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An Economic Model of Transboundary Water Agreements With Groundwater and Surface Water Interaction: Application to a US River Basin With a History of Conflict

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Key Points:
- Allocation of transboundary water resources can cause conflict between regions, especially if mechanisms for allocation are not adequate
- Economic analysis of transboundary water compacts often does not incorporate the connection between groundwater and surface water
- We develop a hydro-economic model that considers this connection and apply it to a case region in the US

Supporting Information:

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

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Abstract This study examines the connection between groundwater and surface water in the design of transboundary compacts. A steady-state hydro-economic model is developed and applied to a river basin in the United States. Simulations demonstrate that when a water compact is designed to govern only surface water, the assigned allocations are nonbinding and lead to decreased river-flow in the downstream region. When the compact is designed to govern surface water and groundwater usage combined, however, the assigned allocations are binding and changes in them can increase overall net benefits, with the extent dependent on flexibility in compact design.

1. Introduction

Freshwater availability is essential for virtually every aspect of society's operation. Over 70% of freshwater in the world is used for agriculture, and water scarcity is an increasing concern for the viability of this sector (United Nations, 2024). In many areas, inter-regional water apportionment facilitates the sharing of water under scarcity (Giordano et al., 2014). These arrangements are often accompanied by a complicated political process involving public and private institutions as rivers and groundwater aquifers seldom abide by state and municipal boundaries (Boinet et al., 2024). Disagreements over transboundary water allocation can lead to conflict between countries and states (Espíndola & Ribeiro, 2020; Koff et al., 2020). These issues may increase with greater attention toward managing water as a common good due to advances in hydrology as emphasized in the OECD Environment Directorate (2024). To better understand optimal allocation and potentially alleviate conflict, economic analysis has been employed to study the efficiency of these water sharing treaties or compacts. However, this prior work has limited attention largely to surface water compacts. It has not given due consideration to the important connection between groundwater and surface water in the economic analysis of inter-regional compacts (Hossen et al., 2024). This is perhaps not surprising since even the evolution of conjunctive use treaties is relatively recent (see, e.g., Lautze et al., 2018).

Our research attempts to address the above limitation. We develop a simple hydro-economic model designed to optimize the economic efficiency of inter-regional compact allocations with consideration of surface water and groundwater interactions. This model is applied to a portion of the Republican River basin in the United States—a large drainage basin that encompasses parts of Colorado, Nebraska, and Kansas. Past water apportionment between these irrigation-heavy states has caused legal conflict culminating in millions of dollars in fines and enhanced compliance practices. An overview of historical water compact disputes which highlights three particular cases regarding groundwater consideration in compacts is provided in Schlager et al. (2012). Earlier versions of compacts within the U.S. were focused primarily on surface water. It was not until after the mid-20th century groundwater revolution that more complicated connections and groundwater pumping began to be prominently considered (Brookfield et al., 2023; Griggs, 2017). Disputes related to this connection, such as the one between Kansas and Nebraska which ultimately cost Nebraska US$5.5 million (not including the legal and administration fees, along with lost time) highlight the importance of river compacts considering groundwater and surface water connections in their established allocations (Kansas vs. Nebraska 126: 574 U.S.). Essentially, before 2002 Nebraska did not fully recognize the connectivity of groundwater to surface water and the resulting over-pumping by the state caused excessive drawdown downstream in Kansas. Prior hydro-economic studies of the basin provide very rigorous analysis of groundwater management, while placing limited emphasis on its connection with surface water (Hrozencik et al., 2017).

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1.1. Transboundary Water Allocation and Conjunctive Water Use

While the growing importance of considering groundwater and surface water connectivity is evident through the examination of inter-regional water compacts, it is sparsely covered in the economics literature related to water allocation. Hydrology research has long accepted this connection (Du et al., 2022; Sophocleous, 2002; Winter 1995), and law reviews have covered many conflicts related to it (see, Griggs, 2017). There are two main avenues of related research in economics: (a) analysis of inter-regional water policies and (b) economics of conjunctive water use. The review presented heretofore is not meant to be exhaustive, as many studies have been carried out in each area, but instead devotes more attention to the literature that is particularly relevant to our topic.

Bennett and Howe (1998) and Bennett et al. (2000) provide the earliest economic modeling of inter-regional river water compacts. These papers examine factors that influence the extent of compliance with a compact involving only shared river water and also carry out an efficiency analysis of the contracts in the context of the United States. Bennett and Howe (1998) provide specific examples of how the interpretation of compacts is very complex while showing that states with percentage allocations, as opposed to fixed terms, are more likely to comply with compact requirements. Bennett et al. (2000) add that percentage allocations are more often efficient than fixed allocations—noting that the upstream basin assumes the risk of a water shortage. Much of the more current literature continues to focus on the efficiency of water allocation mechanisms, such as compacts, across theoretically defined (e.g., agent) or macro-level (i.e., country-level) boundaries (Van der Brink et al., 2012; Ambec et al., 2013; Degefu et al., 2016).

There is also research looking at the viability of inter-regional water markets (e.g., Booker & Young, 1994) and transboundary water quality concerns (Bennett, 2000; Booker & Young, 1994). Ansink and Houba (2015) provide a review of the economics of transboundary river water allocation, paying special attention to the strategic aspects of allocation while emphasizing the reasons to treat water as an economic good. They note the dynamic complexities related to groundwater management and focus primarily on surface water-sharing arrangements, ignoring for simplicity but acknowledging the connection between surface and groundwater and limiting hydrological assumptions. This shortcoming continues to prevail in the more recent work using hydro-economics (Hossen et al., 2024). Overall, while the economics literature has considered the efficiency of transboundary allocation in various ways, it has not fully addressed hydrological aspects that affect water allocation in the context of assessing inter-regional water compacts, particularly when it comes to the connection between groundwater and surface water.

Separate but relevant to work on transboundary water systems, there is extensive literature on conjunctive use of surface water and groundwater. Much of it is resource management oriented and often takes a systems dynamics approach (Sekar et al., 2024). Booker et al. (2012) provide an overview of optimal conjunctive use models employed for economic analysis, many of which are in the context of California. Noel and Howitt (1982) and Provencher and Burt (1994) address optimal water allocations with conjunctive management considerations at basin and county scales respectively. Pulido-Velázquez et al. (2006) address conjunctive use at the basin scale with the objective of minimizing total costs in the system. Cobourn et al. (2017) make important progress by demonstrating the value of a conjunctive use model in water allocation scenarios considering the hydrologic connection between groundwater and surface water through response functions that reflect the proportion of groundwater pumped out of surface water.

Our research brings together the transboundary water allocation literature, the compact allocation modeling work, and the important concept of ground to surface water connectivity from the conjunctive use literature. More specifically, it extends the work of Bennett and Howe (1998) and Bennett et al. (2000) by incorporating considerations similar to those introduced by Cobourn et al. (2017). A hydro-economic model is developed for this purpose and applied to an illustrative case region, the Republican River drainage basin. Simulation results draw out the importance of recognizing the connection between groundwater and surface water, so often ignored in transboundary economic models.

2. Materials and Methods

2.1. Model

A constrained optimization model based on simplifying hydrological and economic assumptions is formulated to assess and analyze the annual net benefits of water re-allocation between sources (i.e., groundwater and surface water) in a basin. The possible implications of relaxing some of these assumptions are discussed in the concluding section. For now, it is assumed that water is used exclusively for irrigating crops in an upstream and a downstream region of a basin with one river and a single underlying aquifer to which the river is connected. All irrigation water withdrawals are taken to be consumptive. Furthermore, to abstract from dynamic considerations, we enforce conditions of steady-state equilibrium (groundwater tables and well-depths in each region do not change). While this simplifying assumption is helpful in putting forth our main arguments, there is a significant drawback to the approach as well since it precludes the potential impacts of aquifer depletion on connected river systems from being examined explicitly. The following notation is used to present our model:

U ≡ upstream region.

