# Two-Way Option Contracts that Facilitate Adaptive Water Reallocation in the Western United States

**Zachary M. Hirsch[1,2], Harrison B. Zeff [1,2], Rohini S. Gupta[3], Chris R. Vernon[4], Patrick M. Reed[3], and Gregory W. Characklis[1,2]**

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

[2] 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

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

[4] Pacific Northwest National Laboratory, Richland, WA, USA 99354

Corresponding author: Zachary Hirsch (zacharyhirsch1@yahoo.com)

**Key Points:**

- Cities manage drought by buying permanent water rights well in excess of average demands as transaction costs deter short-term leasing
- Two-way options facilitate rapid transfers from agricultural-to-urban uses during drought and in the reverse direction during wet periods
- Urban users can maintain high reliability with reduced holdings of expensive permanent rights, while irrigators see gains during wet years

**Abstract**

Many water markets in the Western United States (U.S.) have the ability to reallocate water temporarily during drought, often as short-term water rights leases from lower value irrigated activities to higher value urban uses. Regulatory approval of water transfers, however, typically takes time and involves high transaction costs that arise from technical and legal analyses, discouraging short-term leasing. This leads municipalities to protect against drought-related shortfalls by purchasing large volumes of infrequently used permanent water rights. High transaction costs also result in municipal water rights rarely being leased back to irrigators in wet or normal years, reducing agricultural productivity. This research explores the development of a multi-year two-way option (TWO) contract that facilitates leasing from agricultural-to-urban users during drought and leasing from urban-to agricultural users during wet periods. The modeling framework developed to assess performance of the TWO contracts includes consideration of the hydrologic, engineered, and institutional systems governing the South Platte River Basin in Colorado where there is growing competition for water between municipalities (e.g., the city of Boulder) and irrigators. The modeling framework is built around StateMod, a network-based water allocation model used by state regulators to evaluate water rights allocations and potential rights transfers. Results suggest that the TWO contracts could allow municipalities to maintain supply reliability with significantly reduced rights holdings at lower cost, while increasing agricultural productivity in wet and normal years. Additionally, the TWO contracts provide irrigators with additional revenues via net payments of option fees from municipalities.

**Plain Language Summary**

The inability to quickly and inexpensively reallocate water during drought has pushed municipalities to purchase many more permanent water rights than needed to meet their demands in an average year. Leasing these rights back to agriculture during non-drought years is similarly slow and expensive, so it is uncommon, thus reducing agricultural productivity. States in the Western U.S., including Colorado, have begun to pass laws to make short-term water transfers less costly and time consuming, although few new transfer mechanisms have yet been developed to take advantage of these laws.

This research describes a ‘two-way option’ that coordinates temporary transfers of water rights and corresponding payments between agricultural and urban users, with the direction and timing of transfer dependent on hydrologic conditions (defined by an index as wet or dry). The study uses a detailed water allocation model that considers hydrology, infrastructure, and institutional water rights in testing the effectiveness of these option contracts within the Northern Colorado Water Conservancy District. Results suggest that the two-way option can provide municipal users substantial cost savings while still maintaining high reliability during droughts, while agricultural users benefit from payments from urban users and higher levels of productivity in wet and normal years.

## 1. Introduction

More frequent and severe droughts coupled with increased economic development, population growth, and growing uncertainty over climate change have created more complex water supply management challenges in the western United States (U.S.) (American Water Works Association, 2021; The Water Research Foundation, 2020; The World Bank, 2010; US EPA, 2021; WUCA, 2021). Urban water demands have increasingly reached or exceeded the capacity of local water supplies (Deason et al., 2001; FAO, 2012; Siirila-Woodburn et al., 2021), while at the same time, new sources have become more scarce, more expensive to develop, and more difficult to permit regulatorily (Hansen, 2017; Tidwell et al., 2014). As such, western water utilities have been driven to become less reliant on new infrastructure to meet increases in water demand and have begun to focus more on conservation and their ability to acquire water from other users, usually agricultural. This occurs via various re-allocative mechanisms (Colorado Water Conservation Board, 2020), often involving market-based water rights transfers (Brookshire et al., 2004; Gleick, 2000; Howe et al., 1990; Leonard et al., 2019).

Western water markets operate within the prior appropriation doctrine (Burness & Quirk, 1980), which in times of drought, leads to more senior rights holders (i.e., those with the oldest rights) having priority access to available water, while more junior rights holders often receive little or no water in dry periods (i.e., their rights are "curtailed"). By virtue of historical development patterns, irrigators often hold more senior rights (Dilling et al., 2019), while many municipalities hold more junior rights. As urban demands continue to grow, this disparity in seniority as well as differences in the value of water in urban and agricultural uses, drives activity in water markets. At present, water market transactions take the form of either permanent right transfers, or temporary leases, usually with water moving from agricultural to urban uses (Brewer et al., 2008; Carey & Sunding, 2001; Payne et al., 2014). The state of Colorado has the second most active market for permanent water rights of any state in the U.S., as measured by the value of transactions ($79 million in 2015) (Womble & Hanemann, 2020b). Activity in Colorado's water markets is largely influenced by growing urban demands, particularly along the Front Range which includes Denver and surrounding communities (WestWater Research, 2016). Given that the state's surface water resources are fully allocated (Shupe et al., 1989; Womble, 2020), any group seeking to acquire rights to surface water, the primary source for most urban areas, must do so by purchasing existing rights. Water rights purchases from irrigators have often been the lowest cost alternative when a community is seeking additional supplies (Carey & Sunding, 2001; Easter et al., 1999; Howe et al., 1990; Leonard et al., 2019; Schwabe et al., 2020) making it likely that the market for transfers of permanent rights will continue to be very active (Christensen et al., 2004).

In order to ensure high levels of supply reliability in the face of both drought and future demand growth, Front Range municipalities, like many others across the Western U.S., have purchased a substantial volume of senior water rights from irrigators over time (Nichols et al., 2016; Payne et al., 2014). This shift in water right ownership has been in process for many years and has allowed municipalities to increase their supply in a manner commensurate with demand growth. During drought, however, the yield of a water right can decline, such that 1233 $m^3$ (one acre-foot) of rights is allocated less than 1233 $m^3$ (one acre-foot) of "wet" water (or sometimes none at all), so maintaining urban supply reliability during dry periods has typically been achieved through cities holding significantly more water rights then are required to meet demand under normal or wet conditions (Frick et al., 1990; Shupe et al., 1989). As an alternative, urban areas could maintain smaller volumes of permanent rights and supplement supplies to meet demands during drought via short-term water leases, which are also allowed in Western U.S. markets. The regulatory approval process for leases is, however, often lengthy and expensive making them less useful and/or practical for managing short-term drought (Womble & Hanemann, 2020b). Thus, municipalities typically maintain large volumes of infrequently used, but expensive, permanent water rights in order to manage drought risk, which reduces shortfalls in all but the driest years, but leaves them with substantial volumes of surplus water most of the time. This contrasts with the situation faced by irrigators, who have been transferring permanent rights to municipalities for many years and often experience significant collective shortages during drought. These historical transfers out of agriculture have also left considerable acreages of arable land that could be made more productive via irrigation in wet and normal years (Malek et al., 2020). As a result, relative to the volume of water they could put to productive use, irrigators experience some level of water supply shortage in almost all years, leading to decreased agricultural production and decreased regional economic productivity (D. H. Smith et al., 1996). Having municipalities lease back some of their surplus water back to irrigators in normal and/or wet years could increase agricultural productivity, but once again, the time and costs associated with approving short-term transfers acts as a deterrent.

Historically, water transfers in Colorado have largely taken the form of permanent rights transfers (Howe & Goemans, 2003), with municipal buyers tolerating the lengthy and expensive regulatory approval process, at least in part because they are not responding to long-term demand growth trends and because the additional costs are somewhat diluted by the size of the transactions (Womble & Hanemann, 2020b). Approval processing times for a single permanent transfer can range between 22 and 42 months, making this an impractical means of managing drought. In addition, the transaction costs associated with technical and legal consulting often exceed 100% of the water rights sales price (Colby, 1990; Womble & Hanemann, 2020b). Similar processing times occur with temporary water leases, and transaction costs can be even larger as a fraction of lease prices (Womble & Hanemann, 2020a), discouraging their use in facilitating rapid reallocation during drought (Howe, 2015). It is therefore unsurprising that municipalities in the Western U.S. overall maintain volumes of water rights well in excess of average demand in order to ensure reliable supplies (Levine, 2007). For example, the

Metropolitan Water District of Southern California (MWD) holds 3.82 $km^3$ (3.1 million acre-feet) of water rights to meet average annual demand of 1.85 $km^3$ (1.5 million acre-feet) (Metropolitan Water District of Southern California, 2021). Similarly, communities along Colorado's Front Range (e.g., Boulder, Loveland, Longmont, Louisville, and Lafayette) currently hold 0.22 $km^3$ (177,000 acre-feet) of rights to meet an average demand of 0.07 $km^3$ (57,800 acre-feet) (Colorado Division of Water Resources, 2023a). It is also worth noting that despite maintaining very large rights surpluses during most years, urban utilities rarely lease water back to irrigators even during wet years (MacDonnell et al., 1990; Pritchett et al., 2008), with the transaction costs identified as contributing to this lack of market activity (Easter et al., 1999; Gardner & Miller, 1982; Leonard et al., 2019).

Recently, the state of Colorado, revised its temporary transfer rules, such that long-term, multi-year leasing agreements need only be approved once as opposed to each time a transfer is made, a change that could significantly reduce the transaction costs of leasing and increase the speed of re-allocation, making leases more attractive as a drought management tool (Justia US Law, 2022; Womble & Hanemann, 2020a). Nonetheless, there has yet to be any detailed analysis of how these new rules might translate into improved transfer agreement structures that would make leasing a more cost-effective reallocation mechanism (McLane & Dingess, 2013). While leasing agreements have often represented an attempt to provide the water market with more flexibility, they have typically been thought of in terms of a single year, one-way transfer, most often from irrigators to municipalities, but occasionally in the opposite direction (Brewer et al., 2008; Michelsen, 1994). This research seeks to explore the potential for a 'two-way option' that facilitates the temporary transfer of water in both directions using predetermined triggers based on hydrologic conditions (dry or wet) that are defined by a 'water availability' index. The option structure is defined such that constant payments (i.e., option fees) flow from buyer-to-seller each year, with a larger "exercise" fee paid when the water is actually transferred. By providing a multi-year contract structure that is well-defined and has received regulatory approval in advance of drought, this tool has the potential to assist both municipalities and irrigators in managing drought more cost-effectively. The two-way option (TWO) is tested in the Northern Colorado Water Conservancy District (Northern Water) that lies within the South Platte River Basin in Colorado, and which includes several urban centers (e.g., Boulder, Longmont), as well as over 4047 $km^2$ (1 million acres) of irrigated agriculture. The region's fully allocated surface water supply, rising urban demands, increasing water rights prices (stemming from increased intersectoral competition), and data availability make it ideal for investigating the performance of a new transfer instrument. The modeling framework developed to assess the performance of the proposed TWO contract structure includes consideration of the hydrologic, engineered, and institutional systems that govern water allocation in the region. The model adapts historical data (e.g., demands, transbasin flows, operations, and water rights) for input into the state of Colorado's basin-specific water allocation model (StateMod) in order to assess water supply and demand conditions at individual irrigation diversion structures. The combination of supply/demand conditions and the value of irrigation water at each irrigation diversion structure allows for a detailed market simulation of lease prices across the historic hydrologic record that is then used to price the TWO contracts. The proposed TWO contracts offer the potential to reduce the surplus volumes of water rights municipalities must maintain as a hedge against drought, ultimately making more water available to agriculture in non-drought years. Results should provide useful information for municipalities and irrigators operating within prior-appropriative institutions in the Western U.S., providing them with new insights into how they might facilitate more responsive and less expensive water reallocation.

## 2 Methods

Maintaining reliable water supplies across the Western U.S. in the face of varying hydrologic conditions and population growth has become increasingly difficult (Hadjimichael et al., 2020; Kasprzyk et al., 2009; Marston et al., 2020; Overpeck & Udall, 2020; R. Smith et al., 2022). This is particularly true for municipalities as they often have relatively junior water rights that are assigned a lower priority in the prior appropriation system and have needed to expand their water rights holdings to meet increased demands, particularly in the driest years (Levine, 2007; Nichols et al., 2016). Therefore, municipalities often purchase more senior water rights from irrigators. Given that the volume of water actually allocated to a right varies with hydrologic conditions (dry = less water delivered), municipalities typically purchase significantly more rights than required to meet their average demands in order to meet demand during drought. Despite continued population growth, these acquisitions have slowed since the early 2000's (Figure 1), largely a result of declining per capita urban usage (Meyer, 2010). Nonetheless, many municipalities continue to maintain many more rights than are used in a typical year, which often results in less water being available for agriculture (Conran, 2013). A primary motivation for the municipal approach is managing drought, as acquiring additional supplies on relatively short notice given current institutions is very difficult. This problem could be mitigated if short-term leases were less expensive and/or quicker to gain regulatory approval, thereby reducing municipalities need to hold large volumes of infrequently used rights. Similarly, reductions in agricultural production might be mitigated in wetter, or even normal, years if municipalities leased surplus water back for agricultural use in these years, but the combination of transaction costs and low willingness-to-pay on the part of irrigators means such transfers are relatively uncommon (Shupe et al., 1989). While the transfer of water rights (either permanently or via lease) from irrigators to municipalities, especially as a means of mitigating drought has received significant attention in the literature (Burns et al., 2022; Characklis et al., 1999, 2006; Colby, 1988; Howe & Goemans, 2003; Kirsch et al., 2009; MacDonnell et al., 1990; Marston & Cai, 2016; McLane & Dingess, 2013; Pritchett et al., 2008), approaches involving transferring water in the opposite direction, from municipalities to irrigators during wet/normal years, has received much less attention (Colorado Water Conservation Board, 2020).

