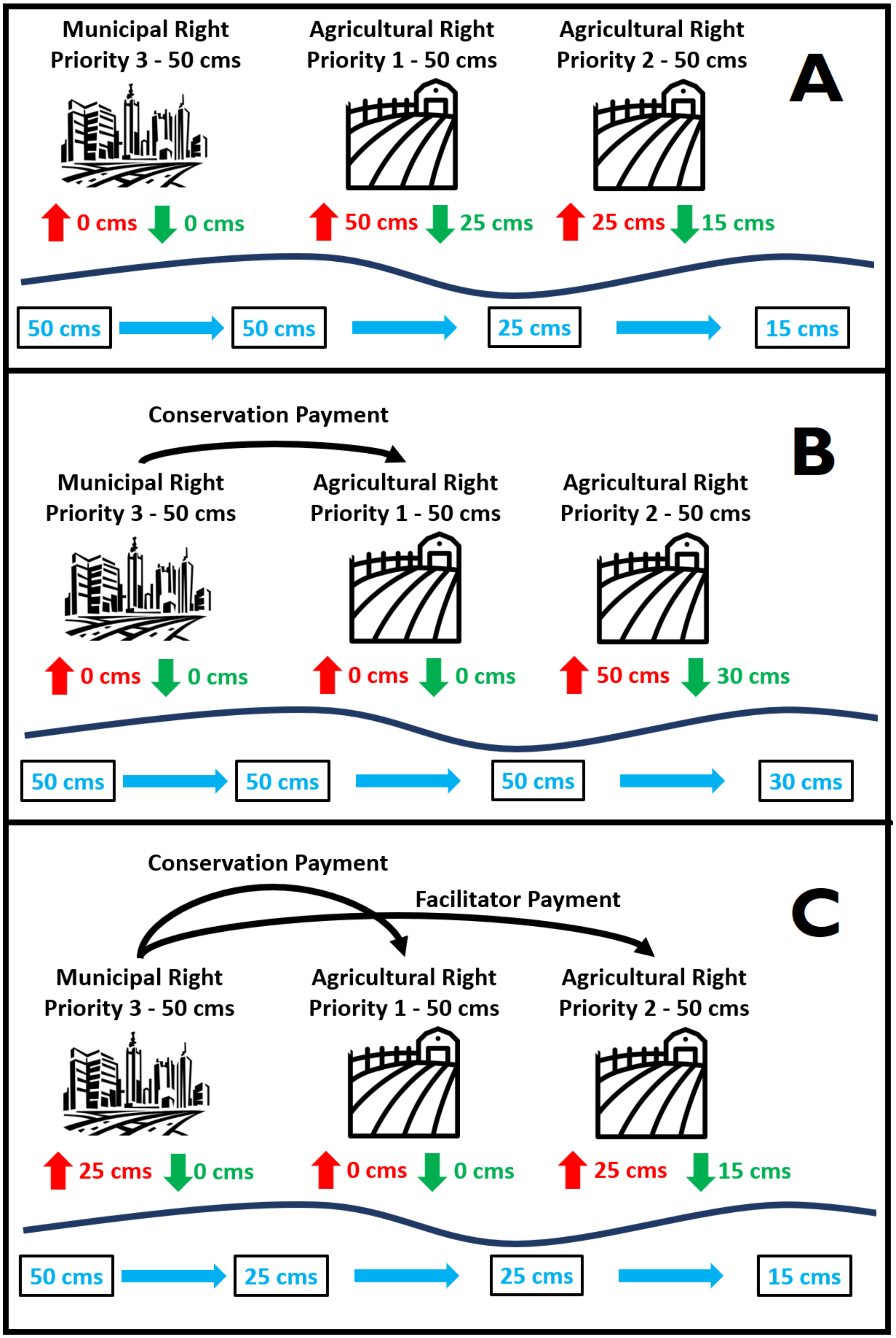


Figure 1: *Colorado-Big Thompson (C-BT) project transbasin diversions from the UCRB to their Front Range service area via the Adams Tunnel and Lake Granby. Showing the location of Lake Granby - Adams Tunnel diversion complex, where the C-BT stores water under its rights within the UCRB and exports them to municipal customers on the Front Range, as well as the Shoshone Power Plant and Grand Valley Project, two large right holders in the UCRB with more seniority than the C-BT.*


A
Municipal Right
Priority 3 - 50 cms
Agricultural Right
Priority 1 - 50 cms
Agricultural Right
Priority 2 - 50 cms
0 cms
0 cms
50 cms
25 cms
25 cms
15 cms
50 cms
50 cms
25 cms
15 cms
B
Conservation Payment
Municipal Right
Priority 3 - 50 cms
Agricultural Right
Priority 1 - 50 cms
Agricultural Right
Priority 2 - 50 cms
0 cms
0 cms
0 cms
0 cms
50 cms
30 cms
50 cms
50 cms
50 cms
30 cms
C
Conservation Payment
Facilitator Payment
Municipal Right
Priority 3 - 50 cms
Agricultural Right
Priority 1 - 50 cms
Agricultural Right
Priority 2 - 50 cms
25 cms
0 cms
0 cms
0 cms
25 cms
15 cms
50 cms
25 cms
25 cms
15 cms

1014

Figure 2: *A simple schematic of water reallocation via informal leases, including: (A) a junior, municipal right being 'shorted' by a downstream agricultural user with a more senior right. The junior municipal user can (B) pay the senior agricultural right holder to leave the water instream, but the additional flows created can be diverted by another agricultural right, further downstream, with more seniority than the municipal right. In response, the municipal right can (C) pay this second agricultural right to 'facilitate' the informal lease by maintaining their level of diversions after the additional water is created, allowing the municipal right to divert.*

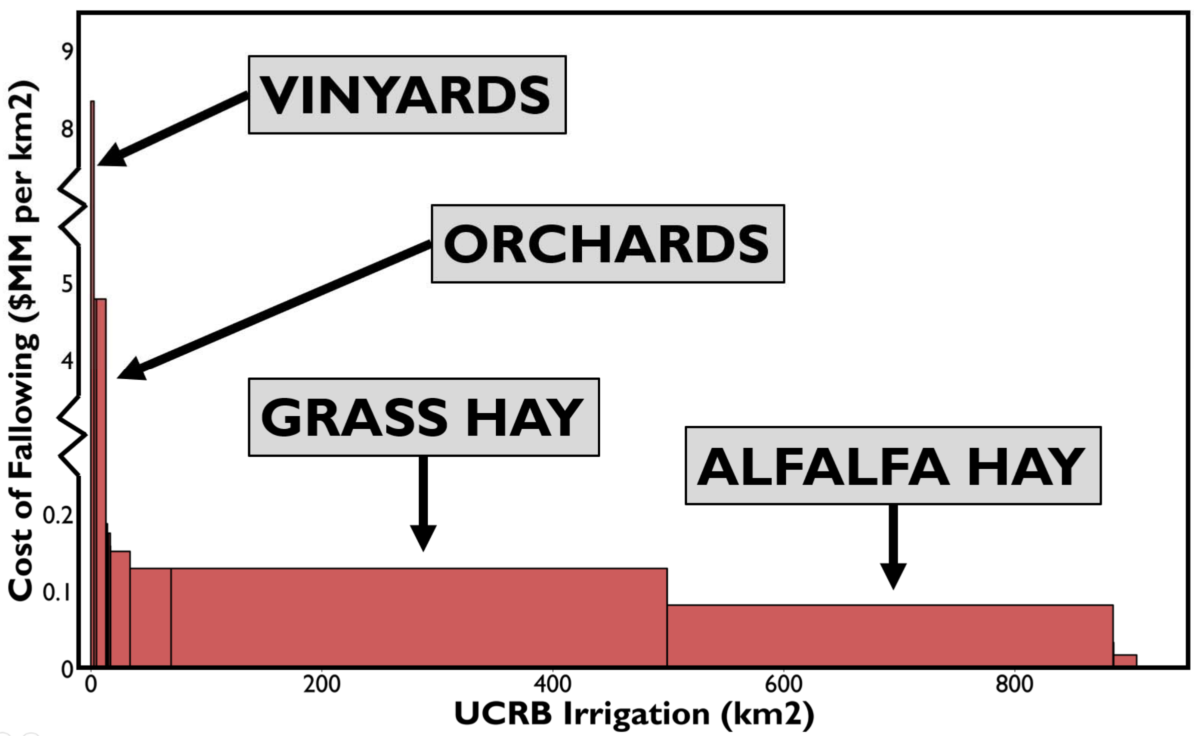


Figure 3: *Marginal value of crop production, per acre-foot of consumptive water use, vs. total irrigated acreage in the Upper Colorado River Basin.*