D ≡ downstream region.

S ≡ stock of groundwater (groundwater storage).

GW ≡ groundwater withdrawals.

RW ≡ surface (river) water withdrawals.

TW ≡ total withdrawals (i.e., $GW + RW$).

TB ≡ Benefits from total withdrawals.

APC ≡ Average pumping cost.

AWD ≡ Average well depth.

ET ≡ annual evapotranspiration.

PR ≡ annual precipitation.

RO ≡ annual surface (river) water runoff.

RF ≡ annual river flow.

R ≡ groundwater stock recharge rate.

B ≡ baseflow (groundwater that contributes to surface water).

DS ≡ deep groundwater seepage.

IFS ≡ instream flow requirement.

Ground WR ≡ groundwater rights.

Surface WR ≡ surface water rights.

Compact ≡ water allotment determined by compact across regions.

The area under a crop's irrigation water demand function is taken to measure total economic benefits, *TB*, from all water withdrawn, *TW*, and is an increasing function of this variable. Holding crop selection as exogenous for simplification, a likely split of irrigation water used between groundwater and surface (river) water is shown in Figure 1. Under the assumption that surface (river) water is less expensive than groundwater to withdraw and distribute, the Figure indicates that available river water is used first, with more expensive groundwater filling in the gap to fulfill total irrigation demand. Note that the implied water price at quantity *TW* is determined by groundwater pumping costs (as long as groundwater use is positive). Surface water is assumed to be available at no cost and average groundwater pumping cost, *APC*, is taken to be an increasing function of average well depth, *AWD*.

Our model employs simplified hydrological assumptions to connect groundwater and surface water availability for crop irrigation. Adapting a basic water budget from the World Meteorological Organization's *Guide to Hydrological Practices* (4.27) (WMO, n.d.), annual evapotranspiration is determined as:

$$\mathrm{PR} = \mathrm{ET} + \mathrm{RO} + \mathrm{DS} + \mathrm{R} \tag{1}$$

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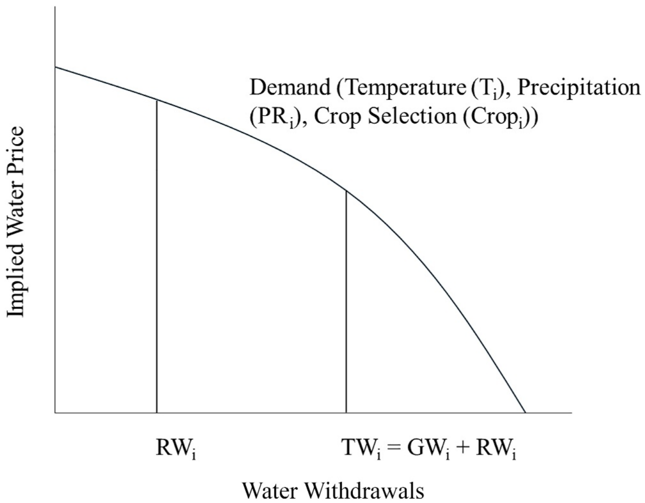

Figure 1. *River and Groundwater Demand Function.* This figure shows the demand equation for a region (e.g., a US county) as a function of irrigated water used for agriculture. Assuming surface (or river) water is inexpensive or costless to use, it will be used first before groundwater is pumped.

This water budget formula provides a high-level overview of water availability in a region—it includes the main drivers of water coming into (precipitation) and out of the system (evapotranspiration and runoff). What is leftover can go into the stock of groundwater as recharge (R). Through this setup, it is possible to make explicit the connection between surface water and groundwater.

Assuming that deep seepage, DS, is minimal and can be ignored for simplification (we take it that much of the groundwater in the case area is alluvial), Equation 1 yields groundwater recharge in region i as:

$$R_i = PR_i - ET_i - RO_i \text{ for } i = U, D \tag{2}$$

This formula is consistent with a simplified water budget equation from USGS's *Water Budgets: Foundations for Effective Water-Resources and Environmental Management* guide adapted from Scanlon et al. (2002). The formula applies to drainage basins; the case study region is contained within a drainage basin, the Republican River watershed.

Baseflow is the amount of groundwater discharge into a stream (Scanlon et al., 2002). Recognizing that recharge is the annual addition to groundwater stock, while groundwater withdrawals (GW_i) and baseflow (B_i) are annual deductions, the annual change in groundwater stock may be written as $\Delta S = R_i – B_i – GW_i$. Under the assumed conditions of steady-state, $\Delta S = 0$. This results in:

$$R_i = GW_i + B_i \text{ for } i = U, D \tag{3}$$

Equation 3 also assumes no induced recharge from the associated streamflow in region i—that is, that baseflow is present in the study region and implies for gaining streams that groundwater recharge not being withdrawn goes into the stream as baseflow. Additionally, no deep aquifer gradient movement is assumed—complex aquifer hydrology is ignored.

Reverting to upstream and downstream notation to create formulas for the annual river, or stream, flow (RF_i) yields:

$$\mathrm{RF_U = RF_E + R_U + RO_U - RW_U - GW_U} \tag{4}$$

$$\mathrm{RF_D = RF_U + R_D + RO_D - RW_D - GW_D} \tag{5}$$

wherein RF_E is exogenous flow coming into the upstream region itself. Equations 4 and 5 essentially state that river flow going out of a region is equivalent to water coming into the system excluding withdrawals.

Given these equations, groundwater recharge can be re-written as:

$$\mathrm{R_U = RF_U + GW_U + RW_U - RO_U - RF_E} \tag{6}$$

$$\mathrm{R_D = RF_D + GW_D + RW_D - RO_D - RF_U} \tag{7}$$

The above equations reflect that recharge is equivalent to water coming out of the system minus water coming into the system. This implies that runoff in the system goes into the stream and that runoff coming from further upstream of the upstream region is reflected in the exogenous streamflow (RF_E).

Finally, assuming conditions of steady-state hold, Equation 3 is used in Equations 4 and 5 to provide baseflow as:

$$\mathrm{B_U = RF_U + RW_U - RF_E - RO_U} \tag{8}$$

$$\mathrm{B_D = RF_D + RW_D - RF_U - RO_D} \tag{9}$$

Surface water and groundwater water withdrawals may also be constrained by environmental and institutional considerations. For example, many regions of the world, including several states in the U.S., such as Kansas under the Water Appropriation Act, have instream flow requirements that legally prevent streamflow from going under a certain threshold to protect fishery and other biological resources. In addition, water withdrawals may be limited by allocative laws, such as the doctrine of prior appropriation in the U.S., and by inter-regional water sharing compacts. Our model allows for incorporation of these constraints as follows:

$$\mathrm{IFS}_i \leq \mathrm{RF}_i \text{ for } i = U, D \tag{10}$$

$$\mathrm{Surface\_WR}_i \geq \mathrm{RW}_i \text{ for } i = U, D \tag{11}$$

$$\mathrm{Ground\_WR}_i \geq \mathrm{GW}_i \text{ for } i = U, D \tag{12}$$

$$\mathrm{Compact}_i \geq \mathrm{GW}_i + \mathrm{RW}_i \text{ for } i = U, D \tag{13}$$

wherein IFS_i, $\mathrm{Surface\_WR}_i$, $\mathrm{Ground\_WR}_i$, and $\mathrm{Compact}_i$ indicate, respectively, the instream flow requirement, the surface water right, the groundwater right, and the compact determined water allotment of a particular region in a given year. For this analysis, IFS_i is based on a yearly average desired or required river flow.