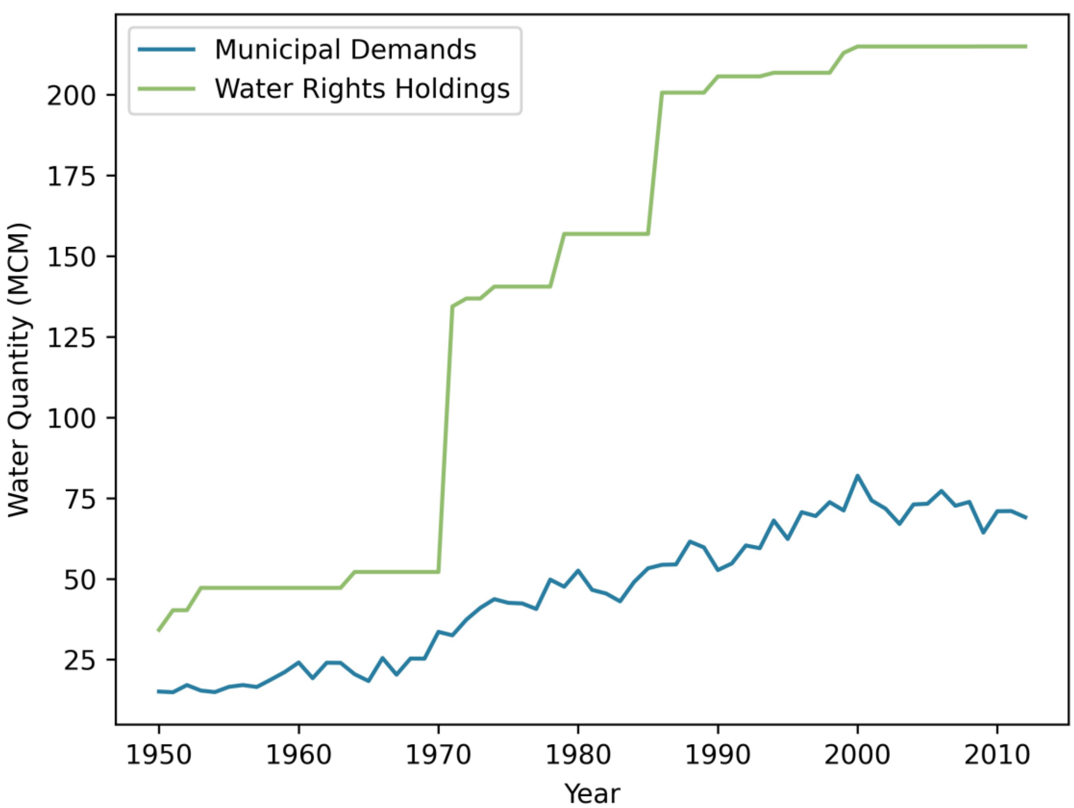



**Figure 1.** Aggregate *water right holdings (storage) for Front Range communities of Loveland, Longmont, Louisville, Lafayette, and Boulder (hereafter Northern Water Municipalities) and their historical collective demands (1950-2012)*

This research develops the Transbasin Water Allocation Model (TBWAM) framework (Figure 2) to explore the proposed two-way option (TWO), which involves pre-arranged multi-year contracts that facilitate the transfer of water in both directions depending on hydrologic conditions.

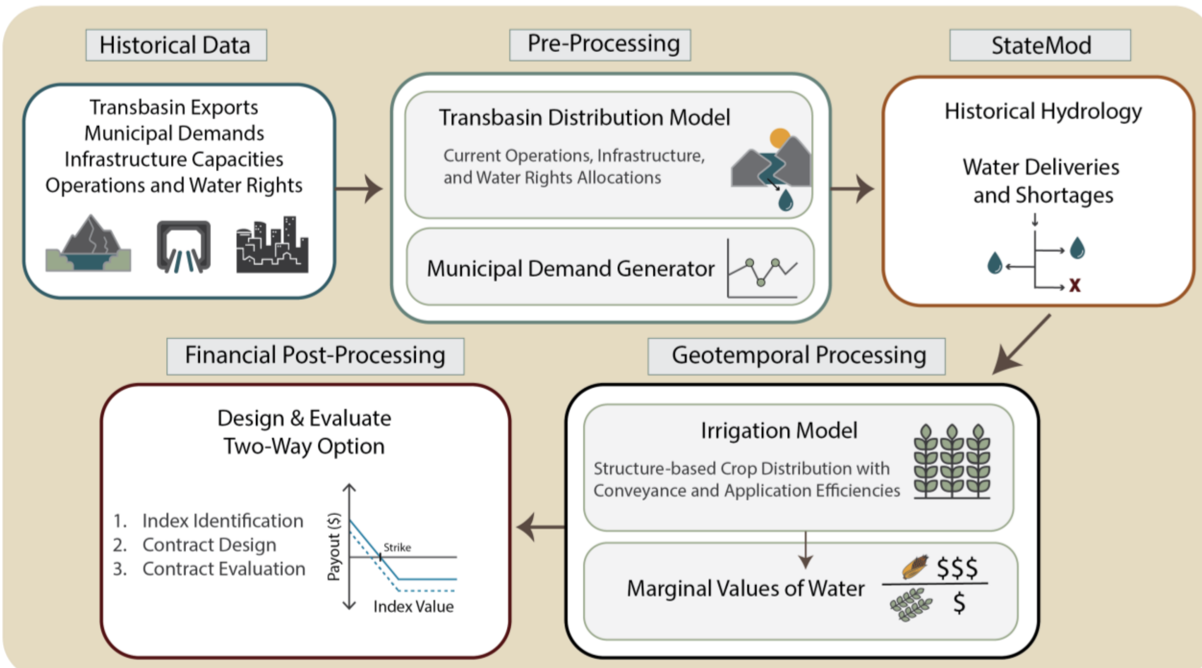



**Figure 2.** *Transbasin Water Allocation Model (TBWAM)*

The TBWAM framework is central to our evaluation of the performance of the proposed TWO contracts. Its components link the natural (where and when water is hydrologically available), engineered (how much water can be delivered to each location and when), and institutional (to whom the water is delivered as determined by water rights priority) systems that shape supply, demand, and financial outcomes. The TBWAM framework is initiated by adapting and then calling historical data (e.g., demands, transbasin flows, operations, and water rights) as inputs into StateMod (Section 2.2.1), a basin-specific water allocation model used by the state of Colorado to administer water rights. Each of these steps described is required in order to assess water supply and demand conditions. Supply and demand outputs then serve as inputs to the irrigation model (Section 2.2.4) which determines irrigation water deliveries, in accordance with prior appropriation rules, to individual diversion structures that serve acreage with a defined mix of crops and irrigation technologies. This information is used in combination with crop budget data (Colorado State University Extension, 2019) to calculate the marginal value of water for each irrigated parcel. These marginal values are then ordered to create irrigation water demand functions (i.e., from highest to lowest marginal value), which are then reversed to create what is in effect a municipal supply function (i.e. irrigation marginal values are reordered from lowest to highest) which is then combined with information on municipal water demands to identify a market-clearing price for leases. It should be noted that the operative value for municipal demand is actually the municipal "shortfall" defined as the difference between municipal demand and the allocation to municipal use in that year. Municipal demand is considered to be completely inelastic over the range of relevant marginal water values, with the intersection of the municipal supply function (i.e. the reordered irrigation supply function) and the demand shortfall determining the lease price. The distribution of lease prices in dry years (defined later) across the 63-year hydrologic record is then used to price option contracts moving water from irrigation-to-urban uses. A similar process is used to characterize the marginal value of irrigation water (demand) in wet years, with the supply available for leasing from municipalities defined based on municipal surplus (defined later), and prices defined by their intersection. The distribution of lease prices in wet years is then used to price option contracts transferring water from urban-to-agricultural users. Lastly, the performance of the TWO contracts is evaluated across two distinct water right allocation regimes (one current, one historical) and four different pricing scenarios.

This analytical approach could be adapted for use in many regions across the Western U.S., but data availability, increasing scarcity, and the resulting competition for water along the Front Range, and in the Northern Colorado Water Conservancy District in particular, make it an ideal region to explore the potential for this tool to effectively support dynamic and adaptive reallocation of water resources in the Western U.S., even as transfers in this region are subject to fewer transaction costs relative to those in most Western water markets.

## 2.1 Study Region

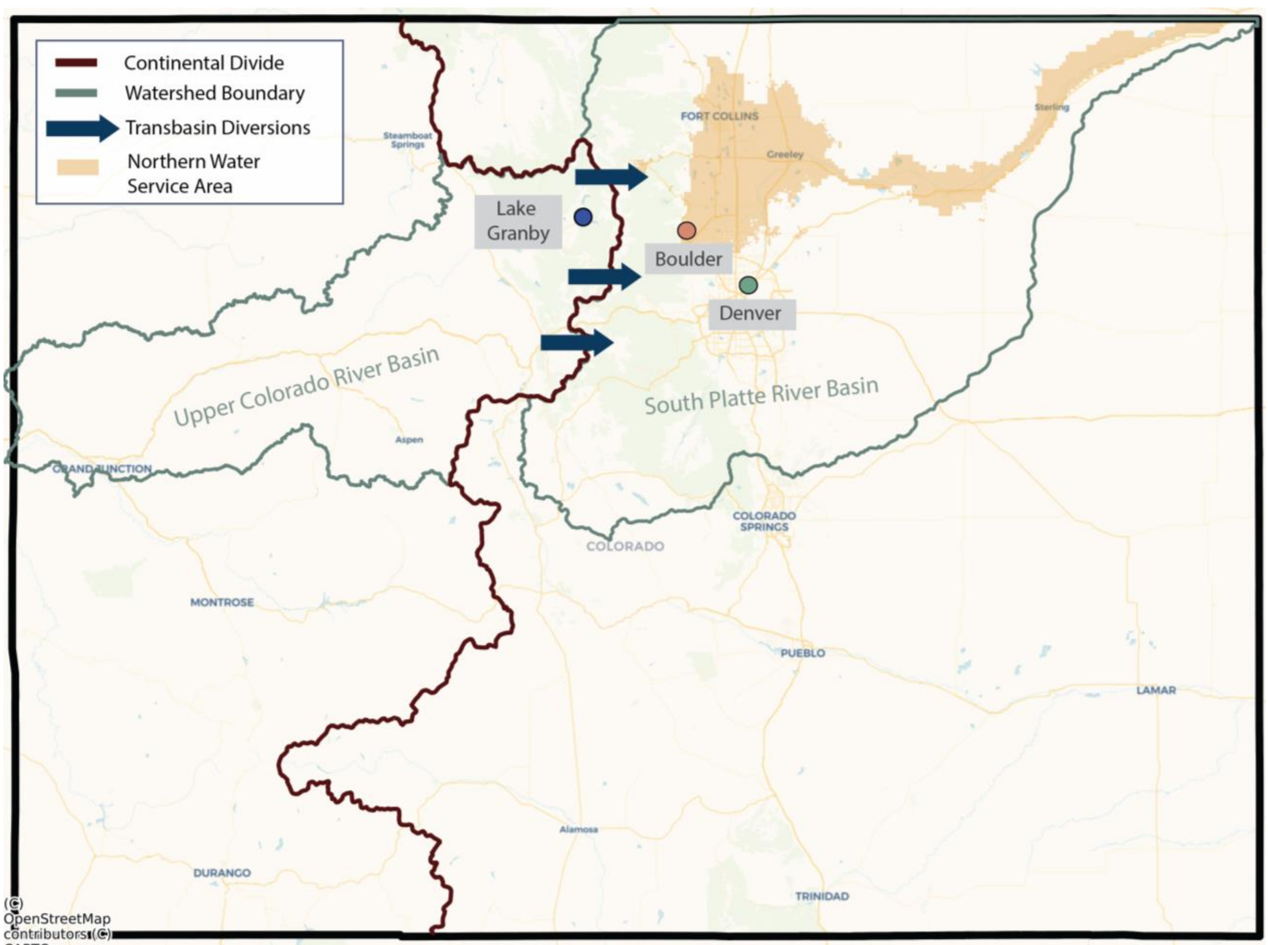



**Figure 3.** *The Upper Colorado and South Platte River Basins including notable Northern Water infrastructure (Lake Granby) and key transbasin diversions.*

The South Platte River Basin (SPRB) is located on the eastern slope of the Continental Divide (the "Front Range") and is the most populous of all Colorado river basins, home to approximately 3.8 million people in 2020 (~70% of the state's population) (South Platte Regional Opportunities Water Group, 2020). While the SPRB (Figure 3) includes several major urban centers (e.g., Denver, Boulder, and Fort Collins), agriculture is the dominant water user with 2.7 $km^3$ (2.2 million acre-feet) out of 3.7 $km^3$ (3 million acre-feet) (non-storage uses) per year being used to irrigate 4452 $km^2$ (1.1 million acres) (Thorvaldson & Pritchett, 2005). The basin's location on the east slope of the Continental Divide drives orographic dynamics that result in it receiving significantly less precipitation than the west slope basins.

