



RESEARCH ARTICLE

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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

Supporting Information:

Supporting Information may be found in the online version of this article.

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Using Financial Contracts to Facilitate Informal Leases Within a Western United States Water Market Based on Prior Appropriation

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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, 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.

Plain Language Summary In much of the developed world, there is little ability to sustainably manage water resources by building more dams or digging new wells. Water stressed regions are increasingly adapting to droughts through agreements to conserve or reallocate water between members of the community. In some places, markets make this easier by allowing users to buy and sell water. However, in most of the Western U.S., the legal system that approves these transactions makes them very costly and time consuming, reducing the benefits from trade. In particular, it is very hard to buy and sell short-term leases. Here, we propose a new type of leasing contract, “informal leases,” that avoid the legal system by relying on contractual agreements between water users. Instead of buying water via the legal system water users pay other users to conserve, coordinated through simple index contracts. When these contracts are designed correctly, they can perfectly recreate the effect of a formal water sale, for a fraction of the price. In this manuscript, we show how contracts for informal leases can be designed and evaluated, creating savings for water buyers/sellers, additional revenue for their neighbors, and a win/win response to environmental stress (for everyone except the lawyers).

1. Introduction

Unprecedented water scarcity across the American West (CADWR, 2022; CAP, 2022; USBR, 2022a) 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 (AghaKouchak et al., 2015; Veldkamp et al., 2017; Vorosmarty et al., 2000). Additional groundwater development in many water-stressed regions has similarly slowed as concerns over unsustainable pumping have grown

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(Konikow, 2015). The inability of new supply development to keep pace with growing demands has motivated a transition toward “soft-path” water management strategies that emphasize conservation, water-saving technologies, and the reallocation of existing supplies through economic development and markets (Gleick, 2003; Pahl-Wostl et al., 2007). 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 (Brewer et al., 2007; Hall et al., 2014; Howe et al., 1986; Schwabe et al., 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 (Cantor et al., 2022; Cohen et al., 2013). 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 & 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 & Sunding, 2001; Garrick & Aylward, 2012; Garrick et al., 2013; Ruml, 2005), and, in some cases, the risk that water rights could be reduced through new adjudication processes. 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 & 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 (Basta & Colby, 2010; CCGA, 2011; Dilling et al., 2019; 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 in its native water markets (Howitt & Hansen, 2005; Womble & Hanemann, 2020a). 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-Salida, 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 (Chaudhry & Fairbanks, 2022; Maas et al., 2017). Recent research suggests that larger water rights sales typically incur millions of dollars in transaction costs (Womble & Hanemann, 2020b), providing a significant deterrent to reallocation.

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 toward 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., 2022). 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

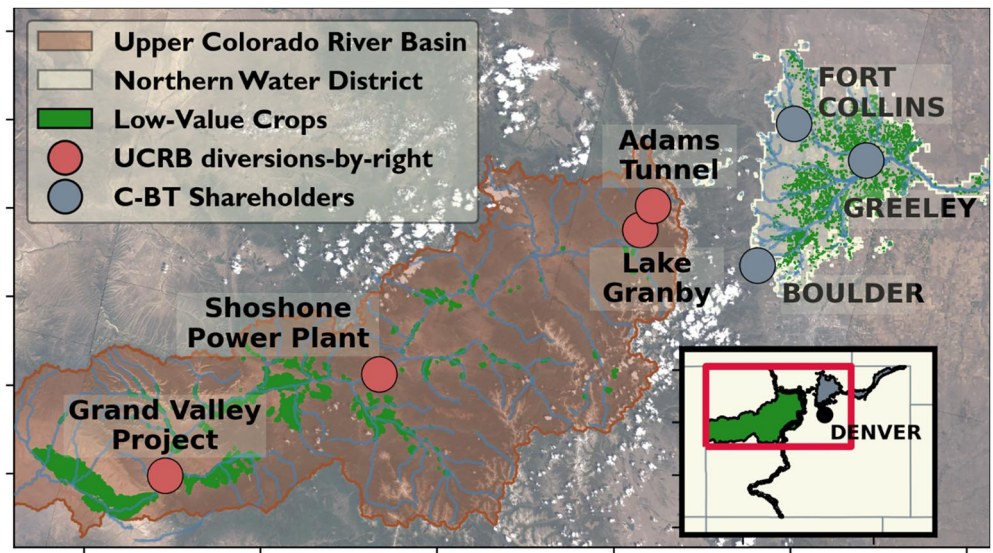


Figure 1. Colorado-Big Thompson (C-BT) project transbasin diversions from the Upper Colorado River Basin (UCRB) to their Front Range service area via the Adams Tunnel and Lake Granby. Showing the location of Lake Granby—Adams Tunnel diversion complex, where the C-BT stores water under its rights within 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 full network map of the UCRB system can be found in the UCRB Water Resources Planning Model User's Manual (CWCB & CDWR, 2009).