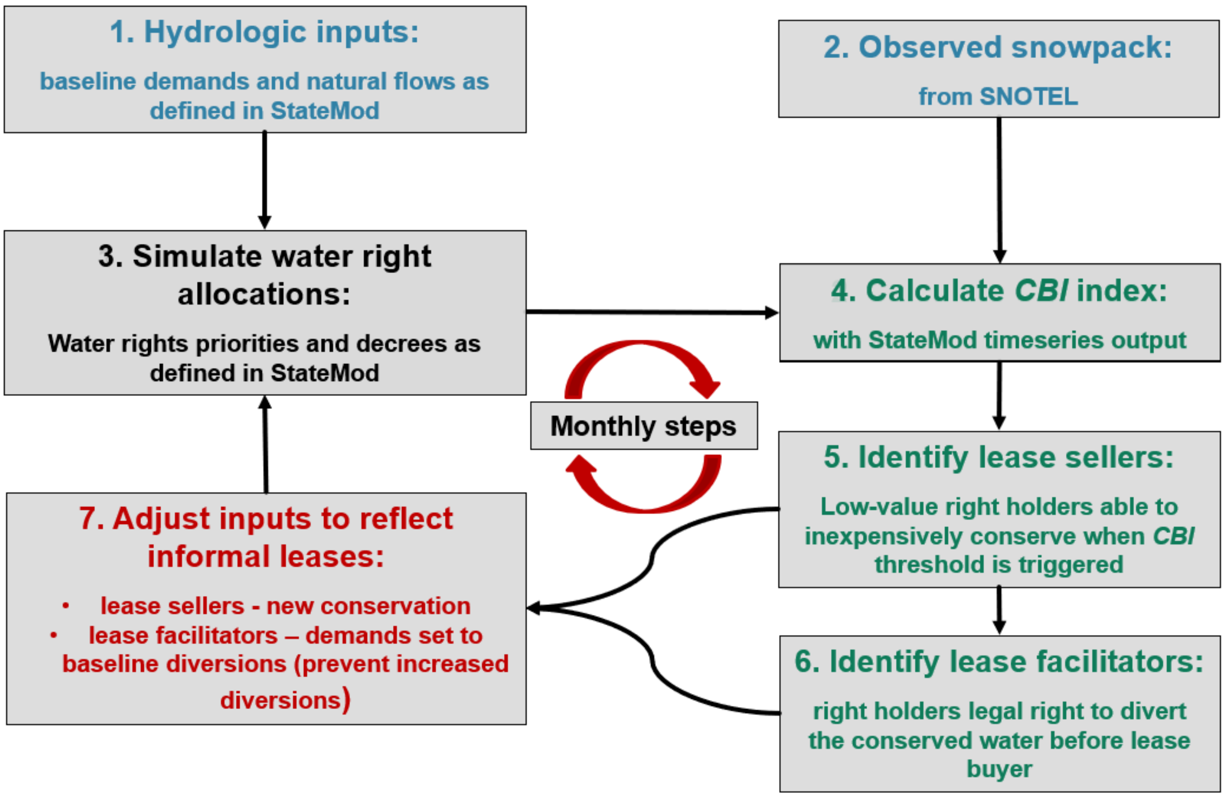


Figure 4: *Flowchart representing the steps required to evaluate the potential for informal leases using StateMod.*

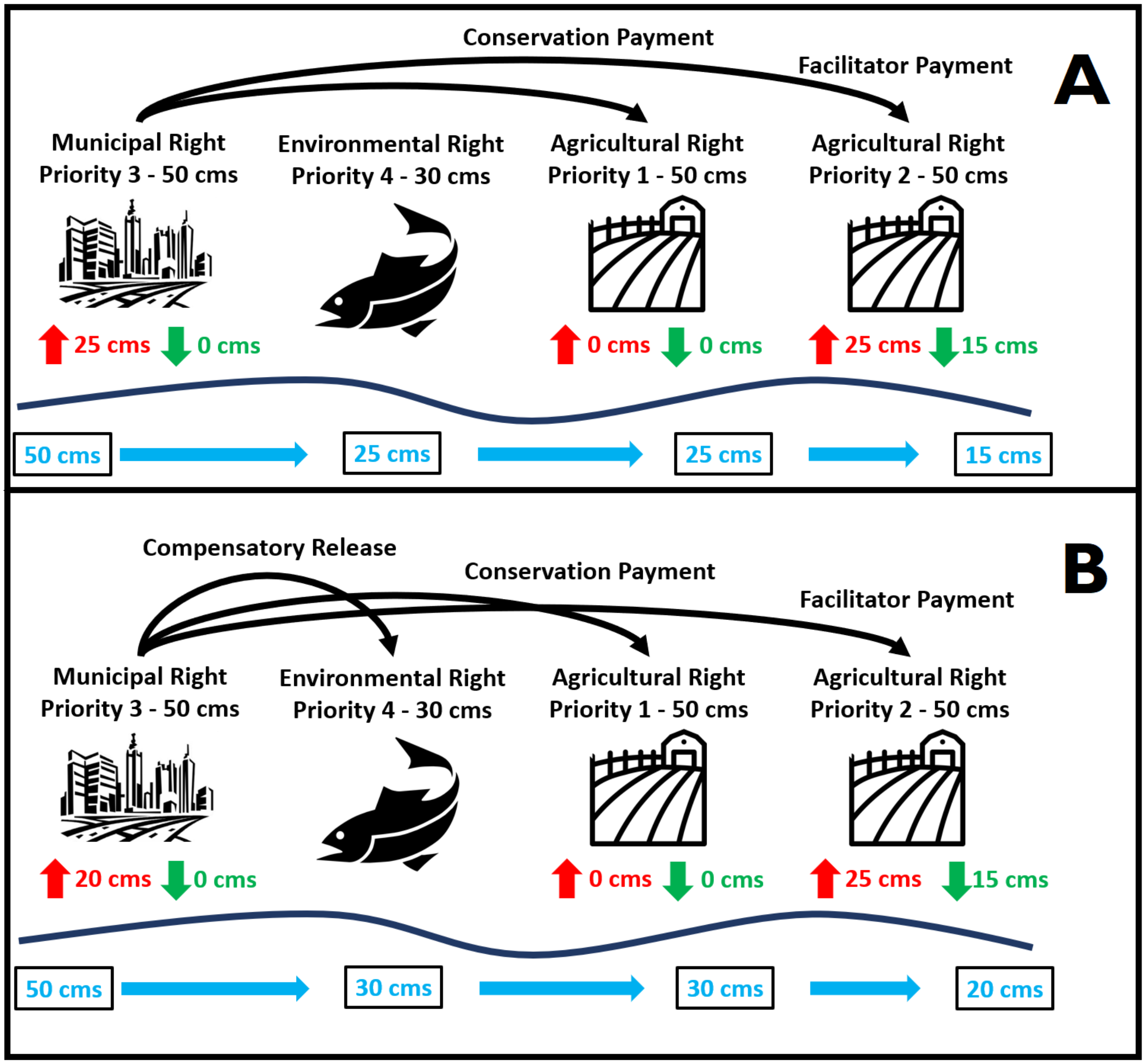


Figure 5: *A more complex schematic of water reallocation via informal leases with a junior environmental right located between the informal lease buyer and the informal lease seller. After the conservation and facilitator payments are made (A), flow in the reach covered by the right decreases, causing injury to the environmental right holder. Compensatory releases (B) are required by the municipal right holder in order to mitigate their injury.*

