

1 **Two-Way Option Contracts that Facilitate Adaptive Water Reallocation in the**  
2 **Western United States**

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15 **Key Points:**

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

22 **Abstract**

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

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46 **Plain Language Summary**

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

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

63 **1. Introduction**

64         More frequent and severe droughts coupled with increased economic development,  
65 population growth, and growing uncertainty over climate change have created more complex  
66 water supply management challenges in the western United States (U.S.) (American Water  
67 Works Association, 2021; The Water Research Foundation, 2020; The World Bank, 2010; US  
68 EPA, 2021; WUCA, 2021). Urban water demands have increasingly reached or exceeded the

69 capacity of local water supplies (Deason et al., 2001; FAO, 2012; Siirila-Woodburn et al., 2021),  
70 while at the same time, new sources have become more scarce, more expensive to develop, and  
71 more difficult to permit regulatorily (Hansen, 2017; Tidwell et al., 2014). As such, western water  
72 utilities have been driven to become less reliant on new infrastructure to meet increases in water  
73 demand and have begun to focus more on conservation and their ability to acquire water from  
74 other users, usually agricultural. This occurs via various re-allocative mechanisms (Colorado  
75 Water Conservation Board, 2020), often involving market-based water rights transfers  
76 (Brookshire et al., 2004; Gleick, 2000; Howe et al., 1990; Leonard et al., 2019).

77         Western water markets operate within the prior appropriation doctrine (Burness & Quirk,  
78 1980), which in times of drought, leads to more senior rights holders (i.e., those with the oldest  
79 rights) having priority access to available water, while more junior rights holders often receive  
80 little or no water in dry periods (i.e., their rights are “curtailed”). By virtue of historical  
81 development patterns, irrigators often hold more senior rights (Dilling et al., 2019), while many  
82 municipalities hold more junior rights. As urban demands continue to grow, this disparity in  
83 seniority as well as differences in the value of water in urban and agricultural uses, drives  
84 activity in water markets. At present, water market transactions take the form of either permanent  
85 right transfers, or temporary leases, usually with water moving from agricultural to urban uses  
86 (Brewer et al., 2008; Carey & Sunding, 2001; Payne et al., 2014). The state of Colorado has the  
87 second most active market for permanent water rights of any state in the U.S., as measured by  
88 the value of transactions (\$79 million in 2015) (Womble & Hanemann, 2020b). Activity in  
89 Colorado’s water markets is largely influenced by growing urban demands, particularly along the  
90 Front Range which includes Denver and surrounding communities (WestWater Research, 2016).  
91 Given that the state’s surface water resources are fully allocated (Shupe et al., 1989; Womble,

92 2020), any group seeking to acquire rights to surface water, the primary source for most urban  
93 areas, must do so by purchasing existing rights. Water rights purchases from irrigators have often  
94 been the lowest cost alternative when a community is seeking additional supplies (Carey &  
95 Sunding, 2001; Easter et al., 1999; Howe et al., 1990; Leonard et al., 2019; Schwabe et al., 2020)  
96 making it likely that the market for transfers of permanent rights will continue to be very active  
97 (Christensen et al., 2004).

98         In order to ensure high levels of supply reliability in the face of both drought and future  
99 demand growth, Front Range municipalities, like many others across the Western U.S., have  
100 purchased a substantial volume of senior water rights from irrigators over time (Nichols et al.,  
101 2016; Payne et al., 2014). This shift in water right ownership has been in process for many years  
102 and has allowed municipalities to increase their supply in a manner commensurate with demand  
103 growth. During drought, however, the yield of a water right can decline, such that 1233 m<sup>3</sup> (one  
104 acre-foot) of rights is allocated less than 1233 m<sup>3</sup> (one acre-foot) of “wet” water (or sometimes  
105 none at all), so maintaining urban supply reliability during dry periods has typically been  
106 achieved through cities holding significantly more water rights than are required to meet demand  
107 under normal or wet conditions (Frick et al., 1990; Shupe et al., 1989). As an alternative, urban  
108 areas could maintain smaller volumes of permanent rights and supplement supplies to meet  
109 demands during drought via short-term water leases, which are also allowed in Western U.S.  
110 markets. The regulatory approval process for leases is, however, often lengthy and expensive  
111 making them less useful and/or practical for managing short-term drought (Womble &  
112 Hanemann, 2020b). Thus, municipalities typically maintain large volumes of infrequently used,  
113 but expensive, permanent water rights in order to manage drought risk, which reduces shortfalls  
114 in all but the driest years, but leaves them with substantial volumes of surplus water most of the

115 time. This contrasts with the situation faced by irrigators, who have been transferring permanent  
116 rights to municipalities for many years and often experience significant collective shortages  
117 during drought. These historical transfers out of agriculture have also left considerable acreages  
118 of arable land that could be made more productive via irrigation in wet and normal years (Malek  
119 et al., 2020). As a result, relative to the volume of water they could put to productive use,  
120 irrigators experience some level of water supply shortage in almost all years, leading to  
121 decreased agricultural production and decreased regional economic productivity (D. H. Smith et  
122 al., 1996). Having municipalities lease back some of their surplus water back to irrigators in  
123 normal and/or wet years could increase agricultural productivity, but once again, the time and  
124 costs associated with approving short-term transfers acts as a deterrent.

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

138 Metropolitan Water District of Southern California (MWD) holds 3.82 km<sup>3</sup> (3.1 million acre-  
139 feet) of water rights to meet average annual demand of 1.85 km<sup>3</sup> (1.5 million acre-feet)  
140 (Metropolitan Water District of Southern California, 2021). Similarly, communities along  
141 Colorado's Front Range (e.g., Boulder, Loveland, Longmont, Louisville, and Lafayette)  
142 currently hold 0.22 km<sup>3</sup> (177,000 acre-feet) of rights to meet an average demand of 0.07 km<sup>3</sup>  
143 (57,800 acre-feet) (Colorado Division of Water Resources, 2023a). It is also worth noting that  
144 despite maintaining very large rights surpluses during most years, urban utilities rarely lease  
145 water back to irrigators even during wet years (MacDonnell et al., 1990; Pritchett et al., 2008),  
146 with the transaction costs identified as contributing to this lack of market activity (Easter et al.,  
147 1999; Gardner & Miller, 1982; Leonard et al., 2019).

148         Recently, the state of Colorado, revised its temporary transfer rules, such that long-term,  
149 multi-year leasing agreements need only be approved once as opposed to each time a transfer is  
150 made, a change that could significantly reduce the transaction costs of leasing and increase the  
151 speed of re-allocation, making leases more attractive as a drought management tool (Justia US  
152 Law, 2022; Womble & Hanemann, 2020a). Nonetheless, there has yet to be any detailed analysis  
153 of how these new rules might translate into improved transfer agreement structures that would  
154 make leasing a more cost-effective reallocation mechanism (McLane & Dingess, 2013). While  
155 leasing agreements have often represented an attempt to provide the water market with more  
156 flexibility, they have typically been thought of in terms of a single year, one-way transfer, most  
157 often from irrigators to municipalities, but occasionally in the opposite direction (Brewer et al.,  
158 2008; Michelsen, 1994). This research seeks to explore the potential for a 'two-way option' that  
159 facilitates the temporary transfer of water in both directions using predetermined triggers based  
160 on hydrologic conditions (dry or wet) that are defined by a 'water availability' index. The option

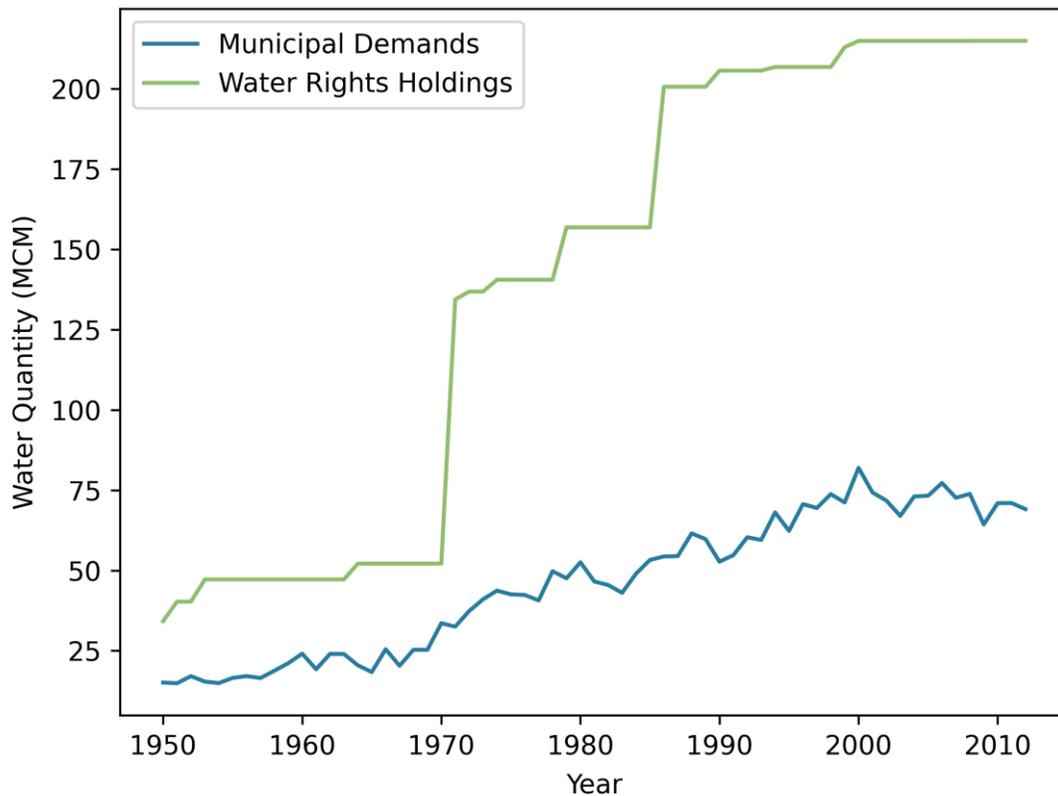
161 structure is defined such that constant payments (i.e., option fees) flow from buyer-to-seller each  
162 year, with a larger “exercise” fee paid when the water is actually transferred. By providing a  
163 multi-year contract structure that is well-defined and has received regulatory approval in advance  
164 of drought, this tool has the potential to assist both municipalities and irrigators in managing  
165 drought more cost-effectively. The two-way option (TWO) is tested in the Northern Colorado  
166 Water Conservancy District (Northern Water) that lies within the South Platte River Basin in  
167 Colorado, and which includes several urban centers (e.g., Boulder, Longmont), as well as over  
168 4047 km<sup>2</sup> (1 million acres) of irrigated agriculture. The region’s fully allocated surface water  
169 supply, rising urban demands, increasing water rights prices (stemming from increased  
170 intersectoral competition), and data availability make it ideal for investigating the performance  
171 of a new transfer instrument. The modeling framework developed to assess the performance of  
172 the proposed TWO contract structure includes consideration of the hydrologic, engineered, and  
173 institutional systems that govern water allocation in the region. The model adapts historical data  
174 (e.g., demands, transbasin flows, operations, and water rights) for input into the state of  
175 Colorado’s basin-specific water allocation model (StateMod) in order to assess water supply and  
176 demand conditions at individual irrigation diversion structures. The combination of  
177 supply/demand conditions and the value of irrigation water at each irrigation diversion structure  
178 allows for a detailed market simulation of lease prices across the historic hydrologic record that  
179 is then used to price the TWO contracts. The proposed TWO contracts offer the potential to  
180 reduce the surplus volumes of water rights municipalities must maintain as a hedge against  
181 drought, ultimately making more water available to agriculture in non-drought years. Results  
182 should provide useful information for municipalities and irrigators operating within prior-

183 appropriate institutions in the Western U.S., providing them with new insights into how they  
184 might facilitate more responsive and less expensive water reallocation.