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 modeling 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 km² (220,000 acres) of irrigated agriculture, primarily dedicated to relatively

low-value activities such as alfalfa and pasture (hay) irrigation (CDWR, 2022a). 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 & Grigg, 2019; Womble & 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 km³ (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, 2022b). 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, 2022a). 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 m³ (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 m³ (0.5 acre-feet, or roughly 30% below average) (Northern Water, 2022b). 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/m³ (\$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. Evidence suggests that more active leasing markets in Colorado, particularly during dry periods, could relieve some of this pressure on the price of permanent C-BT shares (Rimsaite et al., 2021; Taylor et al., 1993). 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, 2012). The CWCB has historically used StateMod to evaluate the impact of institutional changes to water rights and right holder demands and operations (Parsons & 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 UCRB contains over 800 diversion nodes, 2,000 individual water rights, and the entirety of the basin's 1.8 billion m³ (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 modeling 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 modeling 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. Modeling Informal Leasing Transactions

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. To account for the impact of changing return flows, updated simulations are evaluated one timestep at a time, with results from the previous timestep being used to update steps 2–4 in the next timestep. 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.

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 10 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:

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

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_f); 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

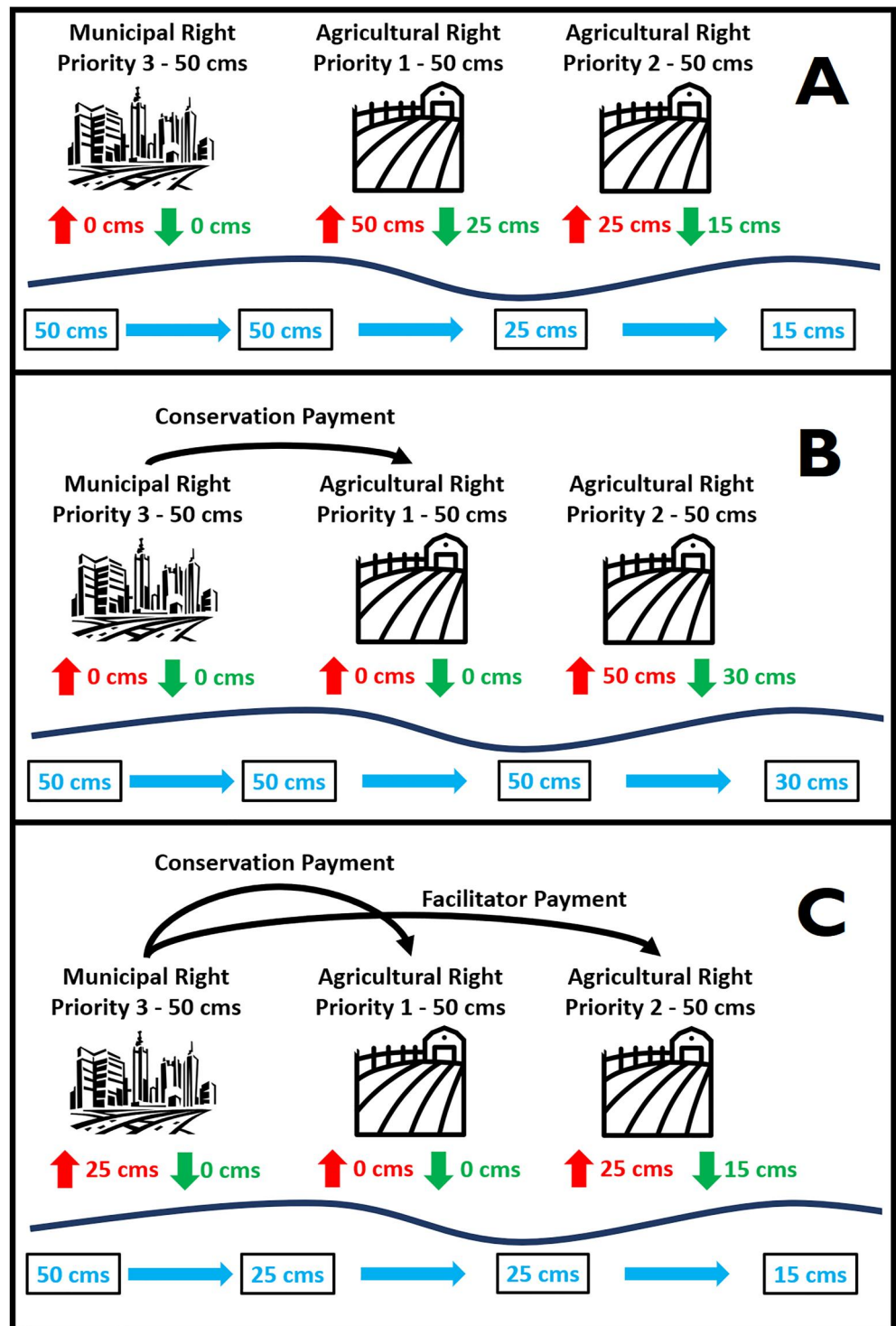


Figure 2. A simple schematic of water reallocation via informal leases, including: (a) a junior, municipal right being “shorted” by a downstream agricultural user with a more senior right. The junior municipal user can (b) pay the senior agricultural right holder to leave the water in-stream, but the 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.