The South Platte River is also relatively small, having a native annual supply (water available without human intervention) of only 1.78 $km^3$ (1.44 million acre-feet), whereas the Colorado River which originates on the west slope of the Divide has a native annual supply of 8.3 $km^3$ (6.74 million acre-feet) (Colorado Water Resources Research Institute, 1995). In order to meet growing demands along the Front Range, high capacity transbasin tunnels divert water from the Upper Colorado River Basin (UCRB) into the SPRB. Fifty percent of the Front Range communities' water supplies comes from transbasin diversions, accounting for approximately 0.65 $km^3$ (530,000 acre-feet) of water per year on average (State of Colorado, 2015; Water Education Colorado, 2019). The Colorado Big-Thompson Project (C-BT) is the largest transbasin diversion system and was developed by the U.S. Bureau of Reclamation. Operated by the Northern Colorado Water Conservancy District (Northern Water), the C-BT exports up to 0.38 $km^3$ (310,000 acre-feet) of water from the UCRB into the Northern Water Conservancy District (Northern Water) where it supplies over 1 million residents and 2428 $km^2$ (600,000 acres) of irrigated farmland along the Front Range. The C-BT system consists of 56 km (35 miles) of tunnels, 153 km (95 miles) of canals, and 12 reservoirs. Within the UCRB, Northern Water holds relatively junior water rights, which it uses to divert Colorado River water into Lake Granby, the largest reservoir within the C-BT with a total storage capacity of 0.67 $km^3$ (539,800 acre-feet). Water allocation from the UCRB to Northern Water is governed by prior appropriation based on the rights it holds in the UCRB, however, once water crosses the Continental Divide it is allocated to C-BT rights holders on a pro rata basis according to the number of C-BT "units" each user maintains.

Northern Water treats the maximum export volume as 310,000 individual units, which translates to 1233 $m^3$ (1 acre-foot)/unit when the maximum amount of water is available. Actual export volumes, however, depend on both hydrologic conditions in the UCRB (i.e., available supply), including available reservoir storage and snowpack, as well as water supply and demands in the SPRB. Initial determinations of the "quota" (the fraction of each unit allocated water, measured as 1233 $m^3$ (1 acre-foot) water/1233 $m^3$ (1 acre-foot) units) is made by the Northern Water Board of Directors on November 1 each year. This quota often remains constant over the course of the following water year (Nov 1 – Oct 31), however, final determinations can vary and are made on April 1 (in conjunction with the April-October irrigation season) (Northern Colorado Water Conservancy District, 2023). For example, if there is below-average precipitation in the SPRB, indicating greater scarcity, and ample available water in the UCRB (i.e., storage in Lake Granby), the quota may be 80% (resulting in delivery of 987 $m^3$ (0.8 acre-foot)/unit), but could go as high as 100% (or 1233 $m^3$ (1.0 acre-foot)/unit). Alternatively, if there is above-average precipitation in the SPRB and/or low snowpack/storage in the UCRB, the quota may be only 60% (resulting in delivery of 741 $m^3$ (0.6 AF)/unit) of the maximum. On average, the C-BT project quota is 70% each year.

The C-BT serves both municipal and agricultural users and the value of C-BT units has risen with increasing urban demands such that the purchase price of a single unit has recently been as high as $75,000 (or nearly $97,500/AF based on an average annual yield of 862 $m^3$ (0.7AF)/unit. The C-BT water is paired with native supplies in the SPRB which are subject to prior-appropriation, and users within Northern Water's boundaries use water from both sources to meet their demands.

Water allocated via C-BT units can be bought, sold, or leased between Northern Water users without the same regulatory approval processes required by the State of Colorado, substantially reducing transaction costs that would accrue as a result of similar transfers in other parts of Colorado (or the western U.S. for that matter). Given that one of the primary motivators of this research is identifying transfer mechanisms that reduce transaction costs, the situation in the Northern Water District may at first seem a strange choice of study region. However, the transactions considered here are the same as in any other basin subject to growing threats from scarcity, and the data availability and intersectoral competition for water make it a useful testing ground for evaluating the two-way option, even if its application in other basins around the state (or the western U.S.) would likely lead to a greater reduction in transaction costs (which are not explicitly evaluated in this work).

## 2.2 Transbasin Water Allocation Model Framework (TBWAM)

### 2.2.1 StateMod

To evaluate the potential of the two-way option, the TBWAM framework (Figure 2) is built around StateMod, a nodal network water system model developed for all major Colorado sub-basins as part of the Colorado Decision Support Systems (CDSS), which is capable of simulating water allocations consistent with prior appropriation rules. The South Platte StateMod version, in particular, simulates water allocations through a 63-year hydrologic record (1950-2012) at approximately 1,000 diversion nodes and includes 1.92 $km^3$ (1,556,000 acre-feet) of reservoir storage capacity (Colorado Water Conservation Board, 2017). StateMod is currently used by the state to analyze and assess historical and future water management policies and decisions, such as monitoring allocations and approving proposed water market transactions. The state's usage of StateMod as a decision-support tool makes this an appropriate model for understanding how a new type of water transfer contract could promote re-allocative efficiency in this complex basin.

StateMod has also been used to evaluate a number of water resource management questions. The StateMod model for the Upper Colorado River Basin (UCRB) serves as a building block for a recent model developed to investigate a coordinated informal water leasing program, one that involves using financial contracts to incentivize conservation by irrigators with the savings then diverted by other users in the basin (Zeff et al., 2023). The work by Zeff et al. built on previous research to explore the vulnerabilities faced by water users in the UCRB as a result of hydrologic extremes, demand growth, infrastructure and institutional changes (Hadjimichael et al., 2020). Both analyses took advantage of the UCRB's available 'baseline' model in which water is allocated based on historical hydrology, existing demands, infrastructure, infrastructure operations, and water rights.

While 'baseline' StateMod models exist for all other basins in Colorado, the open source 'historical' dataset for the South Platte model only tracks water allocations historically through time. To answer the questions posed in this analysis, the inputs to the South Platte model must be carefully adapted to represent the basin as it was operated at the end of the available hydrologic record (2012), a point at which conditions with respect to infrastructure, demands, and sectoral water use are consistent with current conditions. This includes updating infrastructure, demands, operations and water rights, such that the version of StateMod used to represent the SPRB in this work differs significantly from that currently used by the State of Colorado (which plans to update this model to provide similar capabilities as the model used in this work in the coming years). For more information on modifications to StateMod made in this work, see Supplemental Information Text S1 and Table S1.

### 2.2.2 Transbasin Distribution Model

The Transbasin Distribution Model (housed within TBWAM, Figure 2) is a Python-based modeling platform designed around StateMod that adapts transbasin diversions from the UCRB (where supplies originate) into a nodal network of deliveries within the SPRB, including Northern Water (where the demands are met) based on water rights holdings and infrastructure operations at the end of the available hydrologic record. The first step in the model identifies changes in storage and conveyance infrastructure (e.g., tunnels), as well as water right holdings (including reservoir and direct diversion rights) throughout the historical hydrologic record and updates them to represent the current state of the system. This allows for the 63-year historical hydrologic record to be run entirely through a system representative of the current infrastructure, demands and water rights such that a probabilistic assessment of current (or close to it) supply and demand dynamics, is developed.

The transbasin diversion values are then updated to those used in the 'baseline' UCRB StateMod model (Colorado Water Conservation Board, 2016), and distributes them throughout the SPRB (including the C-BT system) based on current water delivery rules within the StateMod nodal network (Colorado Water Conservation Board, 2017).

### 2.2.3 Municipal Demand Generator

Population growth and increasing municipal demands throughout the historical record are evident across the SPRB, and particularly in the Northern Water District (Figure 4A). Historical SPRB municipal demands are normalized by removing the growth trend such that demands varies around a mean level reflective of current demands (Figure 4B).

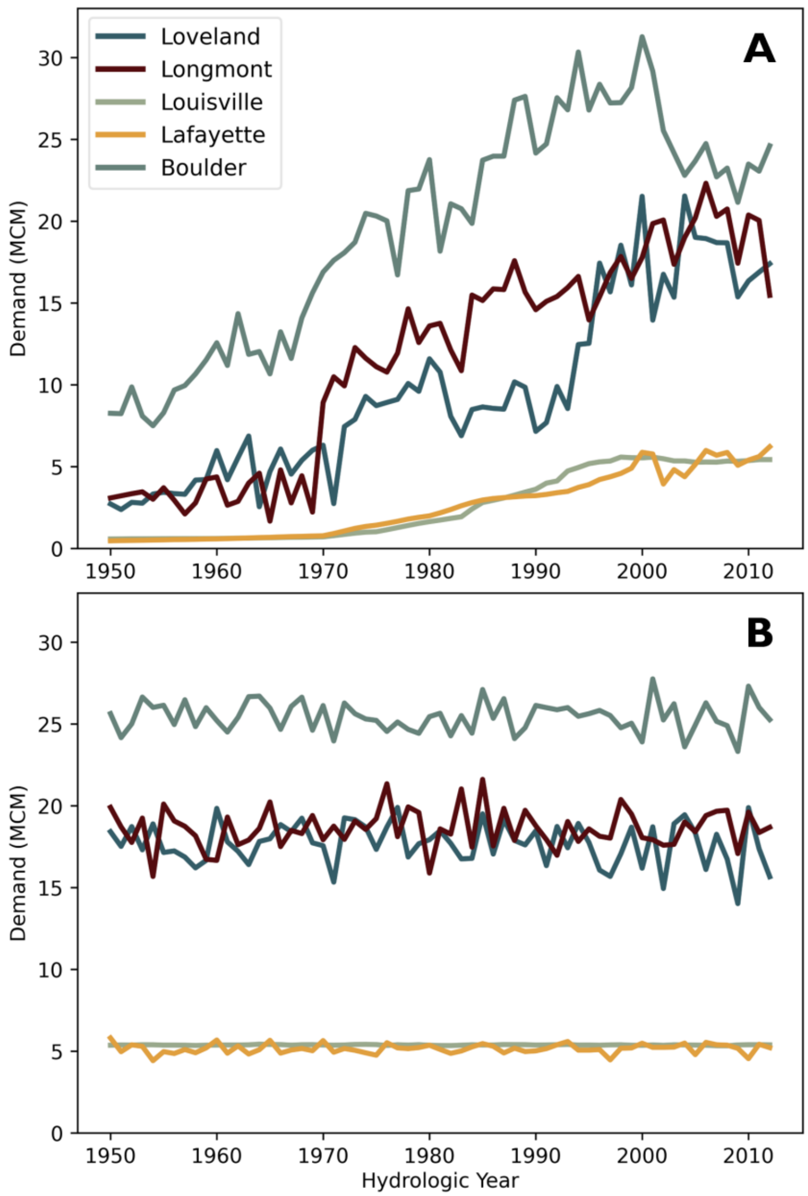



**Figure 4.** A) *Observed Northern Water Municipality demands from 1950-2012; B) Northern Water Municipalities normalized demand after having removed the growth trend.*

While Northern Water municipal demands (including the communities of Loveland, Longmont, Louisville, Lafayette, and Boulder) are of particular interest for this analysis, the native SPRB supplies with which these are combined are distributed according to prior appropriative rules, so all Front Range municipalities' demands are adapted to account for SPRB water right seniority differences between cities.

### 2.2.4 Value of Irrigation Water

The TBWAM framework uses crop data, resolved to the individual land parcel scale, provided by the State of Colorado (Colorado Division of Water Resources, 2023b) to characterize the supply of irrigation water available to municipalities in dry years and the demand for irrigation water from municipalities in wet years (municipal demand for water in dry years and the supply of municipal water available in wet years is described later). With regard to wet years, it is important to note that the transfer of water rights from agricultural to urban use in recent decades has resulted in significant tracts of fertile, but unirrigated land that could make productive use of irrigation water even during relatively wet years (Water Education Colorado, 2021). Irrigation water is often diverted from either a stream or primary canal at a diversion structure (e.g., weir) that directs water to individual land parcels. StateMod represents irrigators in the SPRB with a unique diversion structure identifier, one that can be connected with Colorado's irrigated lands geographic information system (Colorado Division of Water Resources, 2023b). This model first links individual parcels with the identifier, after which StateMod generates outputs on water delivery/shortage at the diversion structure in accordance with water rights priority. At each parcel, the acreage, crop type, conveyance losses (from diversion structure to the field) and application (flood or sprinkler) efficiencies are known from the State of Colorado's Consumptive Use Model, StateCU (Colorado's Department of Natural

Resources, 2023), which was developed to estimate consumptive use for each crop type across the different major sub-basins in Colorado. The StateCU model utilizes the modified Blaney-Criddle method to estimate crop specific potential evapotranspiration based on average temperature and daylight hours at a diversion structure's specific geographic location (Colorado Water Conservation Board, 2012). This detailed information allows for quantification of water usage at each parcel and is important for estimating the marginal value of water at each.