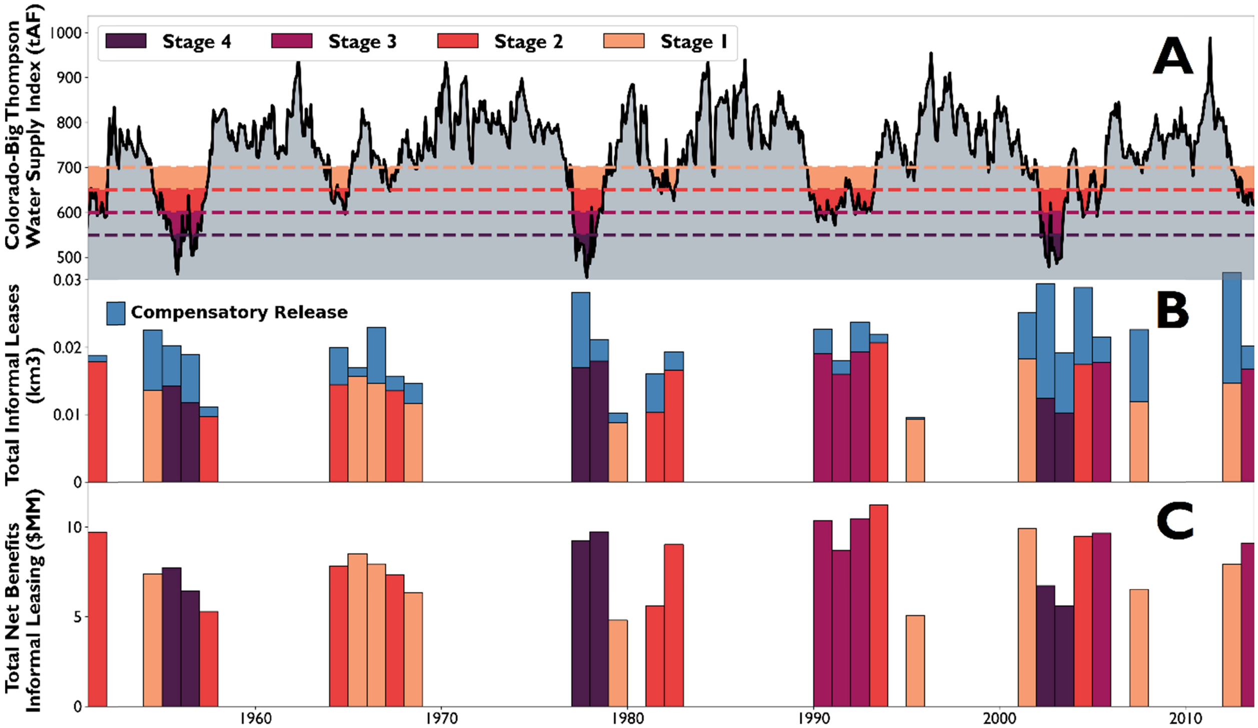


Figure 6: *C-BT water supply index (CBI) calculated at a monthly timestep over the historical simulation period, 1950 – 2013, with four thresholds used to distinguish the stages of drought in which leases are purchased (A), the total informal leases delivered in each of those years, accounting for compensatory releases (B), and the annual net benefit from water reallocation (C). CBI thresholds are used to distinguish four stages of drought during which informal leases can be purchased, and years are colored based on that year's drought stage (1-4).*

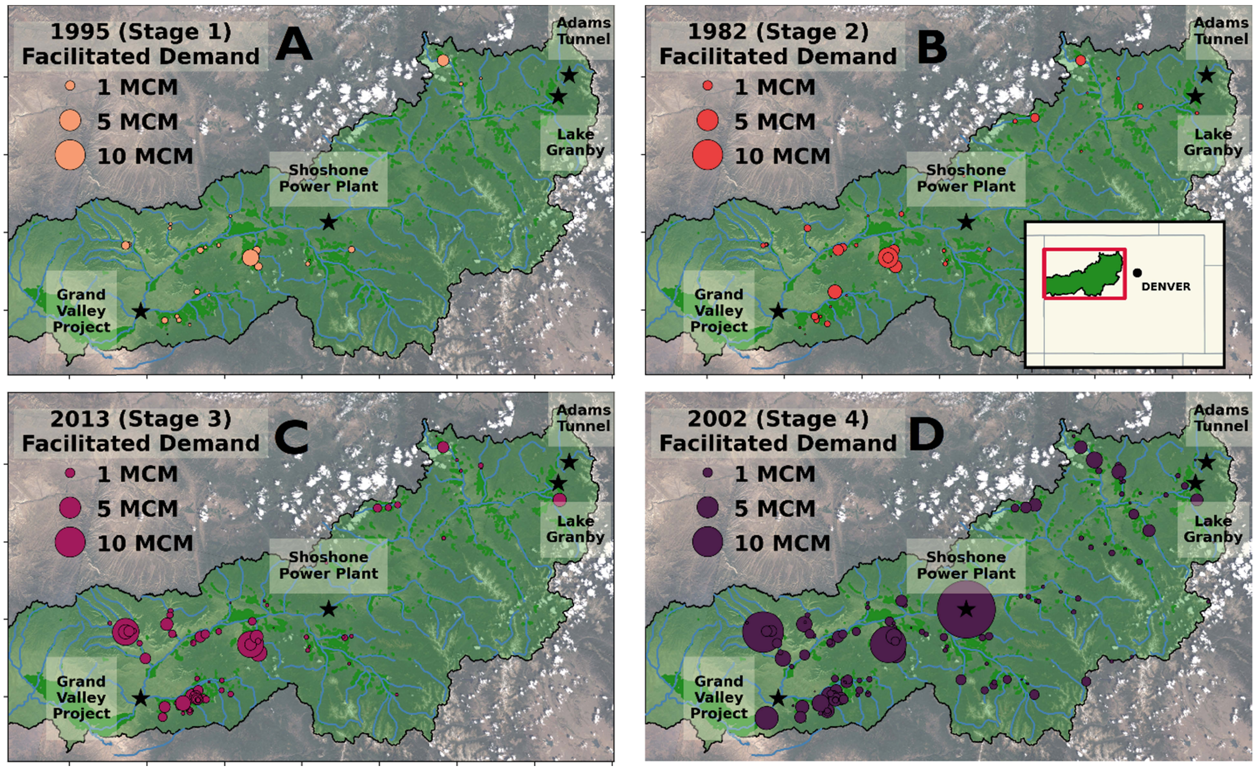


Figure 7: *The spatial distribution of lease facilitators for informal leases purchased during one example simulation year from each of the Stage 1 – 4 drought conditions, in MCM (million m^3). The size of the marker is equal to the total volume of shortage associated with each facilitator's water right in the sample year. Lease facilitators are paid not to exercise this unfulfilled portion of their water right, and exercise payments are scaled volumetrically based on the size of that unfulfilled portion, shown here for a Stage 1 drought (A), 1995; a Stage 2 drought (B), 1982; a Stage 3 drought (C), 2013; and a Stage 4 drought (D), 2002.*