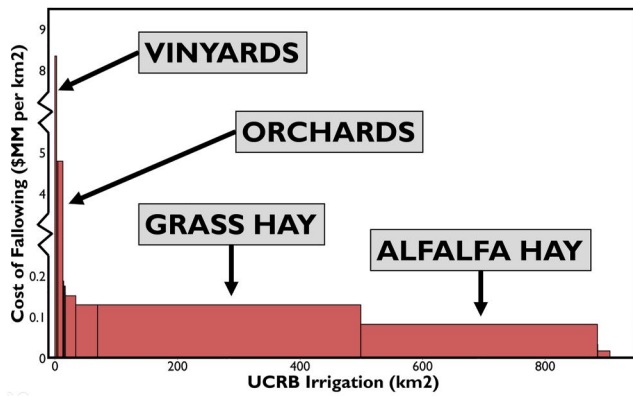


Figure 3. Cost of following as determined from the marginal value of crop production, per km² of consumptive water use, versus total irrigated acreage in the Upper Colorado River Basin.

store up to 0.57 km³ (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 & Carriquiry, 2007; Chantarat et al., 2013; Hamilton et al., 2020; Meyer et al., 2016). 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 (m³); S_t = storage in Lake Granby (m³); sm = remaining snowmelt estimate (m³); and D = year-to-date diversions through the Adams Tunnel.

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. For more information about the calculation of the CBI values, see Text S1 (Figure S1 in Supporting Information S1). Historically, the C-BT has cut annual delivery quotas to conserve their supplies during extreme drought conditions, such as during the 2002–2003 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).

Potential lease sellers are identified at monthly timesteps via simulated values for flow, diversions and storage using the baseline StateMod historical scenario (1950–2013). Water rights holders downstream from the lease buyer (C-BT) can only serve as lease sellers when the exchange does not reduce instream flow below certain limits. For more information on identifying lease sellers, see Text S2 (Figure S2 in Supporting Information S1). 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. 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

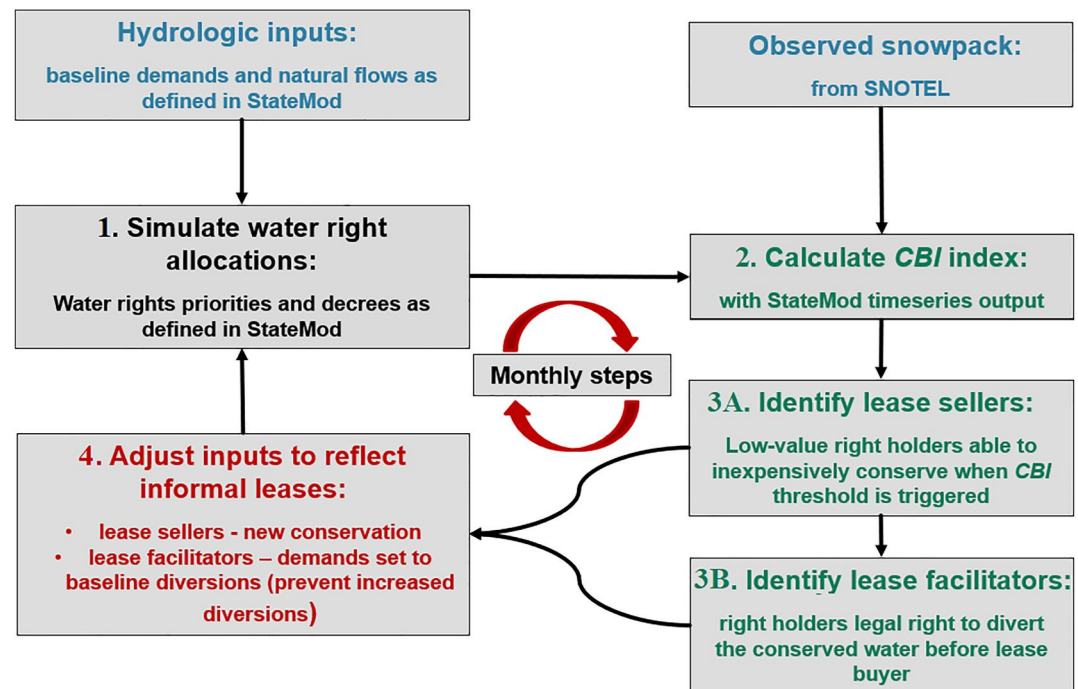


Figure 4. Flowchart representing the steps required to evaluate the potential for informal leases using StateMod.