The model is set up to only allocate the water in a certain region as allotted by compact assumptions and water rights estimates where specified (see Appendix A1 in Supporting Information S1). Consistent with general interstate compact assumptions in the U.S., groundwater that is not hydrologically connected to a river basin, for example, would not be considered in the scope of this analysis (Griggs, 2017). This limits the scope of our analysis to the counties identified as those parts of the county within a river basin. While instream flow requirements are taken as given, the set up allows for scenarios in which the social planner can modify the water rights and compact based allocations for optimality—that is, making $\mathrm{Surface\_WR}_i$ $\mathrm{Ground\_WR}_i$, and $\mathrm{Compact}_i$ additional choice variables that constrain TW_i.

If an inter-regional compact is to improve overall economic welfare, then the combined regional net benefits under a social planner should exceed the sum of the net benefits under planners of each individual region acting on their own. The objective function (14) below shows the formulation for regional net benefits with independent actors, while objective function (15) shows social planner optimization. As steady-state is assumed, groundwater levels do not change. Therefore, in this simple setup, pumping costs are based on average well-depths in the region, unaffected by pumping levels. APC_i reflects average pumping costs in region i.

Region i, acting on its own, would maximize net benefits as follows:

$$\boldsymbol{Max}_{\mathrm{GW}_i,\mathrm{RW}_i} \left(\mathrm{TB}_i(\mathrm{TW}_i) - \mathrm{APC}_i * \mathrm{GW}_i\right) \tag{14}$$

s.t.

10, 11, 12, and 13.

Rather than considering benefits for one region, the social planner maximizes net benefits of irrigation to both the upstream and downstream regions taken together as:

$$\mathrm{Max}_{\mathrm{GW}_i,\mathrm{RW}_i} \sum_{i=U,D} \left(\mathrm{TB}_i(\mathrm{TW}_i) - \mathrm{APC}_i * \mathrm{GW}_i\right) \tag{15}$$

s.t.

10, 11, 12, and 13.

Following these formulas, total benefits, using an estimated demand equation can be calculated by assessing the area under the demand curve. Total costs for a region, for our purposes and simplicity, are assumed to be a function of pumping costs for groundwater: $\mathrm{TC}_i = \mathrm{APC}_i * \mathrm{GW}_i$. T and PR reflect annual averages of temperature and precipitation, respectively (in our application, we rely on Fahrenheit and inches per year).

We could, of course, allow additional flexibility to the social planner by making reallocation of water rights across regions a matter of choice, subject to prior limits for the regions taken together. In other words, (11) or (12) could be relaxed appropriately. Some of this possible flexibility is explored in the application of our model reported below.

Moreover, the model can be extended to m regions, wherein $m = \text{U, D}$ in the case of an upstream and downstream set of regions. For instance, if the downstream region does not utilize all available water for irrigation, we assume that "leftover" water can be used even further downstream. Thus, it is important to note that "upstream" and "downstream" are relative terms: a region can be both upstream and downstream at the same time in a broader system with more than two regions sharing water. To account for the benefits and costs of using this water, we assume that the regions further downstream derive average levels of value per acre foot of water used based on the net benefits derived per acre feet of water irrigated in regions upstream.

2.2. Application

2.2.1. Study Region

The model is applied to four counties in the Republican River basin—Nebraska is the upstream state, and Kansas is the downstream state. The study region is selected partly because of the prominence of hydrologic connectivity, usage of both groundwater and surface water along state boundaries, and dominance of irrigation in terms of water allocation (U.S. Department of the Interior: Bureau of Reclamation, 2016). The counties we study are Webster and Nuckolls (Nebraska) and Jewell and Republic (Kansas). These counties were chosen as they lie directly where the Republican River meets the Nebraska-Kansas state line and are major producers of similar crops (wheat, corn, sorghum, and soybeans) (USDA National Agricultural Statistics Service, 1997-2017). Webster and Nuckolls are within the basin's main stem, whereas Kansas is within the lower Republican basin. Notably, this region also overlaps with the Big Blue River Compact between Kansas and Nebraska (Kansas Department of Agriculture, n.d.). This compact provides guidance for streamflow that is not related to the Republican River and is thus not considered in the scope of this analysis. Appendix A3 through Appendix A5 in Supporting Information S1 provide additional details on the region, including streamflow gauge data, crop usage, and well locations.

2.2.2. Benefits and Costs: Estimation of Groundwater Pumping Cost and Water Demand

Pumping cost estimates for each region i are based on the following equation from Williams et al. (2017), incorporating average well depth (AWD_i):

$$\text{PC}_i = (\text{US}3.14 + \text{US}0.007(\text{AWD}_i)) * 12 \tag{16}$$

The setting of Williams et al. (2017) was the Southern Ogallala Aquifer, primarily in Texas and New Mexico. The assumptions used for deriving this cost function from the IRRIGCOST. xlsx calculator in Williams et al. (2017) are as follows: center-pivot LEPA irrigation system, natural gas-powered pumping (natural gas cost = US$3.60 per MCF), 160 acres operation system requiring 15 PSI (Williams et al., 2017, p. 297). The estimates are based on 1997–2004 data and are therefore likely conservative. This research is applied to a region close to the Ogallala; therefore, it is assumed that these estimates are relevant. To acquire pumping costs for a different region, one can follow Williams et al.'s (2017) approach using an irrigation cost calculator with varying assumptions on the cost of energy resources (e.g., natural gas) and set up.

A similar technique to Silva et al. (2019) is used to derive normalized prices of water NPC_i by dividing pumping costs per acre-foot (PC_i) by a regional, weighted average crop price per bushel (ACP_i):

$$\text{NPC}_i = \frac{\text{PC}_i}{\text{ACP}_i} \tag{17}$$

This implied pumping cost serves as a proxy price for water in the analysis hereafter—it pertains to the input prices (pumping costs) assumed in the model divided by the output prices (crop prices). Unlike Silva et al., instead of dividing the market value of all crops produced in the regions of focus by tons of biomass produced, a weighted average crop price per bushel based on the acreage of the top crops is used. Other crop inputs, such as fertilizer and chemicals, are ignored as benefits to water consumption are the primary concern and for simplification.

Econometric estimation of the following water demand function for each region i is carried out using 20 years of annual averages of precipitation (PR_i) and temperature (T_i) data from 1997 to 2017:

$$\mathrm{NPC}_i = \beta_0 + \beta_1 \mathrm{PR}_i + \beta_2 {\mathrm{PR}_i}^2 + \beta_3 T_i + \beta_4 {T_i}^2 + \beta_5 \mathrm{TW}_i \tag{18}$$

Figure 1 shows the demand curve described in (18). Thus, the total benefits to irrigation may be calculated as $\int_0^{\mathrm{TW}_i} \frac{\mathrm{PC}_i}{\mathrm{ACP}_i} dTW = \int_0^{\mathrm{TW}_i} \left(\beta_0 + \beta_1 \mathrm{PR}_i + \beta_2 \mathrm{PR}_i^2 + \beta_3 T_i + \beta_4 T_i^2 + \beta_5 \mathrm{TW}_i\right) dTW.$

Given variation between data sources, irrigated acreage data is more reliable than irrigation estimates for the study region. TW_i is therefore proxied by $\mathrm{Acres}_{i,}$ which indicates historically irrigated acreage in region i. Acres_i can be transformed to TW_i as follows:

$$\mathrm{Acres}_i * \mathrm{AF}_i = \mathrm{TW}_i \tag{19}$$

where AF_i is a factor that is the estimated annual average acre-feet of water applied to irrigated acres in region i (assumed 0.52 for Nebraska and 0.59 for Kansas based on historical data). The parsimony and relative predictive validity of estimation Equation 18 for the studied regions make it ideal for simulation purposes, despite its coarse operationalization. Also, this formulation provides a reasonable basis for water demand estimation in that climate (i.e., reflective of precipitation, where water recharge is primarily sourced from) and the amount of irrigation used (where the water is needed) in a given year would intuitively have very important effects on demand for crop water.