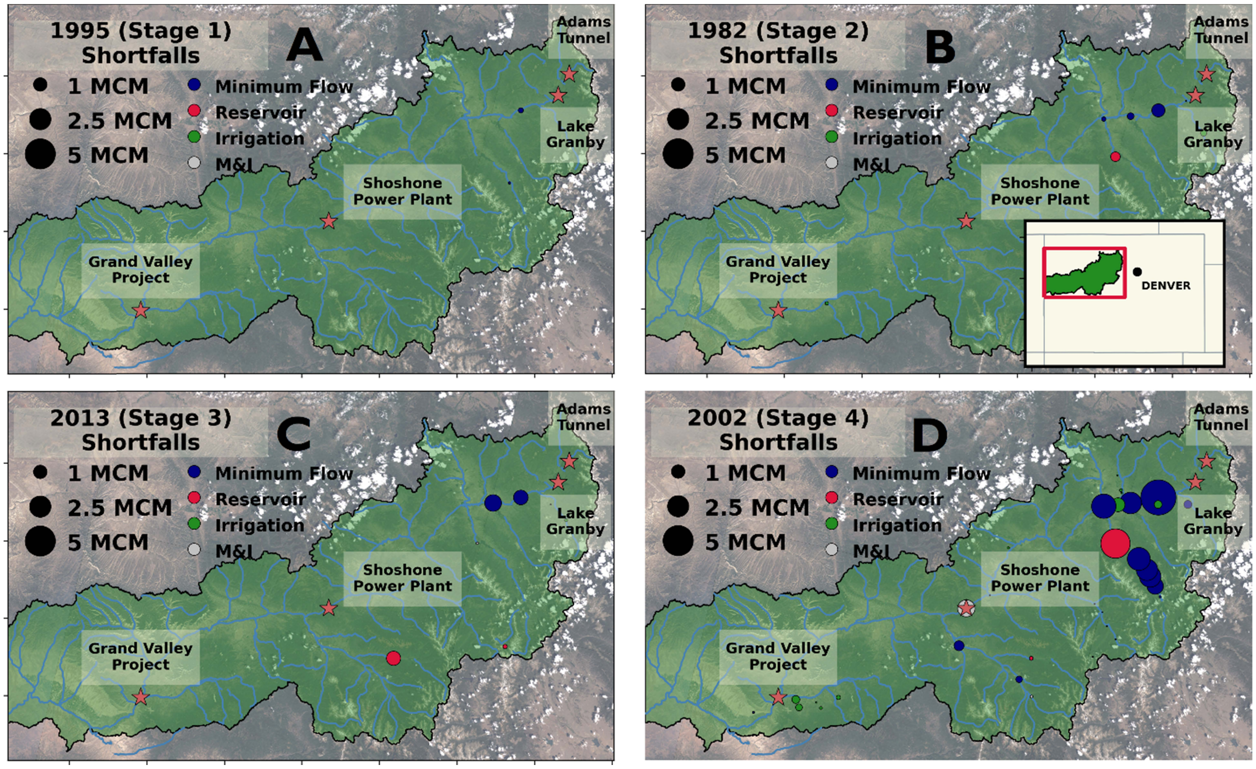


Figure 8: *The spatial distribution of compensatory releases made as part of informal leases purchased during one example simulation year from each of the Stage 1 – 4 drought conditions. The size of the marker is equal to the total volume of additional shortfalls experienced by a UCRB water right holder as a result of informal leases. Agricultural conservation results in reduced return flows that cause shortages for some downstream right holders. The shortfalls create a mitigation cost for informal lease buyers that must be addressed through compensatory releases. The size of the compensatory release for each right is shown during a Stage 1 drought (A), 1995; a Stage 2 drought (B), 1982; a Stage 3 drought (C), 2013; and a Stage 4 drought (D), 2002.*

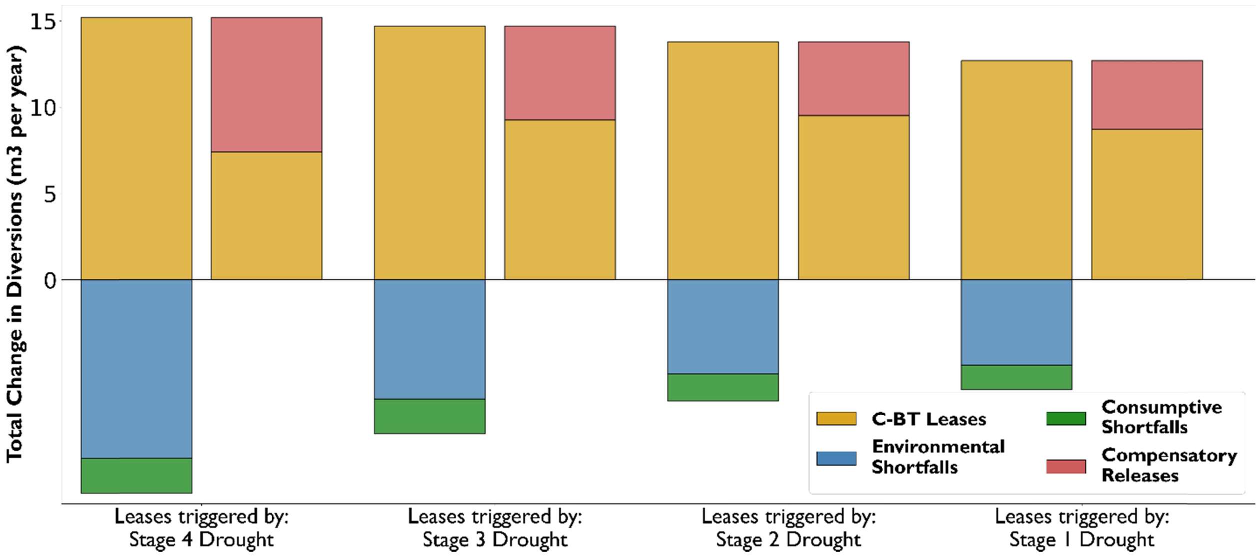


Figure 9: *Total leased volumes and aggregate impact to third-party right holders (both environmental and other consumptive uses), with and without the use of compensatory releases. Values are aggregate leases across all 64 simulation years in each informal leasing scenario.*

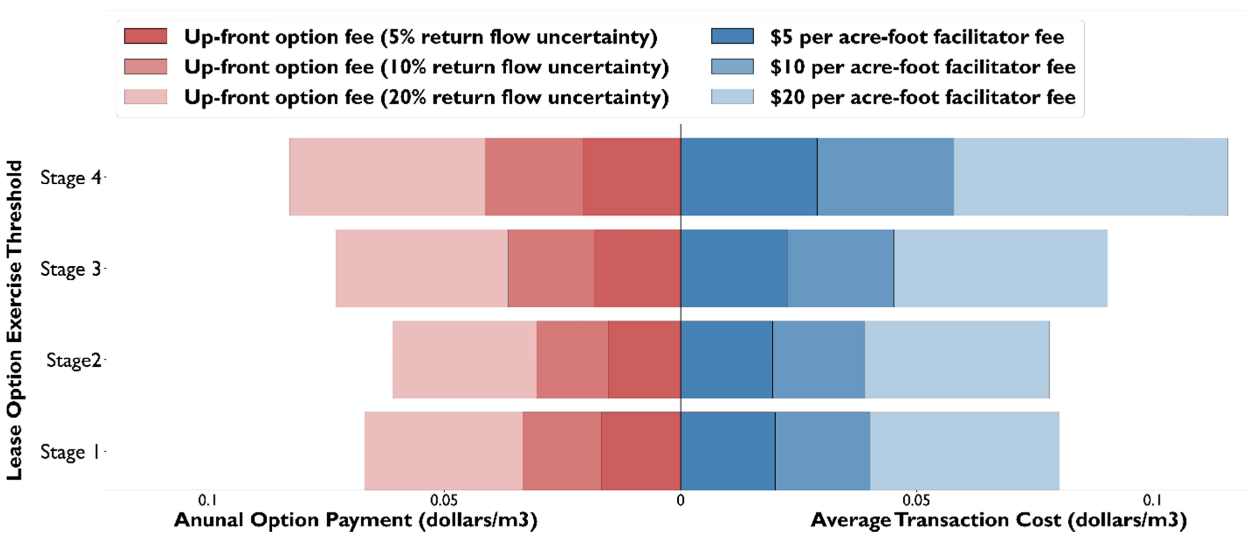


Figure 10: *Average transaction costs for informal leases in each leasing scenario. Transaction costs have two components: annual, up-front option payments (in red), overall payments per m^3 of informal leases purchased during the simulation (after accounting for consumptive releases), and exercise fees (in blue) paid only in years when leases are purchased, overall payments per m^3 of informal leases*

.

Supplemental Section A

Informal leasing contracts are designed as 'options', which give the lease buyer the right, but not the obligation, to exercise the option when the appropriate *CBI* threshold has been crossed. Only specific water right holders can function as lease sellers (Figure S1). In the case of the UCRB, only a subset of right holders are eligible to act as informal lease sellers because (a) the C-BT exports water from a site (Lake Granby) located in the headwaters of the UCRB, meaning there are relatively few upstream irrigators from which to lease water, and (b) the C-BT operates an auxiliary reservoir, Green Mountain, located downstream of Lake Granby. The C-BT cannot export water directly from Green Mountain Reservoir, but some of the C-BT obligations to downstream senior right holders can be released from Green Mountain, instead of Lake Granby, preserving additional water in Lake Granby that can be exported to the Front Range. As a result, releases from Lake Granby are only large enough to meet the demand of a limited number of local senior right holders, constraining leases from downstream users by restricting in-stream flow that can be used for exchange, according to equation (7). However, this case study illustrates how informal leases can be particularly adept at managing complex institutional settings.

These right holders all have senior water rights that enable them to sell leases under all hydrologic conditions experienced during the historical (1950 – 2013) simulation of water allocation in the UCRB, including an example of Stage 1 drought conditions (Figure S1A), Stage 2 drought conditions (Figure S1B), Stage 3 drought conditions (Figure S1C) and Stage 4 drought conditions (Figure S1D). All lease sellers are located in the immediate vicinity of Lake Granby, because these are the senior right holders for who can make a claim on inflows to Lake Granby. Although there are senior right holders further downstream, the C-BT can release water from Green Mountain Reservoir, located on the Blue River, as an exchange that enables them to keep more water in Lake Granby.