(C-BT). Any out-of-priority right holder who has more seniority than the C-BT and is physically able to divert additional water acts as a lease facilitator. For more information on identifying lease facilitators, see Text S2 in Supporting Information S1.

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:

$$D_{s,t}^* = DIV_{s,t} - R_{s,t} \quad (5)$$

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:

$$D_{f,t}^* = DIV_{f,t} \quad (6)$$

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

Equations 5 and 6 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

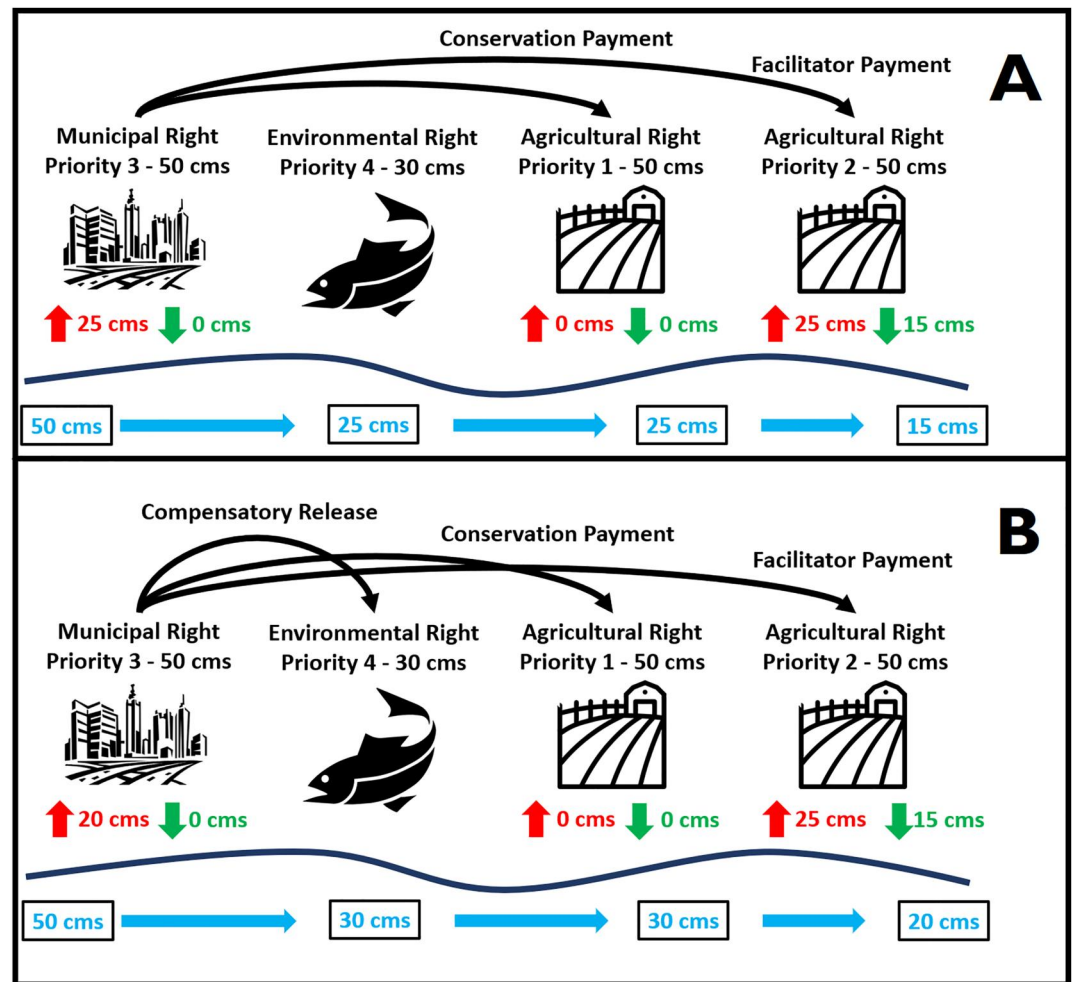


Figure 5. A more complex schematic of water reallocation via informal leases with a junior environmental right located between the informal lease buyer and the informal lease seller. After the conservation and facilitator payments are made (a), flow in the reach covered by the right decreases, causing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

throughout the basin, impacting the informal leasing water balance calculations in Equations 5 and 6. 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” (Banks & Nichols, 2015; Thompson et al., 2012) 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:

$$MC_{r,t} = DIV_{r,t} - DIV_{r,t}^* - R_{r,t} \quad (7)$$

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 Equation 7. 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:

$$CR_t = \max_r \left[MC_{r,t} + \sum_{n=upstream} MC_{n,t} * cf_n \right] \quad (8)$$

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 modeling. 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 modeling 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. Contracts specify what portion of the overall informal lease must be released downstream by the buyer as compensation for any potential injury because of return flows. As part of this analysis, we estimate the sensitivity of each water right holder in the basin to potential uncertainty in the specified compensatory release, and calculate a proportional up-front option payment to compensate for that potential risk. For more information on the calculation of up-front option payments, see Text S3 in Supporting Information S1. 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 (Figure S3 in Supporting Information S1).