If a crop type is grown on land and serviced by the diversion structure, the irrigation water requirement ($IWR$) value is calculated such that,

$$IWR_{s,crop} = PET_{s,crop} - ER_{s,crop} \quad (1)$$

Where, $IWR$ = irrigation water requirement (in), $s$ = structure identifier, *crop* = crop type, $PET$ = potential evapotranspiration (in), and $ER$ = effective rainfall (in)

If no diversion structure specific information is available, the average $IWR$ is assumed based on the aggregate $IWR$ of the parcels within Northern Water's Boundaries. Using the $IWR$ and known acreages of individual parcels, and data on the crops grown on them, the water delivered to the diversion structure to grow a given crop is calculated such that:

$$W_{s,crop}(AF) = A_{s,crop} * \frac{IWR_{s,crop}}{12} * \frac{1}{n_{s,app}} * \frac{1}{n_{s,ditch}} \quad (2)$$

Where, $W$ = water delivered (AF), $s$ = structure identifier, *crop* = crop type, $A$ = area (acres), $IWR$ = irrigation water requirement (in), and $n_{app}$ = application efficiency, $n_{ditch}$ = conveyance efficiency

The marginal value of water (or the value of an additional 1233 $m^3$ (1 acre-foot) of usage) is derived by using the marginal value of production ($MNB_{crop}$, or the value from an additional 0.4047 hectares (1 acre) of production) from crop enterprise budgets developed by Colorado State University (see Supplemental Information Table S2), as well as the diversion structure and crop specific water delivery values calculated above to estimate the marginal value of water for each crop type at each diversion structure ($MNB_{H2O,s,crop}$) such that:

$$MNB_{H2O,s,crop} = \frac{MNB_{crop}}{W_{s,crop}} \tag{3}$$

With knowledge of the marginal value of water for each crop type and diversion structure, and water rights information that determines which parcels will be allocated water under variable hydrologic conditions, highly resolved supply/demand functions can be developed for a range of conditions using the 63-year historic hydrologic record (with crop acreages, infrastructure, and water rights holdings representative of current conditions) (Figure 5).

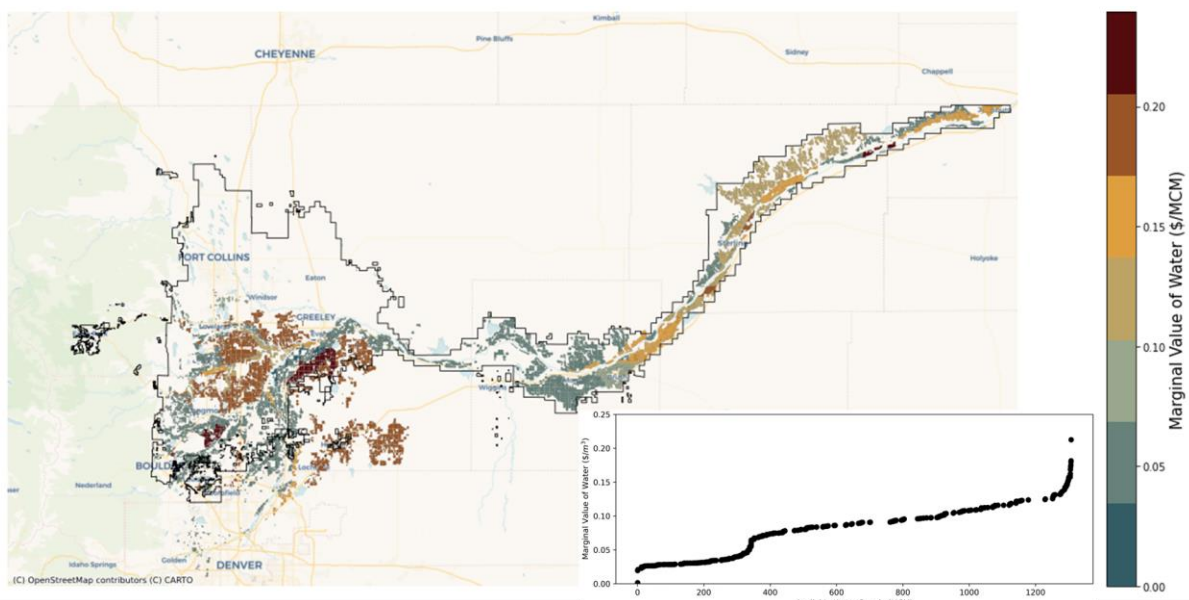



**Figure 5.** *Marginal value of water at each diversion structure under hydrologic conditions reflective of the year 1955 (the driest year on record). The municipal supply function (at lower right) represents all irrigation water allocated to individual land parcels in the Northern Water District and which could be leased by municipalities to compensate for shortfalls.*

In this case, the marginal value of irrigation water is represented as a supply function for municipal buyers in dry years, such that the market price of leases can be determined with knowledge of the municipal shortfall, that is the difference between municipal supply and demand (with demand assumed to be inelastic over the relevant price range). It is important to note that most studies involving estimations of irrigation water supply/demand characterize the marginal value of irrigation water for all acreage of a particular crop type as a single value, in this case different parcels growing the same crop (e.g., corn) can have very different marginal values based on differences in conveyance losses from the diversion structure to the field gate and application efficiency, as dictated by irrigation technology (e.g., flood, sprinkler).

In wet years, the marginal values of irrigation water at each parcel are presented by ordering them from highest to lowest in order to represent a demand function, which can then be paired with information on municipal surplus (which will be defined shortly) to identify market-clearing prices across the historical record. The two distributions of these lease prices, one for dry years and one for wet, are then used to price both sides of the two-way option (TWO) in a manner consistent with financial theory (Hull, 2003).

### 2.3 Two-Way Option (TWO) Contracts

The Two-Way Option (TWO) is actually a pair of option contracts that facilitate the transfer of water from irrigators to municipalities in dry years and in the opposite direction during wet years, with the triggering and direction of transfers linked to the prevailing water supply conditions (Figure 6). The municipalities buying water in dry years are not necessarily those selling water to irrigators in wet years, nor are the irrigators selling to cities in dry years necessarily the same ones that buy water from cities in wet years, so the operation of the market for these contracts would be facilitated by one entity serving as the "market maker" and offering both simultaneously. In this case, Northern Water is well positioned to play this role.

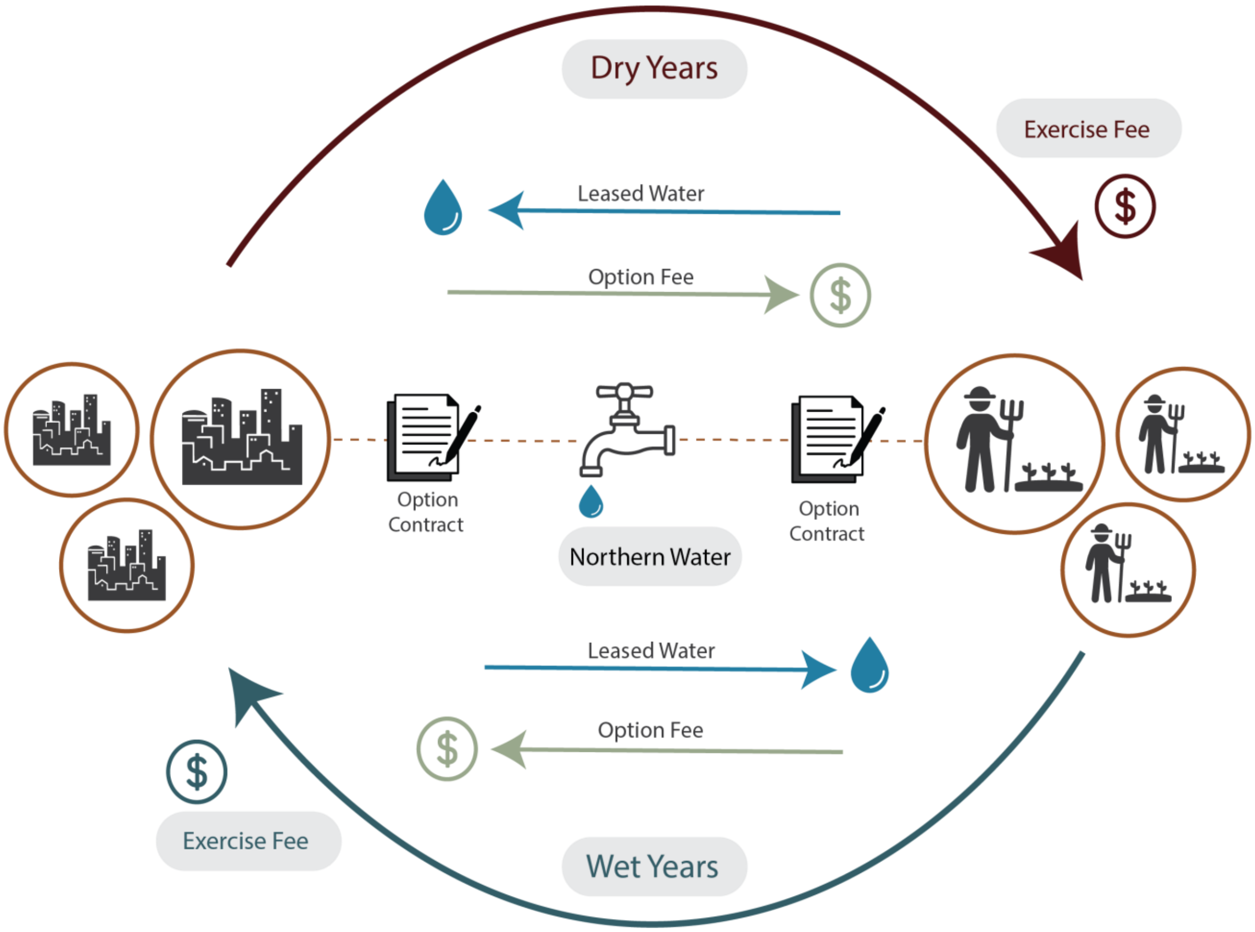



**Figure 6.** *Structure of two-way option contract*

Option contracts are widely used in financial markets, and while their consideration in a water market context is not unprecedented (Characklis et al., 2006; Hadjigeorgalis, 2009; Kirsch et al., 2009; Palomo-Hierro et al., 2015; Villinski, 2004; Williamson et al., 2008), they have typically facilitated one-way transfers from irrigators to urban users. The TWO contracts give both urban and agricultural users the right, but not the obligation, to lease water (i.e., exercise the option) when specified conditions linked to water availability (described in the next section) prevail. The option contract includes both an up-front fixed yearly payment, the “option fee”, and a pre-determined “exercise fee” paid when conditions lead to the option being triggered and the transfer of the leased water completed. The exercise fee is constant each year, and is set at what is considered a reasonable level (in most pricing scenarios values from \$0.01/$m^3$ - \$0.02/$m^3$ (\$15-25 per AF) per year were tested), and the annual option fee is then determined using this exercise fee and information on the distribution of lease prices derived from simulations across historical hydrologic conditions, with the option fee then adjusted to account for risk. For greater detail on option pricing, see Supplemental Information Text S2.

The process described above is intended to simulate a market for the option contracts, which is assumed to be administered by Northern Water as it already oversees leasing activity within its boundaries. Such an arrangement would not be uncommon, as large water/irrigation districts often play a similar role with respect to water transfers within their districts. To facilitate the market, Northern Water could set up a pooled system into which buyers and sellers would submit bids and offers. These bids and offers would be informed by water lease prices in the dry/wet years in which the options would be exercised, as described above, with the exercise fee determined for each type of year (wet/dry) by ordering bids from highest-to-lowest and offers from lowest-to-highest. The intersection of these two functions would determine the option exercise price, with all bids above this price and all offers below being accepted and the option contracts then signed accordingly. Since water units within the Northern Water service area are considered homogeneous and transfer approvals a relatively simple process, the contracts could be standardized, with Northern Water acting as the market maker and no need for coordinating contracts between individual buyers and sellers.

### 2.3.1 Colorado Big-Thompson Water Supply Index (CBI)

This analysis uses the 'Colorado Big-Thompson Water Supply Index', or CBI, developed by Zeff et al. (2023) as a measure of water availability on the west slope of the Continental Divide that is the source of transbasin diversions moved to the Northern Water District. The CBI is computed monthly and includes the sum of water storage in Northern Water's largest west slope reservoir, Lake Granby, snowpack in the UCRB (another measure of stored water), as well as year-to-date transbasin diversions from the UCRB to the Northern Water District (Equation 4). Snowpack estimates are calculated assuming a linear relationship between observed snowpack observations (provided by the USDA National Water Climate Center) and remaining cumulative inflows into Lake Granby as calculated by Zeff et al. (2023). The combination of these components gives a running monthly estimate of C-BT water supplies available in the UCRB for diversion across the Continental Divide to the Northern Water District, such that:

$$CBI_t = S_t + Sm_t + D_t \tag{4}$$

Where, $t$ = time (month); $CBI_t$ = C-BT water supply index ($km^3$); $S_t$ = storage in Lake Granby ($km^3$); $Sm_t$ = remaining snowmelt estimate ($km^3$); and $D_t$ = year-to-date diversions through the Adams Tunnel ($km^3$)

This analysis uses the CBI value as an index with defined thresholds for dry and wet years that 'triggers' the exercise of the two-way options, leading to leases from agriculture-to-urban in dry years and from urban-to-agriculture in wet years. The CBI index is compared to the defined wet/dry threshold values (defined in the next sections) on March 1st, thereby triggering the exercise of options (i.e. leasing) in advance of the April to October growing season in the South Platte region (National Center for Interstate Compacts, 1926).