## 185 **2 Methods**

186       Maintaining reliable water supplies across the Western U.S. in the face of varying  
187 hydrologic conditions and population growth has become increasingly difficult (Hadjimichael et  
188 al., 2020; Kasprzyk et al., 2009; Marston et al., 2020; Overpeck & Udall, 2020; R. Smith et al.,  
189 2022). This is particularly true for municipalities as they often have relatively junior water rights  
190 that are assigned a lower priority in the prior appropriation system and have needed to expand  
191 their water rights holdings to meet increased demands, particularly in the driest years (Levine,  
192 2007; Nichols et al., 2016). Therefore, municipalities often purchase more senior water rights  
193 from irrigators. Given that the volume of water actually allocated to a right varies with  
194 hydrologic conditions (dry = less water delivered), municipalities typically purchase significantly  
195 more rights than required to meet their average demands in order to meet demand during  
196 drought. Despite continued population growth, these acquisitions have slowed since the early  
197 2000's (Figure 1), largely a result of declining per capita urban usage (Meyer, 2010).  
198 Nonetheless, many municipalities continue to maintain many more rights than are used in a  
199 typical year, which often results in less water being available for agriculture (Conran, 2013). A  
200 primary motivation for the municipal approach is managing drought, as acquiring additional  
201 supplies on relatively short notice given current institutions is very difficult. This problem could  
202 be mitigated if short-term leases were less expensive and/or quicker to gain regulatory approval,  
203 thereby reducing municipalities need to hold large volumes of infrequently used rights.  
204 Similarly, reductions in agricultural production might be mitigated in wetter, or even normal,  
205 years if municipalities leased surplus water back for agricultural use in these years, but the

206 combination of transaction costs and low willingness-to-pay on the part of irrigators means such  
 207 transfers are relatively uncommon (Shupe et al., 1989). While the transfer of water rights (either  
 208 permanently or via lease) from irrigators to municipalities, especially as a means of mitigating  
 209 drought has received significant attention in the literature (Burns et al., 2022; Characklis et al.,  
 210 1999, 2006; Colby, 1988; Howe & Goemans, 2003; Kirsch et al., 2009; MacDonnell et al., 1990;  
 211 Marston & Cai, 2016; McLane & Dingess, 2013; Pritchett et al., 2008), approaches involving  
 212 transferring water in the opposite direction, from municipalities to irrigators during wet/normal  
 213 years, has received much less attention (Colorado Water Conservation Board, 2020).

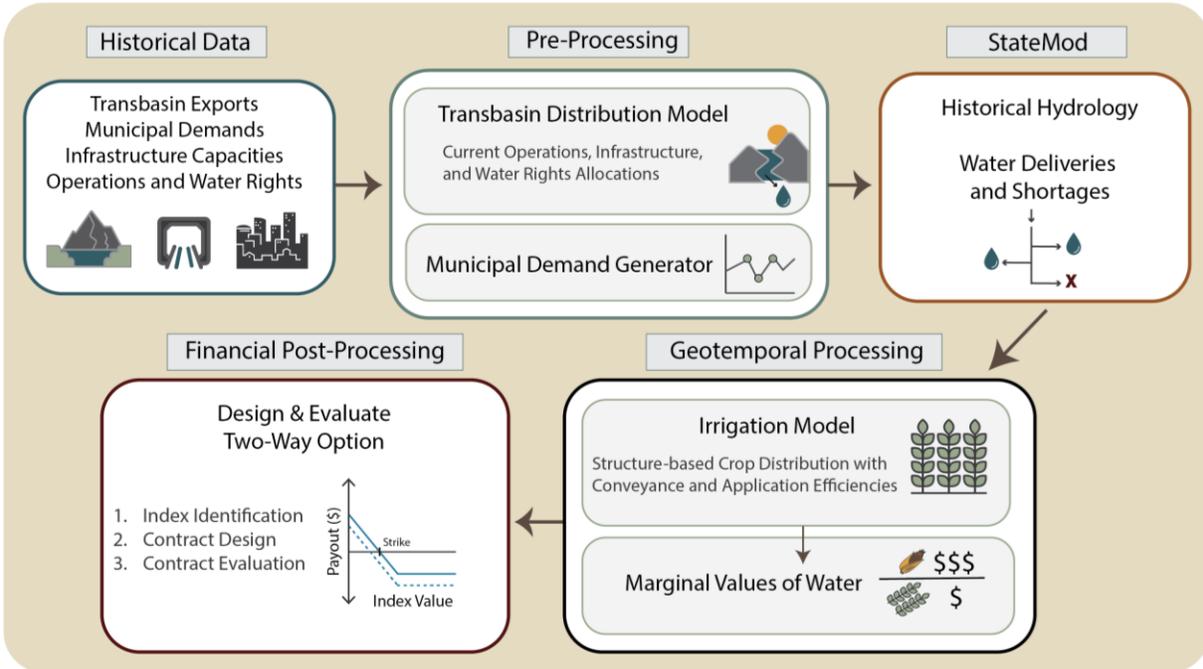


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215 **Figure 1.** Aggregate water right holdings (storage) for Front Range communities of Loveland, Longmont,  
 216 Louisville, Lafayette, and Boulder (hereafter Northern Water Municipalities) and their historical  
 217 collective demands (1950-2012)

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

222



223

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

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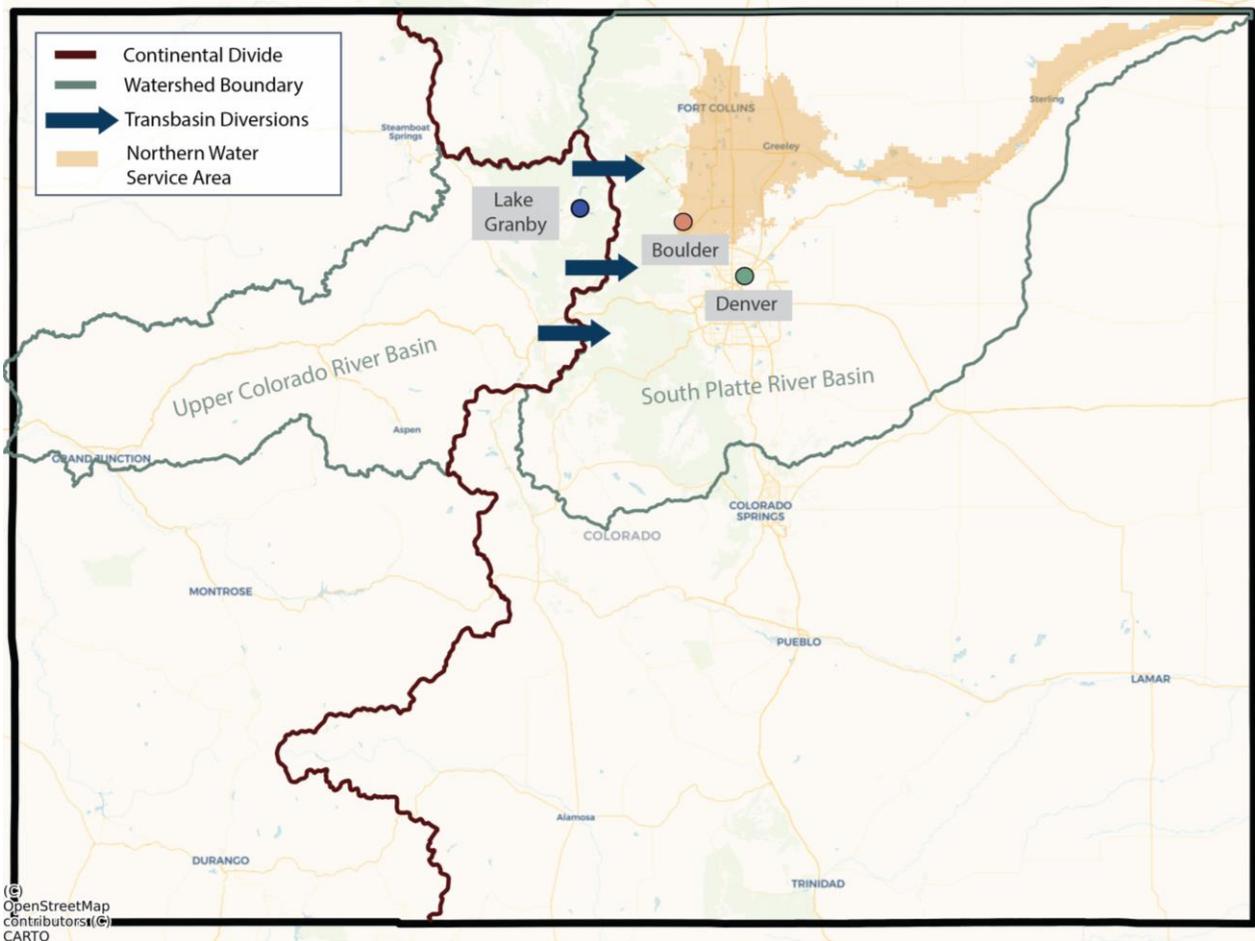
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227 The TBWAM framework is central to our evaluation of the performance of the proposed  
 228 TWO contracts. Its components link the natural (where and when water is hydrologically  
 229 available), engineered (how much water can be delivered to each location and when), and  
 230 institutional (to whom the water is delivered as determined by water rights priority) systems that  
 231 shape supply, demand, and financial outcomes. The TBWAM framework is initiated by adapting  
 232 and then calling historical data (e.g., demands, transbasin flows, operations, and water rights) as  
 233 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

234 water supply and demand conditions. Supply and demand outputs then serve as inputs to the  
235 irrigation model (Section 2.2.4) which determines irrigation water deliveries, in accordance with  
236 prior appropriation rules, to individual diversion structures that serve acreage with a defined mix  
237 of crops and irrigation technologies. This information is used in combination with crop budget  
238 data (Colorado State University Extension, 2019) to calculate the marginal value of water for  
239 each irrigated parcel. These marginal values are then ordered to create irrigation water demand  
240 functions (i.e., from highest to lowest marginal value), which are then reversed to create what is  
241 in effect a municipal supply function (i.e. irrigation marginal values are reordered from lowest to  
242 highest) which is then combined with information on municipal water demands to identify a  
243 market-clearing price for leases. It should be noted that the operative value for municipal  
244 demand is actually the municipal “shortfall” defined as the difference between municipal  
245 demand and the allocation to municipal use in that year. Municipal demand is considered to be  
246 completely inelastic over the range of relevant marginal water values, with the intersection of the  
247 municipal supply function (i.e. the reordered irrigation supply function) and the demand shortfall  
248 determining the lease price. The distribution of lease prices in dry years (defined later) across the  
249 63-year hydrologic record is then used to price option contracts moving water from irrigation-to-  
250 urban uses. A similar process is used to characterize the marginal value of irrigation water  
251 (demand) in wet years, with the supply available for leasing from municipalities defined based  
252 on municipal surplus (defined later), and prices defined by their intersection. The distribution of  
253 lease prices in wet years is then used to price option contracts transferring water from urban-to-  
254 agricultural users. Lastly, the performance of the TWO contracts is evaluated across two distinct  
255 water right allocation regimes (one current, one historical) and four different pricing scenarios.