Based on the outlined assumptions and linear ordinary least squares regression, our estimates for the marginal benefit of each additional acre-foot of water irrigated in the selected study regions are as follows:

$$\begin{aligned}\text{Nebraska counties (upstream)}: \mathrm{NPC_U} = & -1074.92 + 3.339255769 PR_U - 0.065223376 {PR_U}^2 \\ & + 40.148723361 T_U - 0.374641741 {T_U}^2 \\ & - 0.000452785 Acres_U\end{aligned} \tag{20}$$

$$\begin{aligned}\text{Kansas counties (downstream)}: \mathrm{NPC_D} = & -3235.013021 - 1.699255915 PR_D + 0.0257613 {PR_D}^2 \\ & + 122.91125947 T_D - 1.1502344485 {T_D}^2 - 0.000165336 Acres_D\end{aligned} \tag{21}$$

We are less interested in individual parameter estimates from these regressions, and rather consider them an input for our model's demonstrative application. Further and consistent with our theory, these parameters suggest that the average pumping cost of water decreases when irrigated acres increase (see Figure 1). Moreover, the coefficient estimates on $Acres_U$ and $Acres_D$ are relatively unchanged when we exclude precipitation and temperature from the models, suggesting that collinearity does not affect the interpretation of the main drivers of demand change in the optimization procedures. Further, other specifications did not yield a downward sloping curve on irrigation, to which we advise future research to consider more precise econometric models to determine water pumping costs.

The regression table is provided in Appendix A2 in Supporting Information S1. The R-squared values for the Nebraska and Kansas regions were 0.64 and 0.37, respectively ($N = 21$ region-year observations, including annual data that was linearly interpolated). While this estimation technique is limited by data availability, it captures the marginal benefits to water which cannot be obtained simply through costs, as these are often close to free for surface water. Instead, the implied price considers power for water distribution through Williams et al.'s (2017) pumping cost estimate. Given that the model is static, the precipitation and temperature figures used in the simulation exercises in the following sections are averages of 1997–2017 (shown in Table 1). Therefore, the amount of water irrigated ($Acres_\mathrm{i}$) is isolated as a choice, or changing, variable depending on the simulated policy scenarios.

2.2.3. Initial Conditions and Model Scenarios

Within the context of a constrained optimization problem with an upstream and downstream region, many scenarios and policy mechanisms can be simulated. This analysis is separated into two sections: (1) viewing the interstate compact from a "historical" perspective in which it only governs surface water allocation and does not

Table 1
Model Inputs, Data Sources, and Definitions

Initial parameters and assumptions (prior to optimization/Withdrawals)

Upstream region		Downstream region		Notes on definitions/Assumptions:	Source
Climate Information Affecting Demand for Water					
PR_U	26.24	**PR_D**	27.42	Precipitation: average of annual data (1997–2017) in inches	NOAA
T_U	52.26	**T_D**	53.28	Temperature: average of annual data (1997–2017) in Fahrenheit	NOAA
Water Supply from Water Budget Assumptions					
RF_e	73,523	**RF_U**	156,162	RFe: estimated annual average upstream river flow: average of gauge near Orleans and Guide Rock, NE in acre feet	USGS NWIS
LA_U	340,192	**LA_D**	614,522	Total agricultural land in acres multiplied by estimate percentage of land within the basin	USDA NASS
PRA_U	743,751	**PRA_D**	1,404,412	Amount of annual precipitation in acre feet based on land devoted to agriculture within the basin; follows PR in water budget formulas	calculated
R_U	24,792	**R_D**	39,284	Estimated groundwater recharge based on water budget formulation in acre feet	calculated
B_U	24,792	**B_D**	39,284	Estimated baseflow based on water budget formulation in acre feet	calculated
RF_U	156,162	**RF_D**	340,580	Estimated river flow (flow assumed to be going out of the region) in acre feet	USGS NWIS
RO_U	57,847	**RO_D**	145,133	Annual runoff based on water budget assumptions (exogenous) in acre feet; goes into river	state water budget maps
ET_U	661,112	**ET_D**	1,219,994	Annual evapotranspiration based on water budget assumptions (exogenous) in acre feet	state water budget maps
Withdrawals for Irrigation					
RW_U	-	**RW_D**	-	Annual river water withdrawals (acre-feet)	model chooses
GW_U	-	**GW_D**	-	Annual groundwater withdrawals (acre-feet)	model chooses
TW_U	-	**TW_D**	-	Total annual withdrawals (acre-feet)	calculated
$Acres_U$	-	**$Acres_D$**	-	Assumed irrigated acres based on withdrawals	calculated
Constraints					
IFS_U	87,479	**IFS_D**	87,479	Based on Kansas downstream MDS flow requirements (annual average flow requirement transferred to acre-feet)	Kansas Geological Survey
$Compact_U$	46,481	**$Compact_D$**	48,572	Percentage allocation *x* total compact allotment (acre-feet)	RRCA documentation - see Appendix A1 in Supporting Information S1
$Compactpct_U$	48.9%	**$Compactpct_D$**	51.1%	Mainstem and unallocated percentage allocation from Republican River Accounting documents (%)	RRCA documentation - see Appendix A1 in Supporting Information S1
$Compact\_total_U$	95,052	**$Compact\_total_D$**	95,052	Total compact allotment in acre feet based on assumptions in Appendix A1 in Supporting Information S1 (acre-feet)	RRCA documentation - see Appendix A1 in Supporting Information S1
TAC_U	107,739	**TAC_D**	145,106	Total irrigated acres constraint based on water demand formula	see Appendix A2 in Supporting Information S1
$Surface\_WR_U$	5,648	**$Surface\_WR_D$**	42,232	Assumed surface water rights constraint in acre feet based on assumptions in Appendix A1 in Supporting Information S1	Multiple state sources; see Appendix A1 in Supporting Information S1
Other Exogenous Information					
APC_U	$48.03	**APC_D**	$46.13	Average estimated pumping cost per acre-foot of groundwater withdrawal (1997–2017)	Williams et al., 2017
ACP_U	$4.79	**ACP_D**	$4.99	Average fuzzy crop price per bushel (1997–2017)	USDA NASS
$AvgAF_U$	0.52	**$AvgAF_D$**	0.59	Average estimated acre-feet of water applied per irrigated acre in selected regions (1997–2017)	USGS and state Geological Surveys

Note. These inputs were used for the optimization and simulation exercises, and illustrate the type of information needed for more general extensions of the model.

consider groundwater withdrawals; (2) viewing the interstate compact as governing both surface-water and groundwater allocations (i.e., conjunctively). In both sections, individual planning is compared to regions planning together (i.e., the social planner model). We allow the social planner to select water withdrawals, compact allocation, and water rights. In total, there are four situations considered: two for the historical perspective case and the same two for the conjunctive perspective case. These scenarios, which will be explained in more detail for both the historical and conjunctive use perspectives, are summarized below:

1. *Individual planning*: the upstream and downstream regions decide their allocations of irrigated water withdrawals separately.
2. *Social planner with compact allocation flexibility*: the upstream and downstream regions plan together to maximize total net benefits to irrigation water across both regions. The social planner can change compact allocations, water withdrawals, and surface water rights. Groundwater rights are excluded from the planner choice set as regions are assumed to be in total compact compliance.

In all scenarios, regions are assumed to be in compliance with total compact allocations, which are derived from water rights constraints (see Appendix A1 in Supporting Information S1). Therefore, the models are flexible to consider one type of water right at a time along with compact allocations. As surface water is assumed to be much cheaper than groundwater (free in our model), regions optimize by choosing as much surface water as permissible. Indeed, surface water irrigation costs are often limited to little more than administration costs to maintain permits in our region of study. Remaining water allocation, in compliance with compact considerations, are assumed to be groundwater rights. Initial conditions set forth prior to each simulation and a summary of data sources are shown in Table 1.