Option contracts include two parts, the option exercise fee and the up-front option payment. The option exercise fee, negotiated ahead of time as a volumetric rate, is only paid if/when the option is exercised. However, the option purchase price, a payment made by the lease buyer at the beginning of each contract period, compensates right holders for the risk that they will be somehow worse off when the contract is exercised. Lease facilitator contracts are structured such that the lease facilitator has no net change in diversions when the contracts are exercised. However, in practice, determining a lease facilitator's 'unchanged' diversion rate requires assumptions about in-stream flows in the hypothetical scenario where the leases do not occur. In this analysis, these counterfactual flow rates are calculated using baseline StateMod simulations, which make estimations of natural flow rates based on deterministic assumptions about the return flows of individual users. If the acutal return flow fractions are higher than those assumed within the baseline StateMod simulations, the allowed informal leasing volumes (e.g., increase in lease buyer diversions) will be too high. In turn, the diversion rate calculated for lease facilitators will be lower than the counterfactual, 'no informal leases' diversion. This risk of losses via reduced diversions for lease facilitators can be reflected in lease facilitator option fees.

Because lease buyers are purchasing the right to impose potential losses on lease facilitators by exercising their lease facilitator contracts, a fair contract compensates lease facilitators for this risk with an option fee. The risk to the lease facilitator depends on the expected frequency and magnitude of informal leases. Leases are triggered based on changes to an index, called the Colorado-Big Thompson Water Supply Index (*CBI*), that measures water scarcity for the lease buyer, the Colorado-Big Thompson Project. This water supply index tracks three variables: snowpack in the UCRB, reservoir storage at Lake Granby, and exports through the Adams Tunnel that measure the UCRB water available to the C-BT in a given year. The index can be calculated in each month of the water year to track water supply expectations throughout the year. Water is exported from Lake Granby via the Adams Tunnel, so any deliveries over the course of the year have a net neutral effect on the index (e.g., a delivery would reduce the storage in Lake Granby but increase diversions through the Adams Tunnel, a net effect on the index of zero).

The 'expectations' built into the index, however, are derived from the snowpack variable. Snowpack accumulates over the course of the water year, beginning in October, peaking around April, when it begins to melt until streamflow typically hits a nadir sometime around the end of the water year in September. The magnitude and the timing of runoff, of course, are subject to some variability, but the timing follows some basic seasonal patterns and magnitudes are correlated with the volume of the snowpack. As a result, linear regressions can be built which predict the magnitude of streamflow remaining between any month of the year and the snowpack in that month. Relationships become meaningful around February, and can be used to predict remaining snowmelt for the season (Figure S2). As a result, we can calculate a monthly value of the *CBI* index, using an observation of snowpack, an observation of storage, and the sum total of exports up to that point in the year. As the calculation steps through time, it is able to respond to changing conditions with an estimate of what water supply conditions would have appeared to be at any given moment, from the perspective of a lease seller. Here, we can calculate the value of *CBI* at the beginning of every irrigation season (April/May). If *CBI* is below the threshold at the beginning of the irrigation season, the contract is triggered for the entire year (April – September). *CBI* thresholds must be agreed upon at the outset of the contract, because the thresholds determine how often leases are triggered, which is important for determining a fair price for up-front option payments. The option fee can be estimated as the expected losses from potential lost facilitator diversions, plus some contract 'loading', such that:

$$O_{f,t} = \frac{(1 + LOAD_f)}{n_{sim}} \sum_{y_{sim}=0}^{n_{sim}} LD_{f,y_{sim}} * \left(MNB_f - k_p^*\right) \quad \text{(A1)}$$

where O_f = the option fee for lease facilitator *f* ($); $LOAD_f$ = the contract loading (%); n_{sim} = number of years in informal leasing simulation; LD_f = total potential lost diversions from lease facilitator *f* (m^3); *MNB* = marginal value of water use for facilitator *f*; and k^*_p = buyout price ($/$m^3$)

The Colorado Decision Support System (CDSS) contains agricultural data, updated every five years, that links cropping patterns to diversion nodes within the StateMod river network (CDWR, 2022) such that the type of crop irrigated at each node is known. The marginal value of each crop grown in the basin is estimated using agricultural enterprise budgets (ABM-CSU, 2022) and crop water requirements (Scheekloth and Andales, 2017) developed by the Colorado State University Agricultural Extension, such that:

$$MNB_c = (1 - rf_{s,t}) * \frac{P_c * Y_c - MC_c}{ET_c} \quad \text{(A2)}$$

where *MNB* = marginal value of crop type; ($); *R* = reduction in diversions for lease seller *s* (m^3); *rf* = return flow fraction for diversions made by lease seller *s* (-); *P* = estimated crop price ($/ton); *Y* = estimated crop yield (ton/acre); *MC* = crop marginal cost of production ($/acre); *ET*= crop evapo-transpirative demands (m), and c is an index of crops grown in the UCRB

Marginal value for municipal and industrial right holders are set at $0.73/m³ ($900/acre-foot), and for environmental rights at $0.093/m³ ($115/acre-foot). The marginal value of raw water for municipal and industrial right holders are based on the cost associated with conservation. Water utilities typically generate most of their revenues through volumetric fees, which drop significantly when conservation measures are in place, but their costs, driven by infrastructure maintenance, salaries, debt payments, and other fixed costs are largely independent of the volume of water delivered (Zeff and Characklis, 2013). If we assume that any leased water enables municipal water providers to avoid the same volume of conservation, the annual benefits of agricultural-municipal water reallocation enabled by informal leases can be estimated by comparing the marginal value of the leased water to the lost municipal revenues that would have resulted from conservation. To arrive at a value of $0.73/m³, we use recent data from the City of Boulder (City of Boulder, 2021) that documents the total revenue ($35.7 million) from treated water sales and total operating expenses ($17.8 million, not counting depreciation). We consider only operating expenses, excluding depreciation, because these are volumetric costs (treatment, conveyance, etc.) that will be reduced under conservation. The net operating profits generated by the City of Boulder water utility totaled $16.9 million in 2021, from selling approximately 0.024 km³ (20,000 acre-feet) of water. If we assume conservation measures have a linear impact on both water revenues and operating expenses, every m³ of conservation costs the City of Boulder $0.73 ($900/acre-foot).

Likewise, the marginal value of environmental (minimum flow) water is estimated from data on short-term leases of water across five Colorado River Basin states, Arizona, Colorado, New Mexico, Utah, and Wyoming (Womble et al., 2021). Data shows that between 2014 and 2020, a total of 445 million m³ (360 thousand acre-feet) of water had been acquired for explicitly ecological purposes via short-term leases for a total cost of $42.3 million, an average of $0.093/m³ ($115/acre-foot).

Contract loading for an option contract can be estimated using the Wang Transform, an actuarial method that transforms the weights of a potential payout/loss distribution to generate a 'risk-neutral' payout distribution (Meyer et al., 2016). This transformation is applied using a 'Sharpe ratio', such that:

$$S^*(x) = \phi\left[\phi^{-1}\left(S(x)\right) + \gamma\right] \quad \text{(A3)}$$

where $S^*(x)$ = risk neutral probability distribution; $S(x)$ = original loss distribution; ϕ = cumulative normal distribution ϕ^{-1} = cumulative normal distribution; γ = Sharpe ratio

The Sharpe ratio is a measure of the risk-adjusted returns for financial instruments. Using evidence from other environmental derivative markets, we price informal leases using a Sharpe ratio of 0.25. The contract loading can be calculated from the expected value of the risk-adjusted return distribution, such that:

$$LOAD_s = \frac{E[S^*(x)]}{E[S(x)]} \tag{A4}$$

where $LOAD_s$ = contract loading (%); $E[S(x)]$ = expected payouts of the simulated distribution of price risk losses ($); and $E[S^*(x)]$ = expected payouts of the risk-adjusted distribution price risk losses ($)

Total payments and contract loadings for contracts with individual lease facilitators are shown in Figure S3.