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

262 **2.1 Study Region**  
 263



264  
 265 **Figure 3.** *The Upper Colorado and South Platte River Basins including notable Northern Water*  
 266 *infrastructure (Lake Granby) and key transbasin diversions.*  
 267

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

277           The South Platte River is also relatively small, having a native annual supply (water  
278 available without human intervention) of only 1.78 km<sup>3</sup> (1.44 million acre-feet), whereas the  
279 Colorado River which originates on the west slope of the Divide has a native annual supply of  
280 8.3 km<sup>3</sup> (6.74 million acre-feet) (Colorado Water Resources Research Institute, 1995). In order  
281 to meet growing demands along the Front Range, high capacity transbasin tunnels divert water  
282 from the Upper Colorado River Basin (UCRB) into the SPRB. Fifty percent of the Front Range  
283 communities’ water supplies comes from transbasin diversions, accounting for approximately  
284 0.65 km<sup>3</sup> (530,000 acre-feet) of water per year on average (State of Colorado, 2015; Water  
285 Education Colorado, 2019). The Colorado Big-Thompson Project (C-BT) is the largest  
286 transbasin diversion system and was developed by the U.S. Bureau of Reclamation. Operated by  
287 the Northern Colorado Water Conservancy District (Northern Water), the C-BT exports up to  
288 0.38 km<sup>3</sup> (310,000 acre-feet) of water from the UCRB into the Northern Water Conservancy  
289 District (Northern Water) where it supplies over 1 million residents and 2428 km<sup>2</sup> (600,000  
290 acres) of irrigated farmland along the Front Range. The C-BT system consists of 56 km (35

291 miles) of tunnels, 153 km (95 miles) of canals, and 12 reservoirs. Within the UCRB, Northern  
292 Water holds relatively junior water rights, which it uses to divert Colorado River water into Lake  
293 Granby, the largest reservoir within the C-BT with a total storage capacity of 0.67 km<sup>3</sup> (539,800  
294 acre-feet). Water allocation from the UCRB to Northern Water is governed by prior  
295 appropriation based on the rights it holds in the UCRB, however, once water crosses the  
296 Continental Divide it is allocated to C-BT rights holders on a pro rata basis according to the  
297 number of C-BT “units” each user maintains.

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

314           The C-BT serves both municipal and agricultural users and the value of C-BT units has  
315 risen with increasing urban demands such that the purchase price of a single unit has recently  
316 been as high as \$75,000 (or nearly \$97,500/AF based on an average annual yield of 862 m<sup>3</sup>  
317 (0.7AF)/unit. The C-BT water is paired with native supplies in the SPRB which are subject to  
318 prior-appropriation, and users within Northern Water's boundaries use water from both sources  
319 to meet their demands.

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

## 331 **2.2 Transbasin Water Allocation Model Framework (TBWAM)**

332

### 333 **2.2.1 StateMod**

334

335           To evaluate the potential of the two-way option, the TBWAM framework (Figure 2) is  
336 built around StateMod, a nodal network water system model developed for all major Colorado  
337 sub-basins as part of the Colorado Decision Support Systems (CDSS), which is capable of  
338 simulating water allocations consistent with prior appropriation rules. The South Platte StateMod

339 version, in particular, simulates water allocations through a 63-year hydrologic record (1950-  
340 2012) at approximately 1,000 diversion nodes and includes 1.92 km<sup>3</sup> (1,556,000 acre-feet) of  
341 reservoir storage capacity (Colorado Water Conservation Board, 2017). StateMod is currently  
342 used by the state to analyze and assess historical and future water management policies and  
343 decisions, such as monitoring allocations and approving proposed water market transactions. The  
344 state's usage of StateMod as a decision-support tool makes this an appropriate model for  
345 understanding how a new type of water transfer contract could promote re-allocative efficiency  
346 in this complex basin.

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

357 While 'baseline' StateMod models exist for all other basins in Colorado, the open source  
358 'historical' dataset for the South Platte model only tracks water allocations historically through  
359 time. To answer the questions posed in this analysis, the inputs to the South Platte model must be  
360 carefully adapted to represent the basin as it was operated at the end of the available hydrologic  
361 record (2012), a point at which conditions with respect to infrastructure, demands, and sectoral

362 water use are consistent with current conditions. This includes updating infrastructure, demands,  
363 operations and water rights, such that the version of StateMod used to represent the SPRB in this  
364 work differs significantly from that currently used by the State of Colorado (which plans to  
365 update this model to provide similar capabilities as the model used in this work in the coming  
366 years). For more information on modifications to StateMod made in this work, see Supplemental  
367 Information Text S1 and Table S1.

### 368 **2.2.2 Transbasin Distribution Model**

369

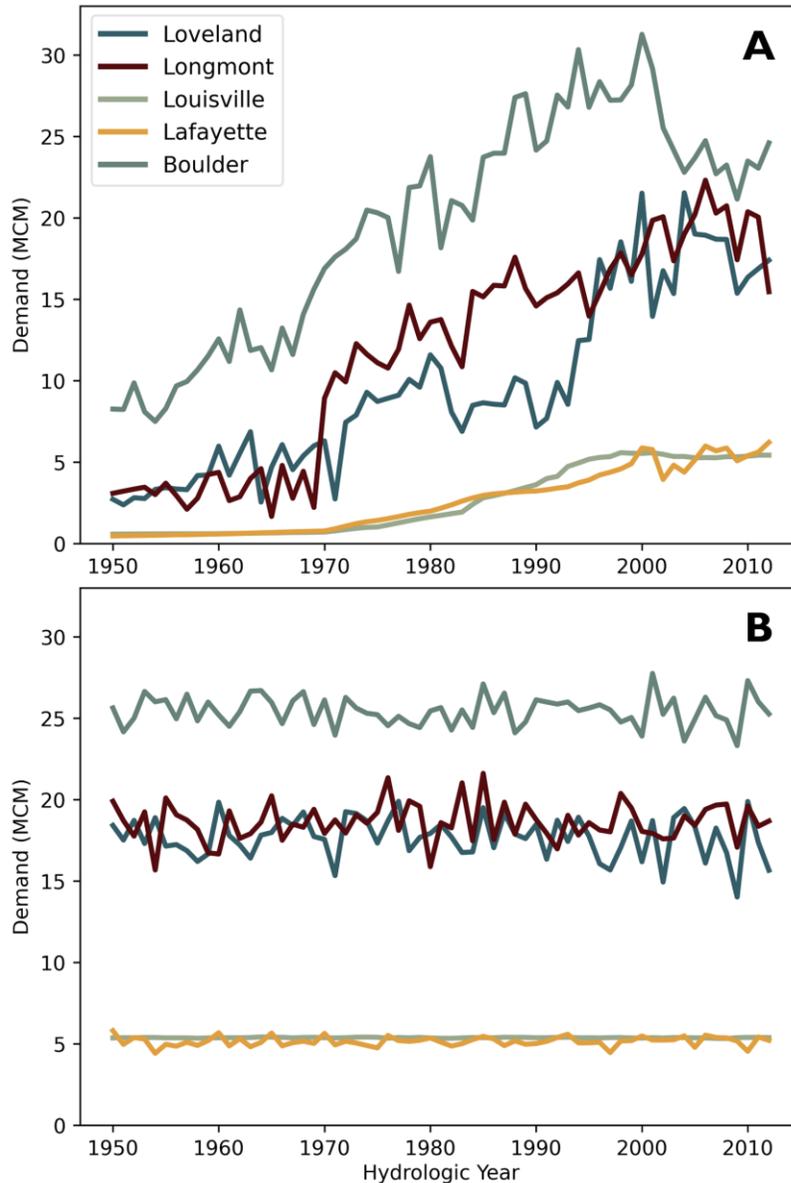
370 The Transbasin Distribution Model (housed within TBWAM, Figure 2) is a Python-based  
371 modeling platform designed around StateMod that adapts transbasin diversions from the UCRB  
372 (where supplies originate) into a nodal network of deliveries within the SPRB, including  
373 Northern Water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

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

385

### 386 2.2.3 Municipal Demand Generator

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



391

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

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

#### 399 **2.2.4 Value of Irrigation Water**

400  
401 The TBWAM framework uses crop data, resolved to the individual land parcel scale,  
402 provided by the State of Colorado (Colorado Division of Water Resources, 2023b) to  
403 characterize the supply of irrigation water available to municipalities in dry years and the  
404 demand for irrigation water from municipalities in wet years (municipal demand for water in dry  
405 years and the supply of municipal water available in wet years is described later). With regard to  
406 wet years, it is important to note that the transfer of water rights from agricultural to urban use in  
407 recent decades has resulted in significant tracts of fertile, but unirrigated land that could make  
408 productive use of irrigation water even during relatively wet years (Water Education Colorado,  
409 2021). Irrigation water is often diverted from either a stream or primary canal at a diversion  
410 structure (e.g., weir) that directs water to individual land parcels. StateMod represents irrigators  
411 in the SPRB with a unique diversion structure identifier, one that can be connected with  
412 Colorado's irrigated lands geographic information system (Colorado Division of Water  
413 Resources, 2023b). This model first links individual parcels with the identifier, after which  
414 StateMod generates outputs on water delivery/shortage at the diversion structure in accordance  
415 with water rights priority. At each parcel, the acreage, crop type, conveyance losses (from  
416 diversion structure to the field) and application (flood or sprinkler) efficiencies are known from  
417 the State of Colorado's Consumptive Use Model, StateCU (Colorado's Department of Natural

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

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

$$426 \quad IWR_{s,crop} = PET_{s,crop} - ER_{s,crop} \quad (1)$$

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

429

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

$$434 \quad W_{s,crop}(AF) = A_{s,crop} * \frac{IWR_{s,crop}}{12} * \frac{1}{n_{s,app}} * \frac{1}{n_{s,ditch}} \quad (2)$$

435 Where,  $W$  = water delivered (AF),  $s$  = structure identifier,  $crop$  = crop type,  $A$  = area (acres),

436  $IWR$  = irrigation water requirement (in), and  $n_{app}$  = application efficiency,  $n_{ditch}$  = conveyance