### 2.3.2 Dry Years

Municipalities interested in contracting to acquire water from irrigators during drought will want to ensure that the water will be available. For this reason, only irrigators whose rights are sufficiently senior that they are fulfilled in even the driest year on record (1955) are allowed to enter into option contracts to lease water to municipalities, providing buyers with confidence that the seller will have water to lease when a severe drought occurs. The use of alternative hydrologic records involving drier periods (i.e. climate change) than those in the historic record could also be used to identify a smaller, but still substantial, number of potential sellers during drought.

Municipalities that enter into the TWO contracts pay the option fee each year and an exercise fee when the transfer/lease actually occurs. If the *CBI* value is below 0.86 $km^3$ (700,000 acre-feet) or 'stage 1 drought' on March 1$^{st}$, a condition that has occurred 20 times over the 63-year historical record, the option can be exercised, and the lease transaction initiated. The amount of water exercised/leased is determined using information on shortfalls by municipalities holding TWO contracts in the Northern Water service area, with these contracts exercised until sufficient water is leased to compensate for the shortfall.

### 2.3.3 Wet Years

The wet-year TWO contracts are 'triggered' when the CBI index value exceeds 0.98 $km^3$ (800,000 acre-feet), an event that has occurred 22 times over the 63-year historical record. This level of water availability has been, throughout the hydrologic record, associated with spills at Lake Granby. The rationale for choosing this threshold is that if Lake Granby is spilling, municipal water rights will have been fulfilled to the decreed amount, and any spilled water not leased would cease to have economic value to the municipal rights holders, so they would have nothing to lose by leasing it. While it is conceivable that municipalities might lease more water during these very wet years or lease in years that were less wet, doing so could reduce their reservoir storage and reduce their ability to meet demand in future years (even if only slightly). As such, the amount of water considered available for wet-year options is likely conservative and should probably be considered a lower bound.

With respect to estimating exactly how much of this surplus (i.e. the difference between water available and water demanded) municipal water would be made available as a part of TWO contracts, a relationship is developed using data from the city of Boulder. Boulder lies within the Northern Water district and has historically leased a percentage of its surplus water back to irrigators (City of Boulder, 2023). Using observed leases by Boulder to irrigators, a relationship is generated between the wetness of conditions (measured by CBI) and the percentage of surplus rights holdings a municipality would lease back to irrigators (for more, see Supplemental Information Text S3 and Figure S3). Information on the quantity of available water, the TWO option contracts and the unmet demand for irrigation water are used to identify how much optioned water is exercised and to which parcels it is directed.

#### 2.3.4 Water Right Holding Regimes

The performance of the TWO contracts is simulated within two separate and unique water right holding regimes. One regime reflects current water right holdings in which municipalities have chosen to purchase water rights well in excess of that required to meet demands in a normal hydrologic year to ensure supply reliability during drought. As municipal right holdings have plateaued since the early 2000's (Figure 7), the use of 2012 right holdings are considered reflective of "current" conditions, and this is also consistent with the availability of data from the state of Colorado in other areas (which is limited after 2012, as described).

The other rights holding regime reflects a hypothetical scenario that assumes the TWO contracts were available several decades ago (1971), before municipalities initiated the purchase of large volumes of irrigators' rights (Figure 7) such that municipalities would only need to maintain a volume of permanent water rights sufficient to meet average demand in a normal hydrologic year and could use the TWO contracts to ensure supply reliability in dry years. In this scenario, it is assumed that the TWO re-allocation mechanism was available, trusted, and institutionally accepted beginning in 1971, and thus well suited to play this role in meeting demands. The approach described in this hypothetical scenario would have had dual benefits in that it would have allowed municipalities to meet their reliability goals without purchasing large volumes of infrequently used rights, while also allowing irrigators to retain ownership of their water rights and thus continue use them for agricultural production in most wet or normal years. Under these circumstances, more water would be transferred from irrigators to municipalities in dry years, but agriculture would maintain more rights overall. While this regime maintains water rights holdings at 1971 levels, model simulations involve running the entire hydrologic record through the engineered (tunnels, reservoirs) and institutional (water rights) systems as they exist under current conditions. In addition to providing a somewhat counterfactual development scenario, results describing the potential value of the TWO contracts in this historical context may also provide some indication of its potential value in the future.

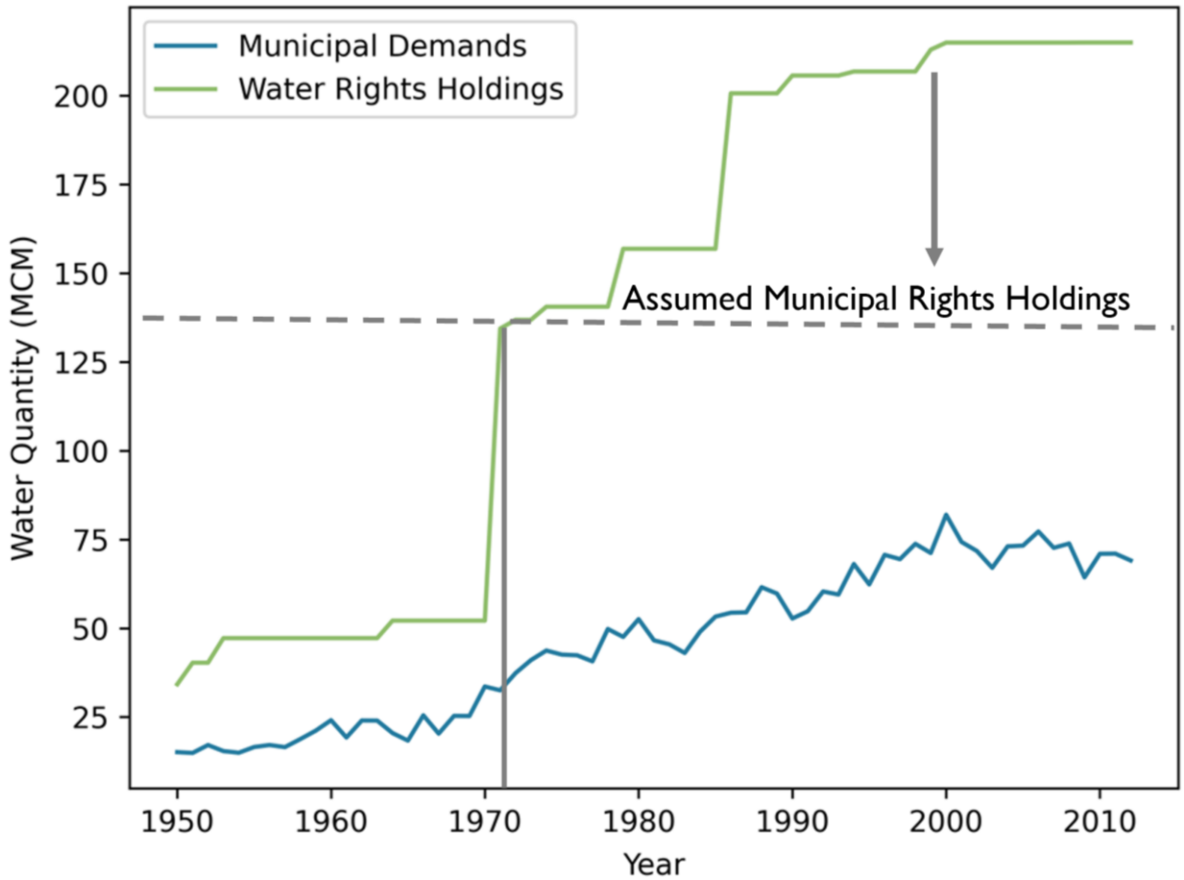



**Figure 7.** *Reduction in water right holdings for Northern Water Municipalities if rights were frozen at 1971 levels, compared with their demands observed historically (1950-2012).*

### 2.3.5 Pricing Scenarios

The two water right holding regimes are also evaluated across four individual pricing scenarios. The simulated market-clearing prices for leases described earlier are generated across the historic hydrologic record and represent a somewhat idealized market with prices predicated on the marginal value of water in irrigated activities. While the prices generated in this way are instructive and consistent with theory, particularly for dry year transfers from irrigators to municipalities, they likely represent something of a lower bound. So, in addition to these "market clearing price" scenarios, several additional pricing scenarios are considered (Table 1). Alternative pricing scenarios 2 and 3 involve prices for dry and wet years, respectively, that were selected on the basis of empirical data from Colorado and other Western U.S. regions. In these, municipalities are assumed to be willing to lease water to irrigators in wet years at a constant rate of \$0.02/$m^3$ (\$30/AF), a price consistent with that recently charged by Boulder when it leased water back to agriculture (City of Boulder, 2023). In scenarios 3 and 4, irrigators are assumed to lease water to municipalities at a price closer to the cities' willingness-to-pay, as opposed to the (lower) marginal value of water in irrigation. In this case, a flat rate of \$0.81/$m^3$ (\$1,000/AF) is used, a price that is consistent with ag-to-urban leases in several of the more competitive water markets in the Western U.S (WestWater Research, 2021).

Throughout this analysis municipal demands are assumed to be inelastic, with the quantity of water demanded remaining constant across the range of water values considered. This seems reasonable as only a relatively small portion of a municipality's total water supply is being purchased using TWO contracts. In the current rights holding regime, less than 5% of the municipalities total water supply is being filled using TWO contracts. If a utility were to buy 5% of its raw water supply (high in the current rights regime) at \$0.81/$m^3$ (\$1,000/AF), that would translate to an increase of \$0.04/$m^3$ (\$50/AF or \$0.15/1000 gallons) in average cost. Using the 1971 rights holding regime (Table 2), a larger fraction of supply is sometimes acquired via the TWO contracts, but even here the maximum increase in the monthly water bill is roughly 9% that of the average municipal water user (fixed + variable charges for 5,000 gallons per month in Boulder is roughly \$44.26, or \$2.34/$m^3$) (City of Boulder, 2022). Assuming typical municipal price elasticities in the range of -0.3 to -0.1 (Olmstead et al., 2007), this would translate into a reduction in consumption of 1-3%.

Cost savings by municipalities can be thought of as the difference between purchasing a permanent water right and the cost of acquiring water as needed through the TWO contracts.

Other results of interest include gains to agriculture from having additional water available in normal and wet years (due to both irrigators retaining more permanent water rights over time and through irrigators leasing water from municipalities in wet years), and the gains from payment of the option and exercise fees. With respect to the option fees, both municipalities and irrigators pay these fees to one another annually, but the volume of leases optioned to municipalities is significantly larger, thus irrigators earn a net positive income on these transactions. With regard to exercise fees, the same reasons result in irrigators receiving significantly larger gains, especially in the pricing scenarios (3 and 4) in which municipalities pay prices more in line with their willingness-to-pay (i.e. \$0.81/m$^3$ (\$1,000/AF)).

Results describe model output for both right holding regimes across all four pricing scenarios, so for eight different sets of circumstances. However, for the sake of brevity and to limit redundancy, only the results from pricing scenarios 1 and 3 (across both rights holding regimes) are described in Results, while results from pricing scenarios 2 and 4 for both rights holding regimes are present in Supplemental Information Tables S5-S6 and Figures S4-S7.

**Table 1.** *Pricing Scenarios used in the Current Water Rights Holding regime*

| | **Current Water Rights Holdings** | |
|---|---|---|
| | **Ag-to-Urban lease price (Dry years)** | **Urban-to-Ag lease price (Wet years)** |
| **Scenario 1** | \$0.01/m$^3$ (\$14.2/AF) * | \$0.04/m$^3$ (\$50.1/AF)* |
| **Scenario 2** | \$0.01/m$^3$ (\$14.2/AF)* | \$0.02/m$^3$ (\$30/AF) |
| **Scenario 3** | \$0.81/m$^3$ (\$1000/AF) | \$0.02/m$^3$ (\$30/AF) |
| **Scenario 4** | \$0.81/m$^3$ (\$1000/AF) | \$0.04/m$^3$ (\$50.1/AF)* |

*Mean market-clearing price, see Supplemental Information Table S3 for distribution of lease prices

**Table 2.** *Pricing Scenarios used in the 1971 Water Rights Holding regime*

| | 1971 Water Rights Holdings | |
|---|---|---|
| | **Ag-to-Urban lease price** | **Urban-to-Ag lease price** |
| **Scenario 1** | $0.02/m$^3$ ($29.3/AF)* | $0.08/m$^3$ ($96.2/AF)* |
| **Scenario 2** | $0.02/m$^3$ ($29.3/AF)* | $0.02/m$^3$ ($30/AF) |
| **Scenario 3** | $0.81/m$^3$ ($1000/AF) | $0.02/m$^3$ ($30/AF) |
| **Scenario 4** | $0.81/m$^3$ ($1000/AF) | $0.08/m$^3$ ($96.2/AF)* |

*Mean market-clearing price, see Supplemental Information Table S4 for distribution of lease prices

## 2.4 Caveats

It should be noted that transfers of water considered here are limited to those between municipal and agricultural users, and do not account for municipal-to-municipal or agriculture-to-agriculture transfers. There is little evidence of the former in wet periods as municipalities typically maintain sufficient rights to meet demands under these conditions, and even less under dry conditions when municipalities can invariably lease water less expensively from irrigators involved in low value activities. With respect to agriculture-to-agriculture transfers, there is some evidence of these in dry periods, but agriculture-to-urban transfers dominate. In wet periods, higher-value irrigated activities that do not receive water could buy it from either low-value irrigators or municipalities, but the wet periods defined here involve years in which municipal water is being spilled from reservoirs, water whose marginal value of essentially zero (lower than even the lowest valued irrigation water), making leasing of this water to meet any agricultural demand attractive. In addition, a primary objective of this work is testing the ability of the TWO contracts to more rapidly and less expensively move both water and money between the two sectors in response to changing hydrologic conditions, such that transfers within sectors, while certainly possible, are not the focus.