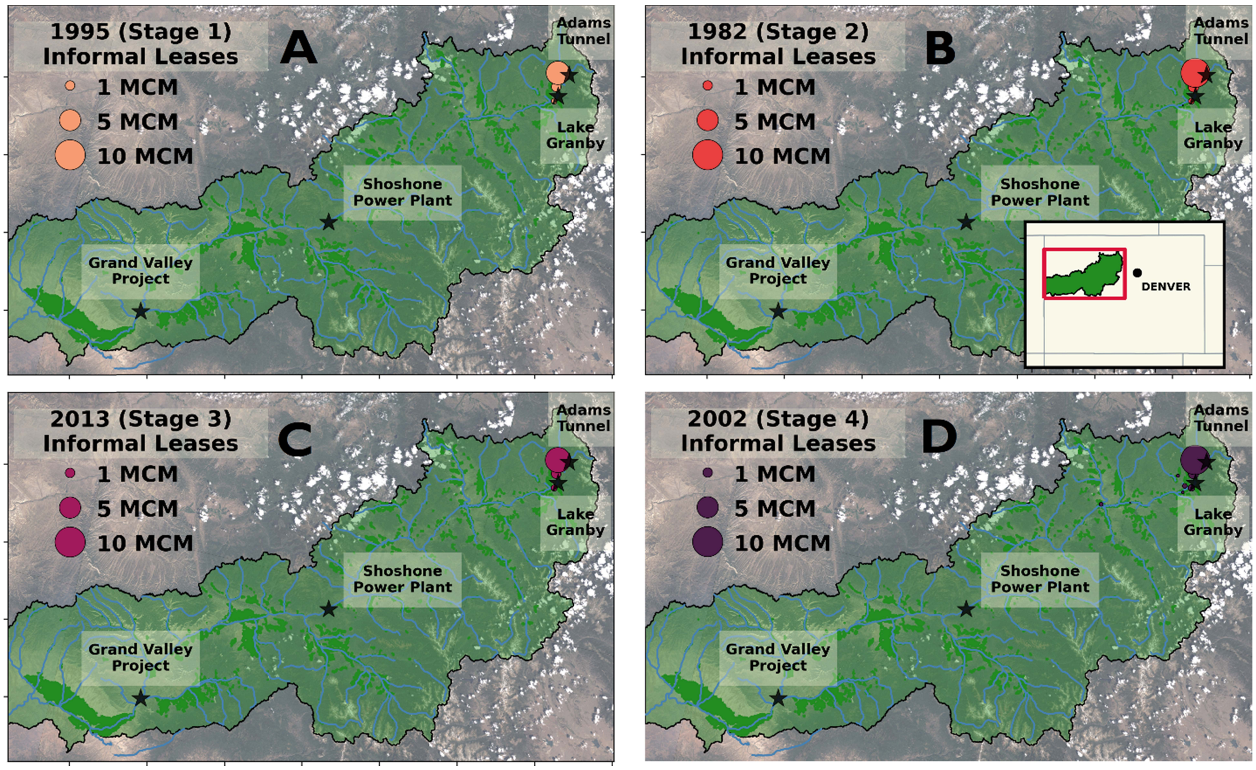


Figure S1: *Location of lease seller right holders for informal leases purchased during one example simulation year from each of the Stage 1 – 4 drought conditions. The size of the marker is equal to the total volume of shortage associated with each facilitator's water right in the sample year. Lease payments are scaled volumetrically based on the volume of the consumptive use of the lease seller, shown here for a Stage 1 drought (A), 1995; a Stage 2 drought (B), 1982; a Stage 3 drought (C), 2013; and a Stage 4 drought (D), 2002.*

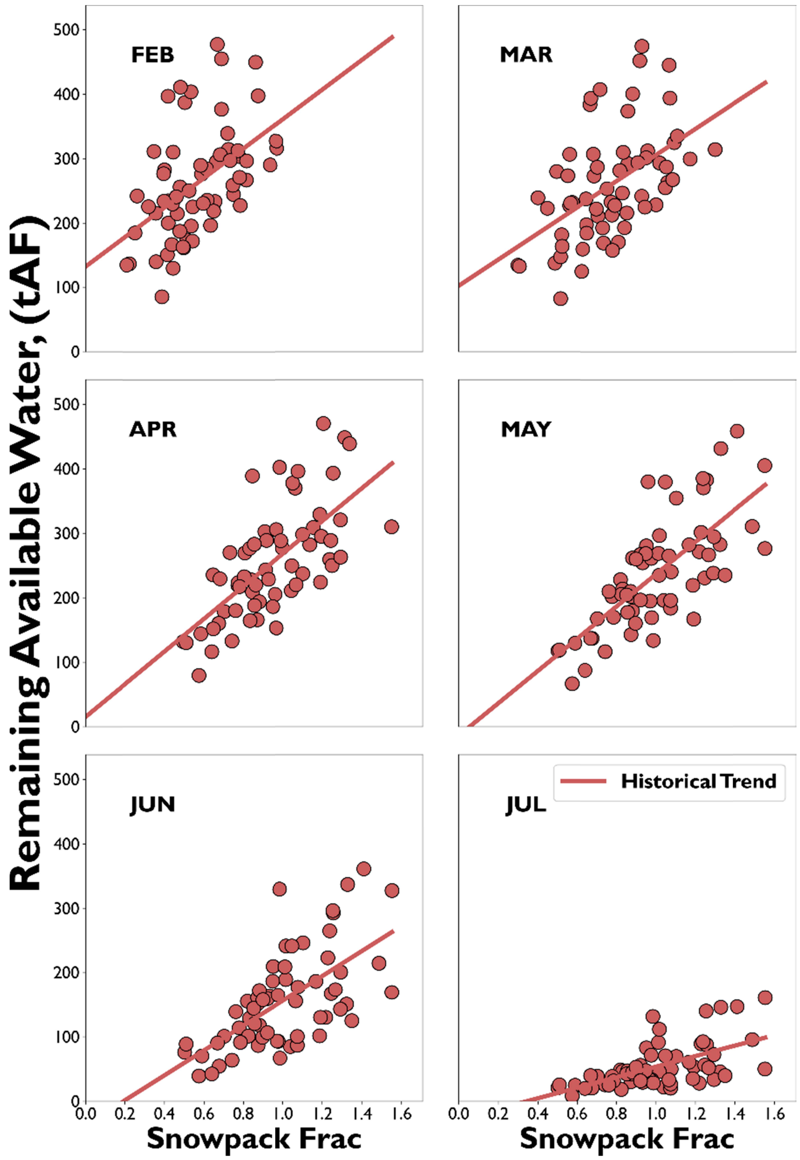


Figure S1: *Relationship between monthly snowpack in the UCRB and the remaining inflow into Lake Granby during the historical simulation period (1950 – 2013). Snowpack values are taken from the USDA's SNOTEL monitoring network and represent the SWE at a number of UCRB locations as a percent of historical average SWE accumulation at those sites.*