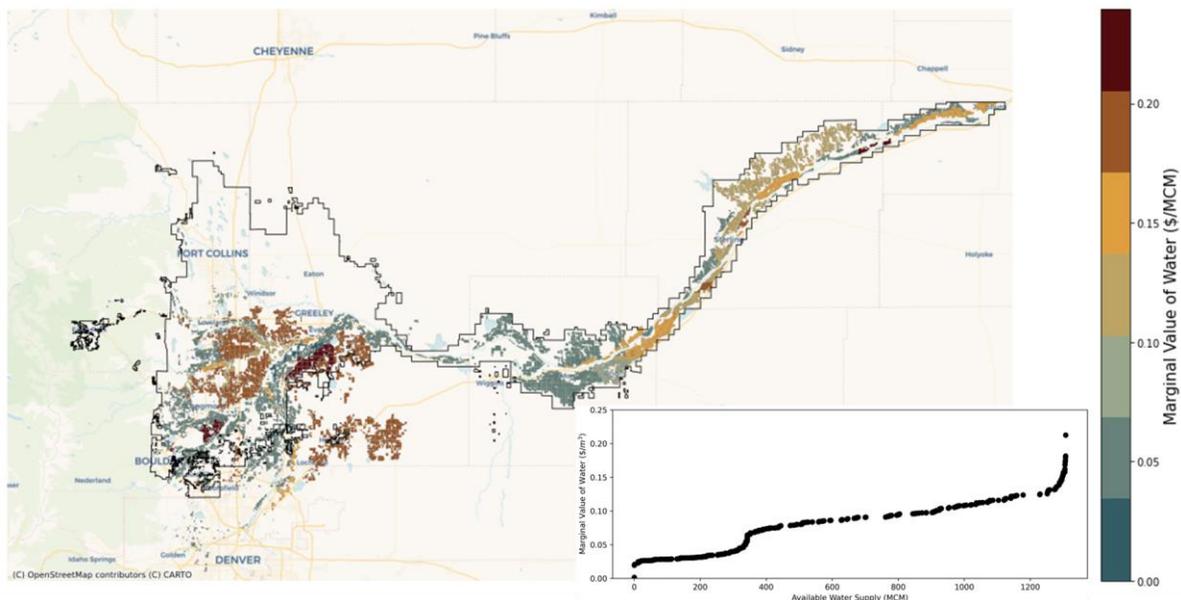
437 efficiency

438

439 The marginal value of water (or the value of an additional 1233 m<sup>3</sup> (1 acre-foot) of usage) is  
 440 derived by using the marginal value of production ( $MNB_{crop}$ , or the value from an additional  
 441 0.4047 hectares (1 acre) of production) from crop enterprise budgets developed by Colorado  
 442 State University (see Supplemental Information Table S2), as well as the diversion structure and  
 443 crop specific water delivery values calculated above to estimate the marginal value of water for  
 444 each crop type at each diversion structure ( $MNB_{H2O,s,crop}$ ) such that:

$$445 \quad MNB_{H2O,s,crop} = \frac{MNB_{crop}}{W_{s,crop}} \quad (3)$$

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



451  
 452 **Figure 5.** Marginal value of water at each diversion structure under hydrologic conditions reflective of  
 453 the year 1955 (the driest year on record). The municipal supply function (at lower right) represents all  
 454 irrigation water allocated to individual land parcels in the Northern Water District and which could be  
 455 leased by municipalities to compensate for shortfalls.

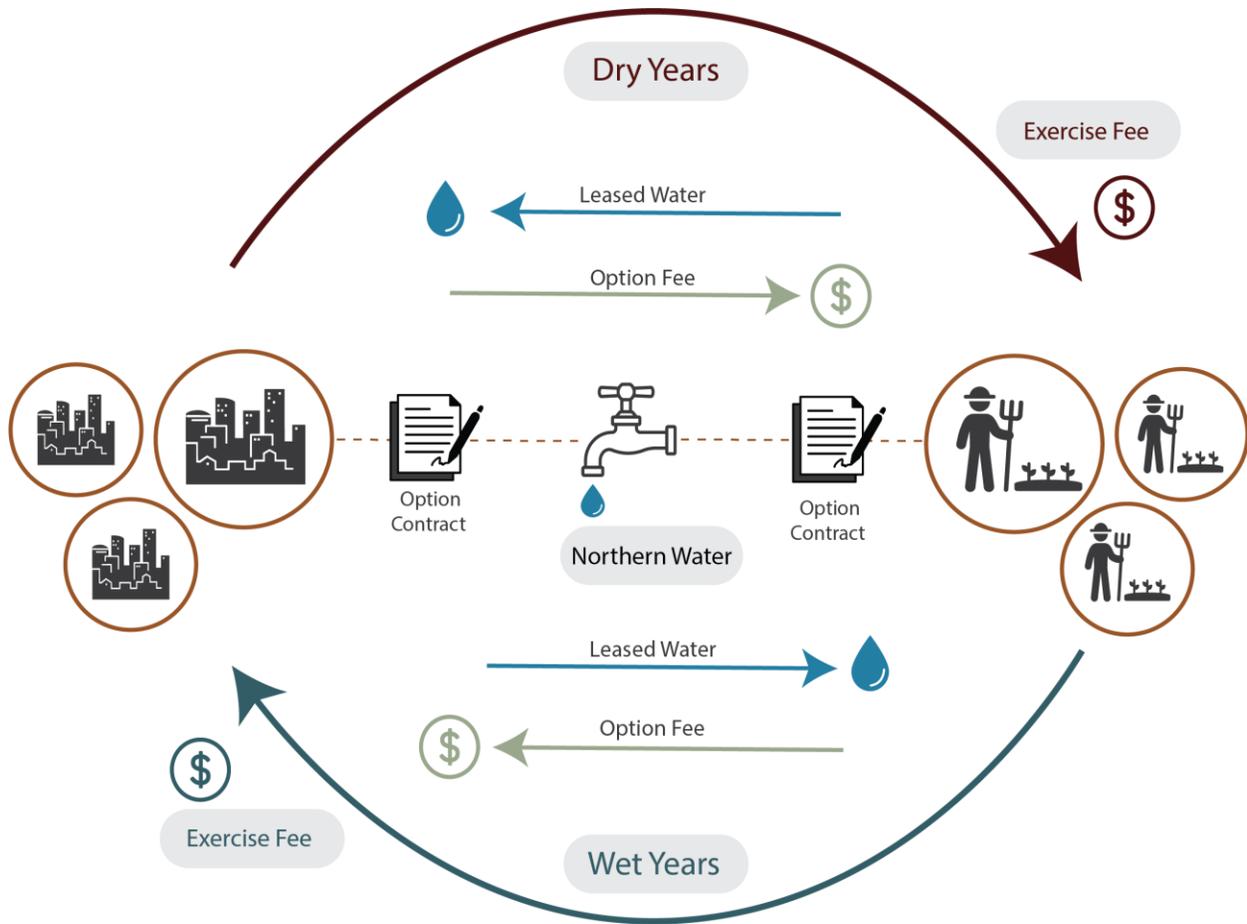
456 In this case, the marginal value of irrigation water is represented as a supply function for  
457 municipal buyers in dry years, such that the market price of leases can be determined with  
458 knowledge of the municipal shortfall, that is the difference between municipal supply and  
459 demand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

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

### 471 **2.3 Two-Way Option (TWO) Contracts**

472 The Two-Way Option (TWO) is actually a pair of option contracts that facilitate the  
473 transfer of water from irrigators to municipalities in dry years and in the opposite direction  
474 during wet years, with the triggering and direction of transfers linked to the prevailing water  
475 supply conditions (Figure 6). The municipalities buying water in dry years are not necessarily  
476 those selling water to irrigators in wet years, nor are the irrigators selling to cities in dry years  
477 necessarily the same ones that buy water from cities in wet years, so the operation of the market  
478

479 for these contracts would be facilitated by one entity serving as the “market maker” and offering  
 480 both simultaneously. In this case, Northern Water is well positioned to play this role.



481  
 482 **Figure 6.** *Structure of two-way option contract*

483  
 484 Option contracts are widely used in financial markets, and while their consideration in a  
 485 water market context is not unprecedented (Characklis et al., 2006; Hadjigeorgalis, 2009; Kirsch  
 486 et al., 2009; Palomo-Hierro et al., 2015; Villinski, 2004; Williamson et al., 2008), they have  
 487 typically facilitated one-way transfers from irrigators to urban users. The TWO contracts give  
 488 both urban and agricultural users the right, but not the obligation, to lease water (i.e., exercise the  
 489 option) when specified conditions linked to water availability (described in the next section)

490 prevail. The option contract includes both an up-front fixed yearly payment, the “option fee”,  
491 and a pre-determined “exercise fee” paid when conditions lead to the option being triggered and  
492 the transfer of the leased water completed. The exercise fee is constant each year, and is set at  
493 what is considered a reasonable level (in most pricing scenarios values from  $\$0.01/\text{m}^3$  -  $\$0.02/\text{m}^3$   
494 ( $\$15$ - $25$  per AF) per year were tested), and the annual option fee is then determined using this  
495 exercise fee and information on the distribution of lease prices derived from simulations across  
496 historical hydrologic conditions, with the option fee then adjusted to account for risk. For greater  
497 detail on option pricing, see Supplemental Information Text S2.

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

512

### 513 **2.3.1 Colorado Big-Thompson Water Supply Index (CBI)**

514

515 This analysis uses the ‘Colorado Big-Thompson Water Supply Index’, or CBI, developed

516 by Zeff et al. (2023) as a measure of water availability on the west slope of the Continental

517 Divide that is the source of transbasin diversions moved to the Northern Water District. The CBI

518 is computed monthly and includes the sum of water storage in Northern Water’s largest west

519 slope reservoir, Lake Granby, snowpack in the UCRB (another measure of stored water), as well

520 as year-to-date transbasin diversions from the UCRB to the Northern Water District (Equation

521 4). Snowpack estimates are calculated assuming a linear relationship between observed

522 snowpack observations (provided by the USDA National Water Climate Center) and remaining

523 cumulative inflows into Lake Granby as calculated by Zeff et al. (2023). The combination of

524 these components gives a running monthly estimate of C-BT water supplies available in the

525 UCRB for diversion across the Continental Divide to the Northern Water District, such that:

$$526 \quad CBI_t = S_t + Sm_t + D_t \quad (4)$$

527 Where,  $t$  = time (month);  $CBI_t$  = C-BT water supply index ( $\text{km}^3$ );  $S_t$  = storage in Lake Granby

528 ( $\text{km}^3$ );  $Sm_t$  = remaining snowmelt estimate ( $\text{km}^3$ ); and  $D_t$  = year-to-date diversions through the

529 Adams Tunnel ( $\text{km}^3$ )

530

531 This analysis uses the CBI value as an index with defined thresholds for dry and wet years that

532 ‘triggers’ the exercise of the two-way options, leading to leases from agriculture-to-urban in dry

533 years and from urban-to-agriculture in wet years. The CBI index is compared to the defined

534 wet/dry threshold values (defined in the next sections) on March 1<sup>st</sup>, thereby triggering the

535 exercise of options (i.e. leasing) in advance of the April to October growing season in the South

536 Platte region (National Center for Interstate Compacts, 1926).

### 537 **2.3.2 Dry Years**

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

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

553

### 554 **2.3.3 Wet Years**

555           The wet-year TWO contracts are 'triggered' when the *CBI* index value exceeds  $0.98 \text{ km}^3$   
556 (800,000 acre-feet), an event that has occurred 22 times over the 63-year historical record. This  
557 level of water availability has been, throughout the hydrologic record, associated with spills at  
558 Lake Granby. The rationale for choosing this threshold is that if Lake Granby is spilling,  
559 municipal water rights will have been fulfilled to the decreed amount, and any spilled water not

560 leased would cease to have economic value to the municipal rights holders, so they would have  
561 nothing to lose by leasing it. While it is conceivable that municipalities might lease more water  
562 during these very wet years or lease in years that were less wet, doing so could reduce their  
563 reservoir storage and reduce their ability to meet demand in future years (even if only slightly).  
564 As such, the amount of water considered available for wet-year options is likely conservative and  
565 should probably be considered a lower bound.