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.

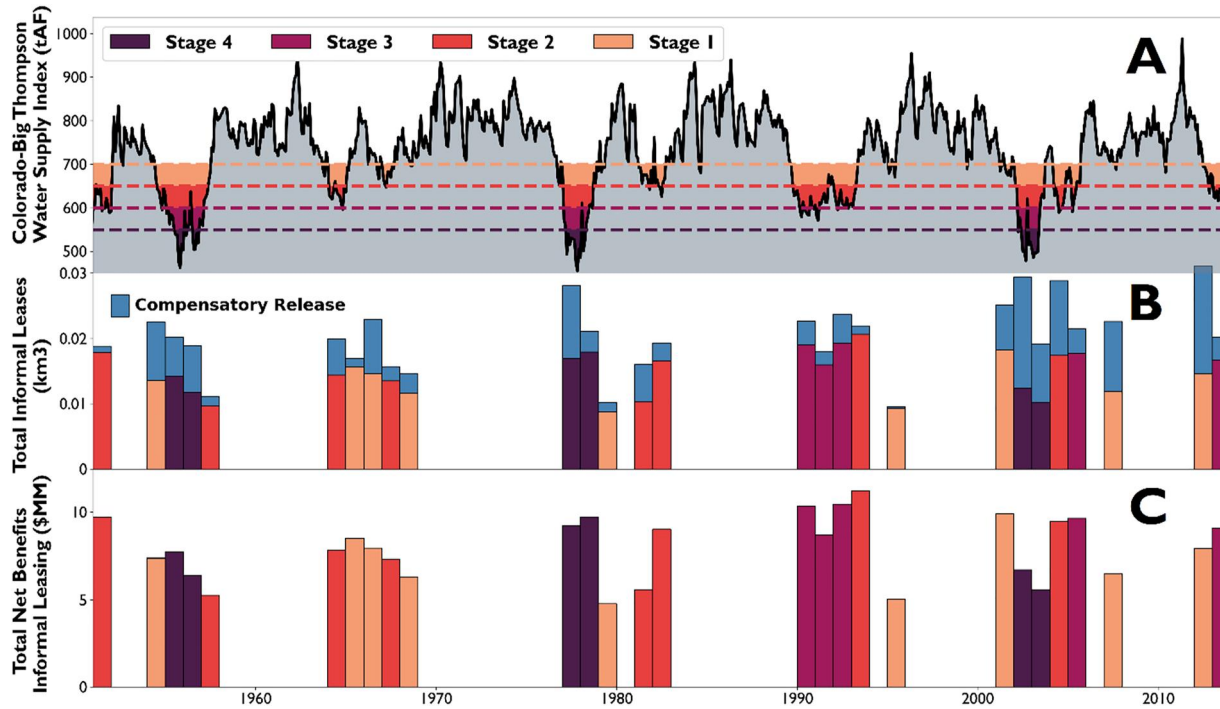


Figure 6. C-BT water supply index (CBI) calculated at a monthly timestep over the historical simulation period, 1950–2013, with four thresholds used to distinguish the stages of drought in which leases are purchased (a), the total informal leases delivered in each of those years, accounting for compensatory 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).

The informal lease sellers irrigate 33.0 km² (8,152 acres) of low-value crops with these water rights. Grass hay comprises 32.2 km² (7,959 acres) of the irrigated area and 0.8 km² (192 acres) acres are used for alfalfa. The 33.0 km² (8,152 acres) of irrigated land has a consumptive water demand of 0.021 km³ (17 thousand acre-feet) per 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 2002–2003 drought (Northern Water, 2022b.), translates to 0.053 km³ (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 km³ (700 thousand acre-feet), Stage 2 corresponds to a CBI threshold of 0.8 km³ (650 thousand acre-feet), Stage 3, 0.74 km³ (600 thousand acre-feet), and Stage 4 to 0.68 km³ (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 km³) 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 m³ (10 and 30 thousand acre-feet) and compensatory releases vary significantly with hydrologic conditions from year to year. After accounting for