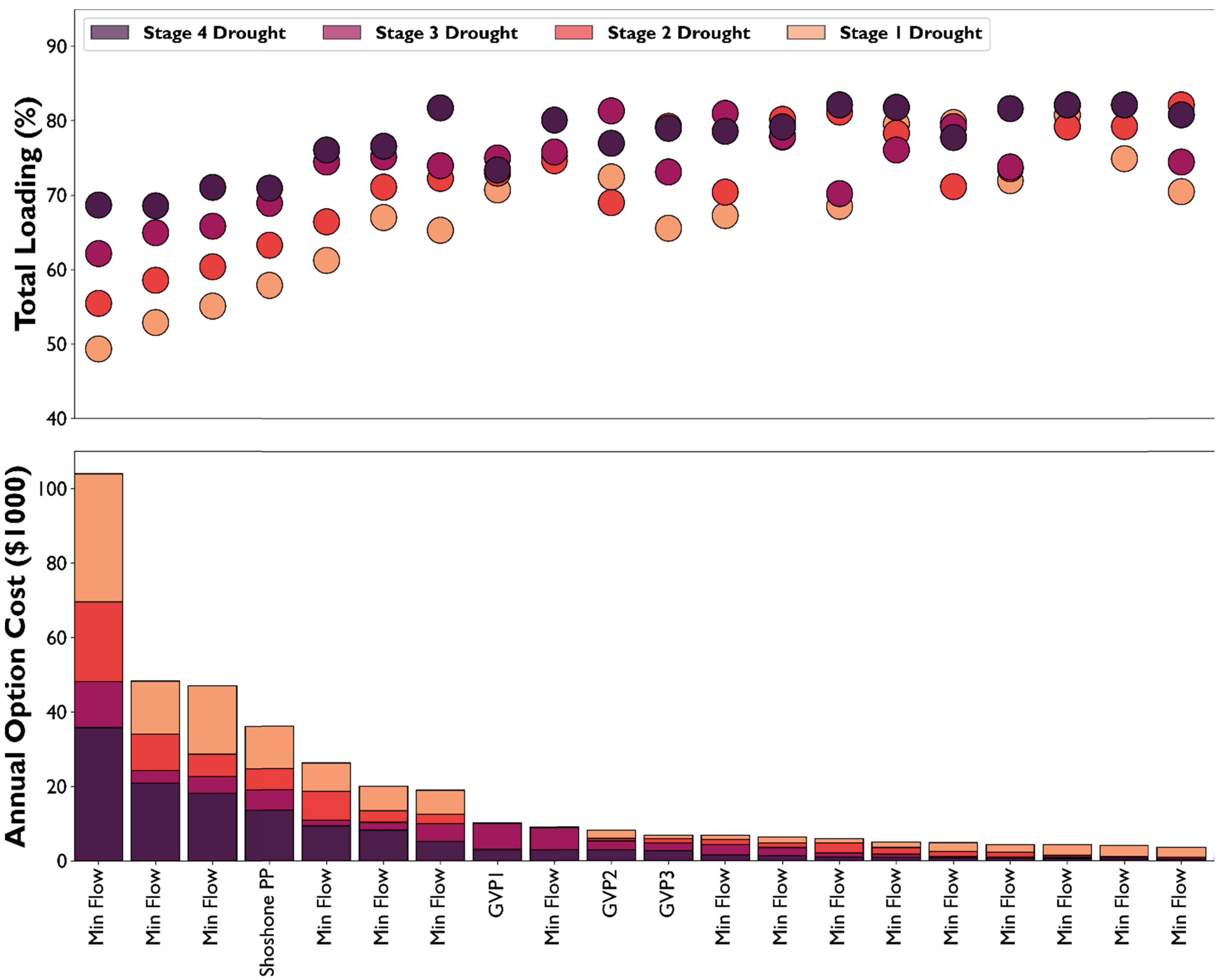


Figure S2: *Loading and total option payments for lease facilitator options with individual right holders. Loading represents the premium paid beyond the expected value of the potential losses due to the option, calculated with the Wang Transform. Option premiums are calculated to compensate for return flow risk for lease facilitators, respectively.*

References

AghaKouchak, A., Feldman, D., Hoerling, M., Huxman, T., and J. Lund (2015). Water and climate: Recognize athropogenic drought. *Nature News* 524: 409.

Agriculture and Business Management – Colorado State University (2022). Enterprise Budgets. Colorado State University Extension, Fort Collins, Colorado. Available at: https://abm.extension.colostate.edu/enterprise-budgets/

Banks, B., and P. Nichols (2015). A roundtable discussion on the no-injury rule of Colorado water law. *The Colorado Lawyer* 44(7), 87-91.

Basta, E. and B.G. Colby (2010). Water market trends: transactions, quantities, and prices. *The Appraisal Journal* 78(1), 50-69.

Benson, R. (2006). Adequate progress, or rivers left behind? Developments in Colorado and Wyoming instream flow laws since 2000. *Environmental Law* 36, 1283.

Bovee, B. (2020). Northern CO needs new water market benchmarks. *Colorado Real Estate Journal*. Available at: https://crej.com/news/northern-co-needs-new-water-market-benchmarks/.

Brewer, J., Glennon, R., Ker, A., and G.D. Libecap (2007). Water markets in the west: prices, trading, and contractual forms. *National Bureau of Economic Research Working Paper*, https://www.nber.org/system/files/working_papers/w13002/w13002.pdf

Brown, T.C. (2006). Trends in water market activity and price in the western United States. *Water Resources Research* 42(9).

Brown, C., and M. Carriquiry (2007). Managing hydroclimatological risk to water supply with option contracts and reservoir index insurance. *Water Resources Research* 43(11).

CADWR (2022). Historically dry conditions impact planned State Water Project deliveries. "Press Release", available at: https://water.ca.gov/News/News-Releases/2022/March-22/SWP-Allocation-March

CAP (2022). Arizona heads into Tier 1 Colorado River shortage for 2022. "Press Release", available at: https://library.cap-az.com/documents/public-information/ADWR-CAP-PressRelease-Arizona_Tier%201_Colorado_River_Shortage_2022-081321.pdf

Cantor, A., Turley, B., Cody Ross, C., and M. Glass (2022). Changes to California alfalfa productions and perceptions during the 2011-2017 drought. *The Professional Geographer,* 1-14.

Carey, J. and D. Sunding (2001). Emerging markets in water: A comparative institutional analysis of the Central Valley and Colorado-Big Thompson Projects. *Natural Resources Journal* 41(2), 283-328.

CDWR (2022a). GIS Data: Division 5 – Colorado. Available at: https://cdss.colorado.gov/gis-data/division-5-colorado

CDWR (2022b). Water Rights. Available at: https://dwr.colorado.gov/services/water-administration/water-rights

Chantarat, S., Mude, A.G., Barrett, C.B., and M.R. Carter (2013). Designing index-based livestock insurance for managing asset risk in northern Kenya. *Journal of Risk and Insurance* 80(1).

Chaudhry, A.M., and D.H.S.K Fairbanks (2022). Distributional implications of supply constraints in water markets. *Journal of Water Resources Planning and Management*. 148(7),

City of Boulder (2021). Annual Comprehensive Financial Report. Available online: https://bouldercolorado.gov/media/9586

Cohen, M., Christian-Smith, J., and J. Bergren (2013). *Water to supply the land*. Pacific Institute, Oakland CA. Available online: https://pacinst.org/wp-content/uploads/2013/05/pacinst-crb-ag.pdf

Colby-Salida, B.G. (1987). Do water markets 'work'? Market transfers and trade-offs in the southwestern states. *Water Resources Research*, 23(7), 1113-1122.

Colorado State University Agriculture and Business Management Extension, 2022. Enterprise Budgets – Crop. Fort Collins, Colorado, available online at: https://abm.extension.colostate.edu/enterprise-budgets-crop

CCGA (Colorado Corn Growers Association), Ducks Unlimited, Aurora Water, and Lower South Platte Water Cooperative (2011). Completion Report: Development of Practical Alternative Agricultural Water Transfer Measures for Preservation of Colorado Irrigated Agriculture. *Prepared by:* Brown and Caldwell, Colorado Water Resources Research Institute, Harvey Economics, and Lawrence Jones Custer Grasmick LLP.

CWCB (2010). Municipal drought management plan guidance document. Colorado Water Conservation Board.

CWCB (2012). Colorado River water availability study phase 1 report: Colorado Water Conservation Board.

CWCB (2019). Renewal of Ute Water Conservancy District Lease of Ruedi Water for Instream Flow Use in the 15-Mile Reach. Memo to Colorado Water Conservation Board Members. Available online: https://dnrweblink.state.co.us/cwcb/0/edoc/209125/17.pdf

CWCB (2022). Proposed Renewal of Ute Water Conservancy District Lease of Ruedi Water for Instream Flow Use in the 15-Mile Reach. Memo to Colorado Water Conservation Board Members. Available online: https://dnrweblink.state.co.us/cwcb/0/edoc/216979/16.pdf

CWCB & CDWR (2016). Upper Colorado River basin water resources planning model user's manual: Colorado Water Conservation Board and Colorado Division of Water Resources. Available at: https://dnrweblink.state.co.us/cwcb/0/edoc/200079/StateMod_Version_15_Documentation.pdf?searchid=0e5e1a87-186a-43a6-ad33-47150c12ec2f

Di Baldassarre, G., Mazzoleni, M., and M. Rusca (2021). The legacy of large dams in the United States. *Ambio* 50, 1798-1808.

Dilling, L., Berggren, J., Henderson, J., and D. Kenney (2019). Savior of rural landscapes or Solomon's choice? Colorado's experiment with alternative transfer methods for water (ATMs). *Water Security*, 6, 100027.

Garrick, D., and B. Aylward (2012). Transaction costs and institutional performance in market-based environmental water allocation. *Land Economics* 88(3), 536-560.

Garrick, D., Whitten, S.M., and A. Coggan (2013). Understanding the evolution and performance of water markets and allocation policy: A transaction costs analysis framework. *Ecological Economics* 88, 195-205.