2.2.4. The Historical Perspective: Individual Planning

As previously mentioned, before the groundwater revolution (and even today), interstate water compacts often considered only surface water. This was the case with the Republican River Compact as well, hence Nebraska's ability to increase groundwater pumping throughout the basin for years without a penalty until Kansas filed a lawsuit against them in the Supreme Court. The model is set up here to simulate river compacts that only allocate surface water. This changes the $Compact_i$ constraint from 13 to:

$$\text{Compact}_i \geq \text{RW}_i, \text{for } i = U, D \tag{22}$$

Additionally, as historical data has shown the Republican River to be a gaining stream (Hansen, 1998, p. 6), it is assumed that baseflow is greater than 0 in the model:

$$B_i \geq 0, \text{for } i = U, D \tag{23}$$

Surface water rights, which reflect limited physical and allowable legal access, also constrain river water allocations. Allowing a limited re-allocative control over these rights leads to the most flexible social planner maximizing net benefits as follows:

$$\text{Max}_{\text{GW}_i,\text{RW}_i,\text{Compact}_i,\text{Surface\_WR}_i} \sum_{i=1}^{m} \left(\text{ACP}_i * \left(\text{TW}_i * \left(\beta_0 + \beta_1 \text{PR}_i + \beta_2 \text{PR}_i^{\,2} + \beta_3 T_i + \beta_4 T_i^{\,2} \right) + \beta_5 \frac{\text{TW}_i^{\,2}}{2} \right) - \text{APC}_i * \text{GW}_i \right) \tag{24}$$

s.t.

$$\sum_{i=1}^{m} \text{Surface}_{\text{WR}i} = \text{SSWR} \tag{25}$$

Wherein $m = \text{U, D}$ in the case of examining only one upstream and one downstream region. Further, 10, 22 and 23 continue to apply where SSWR is the sum of the originally assigned water rights for the two regions. Reduced flexibility would allow the social planner no choice over *Surface WR*, reverting to inclusion of Equation 11 as constraint instead of Equation 25. Moreover, the corresponding optimization problems for regions acting on their own would be formulated along the lines explained in Section 2.

2.2.5. The Collaborative Perspective: Regional Social Planning

In the second set of scenarios, the compact allocations reflect a limit on groundwater and surface water withdrawals in a given year—that is, the allocations reflect consideration of conjunctive management. While we model surface and groundwater as connected throughout (revealing potential water exploitation of upstream regions), such conjunctive considerations *in policy* did not arise until both states recognized this connection. The compact constraint is once again (13; i.e., $Compact_i \geq GW_i + RW_i$, for $i = U, D$). In this case, the social planner with the most flexibility maximizes net benefits as below:

$$\text{Max}_{\text{GW}_i,\text{RW}_i,\text{Compact}_i,\text{Surface\_WR}_i} \sum_{i=1}^{m} \left(\text{ACP}_i * \left(\text{TW}_i * \left(\beta_0 + \beta_1 \text{PR}_i + \beta_2 \text{PR}_i^2 + \beta_3 T_i + \beta_4 T_i^2 \right) + \beta_5 \frac{\text{TW}_i^2}{2} \right) - \text{APC}_i * \text{GW}_i \right) \quad (26)$$

s.t.

10, 12, 13, 23 and 25.

With the regional planning cases, we consider situations when the social planner can change compact allocations, as well as surface water rights (*Surface WR*; i.e., replace Equation 25 with Equation 11 in the set of constraints).

2.2.6. Modeling Software

We run the models using the Excel Solver Add-In, which is a powerful optimization tool built into Microsoft Excel. Specifically, we employ the Generalized Reduced Gradient (GRG) Nonlinear Solving method, one of the solving algorithms available in Excel Solver. We chose this approach as it is intuitive and practical for the illustrative model we are applying. Further, our goal is to solve an optimization problem, as opposed to demonstrating the boundaries of optimization. The GRG Nonlinear method is designed to handle smooth nonlinear optimization problems and is well-suited for our hydro-economic model that incorporates the nonlinear interactions between groundwater and surface water. We set up the objective function to maximize net benefits from irrigation, define the decision variables as the groundwater and surface water withdrawal amounts, and input the hydrological and institutional constraints into the Excel spreadsheet. We then use the Solver Add-In to find the optimal solution that maximizes the objective function subject to the defined constraints.

Notably, we also ran the main set of our results with the scipy.optimize package in Python, which relies on a slightly different standard optimization algorithm. The results of this analysis were virtually the same as those provided in Solver (code available upon request). Further, we note that other researchers use Excel Solver for similar optimization issues (e.g., see, Wada et al., 2023; Greaker & Pade, 2009).

3. Data Availability and Measurement

Data used to estimate each of the parameters outlined in the model are collected from a variety of sources (cited in the bibliography and summarized in Table 1). Most of our data is collected at the county-year level, wherein the upstream and downstream regions are formulated based on the aggregation of two counties in each region. When information is not available at the county-level, reasonable assumptions based on state level information are made. Certain information is not available every year (e.g., agricultural census data); when this information is used to form time series data, linear interpolation is used to fill in missing data.

3.1. Climate and Water Budget Data

Annual average climatic data at the county level is available through the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information online climate monitoring tool. Precipitation data is used in the water demand estimation formula, as well as to derive recharge estimates based on the water budget formula for the study regions. Evapotranspiration and run-off estimations as a percentage of annual precipitation are based on coarse estimates of state-wide water budgets for Kansas and Nebraska.

3.2. Agricultural Data: Crop Prices, Irrigation Acreage, and Groundwater Pumping Costs

Crop prices are inconsistently available at the county-level for the focus region, so historical state-wide estimates from USDA National Agricultural Statistic Service (NASS) are used. We confirmed the validity of this approach by calling the regional USDA office. County agricultural census data provided through the USDA is used to estimate acreage allocation to top crops in each county. Data for this is available every fifth year, wherein linear interpolation is used for in-between years. Well depth information is provided by state resources: the WIZARD database in Kansas, which is operated by the Kansas Geological Survey, and the Registered groundwater wells database for Nebraska, which is operated by the Nebraska Department of Natural Resources (DNR). As the groundwater well databases in each state are not set up in the same manner, +5 feet (1.524 m) is added to "pump depth" for Nebraska wells to assume well-depth—this appeared reasonable based on a scan of registered wells is in the database with information on both well and pump depth. Additionally, this discrepancy creates a relatively small impact on pumping costs. Also, Republic County well depth information is applied to Jewell County as data is unavailable in this time-period for Jewell. Well depth is important for the purposes of estimating an implied price of water—we would not anticipate that the price of water would vary much between the two neighboring counties. Information on historical irrigation use is provided through state-level resources, USDA NASS, and the USGS National Water Information System: Water Use Database. As mentioned earlier, given inconsistencies in irrigation figures across the select counties, the water demand estimation function is derived using acres of irrigated land.

3.3. Water Constraints Data: Streamflow, Compact Allocations, and Water Rights

Streamflow information is used from USGS gauging site data available through the USGS National Water Information System's Web Interface. Instream flow requirements are based on Kansas' Minimum Desirable Flow requirements made available online for specific gauging sites through the Kansas Department of Agriculture's Department of Water Resources. These flow requirements are enforced on the upstream region (Nebraska in these analyses) to ensure that the minimum desirable amount of water is flowing downstream. Updated annual compact allocations are available through the Republican River Compact Accounting documents via the official website of the Republican River Compact Association (republicanriver.org) (Republican River Compact Accounting, 2020). These allocations, along with surface water and groundwater rights data, are used to create compact constraints that reflect historical averages, as described in Appendix A1 in Supporting Information S1. Recognizing the complications of compact accounting, absolute allocations in this study are based on estimations of current surface and groundwater rights acreage allotment under the assumption that past estimated usage generally aligns with compact restrictions. Also recognizing that there have been lawsuits between the states, the compact allocation assumptions are a limitation of this research—they are not defined in the same manner as Republican River Accounting documentation and are again for the purposes of demonstrating the importance of connectivity in the overall model set up. Details of compact allocation assumptions made are provided in Appendix A1 in Supporting Information S1.