Table 1
Informal Leasing Scenarios, With Corresponding Trigger Thresholds for the Colorado-Big Thompson Water Supply Index (CBI) 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 (\$M)
Stage 1	0.86	43	222
Stage 2	0.8	30	158
Stage 3	0.74	17	93
Stage 4	0.68	9	45

compensatory releases, leases totaled between 12.3 and 18.5 million m³ (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 (Colorado State University Agriculture and Business Management Extension, CSU, 2022; Schneekloth & Andales, 2017), we estimate the marginal value of irrigating grass hay in the UCRB at \$0.19/m³ (\$231/acre-feet) and of irrigating alfalfa at \$0.133/m³ (\$164/acre-feet). Considering the most recent purchase prices for a permanent share of the C-BT have been close to \$70/m³ (or \$4.5/m³ 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 km³ (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%–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/m³, equal to municipal lost revenue from conservation) to the marginal value of irrigation on the part of lease sellers (\$0.18/m³ for grass hay irrigators and \$0.133/m³ 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/m³. When informal leases are purchased only during Stage 4 drought, this translates into \$45 million in total reallocation benefits over the entire simulation period, 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 (Womble & Hanemann, 2020b).

This process can be illustrated by observing the spatial dynamics of lease facilitators through increasingly severe droughts (Figure 7). Informal leases

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

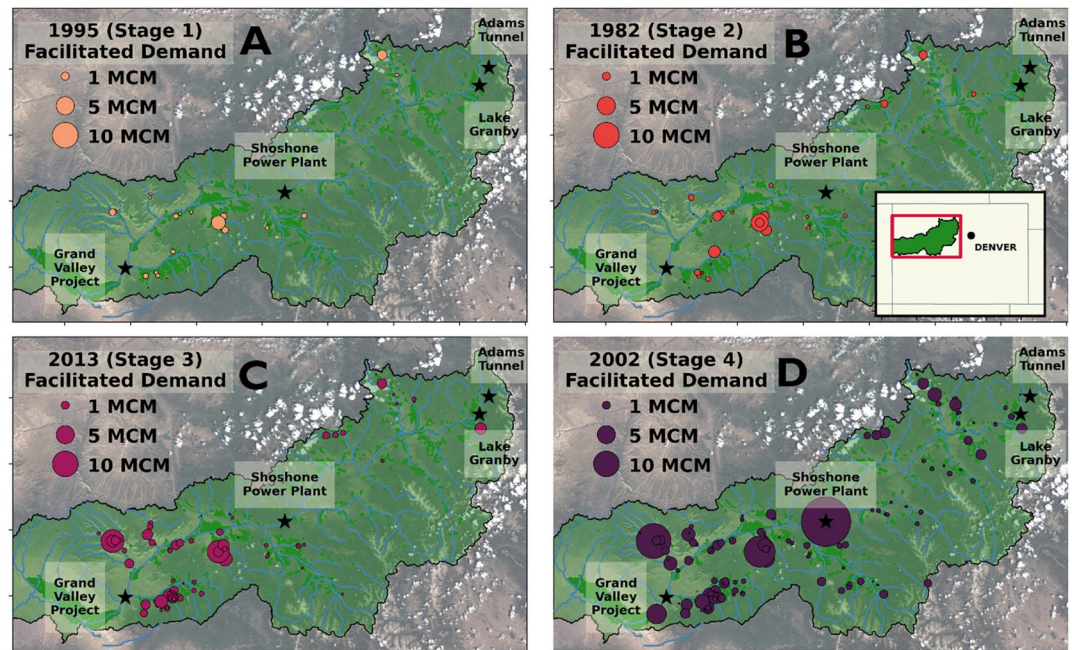


Figure 7. The spatial distribution of lease facilitators for informal leases purchased during one example simulation year from each of the Stage 1–4 drought conditions, in MCM (million m^3). The size of the marker is equal to the total volume of shortage associated with each facilitator's water right 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.

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 toward 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