With respect to the modeled market clearing lease prices used to set option prices, most hover in the $0.01/m$^3$ - $0.08/m$^3$ ($14-$96/AF) range regardless of the conditions or scenario, this is because a high percentage of irrigation water is used in low value activities (e.g., alfalfa, wheat). These market-clearing prices likely represent a lower bound, as irrigators in the Northern Water district will, as in other regions, have an awareness of municipalities higher willingness-to-pay for water and may organize themselves to take advantage of this information. At the same time, this analysis only includes consideration of urban-to-agricultural leases in wet periods associated with spills at Lake Granby. Municipalities may, in fact, be somewhat less risk averse and willing to option water to irrigators under less wet conditions. In any case, municipalities are always keen to avoid any perception that they are "profiting" from water, so while Scenarios 1 and 4 involve cities leasing water to agriculture at prices reflecting the highest marginal value in irrigation during wet periods, evidence from the small amount of urban-to-agricultural leasing suggests that they typically charge a relatively nominal fee 0.02/m$^3$ (~$30/AF) (City of Boulder, 2023). Given all this, Scenario 3 which involves lease prices for agriculture-to-urban during dry periods of $0.81/m$^3$ ($1,000/AF) and urban-to-agriculture leases in wet periods of 0.02/m$^3$ ($30/AF) may be the most realistic.

It is also worth noting that while this analysis focuses on the Northern Water District, the City of Fort Collins (one of the largest cities serviced by Northern Water) is not included as the Cache la Poudre River Basin from which it draws the majority of its water supply is not explicitly modelled within StateMod. This analysis focuses on the other five major municipalities within the Northern Water District, such that when municipal surplus is assumed, it constitutes an underestimate based on a) the limited urban-to-agriculture leasing that has occurred in the past and b) not having all Northern Water municipalities considered.

In addition, the assumption in the 1971 water rights holding regime is that municipalities would not have purchased as many permanent water rights as they currently hold, and that municipalities would instead have met a significant portion of their demands using the TWO contracts. This analysis estimates municipal 'costs avoided' based on the amount of water rights needed to fully meet demands in any hydrologic year, as well as the foregone costs of purchasing C-BT water rights in the past. It is also important to note that the upfront transaction costs associated with these agreements, as well as the institutional structures required to oversee these transactions are likely not to be trivial (although in the case of the latter, many districts, such as Northern Water, already have structures in place to oversee intra-district transfers). The assumption here, however, is that the ability to obtain a one-time approval for transfer agreements of up to ten years will invariably reduce these costs relative to the previous situation in which approvals were required for each transfer.

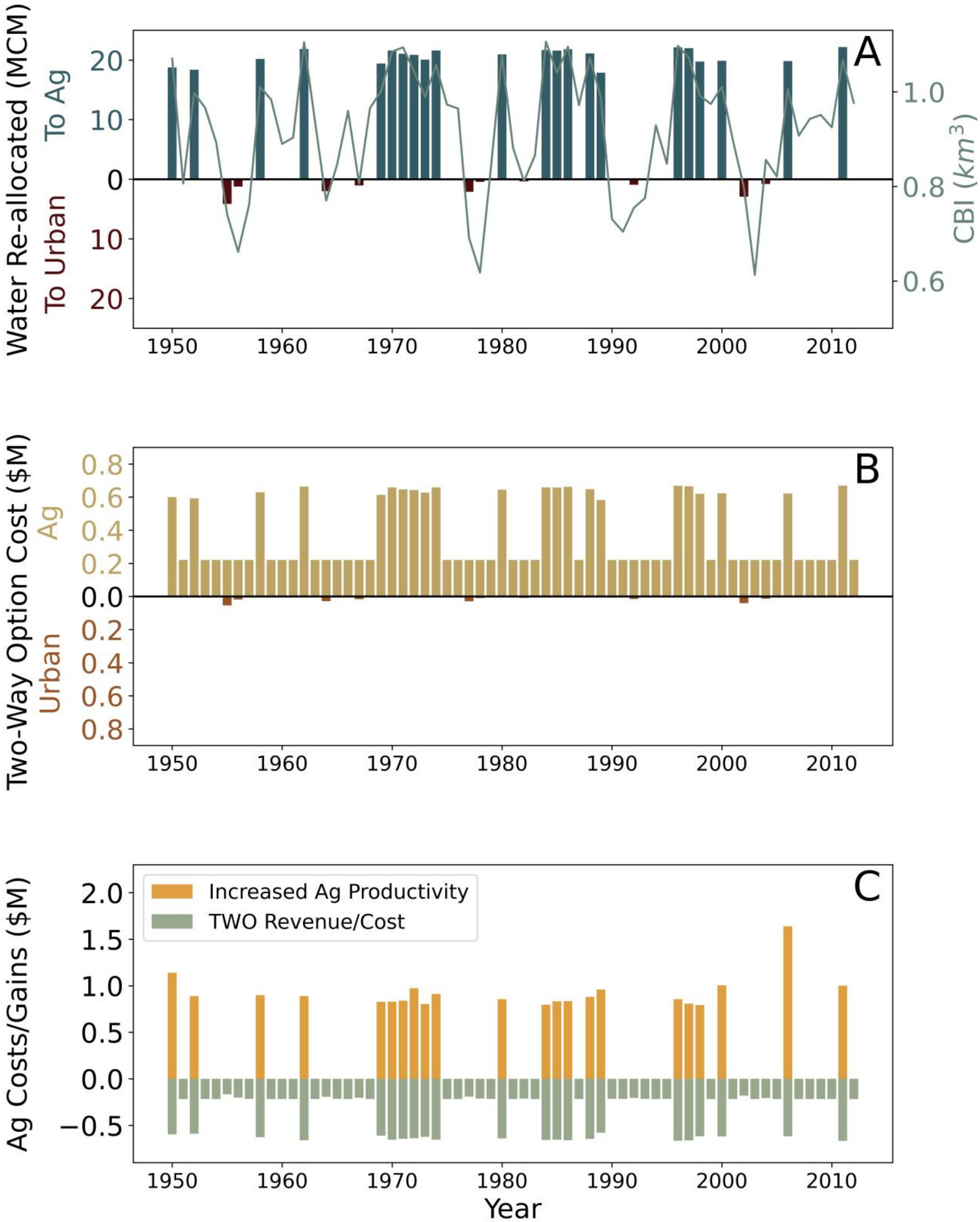
Finally, this study presents the potential improvements in water allocation, costs savings and agricultural productivity that occur only within the Northern Water District. Northern Water accounts for around 4% of Colorado water use, serving 17% of its urban population and 18% of its irrigated acreage. While extrapolating the value of the TWO contracts to the entire state of Colorado as well as the broader western U.S. holds promise, it is beyond the scope of this investigation's preliminary proof of concept, it seems reasonable to assume that the potential benefits of implementing the TWO concept more broadly could be much larger than what is presented here.

## 3 Results

Over the simulation period (1950-2012), TWO contracts exhibit the potential to improve water allocation, reduce costs, and increase agricultural productivity within the Northern Water District. Currently, municipalities achieve supply reliability via holding large (and infrequently used) volumes of permanent rights. Results suggest that TWO contracts can be employed to supplement current municipal rights holdings during more severe droughts, filling relatively small shortages over the simulation period (hydrologic years 1950 – 2012). The alternative rights holding regime (in which municipalities holds rights equivalent to what they held in 1971), demonstrates the potential for the TWO contracts to act as a substitute for a substantial portion of the municipal permanent rights purchased over the intervening years. In both cases, the performance of the TWO contracts is described in terms of the total volume of water re-allocated across sectors, the costs/revenues accruing to the buyers and sellers, the cost savings to municipalities from not buying additional permanent rights, and the increased agricultural productivity enabled by more water being available to irrigators in wet and normal years.

### 3.1 Two-Way Option Performance under Current Water Rights Holdings

Figure 8 presents TWO contract performance in the current rights holding regime under pricing scenario 1 (i.e. that in which options are priced via 'market-clearing' simulations). In order to fulfill municipal shortages across the 63-year historic record, municipalities require a multi-year option contract for the maximum annual shortage they face over this period, which turns out to be 4.1 MCM (3,346 AF).




740

741 **Figure 8.** *Two-way option performance with current water rights under pricing scenario 1, where lease*

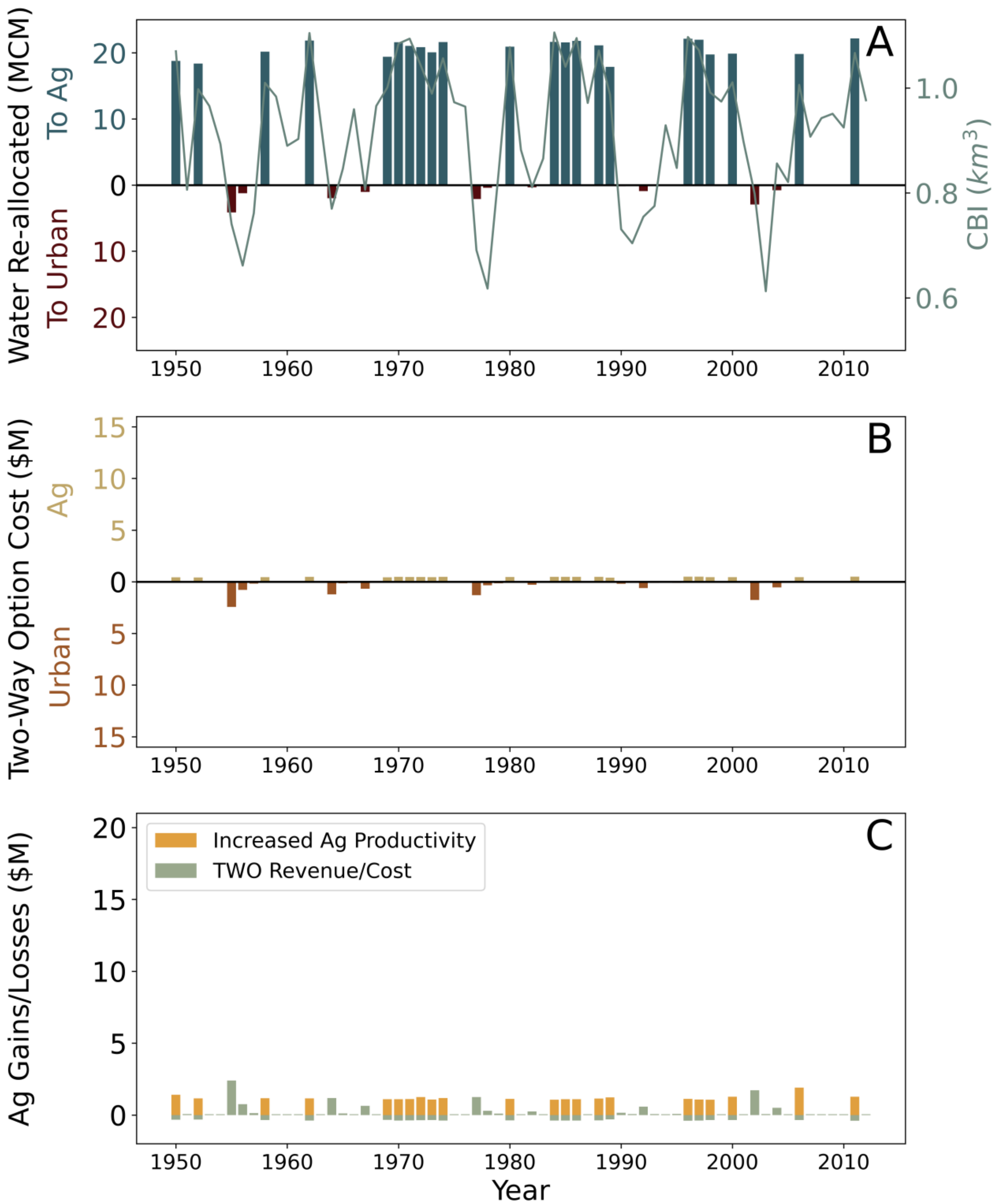
742 *prices are at the intersection of yearly supply and demand curves, or the 'market-clearing' price*

Municipalities exercise some portion of these options in 20 dry years (when CBI < 700) over the 63-year historic record for a cumulative total of roughly 16.4 MCM (13,300 AF) (Figure 8A). Irrigators, meanwhile, sign a multi-year option contract for use in wet years (CBI > 800) of 22.2 MCM (17,982 AF) per year, or their maximum shortage in any wet year, when CBI > 800 in order to avail themselves of surplus municipal water. Irrigators exercise some portion of their yearly options in 22 years over the 63-year simulation for a cumulative added supply of almost 455 MCM (369,000 AF) (Figure 8A). In pricing scenario 1, the 'market-clearing' lease prices used to price the option contracts. Municipalities would pay a fairly nominal fee of $4,000 per year ($0.001/m$^3$/yr or $1.20/AF/yr) in risk-adjusted option fees (or $250K across the 63-year record), and an exercise fee of $0.01/m$^3$ ($15/AF) during dry years (or $200,000 in total) in which the water is actually leased/transferred (Figure 8B). Irrigators, on the other hand, would pay $220K a year ($0.01/m$^3$ or $12.2/AF) in risk adjusted option fees (or $13.9M across the simulation) and $9.2M in exercise fees ($0.02/m$^3$ or $25/AF), as shown above the x-axis in Figure 8B. The relatively small volumes of municipal water leased to irrigators in wet years, and the high potential value of irrigation on some non-irrigated lands even during wet years accounts for the high prices for wet year leases in this market-clearing price scenario.

