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Key Points:
- Heterogeneous economic and environmental benefits of groundwater trading are quantified and spatially illustrated
- Climate change increases the price elasticity of groundwater and leads to increased variation in groundwater price and pumping
- Groundwater overdraft is sensitive to changes in both precipitation and temperature, with a higher sensitivity to changes in precipitation

Supporting Information:
- Supporting Information S1

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Effect of Hydrogeologic and Climatic Variability on Performance of a Groundwater Market

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Abstract Incentive-based policies, such as the cap-and-trade system, have been shown to be useful in the context of groundwater management. This study compares the performance of a groundwater market with water quotas when assumptions of perfect information are violated due to climate change and hydrogeologic heterogeneity and explores how changes in future climate affect market performance. A subbasin of the Republican River Basin, overlying the Ogallala aquifer in the High Plains of the United States, is used as a case study. Building on a previously developed model, a multiagent system model simulating a groundwater market is developed where self-interested agents can trade water use permits to maximize individual benefits subject to irrigation and land constraints. This economic model is coupled with a calibrated physically based groundwater model for the study region that allows for an evaluation of streamflow depletion impacts, which has been the focus of management efforts in the basin. Results show that trading of permits between farmers results in increased economic benefits and, in some cases, reduced environmental violations. However, the benefits of a groundwater market are distributed unequally resulting in “winners” and “losers” across the system. Future changes in climate are shown to significantly influence farmers willingness to pay for groundwater and thus increase the variation in groundwater price and pumping. These findings emphasize the importance of addressing hydroclimatologic variability and change in the design of groundwater markets.

1. Introduction

Water scarcity is recognized as the one of the most serious challenges facing societies globally (World Economic Forum, 2016). Expected increases in population and living standards, especially high in the most water stressed countries, will further exacerbate water shortages and their impact on food and energy production. Discounting freshwater available in the polar ice caps, groundwater constitutes almost 90% of global freshwater, thus making groundwater resource management one of the most important, and critical, natural resource management frontiers (Koundouri, 2004). With the increasing demands on surface waters, groundwater is also increasingly becoming the primary buffer against droughts (Taylor et al., 2013). However, in recent years, harmful impacts of unmanaged groundwater extraction have emerged. A recent analysis shows that storage in 21 of the 37 largest aquifers in the world has decreased over the past decade, with over a third severely depleted, threatening regional water availability (Richey et al., 2015)

It is in this context of water scarcity and increased groundwater stress that calls for improved groundwater management have been made. One such example is the Sustainable Groundwater Management Act passed by the state of California in response to rapidly depleting groundwater resources (Xiao et al., 2017). The law calls for improved groundwater management to ensure sustainable use of the resource and creates groundwater management districts to oversee the implementation but leaves the particular approach to management up to the districts (Nelson & Perrone, 2016).

As is the case with surface waters, centralized governance approaches (also termed “command and control”) have traditionally been adopted for groundwater management globally, such as in the form of groundwater quotas (Dinar & Wolf, 1994). However, in recent years, other more localized and decentralized policies have become increasingly popular as an alternative to the command and control approach. Increased community participation and engagement (Garduño et al., 2009; Rangan, 2016) have been shown to be particularly effective at mitigating problems arising from the common pool resource nature of groundwater.

Markets for groundwater present another alternative approach to groundwater management. These markets can be formally instituted, with regulations and clearly defined governing bodies, or can be informal, where they emerge organically as a response to demand for water (often for irrigation purposes; Easter et al., 1999). Informal groundwater markets are especially prevalent in areas with intensive groundwater use (for agriculture), weak governance, and lack of capital to install tubewells, for example, India and Pakistan (Shah, 2005). In parts of the world with stronger institutional settings, formalized markets for groundwater have been proposed (Raffensperger et al., 2009; Young & Brozović, 2016). This approach to groundwater governance uses economic incentive-based policies, such as the cap-and-trade system, creating financial incentives (in the form of a price) for use of a resource. This paper uses the term groundwater market to refer to a cap-and-trade system for groundwater management. In a groundwater market, tradeable permits are either allocated or auctioned to allow users to access the resource. The total volume of available permits forms a cap on the total groundwater extraction with users allowed to trade the permits allocated to them.