4. Simulation Results

The net benefit results (in US$) and corresponding changes in river and groundwater withdrawals of the constrained optimization exercises are shown in Table 2. As the results demonstrate, the current perspective—that recognizes the connectivity between groundwater and surface water in governing compact constraints—saves the most water for downstream regions. Assuming average net benefits per acre-feet of water to this saved water provides optimal net benefits under these scenarios.

Turning to Scenario 1—wherein regions plan individually and compacts only govern surface water—we find the lowest overall net benefits as provided by irrigated water ($14,562,300). The upstream region uses the maximum allowed surface water (constrained by assumed surface water rights) and groundwater withdrawals. In this case, their groundwater withdrawals are only constrained by the assumed recharge rate of the region (24,792 acre-feet per year). The downstream region also extracts most available recharge (33,362 acre-feet of 39,284). Whereas total surface water withdrawals fall well within compact ranges (47,687), overall water withdrawals (105,841) exceed compact limitations if governing surface and groundwater (95,052 acre-feet per year).

Table 2
Constrained Optimization Results for the Various Planning Scenarios Considered

		Planning scenario			
		Historical perspective (compact governs RW)		Current perspective (compact governs RW and GW)	
		(1) Individual	(2) Social–compact allocation and SW rights adjustable	(3) Individual	(4) Social–compact allocation and SW rights adjustable
Net Benefits ($) before Considering Saved Water	Upstream	$8,021,933	9,390,597	$8,021,933	9,406,062
	Downstream	$6,540,367	6,353,023	$5,874,457	5,825,630
	Total Before Saved Water	$14,562,300	15,743,620	$13,896,390	15,231,692
Compact Allocations (%)	Upstream	48.9%	48.9%	48.9%	44.5%
	Downstream	51.1%	51.1%	51.1%	55.5%
Surface Water Withdrawals (Acre-feet, Rights)	Upstream	5,648	21,284	5,648	34,366
	Downstream	42,039	26,596	42,232	13,514
Groundwater Withdrawals (Acre-feet)	Upstream	24,792	24,792	24,792	7,888
	Downstream	33,362	39,284	6,340	39,284
Total Water Withdrawals (Acre-feet)	Upstream	30,440	46,075	30,440	42,254
	Downstream	75,401	65,881	48,572	52,798
	Total	105,841	111,956	79,012	95,052
Average $NB per acre-foot of Water to Region[a]		$86.74	$140.62	$120.94	$160.25
River flow After Optimization (Acre-feet)	Upstream	125,722	110,087	125,722	113,908
	Downstream	234,739	228,624	261,568	245,527
Downstream Δ Between Perspectives (Water Saved)		n/a	n/a	26,829	16,904
$NB from Saved Water for Further Downstream		0	0	$3,244,849	$2,708,708
Total Net Benefits ($)		$14,562,300	$15,743,620	$17,141,239	$17,940,399

Note. Net benefits are provided in $US dollars. [a]Assumed $NB/acre-foot of water that the region further downstream would attain: based on downstream region average values after optimization for individual planning scenarios and full region average values for social planning scenarios.

When the two regions collectively decide upon water withdrawals and water governance mechanisms (surface water rights and compact allocations) under Scenario 2, we find that net benefits increase to $15,743,620. This 8.1% increase in net benefits is derived from a approximate four-fold increase in surface water rights to the upstream region (from 5,648 to 21,284).

We next turn to the current perspective, wherein compact allocations govern surface water and groundwater irrigation. Compared to excess groundwater withdrawals under Scenario 1, Scenario 3 shows a large increase in river flow to regions further downstream (+26,829 acre-feet for a 11.4% increase per year). If applying average net benefits to water to the downstream region to this saved water, net benefits to the system are significantly (17.7%) greater ($17,141,239 vs. $14,562,300). This increased river flow stems from a decline in downstream groundwater withdrawals, limited by compact constraints that now govern this form of irrigation (6,340 acre feet vs. 33,362 acre feet).

Finally, the optimal net benefits are achieved in Scenario 4, when the social planner has the greatest flexibility and the compact governs both surface and groundwater withdrawals ($17,940,399; 23.2% higher than the baseline case). For this analysis, we assume the average net benefits from saved water further downstream (as compared to the historical perspective case) are based on the optimized solution. The greater net benefits are driven from water saved via river flows for further downstream (+16,904 acre feet, or a 7.4% increase, compared to the historical perspective), as well as a more optimal allocation of surface water rights to the upstream region which otherwise has lower baseflow levels and cannot rely on as much recharge for groundwater withdrawals.

5. Discussion and Conclusion

This research highlights the importance of surface water and groundwater interaction in the context of water allocation through the introduction of a simple, illustrative hydro-economic model for assessing interstate river water compacts with these considerations. It extends and connects prior economics literature related to interstate river water compact allocations and conjunctive water management, particularly that of Bennett et al. (2000) and Cobourn et al. (2017). Our model is applied to the Republican River basin, given the importance of groundwater and surface water supplies in the region, as well as its setting falling under the policy stretches of the Republican River Compact. The historical perspective simulation results reveal that the compact allocations are irrelevant for the study area counties if viewed as constraints only on surface water. Net benefits are higher among all scenarios in which compacts govern both surface water and groundwater, as this saves river flow for optimal use further downstream.

Results also show that compact allocations can change when the compact governs groundwater and surface water, allowing for more total withdrawals for the region further downstream in this particular area. Moreover, when allowing the social planner to adjust surface water rights on top of compact allocations, net benefits are highest and both regions are able to withdraw more than when planning individually. Current perspective results demonstrate that compact allocations between regions can change when interpreted as constraints on surface water and groundwater use, recognizing their hydrologic connection. These exercises provide important implications in terms of water management planning: to set economically efficient compact allocations, the connection between groundwater and surface water should be recognized.

Of particular policy relevance, results suggest that incorporating ground and surface-water constraints into compact agreements can substitute for coordination between regions. Indeed, one of the most difficult aspects of transboundary water management is monitoring shared resources. However, if compact allocations are set in an initially reasonable manner, this can limit coordination costs while improving net benefits by protecting river flows for downstream regions.

5.1. Limitations and Extensions

A variety of limitations and potential opportunities for extension of this research exist. The first major limitation concerns data collection and interpretation. We used relatively coarse region-level estimates for compact allocations, regional water budgets, and water demand. While these measures added realism to our illustrative example at a transboundary point within a basin, assumptions could be modified to more rigorously account for local conditions in agricultural water needs, climate, transboundary sharing, hydrogeology, and supplementary water sources and storage. These modifications would be important for applying this model to public policy analysis.

Related to this limitation, our measures are annual estimates based on historical data that wasn't available for every year; we often had to rely on state-level census data to proxy for the focal counties (at 5-year intervals). Moreover, converting daily or seasonal measures of water usage or limitations to annual measures does not fully capture the variation in water supply and value that may be influential in determining allocations. Future models that account for variation in water allocation by crops and seasons can provide more nuanced recommendations to allocation choices. For instance, research can model whether irrigation should be allocated only to one region in a multi-region system during certain times of the year. Our analysis does not allow for such flexibility.