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

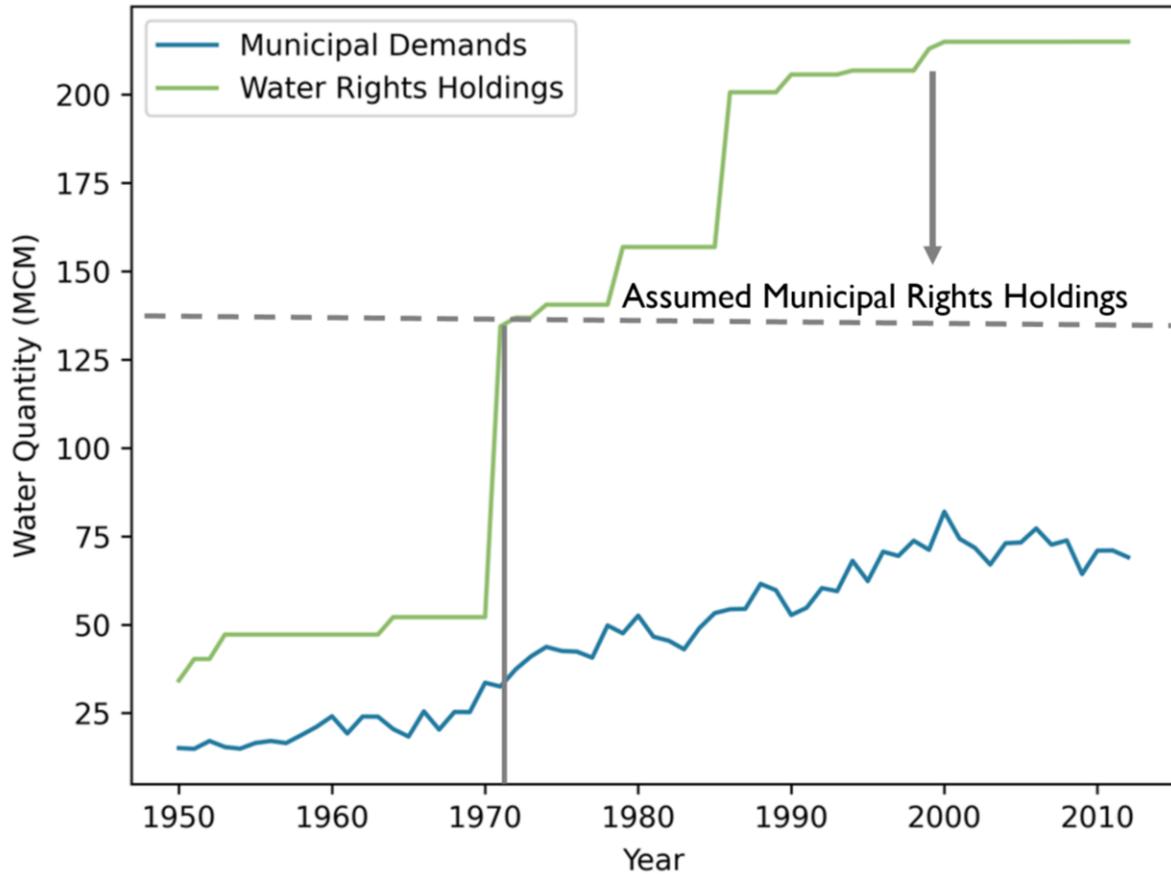
576

#### 577 **2.3.4 Water Right Holding Regimes**

578         The performance of the TWO contracts is simulated within two separate and unique  
579 water right holding regimes. One regime reflects current water right holdings in which  
580 municipalities have chosen to purchase water rights well in excess of that required to meet  
581 demands in a normal hydrologic year to ensure supply reliability during drought. As municipal  
582 right holdings have plateaued since the early 2000's (Figure 7), the use of 2012 right holdings

583 are considered reflective of “current” conditions, and this is also consistent with the availability  
584 of data from the state of Colorado in other areas (which is limited after 2012, as described).

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



603

604 **Figure 7.** Reduction in water right holdings for Northern Water Municipalities if rights were frozen at  
 605 1971 levels, compared with their demands observed historically (1950-2012).

606

607

### 608 2.3.5 Pricing Scenarios

609

The two water right holding regimes are also evaluated across four individual pricing

610 scenarios. The simulated market-clearing prices for leases described earlier are generated across

611 the historic hydrologic record and represent a somewhat idealized market with prices predicated

612 on the marginal value of water in irrigated activities. While the prices generated in this way are

613 instructive and consistent with theory, particularly for dry year transfers from irrigators to

614 municipalities, they likely represent something of a lower bound. So, in addition to these

615 “market clearing price” scenarios, several additional pricing scenarios are considered (Table 1).

616 Alternative pricing scenarios 2 and 3 involve prices for dry and wet years, respectively, that were

617 selected on the basis of empirical data from Colorado and other Western U.S. regions. In these,  
618 municipalities are assumed to be willing to lease water to irrigators in wet years at a constant rate  
619 of  $\$0.02/\text{m}^3$  ( $\$30/\text{AF}$ ), a price consistent with that recently charged by Boulder when it leased  
620 water back to agriculture (City of Boulder, 2023). In scenarios 3 and 4, irrigators are assumed to  
621 lease water to municipalities at a price closer to the cities' willingness-to-pay, as opposed to the  
622 (lower) marginal value of water in irrigation. In this case, a flat rate of  $\$0.81/\text{m}^3$  ( $\$1,000/\text{AF}$ ) is  
623 used, a price that is consistent with ag-to-urban leases in several of the more competitive water  
624 markets in the Western U.S (WestWater Research, 2021).

625         Throughout this analysis municipal demands are assumed to be inelastic, with the  
626 quantity of water demanded remaining constant across the range of water values considered. This  
627 seems reasonable as only a relatively small portion of a municipality's total water supply is being  
628 purchased using TWO contracts. In the current rights holding regime, less than 5% of the  
629 municipalities total water supply is being filled using TWO contracts. If a utility were to buy 5%  
630 of its raw water supply (high in the current rights regime) at  $\$0.81/\text{m}^3$  ( $\$1,000/\text{AF}$ ), that would  
631 translate to an increase of  $\$0.04/\text{m}^3$  ( $\$50/\text{AF}$  or  $\$0.15/1000$  gallons) in average cost. Using the  
632 1971 rights holding regime (Table 2), a larger fraction of supply is sometimes acquired via the  
633 TWO contracts, but even here the maximum increase in the monthly water bill is roughly 9%  
634 that of the average municipal water user (fixed + variable charges for 5,000 gallons per month in  
635 Boulder is roughly  $\$44.26$ , or  $\$2.34/\text{m}^3$ ) (City of Boulder, 2022). Assuming typical municipal  
636 price elasticities in the range of -0.3 to -0.1 (Olmstead et al., 2007), this would translate into a  
637 reduction in consumption of 1-3%.

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

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

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

654

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

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

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

657

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

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

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

660

661 **2.4 Caveats**

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

675 the two sectors in response to changing hydrologic conditions, such that transfers within sectors,  
676 while certainly possible, are not the focus.

677         With respect to the modeled market clearing lease prices used to set option prices, most  
678 hover in the  $\$0.01/\text{m}^3$  -  $\$0.08/\text{m}^3$  ( $\$14$ - $\$96/\text{AF}$ ) range regardless of the conditions or scenario,  
679 this is because a high percentage of irrigation water is used in low value activities (e.g., alfalfa,  
680 wheat). These market-clearing prices likely represent a lower bound, as irrigators in the Northern  
681 Water district will, as in other regions, have an awareness of municipalities higher willingness-  
682 to-pay for water and may organize themselves to take advantage of this information. At the  
683 same time, this analysis only includes consideration of urban-to-agricultural leases in wet periods  
684 associated with spills at Lake Granby. Municipalities may, in fact, be somewhat less risk averse  
685 and willing to option water to irrigators under less wet conditions. In any case, municipalities  
686 are always keen to avoid any perception that they are “profiting” from water, so while Scenarios  
687 1 and 4 involve cities leasing water to agriculture at prices reflecting the highest marginal value  
688 in irrigation during wet periods, evidence from the small amount of urban-to-agricultural leasing  
689 suggests that they typically charge a relatively nominal fee  $0.02/\text{m}^3$  ( $\sim\$30/\text{AF}$ ) (City of Boulder,  
690 2023). Given all this, Scenario 3 which involves lease prices for agriculture-to-urban during dry  
691 periods of  $\$0.81/\text{m}^3$  ( $\$1,000/\text{AF}$ ) and urban-to-agriculture leases in wet periods of  $0.02/\text{m}^3$   
692 ( $\$30/\text{AF}$ ) may be the most realistic.

693         It is also worth noting that while this analysis focuses on the Northern Water District, the  
694 City of Fort Collins (one of the largest cities serviced by Northern Water) is not included as the  
695 Cache la Poudre River Basin from which it draws the majority of its water supply is not  
696 explicitly modelled within StateMod. This analysis focuses on the other five major  
697 municipalities within the Northern Water District, such that when municipal surplus is assumed,

698 it constitutes an underestimate based on a) the limited urban-to-agriculture leasing that has  
699 occurred in the past and b) not having all Northern Water municipalities considered.