While trading permits for groundwater use may lead to increased system-wide economic efficiency, some of the literature on such incentive-based approaches has simplified the actual context in which such interventions would be enacted and consequently possibly overestimated their benefits (e.g., Thompson et al., 2009). Groundwater systems are dynamic with aquifer characteristics (e.g., hydraulic conductivity), depth to groundwater and surface water-groundwater interactions varying spatially. This hydrogeologic variation in groundwater can lead to uneven distributional impacts in the absence of well-designed trading regulations (Brozovic et al., 2010). The term "distributional impacts" as used in this manuscript refers to spatially varying impacts across a system. While trading is a voluntary activity, the third party effects of trade are involuntary (i.e., farmers have no say in transaction between two other farmers in the absence of trading ratios). These uneven distributional impacts, amplified in low-transmissivity aquifers, can lead to drying of wetlands, streamflow reductions, or land subsidence. Possible economic benefits notwithstanding, the presence of uneven distributional impacts can make implementation of incentive-based policies challenging. Analysis of performance of groundwater markets, with the explicit intent of addressing distributional impacts, has been identified as a key area of research (Skurray et al., 2012). We address this knowledge gap in this analysis. Groundwater management policies cannot be meaningfully evaluated if the models used do not realistically simulate hydrogeologic conditions. To represent the spatial and temporal heterogeneity in groundwater conditions across a region, models for groundwater markets need to be supplemented with physically based hydrogeologic models (Mulligan et al., 2014).

In addition to the need to address spatial variation, possible temporal variation caused by future changes in climate needs to be addressed in groundwater market designs (Loch et al., 2013). Climate variability and change can impact groundwater directly, mainly through changes in temperature and precipitation, and indirectly, through change in irrigation-water demand due to reduced surface water availability. Strong links between groundwater and climate, and the influence of energy demand on these linkages, have been shown in regions experiencing groundwater use intensification (Scott, 2011). A thorough investigation of the sensitivity of a market to changes in climatic conditions, so far missing in the literature, can provide useful insight to policy makers regarding appropriate market design to optimally adjust for changing conditions. Sustainable groundwater management that addresses these changes needs to be informed by integrated models that are able to incorporate the interactions between surface water, groundwater and human activity (Taylor et al., 2013).

This work builds upon the growing literature on distributional impacts of incentive-based groundwater management policies to provide two contributions to the aforementioned knowledge gaps. We use a spatially dynamic physically based groundwater model coupled with an agent-based model (representing a groundwater market) to (1) systematically evaluate climate change impacts on groundwater dynamics through a stress testing approach, rather than a scenario-based approach, and the resultant impact on groundwater trading; and (2) quantify and spatially illustrate the heterogeneous economic and environmental impacts of an incentive-based policy (groundwater trading) compared to a command and control approach (water quotas). A subbasin of the Republican River Basin, overlying the Ogallala aquifer in the High Plains of the United States, is used as a case study. The multiagent system model, originally developed by Mulligan et al. (2014) and modified for this analysis, features self-interested agents who can trade their water use permits to maximize individual benefits subject to irrigation and land constraints. This economic model is coupled with a calibrated physically based groundwater model for the study region that helps quantify distributional impacts associated with groundwater trading.

2. Literature Review

Groundwater management has been identified as one of the major natural resource management challenges of the 21st century, especially in the context of climate change (Gorelick & Zheng, 2015). Effective groundwater policies need to be instituted within a quantitative framework. Initial quantitative analyses evaluating the efficacy of groundwater policy instruments represented groundwater using homogenous single cell or "bath tub" models (Feinerman & Knapp, 1983). More recently, work by Brozović et al. (2010) has shown that ignoring the spatial heterogeneity in an aquifer significantly affects welfare gains from optimal management. Recognition of the importance of realistically capturing groundwater dynamics spurred interest in economic studies that model aquifer as multicell basins, with varying spatial resolution (Katic & Grafton, 2012).