Second, our model is simple and parsimonious from hydrological as well as economic perspectives. To this end, we ignore deep seepage and other hydrogeologic conditions not only in our measures, but also in our model development. The steady-state assumption that we make is another important limitation. It should be relaxed to allow for the dynamics of the relationship between groundwater stock and connected river streamflow to be examined. For example, persistent groundwater overdraft would not only lower water tables and raise pumping costs but may also cause gaining streams to eventually become losing streams. Restoration of river flows in these circumstances could require more extreme policy measures, such as region-wide pumping restrictions. A well-known reason for expecting such overexploitation of groundwater resources is the common property problem (Edwards & Guilfoos, 2021). Determination of a socially desirable steady-state groundwater stock level and the optimal time path toward it would be another exercise of policy relevance. Future extensions of our model that cover water resource allocation over time may accommodate these considerations. Additionally, we do not attempt to capture spatial heterogeneity in well depth and thus the costs of water extraction. Nor do we capture spatial variation in the groundwater-surface connection, which for instance, could be different in parts of our study region with higher or lower elevation or groundwater depth. Models that incorporate this heterogeneity may provide more precise estimates and policy prescriptions by considering the relative advantages of irrigation in low-versus high-cost regions. The model can also be extended to larger regions, incorporate multiple up- and down-stream participants, implement crop selection decisions (such as those in Howitt et al., 2012) and carry out climate change scenario analysis as well. Matlab, or comparable advanced software packages, may better accommodate the higher-level programming needed for such spatial dynamics.

Overall, despite limitations and room for extensions, this work lays the foundation of a promising model for assessing the economic efficiency of interstate water compact allocations with consideration of the important dimensions of groundwater and surface water interactions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The authors include a baseline model for the conjunctive use case with all the initial data parameters as a supplemental file. This file has instructions for replicating the conjunctive use case (fourth column of results in Table 2). The constraints and assumptions can be adjusted to replicate the other results shown or be expanded upon for one's own analysis. All data used was available through public sources referenced in this paper. The initial parameters provided in Table 1 along with the formulas from 1 to 26 provide the information needed to replicate the results (Tables 2). Data used in this study were obtained from publicly available sources (see also the reference list):

1. *Climate Data*: Annual average precipitation and temperature data at county level from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information online climate monitoring tool (NOAA National Centers for Environmental Information, n.d.).
2. *Streamflow Data*: USGS site data from the USGS National Water Information System's Web Interface (USGS: National Water Information System, n.d.).
3. *Agricultural Data*:
   - Crop prices and acreage from USDA National Agricultural Statistics Service (USDA National Agricultural Statistics Service, 1997-2017)
   - County agricultural census data from USDA Census of Agriculture (United States Department of Agriculture, 1997, 2002, 2007, 2012, 2017)
   - Farm and Ranch Irrigation Survey data (USDA, 1997–2017)
4. *Groundwater Well Data*:
   - Kansas well depth information from the WIZARD database operated by the Kansas Geological Survey (Kansas Geological Survey, n.d.)
   - Nebraska well data from the Registered Groundwater Wells Database operated by the Nebraska DNR (Nebraska Department of Natural Resources, n.d.)
5. *Water Rights and Compact Information*:
   - Republican River Compact Accounting documents from the Republican River Compact Association website (republicanriver.org) (Republican River Compact Accounting, 2020)
   - Kansas water rights data from Water Information Management and Analysis System (WIMAS) (Kansas Department of Agriculture, n. d.)
   - Kansas Minimum Desirable Flow requirements from the Kansas Department of Agriculture's Department of Water Resources (Kansas Department of Agriculture, n.d.)
   - Nebraska surface water rights from the DNR Surface Water Rights Database (Nebraska DNR, n. d.)

   - Kansas irrigation water use data (Kansas Department of Agriculture and U.S. Geological Survey, 2010–2017)
6. *Water Budget Information*:
   - Evapotranspiration and run-off estimations based on Kansas Water Plan (Kansas Water Plan: Water Budget of Kansas, 2014)
   - Republican River Basin Study (U.S. Department of the Interior: Bureau of Reclamation, 2016)

Geolocation Information

The illustrative case study region is in the Republican River Basin in the states of Nebraska and Kansas in the United States.

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References

Ambec, S., Dinar, A., & McKinney, D. (2013). Water sharing agreements sustainable to reduced flows. *Journal of Environmental Economics and Management*, *66*(3), 639–655. https://doi.org/10.1016/j.jeem.2013.06.003

Ansink, E., & Houba, H. (2015). The economics of transboundary water management. In *Handbook of water economics*. Edward Elgar Publishing.

Bennett, L. L. (2000). The integration of water quality into transboundary allocation agreements Lessons from the southwestern United States. *Agricultural Economics*, *24*(1), 113–125. https://doi.org/10.1111/j.1574-0862.2000.tb00097.x

Bennett, L. L., & Howe, C. W. (1998). The interstate river compact: Incentives for noncompliance. *Water Resources Research*, *34*(3), 485–495. https://doi.org/10.1029/97wr03384

Bennett, L. L., Howe, C. W., & Shope, J. (2000). The interstate river compact as a water allocation mechanism: Efficiency aspects. *American Journal of Agricultural Economics*, *82*(4), 1006–1015. https://doi.org/10.1111/0002-9092.00098

Boinet, E., Tardieu, E., Brachet, C., & Bernard, A. (2024). Lessons from the last 30 Years for future water resource management in national and transboundary basins. *Water International*, *49*(3–4), 255–266. https://doi.org/10.1080/02508060.2024.2343176

Booker, J. F., Howitt, R. E., Michelsen, A. M., & Young, R. A. (2012). Economics and the modeling of water resources and policies. *Natural Resource Modeling*, *25*(1), 168–218. https://doi.org/10.1111/j.1939-7445.2011.00105.x

Booker, J. F., & Young, R. A. (1994). Modeling intrastate and interstate markets for Colorado River water resources. *Journal of Environmental Economics and Management*, *26*(1), 66–87. https://doi.org/10.1006/jeem.1994.1005

Brookfield, A. E., Layzell, A., Zhou, T., & Tian, B. (2023). Monitoring changes in groundwater resources due to increased surface water delivery efficiencies in the lower republican River Basin. *Midcontinent Geoscience*, *4*, 42–49. https://doi.org/10.17161/mg.v4i.20851

Cobourn, K. M., Elbakidze, L., & Ghosh, S. (2017). Chapter 3.1.2—Conjunctive water management in hydraulically connected regions in the western United States. In J. R. Ziolkowska & J. M. Peterson (Eds.), *Competition for Water Resources* (pp. 278–297). Elsevier. https://doi.org/10.1016/B978-0-12-803237-4.00016-1

Degefu, D. M., He, W., Yuan, L., & Zhao, J. H. (2016). Water allocation in transboundary river basins under water scarcity: A cooperative bargaining approach. *Water Resources Management*, *30*(12), 4451–4466. https://doi.org/10.1007/s11269-016-1431-6

Du, E., Tian, Y., Cai, X., Zheng, Y., Han, F., Li, X., et al. (2022). Evaluating distributed policies for conjunctive surface water-groundwater management in large river basins: Water uses versus hydrological impacts. *Water Resources Research*, *58*(1), e2021WR031352. https://doi.org/10.1029/2021WR031352

Edwards, E. C., & Guilfoos, T. (2021). The economics of groundwater governance institutions across the globe. *Applied Economic Perspectives and Policy*, *43*(4), 1571–1594. https://doi.org/10.1002/aepp.13088

Espíndola, I. B., & Ribeiro, W. C. (2020). Transboundary waters, conflicts and international cooperation—Examples of the La plata basin. *Water International*, *45*(4), 329–346. https://doi.org/10.1080/02508060.2020.1734756

Giordano, M., Drieschova, A., Duncan, J., Sayama, Y., De Stefano, L., & Wolf, A. (2014). A review of the evolution and state of transboundary freshwater treaties. *International Environmental Agreements: Politics, Law and Economics*, *14*(3), 245–264. https://doi.org/10.1007/s10784-013-9211-8

Greaker, M., & Pade, L. (2009). Optimal carbon dioxide abatement and technological change: Should emission taxes start high in order to spur R&D? *Climatic Change*, *96*, 335–355.

Griggs, B. W. (2017). Interstate water litigation in the west: A fifty-year retrospective. *University of Denver Water Law Review*, *20*(2), 153–216.