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

712 Finally, this study presents the potential improvements in water allocation, costs savings  
713 and agricultural productivity that occur only within the Northern Water District. Northern Water  
714 accounts for around 4% of Colorado water use, serving 17% of its urban population and 18% of  
715 its irrigated acreage. While extrapolating the value of the TWO contracts to the entire state of  
716 Colorado as well as the broader western U.S. holds promise, it is beyond the scope of this  
717 investigation's preliminary proof of concept, it seems reasonable to assume that the potential

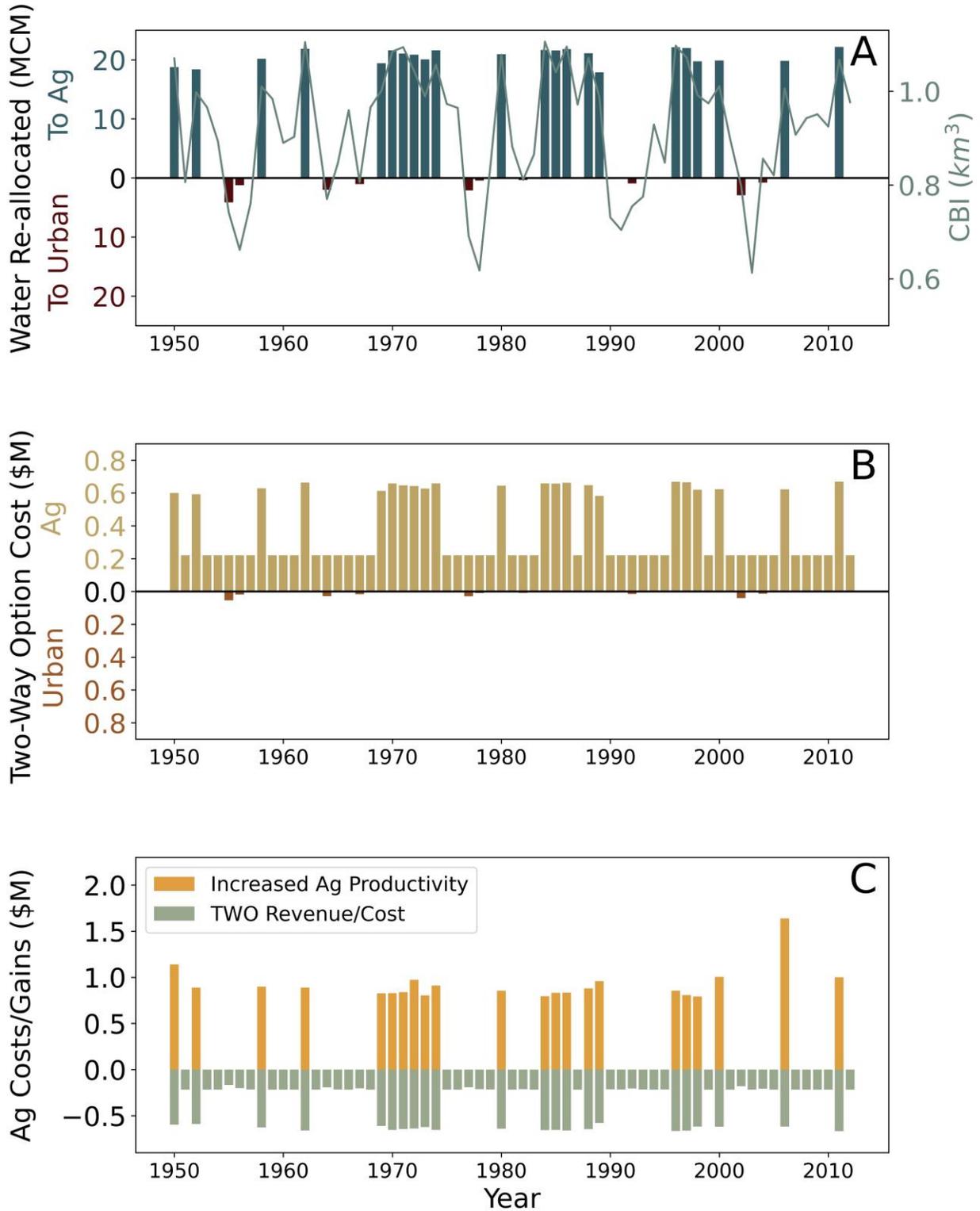
718 benefits of implementing the TWO concept more broadly could be much larger than what is  
719 presented here.

### 720 **3 Results**

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

#### 734 **3.1 Two-Way Option Performance under Current Water Rights Holdings**

735 Figure 8 presents TWO contract performance in the current rights holding regime under  
736 pricing scenario 1 (i.e. that in which options are priced via ‘market-clearing’ simulations). In  
737 order to fulfill municipal shortages across the 63-year historic record, municipalities require a  
738 multi-year option contract for the maximum annual shortage they face over this period, which  
739 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

743 Municipalities exercise some portion of these options in 20 dry years (when CBI < 700)  
744 over the 63-year historic record for a cumulative total of roughly 16.4 MCM (13,300 AF) (Figure  
745 8A). Irrigators, meanwhile, sign a multi-year option contract for use in wet years (CBI > 800) of  
746 22.2 MCM (17,982 AF) per year, or their maximum shortage in any wet year, when CBI > 800  
747 in order to avail themselves of surplus municipal water. Irrigators exercise some portion of their  
748 yearly options in 22 years over the 63-year simulation for a cumulative added supply of almost  
749 455 MCM (369,000 AF) (Figure 8A). In pricing scenario 1, the 'market-clearing' lease prices  
750 used to price the option contracts. Municipalities would pay a fairly nominal fee of \$4,000 per  
751 year ( $\$0.001/\text{m}^3/\text{yr}$  or  $\$1.20/\text{AF}/\text{yr}$ ) in risk-adjusted option fees (or \$250K across the 63-year  
752 record), and an exercise fee of  $\$0.01/\text{m}^3$  ( $\$15/\text{AF}$ ) during dry years (or \$200,000 in total) in  
753 which the water is actually leased/transferred (Figure 8B). Irrigators, on the other hand, would  
754 pay \$220K a year ( $\$0.01/\text{m}^3$  or  $\$12.2/\text{AF}$ ) in risk adjusted option fees (or \$13.9M across the  
755 simulation) and \$9.2M in exercise fees ( $\$0.02/\text{m}^3$  or  $\$25/\text{AF}$ ), as shown above the x-axis in  
756 Figure 8B. The relatively small volumes of municipal water leased to irrigators in wet years, and  
757 the high potential value of irrigation on some non-irrigated lands even during wet years accounts  
758 for the high prices for wet year leases in this market-clearing price scenario.

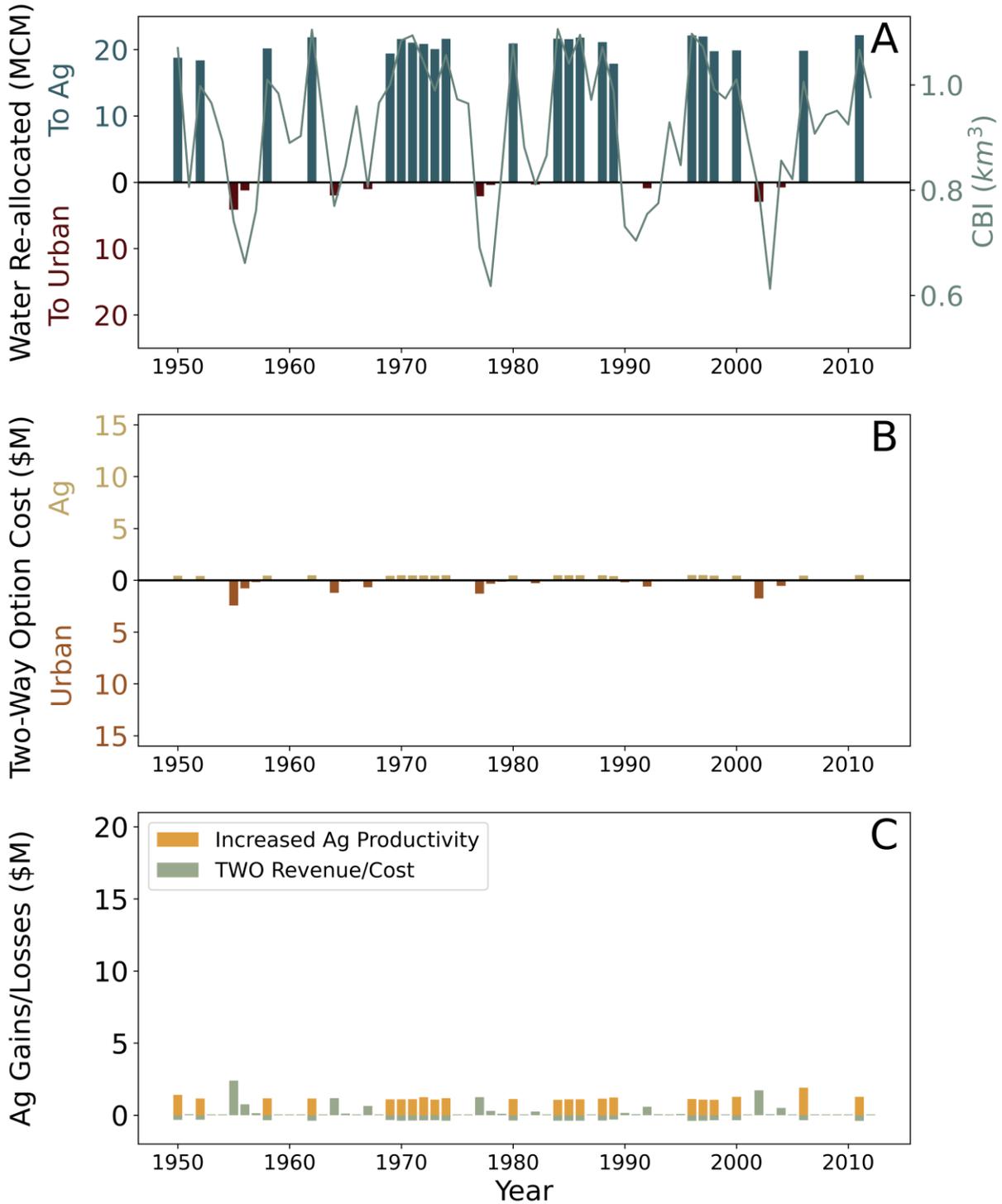
759 Over the simulation period, the average cost for TWO contract usage is  $\$0.02/\text{m}^3$   
760 ( $\$33.8/\text{AF}$ ) for municipalities, and  $\$0.05/\text{m}^3$  ( $\$62.6/\text{AF}$ ) for irrigators. In the driest hydrologic  
761 year, 1955, the maximum of 4.1 MCM (3,346 AF) is exercised by municipalities which the  
762 resulting payments to irrigators via both the option fee and exercise fee reducing the net cost of  
763 the TWO contracts to irrigators (Figure 8C). While irrigators end up paying municipalities more  
764 in option/exercise fees than they receive in return, the increased agricultural productivity  
765 irrigators (above x-axis on Figure 8C) generate as a result of the acquisition of optioned water in

766 wet years far outweighs. Even after irrigators pay \$22.6 million in option and exercise fees, the  
767 total agricultural gains equate to \$11.6 million, as the value of added agricultural productivity  
768 outpaces the cost of TWO contracts. With respect to Figure 8 as a whole, the dynamic  
769 capabilities of the TBWAM modeling framework can be seen in several ways. For example,  
770 when comparing wet years 2006 and 2011, water transfers from municipalities to irrigators are  
771 20 MCM (16,066 AF) and 22.2 MCM (17,982 AF) (Figure 8A). While it may be expected that  
772 agricultural gains would be higher in year 2011 given the larger volume of optioned water  
773 transferred, the gains are actually higher in year 2006 (\$2.3M, vs. \$1.7M), because higher valued  
774 irrigated parcels (e.g., sugar beets) are not allocated water in that year. This more nuanced  
775 finding is a direct result of being able to track the water rights and allocations to individual land  
776 parcels, a feature that is uncommon in the vast majority of similar studies. While irrigators  
777 benefit from the TWO contracts over the simulated period, municipalities also find themselves  
778 being able to lease water and reduce the overall costs of achieving their supply reliability  
779 objectives. To fully meet urban demands (i.e., no shortages over the simulation period) via  
780 permanent rights alone, bought at current prices (\$79/m<sup>3</sup> or \$97,500/AF), municipalities would  
781 have had to pay over \$326M. While this is the cost of owning these rights in perpetuity, so not a  
782 perfect comparison, using the TWO contracts to secure a similar level of supply reliability over  
783 the 63-year simulation period municipalities are only paying \$0.45M.