A growing body of literature highlights the importance of accounting for spatial heterogeneity while evaluating groundwater policy (Kuwayama & Brozović, 2013). Using irrigation well level data, Palazzo and Brozović (2014) demonstrate the effects of heterogeneity (both in farmer behavior and aquifer characteristics) on economic outcomes of groundwater management policies. Building on this work, Guilfoos et al. (2017) present a framework featuring a hydroeconomic model coupled with a market for groundwater permits to assess performance of policies in the context of a dynamic system with significant heterogeneity. Their findings further emphasize the importance of accounting for hydrologic and economic differences between groundwater users by showing the large welfare losses accrued if these differences are ignored. However, while their framework incorporates spatially explicit groundwater, it does not effectively capture streamflow dynamics and quantify third-party impacts. This is addressed in the present study.

More recently, there have been efforts to further improve the representation of the hydrogeology in hydroeconomic modeling through the use of physically based groundwater models that are able to, among other things, capture the dynamic streamflow-aquifer feedback and more holistically quantify groundwater pumping drawdown effects (Kahil et al., 2016). Some of these studies have used optimization models coupled with physically based groundwater models (Reeves & Zellner, 2010; Yu et al., 2003). In one such recent study, Hrozencik et al. (2017) couple an agroeconomic model with a MODFLOW model to evaluate various groundwater management policies including pumping fees, irrigated acreage fees, and quantity restrictions. The results of the study reveal that heterogeneous conditions (e.g., well capacity and soil type) affect policy impacts, with the impacts differing qualitatively across policy types. These findings emphasize the important sociopolitical implications of the distributional impacts resulting from ill-suited policies. Mulligan et al. (2014) compare the economic and environmental performance of an idealized groundwater market with taxes and caps on groundwater use. They find that optimal allocation through the idealized market leads to reduced environmental impacts and increased economic benefits. In another study, Bauman et al. (2015) address the heterogeneity in users by using multiobjective optimization to model "imperfect" surface water trading between agricultural, municipal, and industrial users having different objectives in the western United States. In an attempt to model a more realistic water market, the authors incorporate transaction costs and find that these costs noticeably reduce economic efficiency and highlight their distributional impacts. This work however does not incorporate any physical representation of the hydrology or account for groundwater use as is done in this analysis.

More recently, groundwater management models that minimize externalities resulting from groundwater use have been developed (Elbakidze et al., 2018). Smart water markets provide an avenue for optimal management of groundwater to control the externalities resulting from groundwater overuse. These markets are essentially electronic clearinghouses simultaneously matching many buyers and sellers using optimization algorithms that combine the advantages of decentralized permit ownership with the coordination advantage of central processing (Murphy et al., 2000). In theory, not only can smart water markets account for spatial heterogeneity, they can also mitigate distributional impacts and environmental externalities that result from over use of a common property resource such as groundwater. Using groundwater irrigation in Marlborough, New Zealand, as a case study, Raffensperger et al. (2009) show that smart water markets can increase the reliability of environmental flows and reduce transaction costs and users risk. The Twin Platte Natural Resource District in Nebraska recently became the first region to establish an exchange of groundwater use permits via a smart water market (Young, 2016).

Not only does market design need to account for spatial heterogeneity but also it needs to be robust to temporal variation, most notably future changes in climate. The impact of climate change on groundwater has received much attention recently (Green et al., 2011; Treidel et al., 2012). Climate variability and change can impact groundwater directly, mainly through changes in temperature and precipitation, and indirectly, through change in irrigation-water demand due to reduced surface water availability. Due to the high uncertainty in General Circulation Model (GCM) projections, particularly those for future precipitation, the impact of climate change on groundwater systems is uncertain (Döll & Fiedler, 2008). In addition to the effect of mean changes in climate, changes in daily rainfall distributions are also posited to affect recharge in some aquifers (Crosbie et al., 2013).

Water markets have been proposed as one of the solutions to offset the differential impacts of climate change. Existing literature and past evidence, primarily from Australia, suggest that markets for surface water are effective in mitigating effects of a drier climate (Beare & Heaney, 2002; Loch et al., 2013). A review of water markets in the Murray Darling Basin in Australia documents the increases in efficiencies brought about and concludes that water markets helped the water use structure in the country to adjust to changing climate conditions and was effective at reducing total economic impacts and production losses (Wheeler et al., 2013). A review of existing literature suggests that while studies have attempted to evaluate the impact of climate change on surface water markets (Jiang & Grafton, 2012; Marchlik, 2014), an assessment of the impact of future changes in climate on groundwater market dynamics has not been performed. We address this gap in the literature in this study.