Over the simulation period, the average cost for TWO contract usage is $0.02/m$^3$ ($33.8/AF) for municipalities, and $0.05/m$^3$ ($62.6/AF) for irrigators. In the driest hydrologic year, 1955, the maximum of 4.1 MCM (3,346 AF) is exercised by municipalities which the resulting payments to irrigators via both the option fee and exercise fee reducing the net cost of the TWO contracts to irrigators (Figure 8C). While irrigators end up paying municipalities more in option/exercise fees than they receive in return, the increased agricultural productivity irrigators (above x-axis on Figure 8C) generate as a result of the acquisition of optioned water in wet years far outweighs. Even after irrigators pay $22.6 million in option and exercise fees, the total agricultural gains equate to $11.6 million, as the value of added agricultural productivity outpaces the cost of TWO contracts. With respect to Figure 8 as a whole, the dynamic capabilities of the TBWAM modeling framework can be seen in several ways. For example, when comparing wet years 2006 and 2011, water transfers from municipalities to irrigators are 20 MCM (16,066 AF) and 22.2 MCM (17,982 AF) (Figure 8A). While it may be expected that agricultural gains would be higher in year 2011 given the larger volume of optioned water transferred, the gains are actually higher in year 2006 ($2.3M, vs. $1.7M), because higher valued irrigated parcels (e.g., sugar beets) are not allocated water in that year. This more nuanced finding is a direct result of being able to track the water rights and allocations to individual land parcels, a feature that is uncommon in the vast majority of similar studies. While irrigators benefit from the TWO contracts over the simulated period, municipalities also find themselves being able to lease water and reduce the overall costs of achieving their supply reliability objectives. To fully meet urban demands (i.e., no shortages over the simulation period) via permanent rights alone, bought at current prices ($79/m$^3$ or $97,500/AF), municipalities would have had to pay over $326M. While this is the cost of owning these rights in perpetuity, so not a perfect comparison, using the TWO contracts to secure a similar level of supply reliability over the 63-year simulation period municipalities are only paying $0.45M.

The pricing of leases, and the options prices based on them, is a critical factor in assessing TWO contract performance. Pricing scenario 3 assumes lease prices are similar to those observed in many water markets across the Western U.S., with irrigators leasing to municipalities in dry years for prices much closer to the municipalities willingness-to-pay, in this scenario assumed to be $0.81/m$^3$ ($1000/AF). Conversely, in this pricing scenario municipalities are assumed to lease to irrigators for a constant price of \$0.02/m$^3$ (\$30/AF) in wet/normal years. Municipalities would still hold a multi-year contract for the maximum shortage they face throughout the simulation (4.1 MCM or 3,346 AF), such that the same hydrologic conditions yield the same volume of optioned water in each year (Figure 9A), but the costs to municipalities of securing this water in dry years is considerably higher (Figure 9B). Given the higher lease price of water, municipalities would now pay \$0.02/m$^3$ (\$29.10/AF) (or \$97,000 per year) in risk-adjusted option fees, approximately \$6.1M across the 63-year record, and \$0.57/m$^3$ (\$700/AF) in exercise fees, or roughly \$9.3M across the simulation period (Figure 9B). In total, the higher lease price (\$0.81/m$^3$ or \$1,000/AF) leads to municipalities paying a total of \$15.4M for TWO contracts as opposed to the 'market-clearing' pricing scenario 1 where TWO contracts cost just less than \$0.5M. Meanwhile, irrigators would again sign a multi-year contract for 22.2 MCM (17,982 AF) of options, but as a result of the lower \$0.02/m$^3$ (\$30/AF) lease price from municipalities, now only pay \$0.002/m$^3$ (\$2.40/AF) (or \$42,000 per year) in risk adjusted option fees, roughly \$2.7M across the entire simulation period. The exercise fee paid by irrigators is \$0.02/m$^3$ (\$25/AF), which comes to roughly \$9.2M over the simulation period (Figure 9B).

Now, the average cost of water coming to municipalities via an exercised option is \$0.94/m$^3$ (\$1160.60/AF), while for irrigators it is only \$0.03/m$^3$ (\$32.80/AF). As a result of the increased cost of TWO contracts to municipalities, irrigators end up receiving \$3.6M in gains from the use of the TWO, a change from pricing scenario 1 in which municipalities paid much less and where TWO usage by irrigators had a net cost. Irrigators' acquisition of surplus supplies from municipalities in wet years also adds \$34.2M in agricultural productivity gains over the simulation period, amounting to total agricultural gains (including option/exercise fees) of \$37.8M from the use of the TWO.




812

813 **Figure 9.** *Two-way option performance with current water rights under pricing scenario 3, an empirical*

814 *pricing scenario where ag-to-urban leases are \$0.81/m$^3$ (\$1000/AF) in dry years, and urban-to-ag leases*

815 *are \$0.02/m$^3$ (\$30/AF)*

In terms of the municipal costs savings associated with using the TWO contracts to ensure supply reliability, municipalities would pay \$15.5M (up from \$0.45M using pricing scenario 1) across the 63-year simulation period. Achieving a similar level of reliability through the purchase of the 4.1 MCM (3,346 AF) of permanent water rights required would still cost \$326M.

**Table 4.** *Two-way option performance with current water rights holdings under pricing scenarios 1 & 3*

| **Current Rights Holdings** | Scenario 1 Lease Prices: Ag-Urban: \$0.001/$m^3$ - \$0.02/$m^3$ (\$1.40 -\$28.12/AF) Urban-Ag: \$0.03/$m^3$ - \$0.11/$m^3$ (\$37.69 - \$135.74/AF) | Scenario 3 Lease Prices: Ag-Urban: \$0.81/$m^3$ (\$1000/AF) Urban-Ag: \$0.02/$m^3$ (\$30/AF) |
|---|---|---|
| Agricultural Gains (\$M) | 11.6 | 37.8 |
| Two-way option cost to Ag* ^ (\$/$m^3$) (\$/AF) | 0.05 (62.6) | 0.03 (32.2) |
| Two-way option cost to Urban** ^ (\$/$m^3$) (\$/AF) | 0.03 (33.7) | 0.94 (1160.6) |
| Total two-way option cost to Urban (\$M) | 0.45 | 15.5 |
| Urban savings from Two-way option usage (\$M) | 325.5 | 310.5 |

*Assumes exercise fee of \$0.02/$m^3$ (\$25/AF) in Scenario 1, Assumes \$0.02/$m^3$ (\$25/AF) exercise fee in Scenario 3;
**Assumes exercise fee of \$0.01/$m^3$ (\$15/AF) in Scenario 1, Assumes \$0.57/$m^3$ (\$700/AF) exercise fee in Scenario 3;
^ Average exercised option cost calculated using the sum of all option fees and exercise fees across the simulation, divided by the total amount of water re-allocated.

### 3.2 Two-Way Option Performance assuming 1971 Water Rights Holding Regime

The TWO contract becomes commensurately more valuable in the hypothetical situation in which municipalities stop buying permanent rights in 1971, and instead rely on the TWO to supplement municipal supplies during dry periods. Initially, this 1971 rights holding regime is evaluated under pricing scenario 1 that assumes the 'market-clearing' scenario and results in low prices, particularly for water being transferred from irrigators to municipalities in dry years.

Under this rights holding regime, municipalities require much more water in dry years to meet their supply reliability objectives and purchase 24.2 MCM (19,636 AF) of options (an increase from 4.1 MCM (3,346 AF) when considering the current rights regime). During dry years, municipalities acquire roughly 218 MCM (176,400 AF) over the 63-year simulation period (Figure 10A). Irrigators, meanwhile, contract for 9.7 MCM (7,827 AF) of options and exercise these to acquire roughly 198.1 MCM (160,600 AF) over the simulation period. The relative volumes of water re-allocated to municipalities and irrigators is flipped relative to that which takes place under the current rights holding regime (Figures 8 & 9), as irrigators have sold fewer rights to municipalities who given the purchase of many fewer rights now rely more heavily on the TWO contracts during dry years to meet their supply reliability goals. Using pricing scenario 1, in which lease prices are determined via a 'market-clearing' process, lease prices during dry years increase given the higher volume of transfers, and municipalities pay a risk-adjusted option fee of $0.003/m$^3$ ($3.10/AF), or $61,000 per year (or $3.8M across the 63-year record). Municipalities pay an exercise fee of $0.01/m$^3$ ($15/AF) to acquire the water, or roughly $2.6M over the simulation period (Figure 10B). In this rights holding regime, municipalities have much less surplus water to option to irrigators during wet years, so the risk-adjusted option fee paid by irrigators for access to water in wet years rises to $0.03/m$^3$ ($31.50/AF). Given the smaller volume of options bought by irrigators, they, pay only $247,000 in annual option fees (or $15.5M across the simulation period) and $4M in exercise fees ($0.02/m$^3$ or $25/AF) (Figure 10B).

The average cost of water re-allocated across the simulation is $0.03/m$^3$ ($36.60/AF) for municipalities, and $0.10/m$^3$ ($121.80/AF) for irrigators (as only small volumes of surplus municipal water are available and are purchased for use on highly productive non-irrigated parcels). As a result, irrigators end up paying municipalities more than they receive in return (shown as a net cost across the simulation period in Figure 10C), although the increased agricultural productivity irrigators generate as a result of retaining more of their water rights (as well as acquiring water via wet year options) more than compensates for this. Irrigators pay $19.6 million in option and exercise fees ($3M less than in the current rights regime for pricing scenario 1 as irrigators hold more permanent rights), but the value of added agricultural productivity totals $28.4M, such that total agricultural gains equate to $8.8 million. It is worth noting in key dry years 1955, 1977, 2002 where larger quantities of water are re-allocated from agriculture to municipalities (Figure 10A), the use of TWO contracts drives positive gains for irrigators (Figure 10C). Irrigators, in this way, benefit from not only maintaining more of their water rights in these (and other dry years), but also continue to supplement their income via option/exercise fees in the worst dry years. Municipalities continue to realize considerable savings via reliance on the TWO contracts rather than purchasing permanent rights, but the assumption is that the counterfactual here is that these rights would have been purchased largely circa 1971, at considerably lower prices. Assuming this, municipalities would have had to pay $298M (at 1971 prices, adjusted to 2023 dollars) to acquire permanent rights in the past that would have fulfilled their shortages across the simulation period (24.2 MCM or 19,636 AF), while the use of the two-way option has municipalities paying $6.4M to achieve the same level of supply reliability.

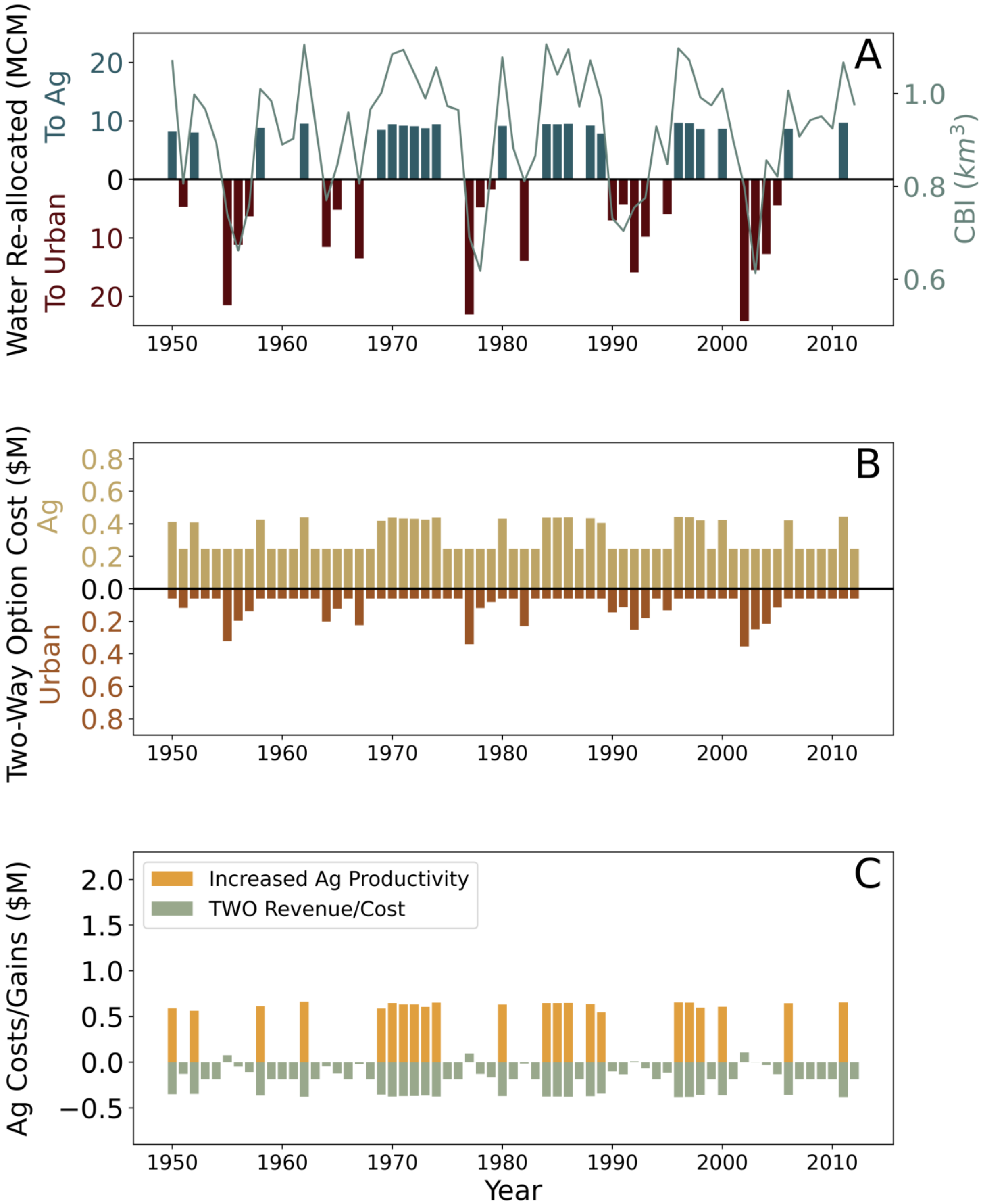



**Figure 10.** *Two-way option performance with 1971 water rights under pricing scenario 1 where lease prices are at the intersection of yearly supply and demand curves, or the 'market-clearing' price*