Garrick, D., De Stefano, L., Yu, W., Jorgensen, I., O'Donnell, E., Turley, L., Aguilar-Barajas, I., Dai, X., de Souza Lea, R., and B. Punjabi (2019). Rural water for thirsty cities: a systematic review of water reallocation from rural to urban regions. *Environmental Research Letters, 14*(4), 043003. https://dx.doi.org/10.1088/1748-9326/ab0db7

Gleick, P.H. (2003). Global freshwater resources: Soft-path solutions for the 21st century. *Science* 302(5650), 1524-1528.

Graf, W.L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research* 35(4), 1305-1311.

Hadjimichael., A., Quinn, J., Wilson, E., Reed, P.M., Basdekas, L., Yates, D., and M. Garrison (2020). Defining robustness, vulnerabilities, and consequential scenarios for diverse stakeholder interests in institutionally complex river basins. *Earths Future* 7.

Hadjimichael, A., Yoon, J., Reed, P.M., Voisin, N., and W. Xu. Exploring the consistency of water scarcity inferences between large-scale hydrologic and node-based water system model representations of the Upper Colorado River Basin. *Journal of Water Resources Planning and Management* 149(2).

Hall, J., Grey, D., Garrick, D., Fung, F., Brown, C., Dadson, S.J., and C.W. Sadoff (2014). Coping with the curse of freshwater variability. *Science* 346(6208), 429-430.

Hamilton, A.L., Characklis, G.W., and P.M. Reed (2020). Managing financial risk trade-offs for hydropower generation using snowpack-based index contracts. *Water Resources Research* 56(10).

Hanak, E. and E. Stryjewski (2012). California's water market, by the numbers, update 2012. Public Policy Institute of California, San Francisco, CA.Howe, C.W., and C. Goemans (2003). Water transfers and their impacts: Lessons from three Colorado water markets. *Journal of the American Water Resources Association*. 39(5), 1055-1065.

Howe, C.W., Schurmeier, D.R., and W.D. Shaw (1986). Innovative approaches to water allocation: the potential for water markets. *Water Resources Research* 22(4), 439-445.

IPCC (2018). Summary for policymakers. In Global warming of 1.5C. An IPCC Special Report on the impact of global warming of 1.5C above pre-industrial levels and related greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. V. Masson-Delmotte, P. Zhai, H.O. Portner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Pean, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield (eds.) *World Meteorological Organization, Geneva, Switzerland,* 32p.

Loomis, J.B., Quattlebaum, K., Brown, T.C., and S.J. Alexander (2003). Expanding institutional arrangements for acquiring water for environmental purposes: transactions evidence for the Western United States. *Water Resources Development* 19(1), 21-28.

Maas, A., Dozier, A., and D.T. Manning (2017). Water storage in a changing environment: The impact of allocation institutions on value. *Water Resources Research* 53, 672-687.

Mahmoudzadeh-Varzi, M., and N. Grigg (2019). Alternative water transfer methods: Review of Colorado experiences. *Journal of Irrigation and Drainage Engineering* 145(7).

Malers, S.A., Ray, R.B., and N.L. Catherine (2001). Colorado's decision support systems: Data-centered water resources planning and administration. *Watershed Management and Operations Management* 2000, 1-9.

McMahon, T.G. and M.G. Smith (2011). The Arkansas Valley Super Ditch: A local response to 'buy and dry' in Colorado water markets. Available at SSRB: http://dx.doi.org/10.2139/ssrn.1922444

Merton, R (1998). Applications of option-pricing theory: twenty-five years later. *The American Economic Review* 88(3), 323-349.

Meyer, E., Characklis, G.W., Brown, C.M., and P. Moody (2016). Hedging the financial risk from water scarcity for Great Lakes shipping. *Water Resources Research* 52(1) 227-245.

National Research Council (2012). *Challenges and opportunities in the hydrologic sciences*. Washington DC: National Academy Press.

Pahl-Wostl, C. (2007). Transitions towards adaptive management of water facing climate and global change. *Water Resources Management* 21(1), 49-62.Pritchett, J., Thorvaldson, J., and M. Frasier (2008). Water as a crop: limited irrigation water leasing in Colorado. *Review of Agricultural Economics* 30(3), 435-444.

Parsons, R., and R. Bennett (2006). Reservoir operations management using a water resources model. *Operating Reservoirs in Changing Conditions*. 304-311.

Richter, B.D., Benoit, K., Dugan, J., Getacho, G., LaRoe, N., Moro, B., Rynne, T., Tahamtani, M., and A. Townsend (2020). Decoupling urban water use and growth in response to water scarcity. *Water* 12(10), 2868.

Rimsaite, R., Fisher-Vanden, K., Olmstead, S., and D.S. Grogan (2021). How Well Do U.S. Western Water Markets Convey Economic Information? *Land Economics, 97*(1), 1-16. https://le.uwpress.org/content/wple/97/1/1.full.pdf

Ruml, C.C. (2005). The Coase Theorem and Western U.S. appropriative water rights. *Natural Resources Journal* 45(1), 169-200.

Schneekloth, J., and A. Andales (2017). Seasonal water needs and opportunities for limited irrigation for Colorado crops. Colorado State University Extension Fact Sheet, 4.718.

Schwabe, K., Nemati, M., Landry, C., and G. Zimmerman (2020). Water markets in the Western United States: Trends and opposrtunities. *Water* 12(233).

Szeptycki, L., Forgie, J., Hook, E., Lorick, K., and P. Womble (2015). Environmental Water Transfers: A Review of State Laws. Stanford, CA: Woods Institute for the Environment.

Taylor, R.G., Young, R.A., and J.R. McKean (1993). Economic impacts of agriculture-to-urban water transfers: A case study of Crowley County, Colorado. Colorado Water Resources Research Institute, Fort Collins, Colorado. Available at: http://hdl.handle.net/10217/1029

Thompson, B.H., Leshy, J.D., and R.H. Abrams (2012). Legal control of water resources: Cases and materials (5th edition). St. Paul, MN, West Publishing Co.

USBR (2022a). 24-Monthly Study Projections. "Press Release", available at: https://www.usbr.gov/lc/region/g4000/riverops/24ms-projections.html

USBR (2022b). Funding Opportunity for Voluntary Participation in the Lower Colorado Conservation and Efficiency Program. available at: https://usbr.gov/infation-reduction-act/docs/LC-Conservation-Program-Letter-with-Enclosures.pdf

USDA-National Agricultural Statistics Service (2019). Quick Stats. United States Department of Agriculture. Washington, D.C. https://quickstats.nass.usda.gov

USDA – Natural Resources Conservation Service (2022). National Water and Climate Center SNOTEL Historic Data. Available at: https://wcc.sc.egov.usda.gov/nwcc/tabget?state=CO

Veldkamp, T.I.E. Wada, Y., Aerts, J.C.J.H., Doll, P., Gosling, S.N., Liu, J., Masaki, Y. and T. Oki (2017). Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. *Nature Communications* 8: 15697.

Vorosmarty, C.J., Green, P., Salisbury, J., and R.B. Lammers (2000). Global water resources: Vulnerability from climate change and population growth. *Science* 289, 284-288.

Water Court Committee, 2022. Non-Attorney's Guidebook to Colorado Water Court. Colorado Supreme Court. Available online: https://www.courts.state.co.us/userfiles/file/Court_Probation/14th_Judicial_District/WaterNon-AttorneysGuidebookToColoradoCourts.pdf

Wiel, S.C (1911). *Water rights in the Western States: The law of prior appropriation of water as applied alone in some jurisdictions, and as, in others, confined to the public domain, with the common law of riparian rights for waters upon private lands: Federal, California, and Oregon statutes in full, with digest of statutes of Alaska, Arizona, Colorado, Hawaii, Idaho, Kansas, Montana, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, Oregon, Philippine Islands, South Dakota, Texas, Utah, Washington, and Wyoming.* Vol 1, Bancroft-Whitney.

Womble, P. and W.M. Hanemann (2020a). Legal change and water market transaction costs in Colorado. *Water Resources Research*. 56, https://doi.org/10.1029/2019WR025508

Womble, P. and W.M. Hanemann (2020b). Water markets, water courts, and transaction costs in Colorado. *Water Resources Research*. 56(4), https://doi.org/10.1029/2019WR0255087

Womble, P., Townsend, A., and L.F. Szeptycki (2022). Decoupling environmental water markets from water law. *Environmental Research Letters* 17(065007).