784         The pricing of leases, and the options prices based on them, is a critical factor in  
785 assessing TWO contract performance. Pricing scenario 3 assumes lease prices are similar to  
786 those observed in many water markets across the Western U.S., with irrigators leasing to  
787 municipalities in dry years for prices much closer to the municipalities willingness-to-pay, in this  
788 scenario assumed to be \$0.81/m<sup>3</sup> (\$1000/AF). Conversely, in this pricing scenario municipalities

789 are assumed to lease to irrigators for a constant price of  $\$0.02/\text{m}^3$  ( $\$30/\text{AF}$ ) in wet/normal years.  
790 Municipalities would still hold a multi-year contract for the maximum shortage they face  
791 throughout the simulation (4.1 MCM or 3,346 AF), such that the same hydrologic conditions  
792 yield the same volume of optioned water in each year (Figure 9A), but the costs to municipalities  
793 of securing this water in dry years is considerably higher (Figure 9B). Given the higher lease  
794 price of water, municipalities would now pay  $\$0.02/\text{m}^3$  ( $\$29.10/\text{AF}$ ) (or  $\$97,000$  per year) in  
795 risk-adjusted option fees, approximately  $\$6.1\text{M}$  across the 63-year record, and  $\$0.57/\text{m}^3$   
796 ( $\$700/\text{AF}$ ) in exercise fees, or roughly  $\$9.3\text{M}$  across the simulation period (Figure 9B). In total,  
797 the higher lease price ( $\$0.81/\text{m}^3$  or  $\$1,000/\text{AF}$ ) leads to municipalities paying a total of  $\$15.4\text{M}$   
798 for TWO contracts as opposed to the 'market-clearing' pricing scenario 1 where TWO contracts  
799 cost just less than  $\$0.5\text{M}$ . Meanwhile, irrigators would again sign a multi-year contract for 22.2  
800 MCM (17,982 AF) of options, but as a result of the lower  $\$0.02/\text{m}^3$  ( $\$30/\text{AF}$ ) lease price from  
801 municipalities, now only pay  $\$0.002/\text{m}^3$  ( $\$2.40/\text{AF}$ ) (or  $\$42,000$  per year) in risk adjusted option  
802 fees, roughly  $\$2.7\text{M}$  across the entire simulation period. The exercise fee paid by irrigators is  
803  $\$0.02/\text{m}^3$  ( $\$25/\text{AF}$ ), which comes to roughly  $\$9.2\text{M}$  over the simulation period (Figure 9B).

804 Now, the average cost of water coming to municipalities via an exercised option is  
805  $\$0.94/\text{m}^3$  ( $\$1160.60/\text{AF}$ ), while for irrigators it is only  $\$0.03/\text{m}^3$  ( $\$32.80/\text{AF}$ ). As a result of the  
806 increased cost of TWO contracts to municipalities, irrigators end up receiving  $\$3.6\text{M}$  in gains  
807 from the use of the TWO, a change from pricing scenario 1 in which municipalities paid much  
808 less and where TWO usage by irrigators had a net cost. Irrigators' acquisition of surplus  
809 supplies from municipalities in wet years also adds  $\$34.2\text{M}$  in agricultural productivity gains  
810 over the simulation period, amounting to total agricultural gains (including option/exercise fees)  
811 of  $\$37.8\text{M}$  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  $\$0.81/\text{m}^3$  ( $\$1000/\text{AF}$ ) in dry years, and urban-to-ag leases  
 815 are  $\$0.02/\text{m}^3$  ( $\$30/\text{AF}$ )

816 In terms of the municipal costs savings associated with using the TWO contracts to  
 817 ensure supply reliability, municipalities would pay \$15.5M (up from \$0.45M using pricing  
 818 scenario 1) across the 63-year simulation period. Achieving a similar level of reliability through  
 819 the purchase of the 4.1 MCM (3,346 AF) of permanent water rights required would still cost  
 820 \$326M.

821 **Table 4.** *Two-way option performance with current water rights holdings under pricing scenarios 1 & 3*  
 822

<b>Current Rights Holdings</b>	<b>Scenario 1 Lease Prices:</b> Ag-Urban: \$0.001/m <sup>3</sup> - \$0.02/m <sup>3</sup> (\$1.40 - \$28.12/AF) Urban-Ag: \$0.03/m <sup>3</sup> - \$0.11/m <sup>3</sup> (\$37.69 - \$135.74/AF)	<b>Scenario 3 Lease Prices:</b> Ag-Urban: \$0.81/m <sup>3</sup> (\$1000/AF) Urban-Ag: \$0.02/m <sup>3</sup> (\$30/AF)
Agricultural Gains (\$M)	11.6	37.8
Two-way option cost to Ag* ^ (\$/m <sup>3</sup> ) (\$/AF)	0.05 (62.6)	0.03 (32.2)
Two-way option cost to Urban** ^ (\$/m <sup>3</sup> ) (\$/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

823 \*Assumes exercise fee of \$0.02/m<sup>3</sup> (\$25/AF) in Scenario 1, Assumes \$0.02/m<sup>3</sup> (\$25/AF) exercise fee in  
 824 Scenario 3;

825 \*\*Assumes exercise fee of \$0.01/m<sup>3</sup> (\$15/AF) in Scenario 1, Assumes \$0.57/m<sup>3</sup> (\$700/AF) exercise fee in  
 826 Scenario 3;

827 ^ Average exercised option cost calculated using the sum of all option fees and exercise fees across the  
 828 simulation, divided by the total amount of water re-allocated.  
 829

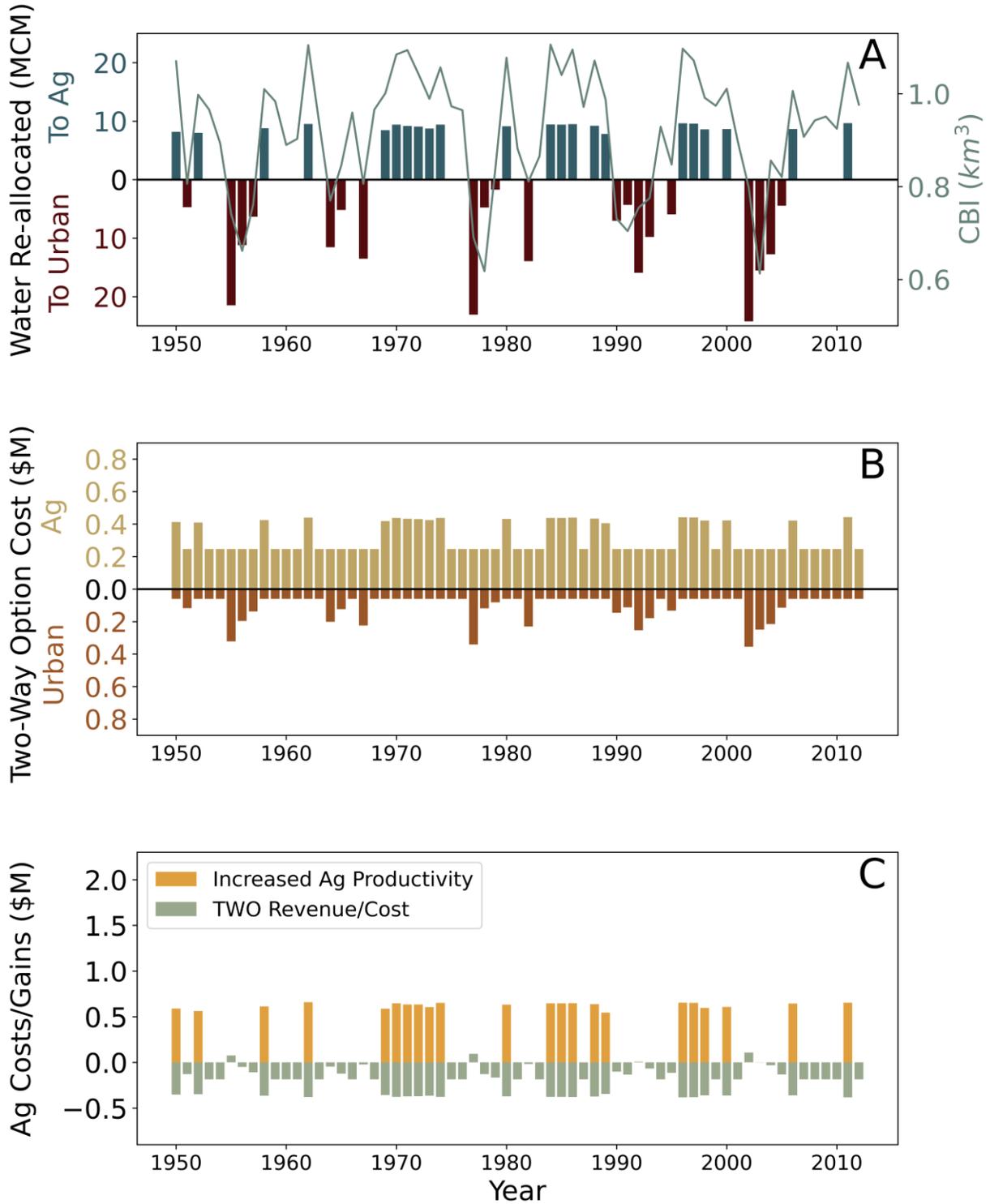
### 830 **3.2 Two-Way Option Performance assuming 1971 Water Rights Holding Regime**

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

836 Under this rights holding regime, municipalities require much more water in dry years to meet  
837 their supply reliability objectives and purchase 24.2 MCM (19,636 AF) of options (an increase  
838 from 4.1 MCM (3,346 AF) when considering the current rights regime). During dry years,  
839 municipalities acquire roughly 218 MCM (176,400 AF) over the 63-year simulation period  
840 (Figure 10A). Irrigators, meanwhile, contract for 9.7 MCM (7,827 AF) of options and exercise  
841 these to acquire roughly 198.1 MCM (160,600 AF) over the simulation period. The relative  
842 volumes of water re-allocated to municipalities and irrigators is flipped relative to that which  
843 takes place under the current rights holding regime (Figures 8 & 9), as irrigators have sold fewer  
844 rights to municipalities who given the purchase of many fewer rights now rely more heavily on  
845 the TWO contracts during dry years to meet their supply reliability goals. Using pricing scenario  
846 1, in which lease prices are determined via a 'market-clearing' process, lease prices during dry  
847 years increase given the higher volume of transfers, and municipalities pay a risk-adjusted option  
848 fee of  $\$0.003/\text{m}^3$  ( $\$3.10/\text{AF}$ ), or  $\$61,000$  per year (or  $\$3.8\text{M}$  across the 63-year record).  
849 Municipalities pay an exercise fee of  $\$0.01/\text{m}^3$  ( $\$15/\text{AF}$ ) to acquire the water, or roughly  $\$2.6\text{M}$   
850 over the simulation period (Figure 10B). In this rights holding regime, municipalities have much  
851 less surplus water to option to irrigators during wet years, so the risk-adjusted option fee paid by  
852 irrigators for access to water in wet years rises to  $\$0.03/\text{m}^3$  ( $\$31.50/\text{AF}$ ). Given the smaller  
853 volume of options bought by irrigators, they, pay only  $\$247,000$  in annual option fees (or  
854  $\$15.5\text{M}$  across the simulation period) and  $\$4\text{M}$  in exercise fees ( $\$0.02/\text{m}^3$  or  $\$25/\text{AF}$ ) (Figure  
855 10B).