The TWO contract performance in the 1971 rights holding regime is also evaluated under pricing scenario 3 in which municipal dry year lease prices are a constant \$0.81/m$^3$ (\$1,000/AF) and agricultural wet year prices are \$0.02/m$^3$ (\$30/AF). In these circumstances, municipalities again rely heavily on the TWO contracts during dry years, purchasing 24.2 MCM (19,636 AF) of options, with some portion of this total exercised in 20 years out of the 63-year record, for a total re-allocation of 218 MCM (176,400 AF) (Figure 11A). Irrigators sign option contracts for 9.7 MCM (7,827 AF) per year, with some portion of these triggered in 22 years out of the 63-year record for a total re-allocation of 198.1 MCM (160,600 AF). Using the higher dry year lease prices as the basis, municipalities pay an option fee of \$0.05/m$^3$ (\$59.80/AF), or \$1.2M per year, in risk-adjusted option fees for a total of \$74M over the entire simulation period. In terms of exercising the options, this exercise fee is \$0.57/m$^3$ (\$700/AF), which comes to a total of \$123M over the same 63-year period. Irrigators, on the other hand, pay much less in this pricing scenario with a risk-adjusted option fee of \$0.002/m$^3$ (\$2.20/AF), or \$17K a year (or \$1M across the simulation), with an exercise fee of \$0.02/m$^3$ (\$25/AF) leading to a total cost of \$4M over the simulation period (Figure 11B).

The average cost of re-allocated water across the simulation now increases to \$0.91/m$^3$ (\$1119.50/AF) for municipalities, and \$0.03/m$^3$ (\$31.60/AF) for irrigators. As a result of municipalities paying much more for water, irrigators receive positive net revenue from the yearly option fee payment from municipalities, and in dry years benefit from the \$0.57/m$^3$ (\$700/AF) in exercise fees. From the TWO contract revenue alone, irrigators receive \$192.4M across the 63-year record, while adding \$21.9M in increased productivity from the receipt of the transfers of municipalities' surplus water in wet years.

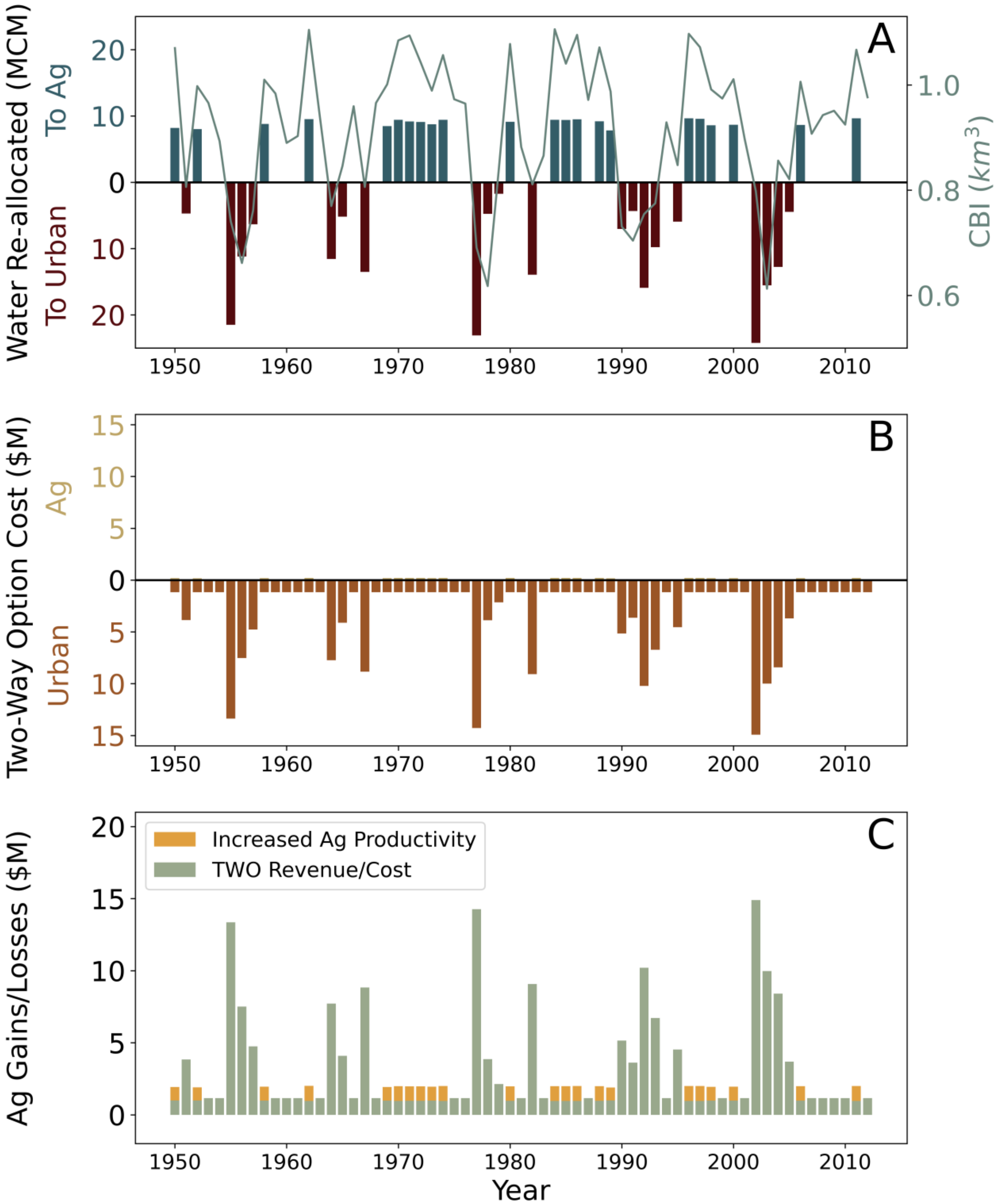



**Figure 11.** *Two-way option performance with 1971 water rights under pricing scenario 3 an empirical pricing scenario where ag-to-urban leases are \$0.81/m$^3$ (\$1000/AF) in dry years, and urban-to-ag leases are \$0.02/m$^3$ (\$30/AF) in wet years.*

Finally, municipalities continue to enjoy some cost savings as they would have had to pay $298.4M (at 1971 prices, adjusted to 2023 dollars) to acquire permanent rights that would fulfill their shortages across the simulation period, but these savings are reduced significantly given that the increased option/exercise fess they are paying amount to a total cost of $197M over the simulation period, but this still yields a savings of over $100M.

**Table 5.** *Two-way option performance with 1971 water rights holdings under pricing scenarios 1 & 3*

| **1971 Rights Holdings** | Scenario 1 Lease Prices:<br>Ag-Urban: $0.023 – 0.026/m$^3$<br>($28.12 - $32.48/AF)<br>Urban-Ag: $0.048 - $0.112/m$^3$<br>($58.93 - $138.11/AF) | Scenario 3 Lease Prices:<br>Ag-Urban: $0.81/m$^3$<br>($1000/AF)<br>Urban-Ag: $0.02/m$^3$<br>($30/AF) |
|---|---|---|
| Agricultural Gains ($M) | 8.8 | 214.2 |
| Two-way option cost to Ag*^ ($/m$^3$) ($/AF) | 0.10 (121.8) | 0.03 (31.6) |
| Two-way option cost to Urban** ^ ($/m$^3$) ($/AF) | 0.03 (36.6) | 0.91 (1119.5) |
| Total two-way option cost to Urban ($M) | 6.5 | 197.5 |
| Urban savings from two-way option usage ($M)^^ | 291.9 | 101 |

*Assumes exercise fee of $0.01/m$^3$ ($15/AF) in Scenario 1, Assumes $0.02/m$^3$ ($25/AF) exercise fee in Scenario 3;
**Assumes exercise fee of $0.02/m$^3$ ($25/AF) in Scenario 1, Assumes $0.57/m$^3$ ($700/AF) exercise fee in Scenario 3;
^ Average option cost calculated using the sum of all option fees and exercise fees across the simulation, divided by the total amount of water re-allocated;
^^Assumes water right purchases in 1971 were at $1.62/m$^3$ ($2000/AF), adjusted to 2023 dollars

## 4 Discussion

This analysis suggests two-way options could be a useful tool for facilitating more rapid re-allocation of water between irrigators and municipalities under variable hydrologic conditions, leading to less expensive municipal supply reliability and increased agricultural productivity. Historically, market-based transfers of water rights have been dominated by permanent sales of senior water rights from irrigators to municipal users, with occasional single year leases of surplus water rights back to irrigators. The continued growth of urban demand, the challenges associated with developing new supplies, and an increasingly volatile climate all suggest that new institutional approaches to managing hydrologic variability are needed. The state of Colorado's Water Plan identifies Alternative Transfer Methods (ATMs), defined as solutions to reallocate water without the permanent transfer of water rights from irrigated lands, as an important step in addressing the state's water challenges (Mahmoudzadeh Varzi & Grigg, 2019). Interest in ATMs increased as a result of the severe drought in 2002-2005, which drove a number of legislative efforts, most relevant to this work, perhaps, is the legislation allowing one-time regulatory approval for multi-year leases (Womble & Hanemann, 2020a). The TWO contracts are well suited to take advantage of this change, as a 10-year contract could easily cover several years in which the option would be exercised and water transferred, cutting transaction costs per lease substantially. Furthermore, if one assumes that the 10-year contract could be renewed relatively easily, given that approvals for it had already been granted, the transaction costs per unit of water transferred would decline even more. In addition, irrigation water across the Western U.S. have long been thought of as a source for meeting growing municipal and industrial demands, and this has generally been seen by irrigators as a threat to the economic vitality of their communities (Devine, 2015; Lounsberry, 2019). While municipalities' goal of providing a reliable water supply will likely continue to be the priority in most regions, these results suggest that this goal can be met with less impact on agricultural activity.

The TWO contracts provide a tool by which irrigators and municipalities could create mutually beneficial agreements that allow irrigators to increase their production in wet and normal hydrologic years, while earning a steady income in all years (option fees) and even more during dry years (exercise fees). This is particularly true in cases where dry year transfers are priced at levels in line with municipalities' willingness-to-pay (pricing scenario 3), which seems most consistent with the behavior observed in many western regions. In addition, the TWO contracts could provide municipalities with an ability to reliably meet their demands during even the worst droughts for substantially less than the cost of doing so through the purchase of sufficient permanent rights to meet the same objective. In this way, the gains from the use of TWO contracts disproportionately accrue during dry periods, when the system is under the greatest stress, ultimately making it a useful tool to mitigate the supply- and financial-risks of drought. Developing new strategies to improve the responsiveness of water markets, or any institutional structure governing water allocation, to variable hydrologic conditions will have increasing importance in a future in which both competition for water and uncertainty as to its availability are growing. New tools such as the two-way option have the potential to contribute to improved strategies in a manner that can benefit both agricultural and urban communities.

## 5 Conclusion

Current tools for reallocating water across the Western U.S. are slow and expensive, leading to a situation in which both irrigators and municipalities are less able to cost-effectively manage drought. When evaluated across the 63-year observed hydrologic record, communities in the Northern Water Conservancy District of Colorado appear to have the potential to use a two-way option contract to more rapidly and less expensively transfer water between the two groups as hydrologic conditions vary. As such, this instrument can provide an attractive alternative to the existing approach which generally involves a one-way flow of permanent rights from agricultural to urban use. While this analysis focused on Colorado, the option contract structure described could be adapted for use across the Western U.S., or in fact any region in which prior appropriative rules are in place, giving water users a water re-allocation tool that improves the responsiveness of existing institutions to water scarcity.

**Acknowledgments**

We thank members of the Center on Financial Risk in Environmental Systems at the University of North Carolina at Chapel Hill, collaborators at Cornell University, as well as the Integrated Multisector Multiscale Modeling (IM3) team for their consistent support and feedback. This research was supported by the U.S. Department of Energy, Office of Science, as part of research in MultiSector Dynamics, Earth and Environmental System Modeling Program under Contract DE-AC05-76RL01830. The authors declare no competing interests.

**Open Research**

All data and code for this project, including figure generation, are available in a live repository (https://github.com/IMMM-SFA/hirsch_etal_2024_ef)

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