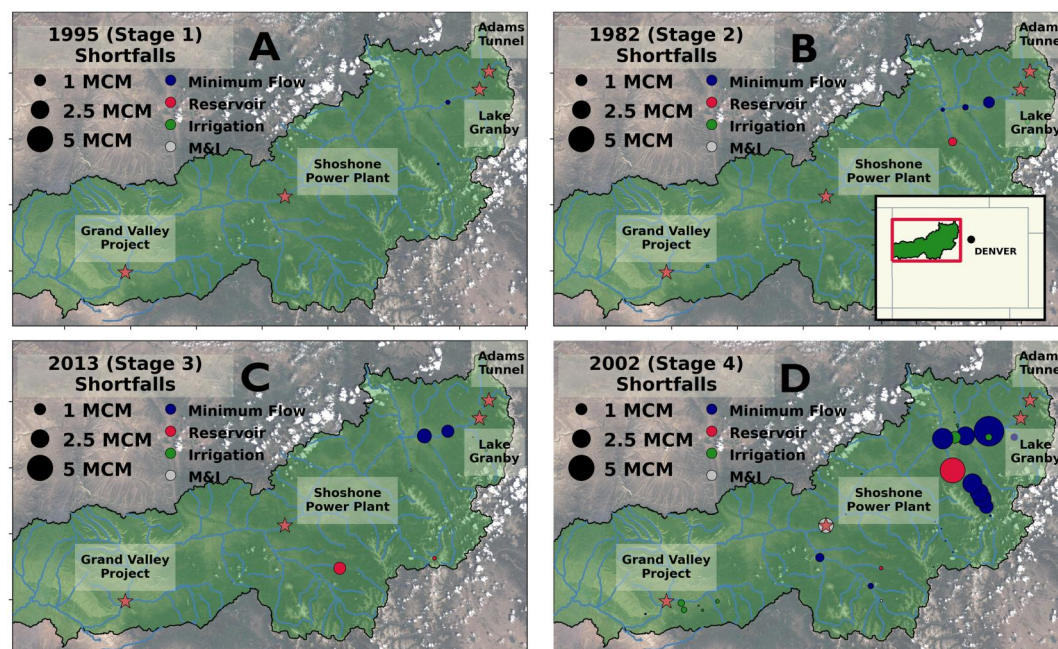


Figure 8. The spatial distribution of potential shortfalls resulting from informal leases purchased during one example simulation year from each of the Stage 1–4 drought conditions. Compensatory releases are needed to address these shortfalls. The size of the marker is equal to the total volume of additional shortfalls experienced by a Upper Colorado River Basin 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.

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). Irrigation methods that generate relatively large proportions of return flows, 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

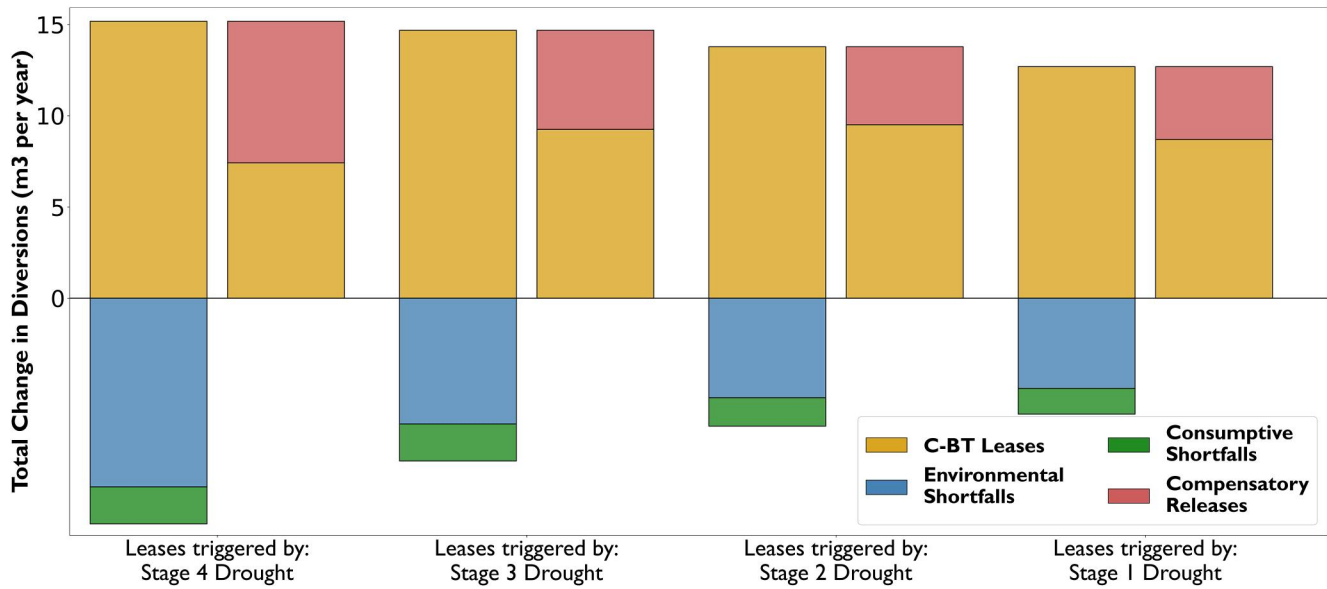


Figure 9. Total leased volumes and aggregate impact to third-party right holders (both environmental and other consumptive uses). The left column in each pair shows total leased water on the positive axis and the impacts caused to consumptive and environmental uses for each informal leasing scenario. The right column show the portion of the leased water which must be devoted to “compensatory releases” eliminating the downstream impacts to consumptive and environmental right holders. Values are aggregate leases across all 64 simulation years in each informal leasing scenario.

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. Lake Granby and other reservoirs in the UCRB have junior rights that can be prevented from filling by more senior rights, but they cannot be forced to release previously stored water. Changes to the timing of return flows can therefore cause shortages even for senior right holders in later timesteps. 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.