856 The average cost of water re-allocated across the simulation is  $\$0.03/\text{m}^3$  ( $\$36.60/\text{AF}$ ) for  
857 municipalities, and  $\$0.10/\text{m}^3$  ( $\$121.80/\text{AF}$ ) for irrigators (as only small volumes of surplus  
858 municipal water are available and are purchased for use on highly productive non-irrigated

859 parcels). As a result, irrigators end up paying municipalities more than they receive in return  
860 (shown as a net cost across the simulation period in Figure 10C), although the increased  
861 agricultural productivity irrigators generate as a result of retaining more of their water rights (as  
862 well as acquiring water via wet year options) more than compensates for this. Irrigators pay  
863 \$19.6 million in option and exercise fees (\$3M less than in the current rights regime for pricing  
864 scenario 1 as irrigators hold more permanent rights), but the value of added agricultural  
865 productivity totals \$28.4M, such that total agricultural gains equate to \$8.8 million. It is worth  
866 noting in key dry years 1955, 1977, 2002 where larger quantities of water are re-allocated from  
867 agriculture to municipalities (Figure 10A), the use of TWO contracts drives positive gains for  
868 irrigators (Figure 10C). Irrigators, in this way, benefit from not only maintaining more of their  
869 water rights in these (and other dry years), but also continue to supplement their income via  
870 option/exercise fees in the worst dry years. Municipalities continue to realize considerable  
871 savings via reliance on the TWO contracts rather than purchasing permanent rights, but the  
872 assumption is that the counterfactual here is that these rights would have been purchased largely  
873 circa 1971, at considerably lower prices. Assuming this, municipalities would have had to pay  
874 \$298M (at 1971 prices, adjusted to 2023 dollars) to acquire permanent rights in the past that  
875 would have fulfilled their shortages across the simulation period (24.2 MCM or 19,636 AF),  
876 while the use of the two-way option has municipalities paying \$6.4M to achieve the same level  
877 of supply reliability.



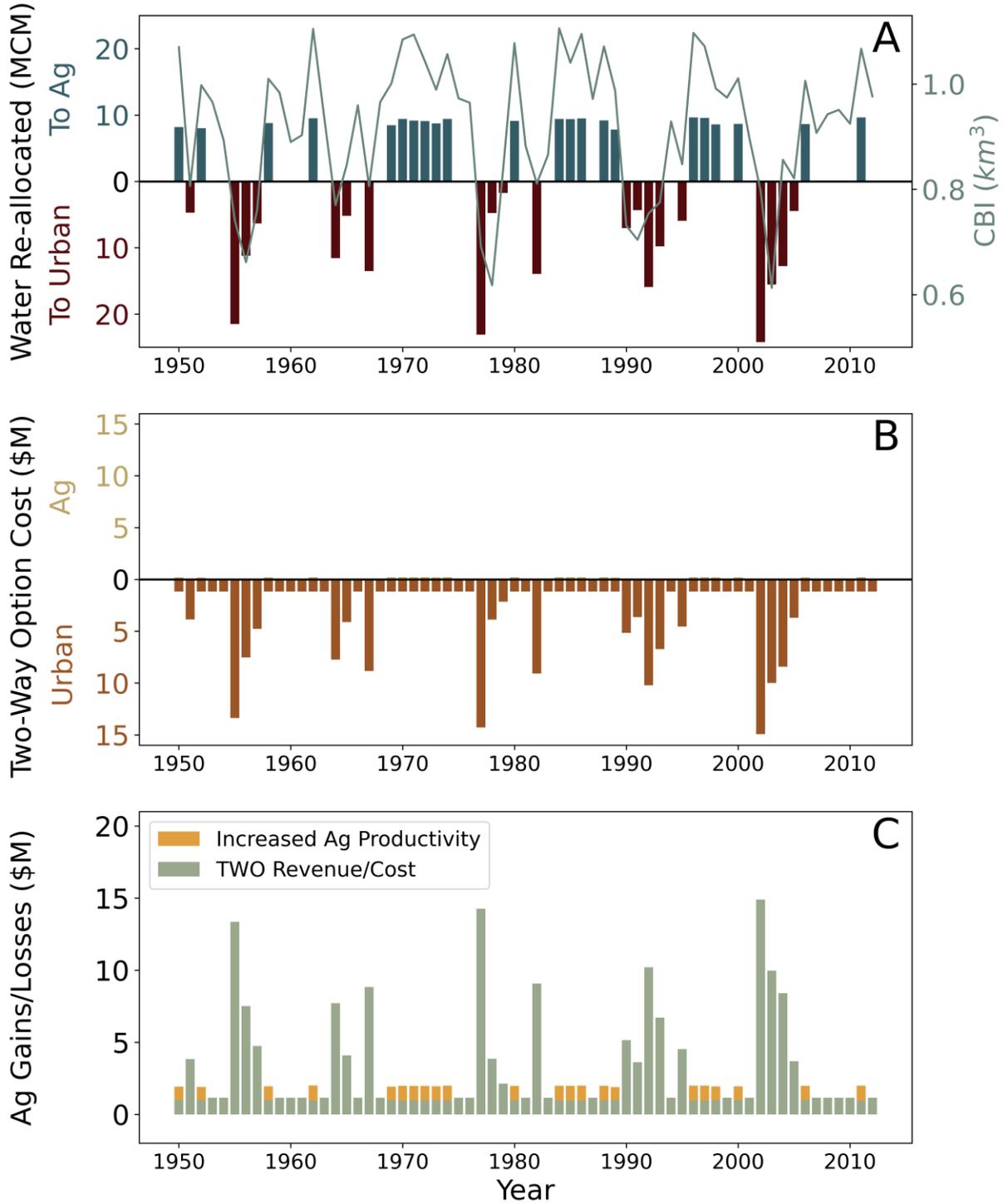
878

879 **Figure 10.** Two-way option performance with 1971 water rights under pricing scenario 1 where lease

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

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

896 The average cost of re-allocated water across the simulation now increases to  $\$0.91/\text{m}^3$   
897 ( $\$1119.50/\text{AF}$ ) for municipalities, and  $\$0.03/\text{m}^3$  ( $\$31.60/\text{AF}$ ) for irrigators. As a result of  
898 municipalities paying much more for water, irrigators receive positive net revenue from the  
899 yearly option fee payment from municipalities, and in dry years benefit from the  $\$0.57/\text{m}^3$   
900 ( $\$700/\text{AF}$ ) in exercise fees. From the TWO contract revenue alone, irrigators receive  $\$192.4\text{M}$   
901 across the 63-year record, while adding  $\$21.9\text{M}$  in increased productivity from the receipt of the  
902 transfers of municipalities' surplus water in wet years.



903

904 **Figure 11.** Two-way option performance with 1971 water rights under pricing scenario 3 an empirical

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

906 are  $\$0.02/\text{m}^3$  ( $\$30/\text{AF}$ ) in wet years.

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

912 **Table 5.** *Two-way option performance with 1971 water rights holdings under pricing scenarios 1 & 3*  
 913

<b>1971 Rights Holdings</b>	Scenario 1 Lease Prices: Ag-Urban: \$0.023 – 0.026/m <sup>3</sup> (\$28.12 - \$32.48/AF) Urban-Ag: \$0.048 - \$0.112/m <sup>3</sup> (\$58.93 - \$138.11/AF)	Scenario 3 Lease Prices: Ag-Urban: \$0.81/m <sup>3</sup> (\$1000/AF) Urban-Ag: \$0.02/m <sup>3</sup> (\$30/AF)
Agricultural Gains (\$M)	8.8	214.2
Two-way option cost to Ag* <sup>^</sup> (\$/m <sup>3</sup> ) (\$/AF)	0.10 (121.8)	0.03 (31.6)
Two-way option cost to Urban** <sup>^</sup> (\$/m <sup>3</sup> ) (\$/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) <sup>^^</sup>	291.9	101

914 \*Assumes exercise fee of \$0.01/m<sup>3</sup> (\$15/AF) in Scenario 1, Assumes \$0.02/m<sup>3</sup> (\$25/AF) exercise fee in  
 915 Scenario 3;

916 \*\*Assumes exercise fee of \$0.02/m<sup>3</sup> (\$25/AF) in Scenario 1, Assumes \$0.57/m<sup>3</sup> (\$700/AF) exercise fee in  
 917 Scenario 3;

918 <sup>^</sup> Average option cost calculated using the sum of all option fees and exercise fees across the simulation,  
 919 divided by the total amount of water re-allocated;

920 <sup>^^</sup>Assumes water right purchases in 1971 were at \$1.62/m<sup>3</sup> (\$2000/AF), adjusted to 2023 dollars

#### 921 **4 Discussion**

922 This analysis suggests two-way options could be a useful tool for facilitating more rapid  
 923 re-allocation of water between irrigators and municipalities under variable hydrologic conditions,  
 924 leading to less expensive municipal supply reliability and increased agricultural productivity.  
 925 Historically, market-based transfers of water rights have been dominated by permanent sales of

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

946         The TWO contracts provide a tool by which irrigators and municipalities could create  
947 mutually beneficial agreements that allow irrigators to increase their production in wet and  
948 normal hydrologic years, while earning a steady income in all years (option fees) and even more

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

## 962 **5 Conclusion**

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

972 appropriate rules are in place, giving water users a water re-allocation tool that improves the  
973 responsiveness of existing institutions to water scarcity.

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981

#### 982 **Open Research**

983 All data and code for this project, including figure generation, are available in a live repository  
984 ([https://github.com/IMMM-SFA/hirsch\\_et al\\_2024\\_ef](https://github.com/IMMM-SFA/hirsch_et al_2024_ef))

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