3. Methodology

This study extends the analysis performed by Mulligan et al. (2014) comparing the performance of optimal water allocation and free market access under different groundwater policy instruments. This analysis aims to (1) evaluate the differential effects climate change on performance of groundwater markets and nontradeable water quotas, (2) quantify the uneven distributional impacts that result from an imperfectly designed groundwater market, and (3) compare the economic and environmental performance of nontradeable water quotas to a realistic groundwater market. To do so, we use the economic optimization agent-based model developed by Mulligan et al. (2014) and make three key changes:

1. The updated agent-based model is configured to allow farmer agents to trade their groundwater allocation, thereby simulating a groundwater market. The algorithm used to setup this market is explained in greater detail in section 3.4.2.
2. Crop irrigation requirements are varied in each growing season based on the climate.
3. Farmer operating costs and pump efficiencies are updated to reflect current conditions.

The farmer decision model is coupled with a calibrated physically based groundwater model; the models are linked through the agents groundwater pumping decision (optimized decision variable in the economic model), which is then input to the groundwater model to calculate updated groundwater levels and streamflows, which affects subsequent pumping decisions. The coupled model is run under scenarios with varying agent characteristics, groundwater allocations, and climate conditions.

3.1. Study Region: Geography (Location and Area), Agriculture, and Climate

As a case study for this coupled modeling framework, we model agricultural water use in the Frenchman River subbasin. Spanning 2,900 mi^2 across Nebraska and Colorado, this subbasin is located in the northwest corner of the Republican River Basin, as shown in Figure 1. Further Figures (S1–S4) illustrating a conceptual cross section of the aquifer, along with spatial heterogeneity of precipitation, hydraulic conductivity, and land use in the region, are provided in the supporting information (Gurdak et al., 2009; Szilágyi, 2014; U.S. Bureau of Reclamation, 2016). The Republican River Compact Authority (RRCA), established in 1959, administers allocation of state water rights in the Basin. In the Republican River Compact of 1942, beneficial consumptive use of flows in the Republican River was set at 66.7×10^6 m^3 for Colorado, 289.3×10^6 m^3 for Nebraska, and 234.7×10^6 m^3 for Colorado; these allocations did not include groundwater extraction. Since then, advances in irrigation technology have led to substantial increases in groundwater pumping and ongoing litigation among states (Palazzo & Brozović, 2014).