Hansen, C. (1998). Effects of water-budget components on streamflow in the Republican River from near Hardy. In *Nebraska, to Concordia, Kansas, October 1980-September 1995*. US Department of the Interior, US Geological Survey. https://doi.org/10.3133/wri984163

Hossen, M., Connor, J., & Ahammed, F. (2024). Review of hydro-economic models (HEMs) which focus on transboundary river water sharing disputes. *Water Policy*, *23*(6), 1359–1374. https://doi.org/10.2166/wp.2021.114

Howitt, R. E., Medellín-Azuara, J., Macewan, D., & Lund, J. R. (2012). Calibrating disaggregate economic models of agricultural production and water management. *Environmental Modelling & Software*, *38*(C), 244–258. https://doi.org/10.1016/j.envsoft.2012.06.013

Hrozencik, R. A., Manning, D. T., Suter, J. F., Goemans, C., & Bailey, R. T. (2017). The heterogeneous impacts of groundwater management policies in the Republican River Basin of Colorado. *Water Resources Research*, *53*(12), 10757–10778. https://doi.org/10.1002/2017WR020927

Kansas Department of Agriculture. (n.d.). Big Blue River Compact. Retrieved from https://www.agriculture.ks.gov/divisions-programs/division-of-water-resources/interstate-rivers-and-compacts/big-blue-river-compact

Kansas Department of Agriculture. (n.d.). Minimum Desirable Streamflow. Retrieved from https://agriculture.ks.gov/divisions-programs/dwr/water-appropriation/minimum-desirable-streamflow

Kansas Department of Agriculture. (n.d.). Water information management and analysis system (WIMAS) for the Web (n.d.). Kansas department of agriculture, division of water resource water rights information system. [data file]. *Kansas Department of Agriculture, Division of Water Resources*. Retrieved from http://hercules.kgs.ku.edu/geohydro/wimas/query_setup.cfm

Kansas Department of Agriculture and U.S. Geological Survey (2010-2017). [data files]. Kansas irrigation water use (2010-2017). U.S. Geological Survey. Retrieved from https://agriculture.ks.gov/divisions-programs/dwr/water-appropriation/water-use-reporting

Kansas Geological Survey. (n.d.). Water Information Storage and Retrieval Database (WIZARD). 1997-2017.

Kansas Water Plan: Water Budget of Kansas. (2014). Kansas water plan: Water budget of Kansas. Retrieved from https://kwo.ks.gov/water-vision-water-plan/water-plan

Koff, H., Maganda, C., & Kauffer, E. (2020). Transboundary water diplomacy among small states: A giant dilemma for central American regionalism. *Water International*, *45*(4), 275–291. https://doi.org/10.1080/02508060.2020.1734758

Lautze, J., Holmatov, B., Saruchera, D., & Villholth, K. G. (2018). Conjunctive management of surface and groundwater in transboundary watercourses: A first assessment. *Water Policy*, *20*, 1–20. https://doi.org/10.2166/wp.2018.033

Nebraska Department of Natural Resources. (n.d.). Groundwater well registration. [data file]. *Nebraska Department of Natural Resources*. Retrieved from http://nednr.nebraska.gov/Dynamic/Wells/Wells

NOAA National Centers for Environmental Information. (n.d.). Climate at a Glance | National centers for Environmental Information (NCEI). Retrieved from https://www.ncdc.noaa.gov/cag/

Noel, J. E., & Howitt, R. E. (1982). Conjunctive multibasin management; an optimal control approach. *Water Resources Research*, *18*(4), 753–763. https://doi.org/10.1029/WR018i004p00753

OECD Environment Directorate. (2024). The Economics of Water: Valuing the Hydrological Cycle as a Global Common Good. Retrieved from https://economicsofwater.watercommission.org/report/economics-of-water.pdf

Provencher, B., & Burt, O. (1994). Approximating the optimal groundwater pumping policy in a multiaquifer stochastic conjunctive use setting. *Water Resources Research*, *30*(3), 833–844. https://doi.org/10.1029/93WR02683

Pulido-Velázquez, M., Andreu, J., & Sahuquillo, A. (2006). Economic optimization of conjunctive use of surface water and groundwater at the basin scale. *Journal of Water Resources Planning and Management*, *132*(6), 454–467. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:6(454)

Republican River Compact. (n.d.). U.S. Congress Public Law 60. Retrieved from http://republicanriver.org/wp-content/uploads/2018/05/Compact_US-version.pdf

Republican River Compact Accounting. (2020). Republican River Compact Association. [data file]. Retrieved from https://www.republicanrivercompact.org/acct/index.html

Scanlon, B. R., Healy, R. W., & Cook, P. G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. *Hydrogeology Journal*, *10*(1), 18–39. https://doi.org/10.1007/s10040-002-0200-1

Schlager, E., Heikkila, T., & Case, C. (2012). The costs of compliance with interstate agreements: Lessons from water compacts in the western United States. *Publius: The Journal of Federalism*, *42*(3), 494–515. https://doi.org/10.1093/publius/pjs017

Sekar, A., Valliammai, A., Nagarajan, M., Sivakumar, S. D., Baskar, M., & Sujitha, E. (2024). Conjunctive use in water resource management: Current trends and future directions. *Water Supply*, *24*(11), 3881–3904. https://doi.org/10.2166/ws.2024.215

Silva, F., Fulginiti, L., Perrin, R., & Schoengold, K. (2019). The effects of irrigation and climate on the high plains aquifer: A county-level econometric analysis. *JAWRA Journal of the American Water Resources Association*, *55*(5), 1085–1101. https://doi.org/10.1111/1752-1688.12781

Sophocleous, M. (2002). Interactions between groundwater and surface water: The state of the science. *Hydrogeology Journal*, *10*(1), 52–67. https://doi.org/10.1007/s10040-002-0204-x

United Nations. (2024). The United Nations World Water Development Report 2024: Water for Prosperity and Peace; Facts, Figures and Action Examples. Retrieved from https://unesdoc.unesco.org/ark:/48223/pf0000388952

United States Department of Agriculture 1997, 2002, 2007, 2012, 2017. *Census of Agriculture: Farm and Ranch Irrigation Survey (1998)*. United States Department of Agriculture: National Agricultural Statistics Service. Retrieved from https://www.nass.usda.gov/Publications/AgCensus/2017/Online_Resources/Farm_and_Ranch_Irrigation_Survey/index.php

USDA National Agricultural Statistics Service. (1997-2017). USDA Agricultural Census Report.

U.S. Department of the Interior: Bureau of Reclamation. (2016). Final Full Report: Republican River Basin Study. Retrieved from https://www.usbr.gov/watersmart/bsp/docs/finalreport/republican/republican-river-basin-study-final-report.pdf

USGS: National Water Information System. (n.d.). USGS surface-water and water use data for Kansas and Nebraska. [data file]. *USGS: National Water Information System*. Retrieved from https://waterdata.usgs.gov/ks/nwis/sw

van den Brink, R., van der Laan, G., & Moes, N. (2012). Fair agreements for sharing international rivers with multiple springs and externalities. *Journal of Environmental Economics and Management*, *63*(3), 388–403. https://doi.org/10.1016/j.jeem.2011.11.003

Wada, C. A., Pongkijvorasin, S., Roumasset, J., & Burnett, K. (2023). Solving optimal groundwater problems with Excel. *Applied Economics Teaching Resources*.

Williams, R. B., Al-Hmoud, R., Segarra, E., & Mitchell, D. (2017). An estimate of the shadow price of water in the southern Ogallala Aquifer. *Journal of Water Resource and Protection*, *9*(3), 289–304. https://doi.org/10.4236/jwarp.2017.93019

Winter, T. C. (1995). Recent advances in understanding the interaction of groundwater and surface water. *Reviews of Geophysics*, *33*(S2), 985–994. https://doi.org/10.3133/cir1139

WMO. (n.d.). Guide to Hydrological Practices. Retrieved from http://www.whycos.org/hwrp/guide/index.php