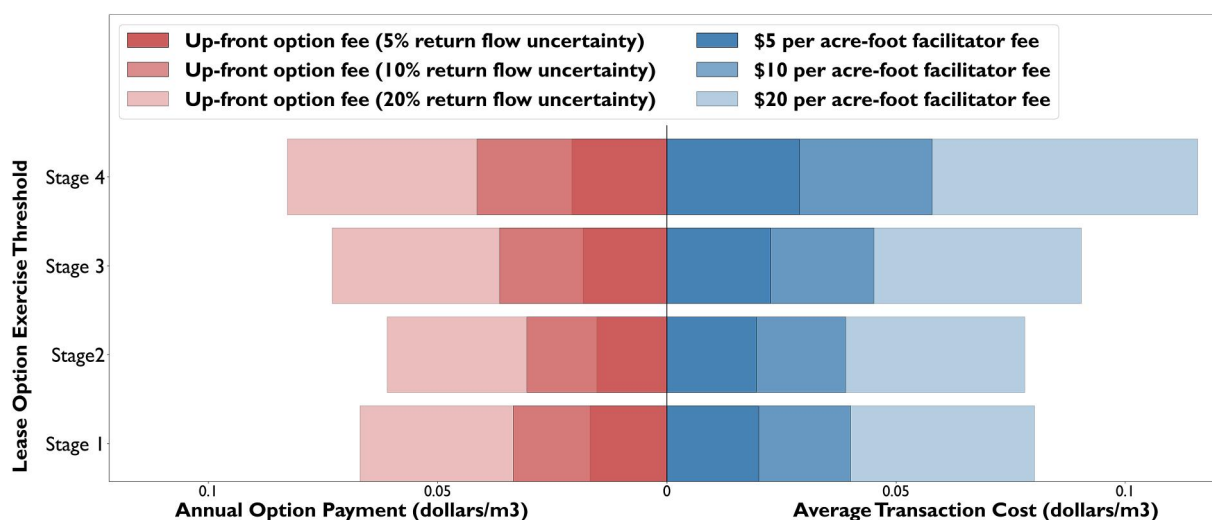


Figure 10. Average transaction costs for informal leases in each leasing scenario. Transaction costs have two components: annual, up-front option payments (in red), overall payments per m^3 of informal leases purchased during the simulation (after accounting for consumptive releases), and exercise fees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

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 $\$0.004\text{--}0.016/m^3$ ($\$5\text{--}20/acre-foot$). 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 (Dilling et al., 2019; Womble & Hanemann, 2020b).

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 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/m³ and \$0.035/m³ (\$46/acre-foot and \$43/acre-foot), respectively. There is a slight decrease in the costs per leased acre when moving from the Stage 1 to Stage 2 scenario because a larger portion of the leased water in the Stage 1 scenario must be released as compensatory releases, driving up the average volumetric cost of the remaining leased water. In the Stage 3 and 4 scenarios, however, average lease costs go up because more facilitators need to be paid. When lease purchases are restricted to only include Stage 3 and above drought conditions, the average transaction costs increase to \$0.041/m³ (\$49/acre-foot). When leases are only purchased during the driest (Stage 4) drought conditions, the average transaction costs increase further to \$0.049/m³ (\$60/acre-foot). If lease facilitators and third parties demand higher price levels as a condition 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/m³ (\$215/acre-foot) during Stage 4 drought conditions, \$0.16/m³ (\$196/acre-foot) when leases are triggered by Stage 3 conditions, and \$0.137/m³ and \$0.142/m³, (\$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/m³–\$0.29/m³ (\$200–\$360/acre-foot) (Dilling et al., 2019; Womble & Hanemann, 2020b).

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 (Table 3). 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/m³–\$0.29/m³ (\$200–\$360/acre-foot) is paid to non-basin participants, including lawyers, technical experts, and court fees (Womble & Hanemann, 2020b). 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.

4. 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. Additionally, much of the analysis here revolves around using StateMod to identify individual water right holders who could likely serve as lease facilitators and lease sellers, and estimate how frequently contracts would be exercised. The group of right holders who fall into each of these groups, and the frequency they engage in informal transfer is dependent on hydrologic conditions. The analysis here represents a relatively limited (1950–2013) set of streamflow conditions, and evaluating the system under a wider range of conditions could identify other right holders who could participate, how much water could be leased, or even change some of the estimates of contract cost. However, even under this more limited set of conditions, this analysis identifies characteristics of informal leases that could be beneficial to the region.

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 toward 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 toward 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 toward 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 km³ (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 toward 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.

5. 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 toward 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 toward a future in which droughts are more common and extreme in the Western United States. Reallocation of supplies from low-value agriculture toward 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.

Data Availability Statement

All data and code for this project, including figure generation, are licensed under MIT and available in a live repository (http://github.com/hbz5000/Adaptive_UCRB) and at a permanent link on Zenodo (<https://zenodo.org/doi/10.5281/zenodo.10627810>) (Zeff, 2024).

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