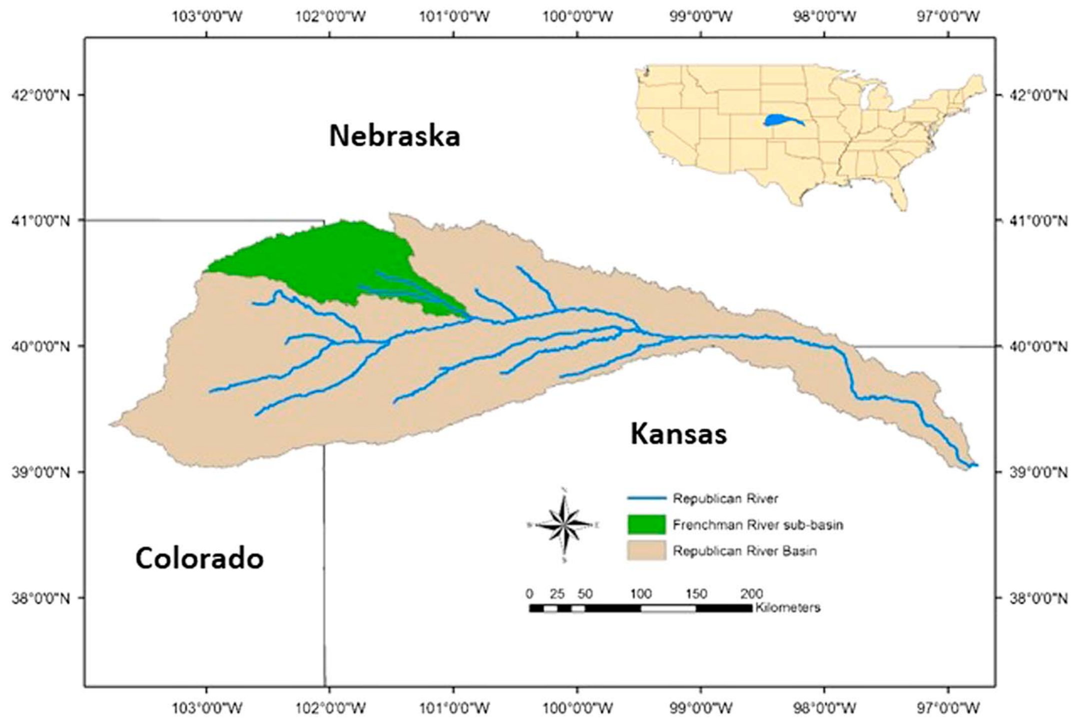

Figure 1. Study region for the analysis overlying the High Plains aquifer.

Overlying the Ogallala aquifer (also known as the High Plains aquifer), the Frenchman River and the groundwater flow eastward. Climate in the Frenchman River subbasin can be classified as semiarid, with average annual precipitation of 32 in. Irrigation accounts for approximately 95% the total groundwater use in the region (Rodell & Famiglietti, 2002). Most of the crop water requirements in the study area are met with groundwater, with conjunctive water use rarely practiced in the study area (Palazzo & Brozović, 2014). Intensive groundwater pumping in this region, primarily for agricultural purposes, is well documented and has been the subject of many investigations (Sophocleous, 2005). The increase in large-scale pumping has led to reductions in streamflow, and a rapidly depleting groundwater table in some parts of the basin emphasizes the need for improved groundwater management (Scanlon et al., 2012).

The impact of groundwater pumping on the surface water-groundwater interaction is the primary focus of management efforts in Nebraska. Within Nebraska, the Frenchman subbasin spans across counties in the Upper and Middle Republican Natural Resource Districts (NRD) that oversee implementation of water management policies. The study area is one of the few areas in the United States to have well-quantified and enforced groundwater rights, stemming from a need to limit transboundary streamflow impacts on neighboring states. Groundwater irrigation allocations in the Upper and Middle Republican NRDs are set at 13 and 12 in., respectively. Nebraska is also home to the first smart market for groundwater trading in the Twin Platte NRD (outside the study area considered here). This smart market practices area-based trading (as opposed to volumetric trading) and accounts for streamflow depletion factors, soil types, and other important hydrogeologic characteristics through trading ratios when matching parties and clearing the market (Young, 2016).

Transaction costs can be an important determinant of the effectiveness of water markets (Garrick & Aylward, 2012; Howe et al., 1990) and should be addressed when evaluating the performance of a market. High transaction costs create significant lags in permit transactions (Neuman, 2004) and have been identified as a barrier to successful implementation of market-based water allocation (Colby, 1990). For our study region, Palazzo and Brozović (2014) make a case for why transaction costs in this region would expected to be low. Among their reasons they cite (i) the existence of some water trading without a formal market, suggesting potential gains from trading are greater than transaction costs; (ii) already completed certification of irrigated area which clearly defines and quantifies groundwater rights (iii) comprehensive well metering and enforcement and monitoring of groundwater pumping making efficient trading more likely. For these reasons, we do not include transaction costs as part of this analysis.

3.2. Groundwater Model

The calibrated MODFLOW groundwater model used in this study was developed by the RRCA to assist with water allocations stipulated in the Republican River Compact (Republican River Compact Administration, 2003). We briefly mention the salient features of the calibrated model here; detailed explanation of the model input and setup can be found in the model documentation. The simulation model runs under a monthly stress period with a biweekly time step and contains approximately 30,000 active rectangular grid cells, each 1 mi^2 in size. Total monthly precipitation and average monthly temperature over 1950–2000 are used as the baseline climatic inputs (recharge and evapotranspiration) for the simulations. Observations from 34 rain gauges and 3 climate stations across the modeling domain are interpolated to assign precipitation and temperature values to each grid cell. Recharge from precipitation at each grid cell is determined using a recharge versus precipitation curve developed by the RRCA for different soil types across the basin, while area weighted evapotranspiration rates are calculated based on the Hargreaves method for each grid cell. For phreatotype vegetation, the Hargreaves method with appropriate equivalent crop coefficients is employed. For crop water requirements, the Hargreaves equation is calibrated to the Penman-Montieth equation. For this analysis, while the simulation model for the entire Republican River Basin is run, pumping decisions are updated for grid cells only in the Frenchman River. Pumping rates for cells outside of the Frenchman River subbasin are fixed at the flow rates for the latest year (2000) available in the RRCA model. Groundwater levels at the end of the simulation run from 1918 to 2000 from the original RRCA model are used as the starting hydraulic heads for this analysis. The STR Package in MODFLOW is used to simulate the interaction between groundwater and surface water. Changes in groundwater head (resulting from the various groundwater fluxes such as groundwater pumping and precipitation) have an impact on the rate and direction of flow between groundwater and surface water (streamflow).

3.3. Agent-Based Model: Agent Characteristics

Agent characteristics in the Frenchman River subbasin as used by Mulligan et al. (2014) are used in this study and briefly summarized here. Using model reduction methods, pumping wells across the Frenchman River Basin are clustered into fifty agents of varying sizes based on the similarity of stress imposed on the groundwater system (Mulligan & Ahlfeld, 2016). Each agent represents a farmer; the same agent delineation is used throughout the different model formulations and scenarios. Each agent makes two decisions: which crop to grow and how much land to irrigate subject to constraints on land and water availability. These decisions determine the amount of water the agent must pump. The agent is modeled to be myopic (does not have foresight for future time steps) and only seeks to maximize benefits in the current time step. It is assumed the agents can determine crop irrigation requirements at the start of the growing season (based on their past experiences and knowledge of current seasons precipitation). This modeling assumption implies that the farmers can make decisions on trading their allocations at the start of the cropping season.

In this modeling framework, the agents can choose between soy and corn, the two crops representing the majority of agricultural production in the region. Productivity of agents is determined by two key parameters: crop yield and crop water requirements. For each model setting, 10 runs are performed using different sets of agent productivity parameters developed by Mulligan et al. (2014). In each set and for each agent, the parameters are randomized to model a more realistic basin setting representing a range of agent productivity from “highly productive” to “less productive” agents. This variation represents the heterogeneity of agents that arises due to various levels of experience, technology adoption, etc. We limit this analysis to 10 unique productivity parameter sets (provided in the supporting information) because of computation time. Historical crop data from three counties (Perkins, Chase, and Dundy) within the Frenchman Basin were used to prepare statistical distributions of crop yields and crop water requirements for each crop.

Annual groundwater irrigation requirements are calculated after accounting for effective precipitation which varies annually. Additionally, for each precipitation and temperature change considered (for the climate scenarios), we update the effective precipitation (rainfall that can be used for irrigation). The balance water requirement (total crop water requirement minus the effective precipitation) for the crops is met with

Table 1
Variables Used in the Agent-Based Economic Model

Variable	Definition
$Q_{a,c,s}$	Flow rate decision variable (L^3/T)
Q_a^u	Upper bound for flow rate
a	Agent (well site)
s	Pumping season
c	Crop
N	Total number of crops
A_a	Maximum land area (L^2)
CAP	Water use cap (L)
p_c	Selling price of crop c ($)
$y_{a,c}$	Crop yield (bushel/L^2)
d	Pumping duration (T)
e	Pumping efficiency (proportion)
h	Total lift (L)
γ	Specific weight (F/L^3)
$w_{a,c}$	Crop irrigation requirements (L)
p_e	Electricity price ($/P–T)
f_c	Farm operating costs ($/$L^2$)

groundwater irrigation. The deficit irrigation strategy adopted in this model assumes that the farmer adjusts the amount of irrigated land based on the pumping decision. If the farmer is constrained below the required irrigation depth for his/her land, the model allows the farmer to increase irrigation depth above the regulatory limit on a subset of the irrigated area while at the same time reducing total irrigated area and increasing dryland area. For instance, consider a farmer who possesses 50 acres of land and requires 10 in. of water for corn. Due to regulatory or economic constraints, the farmer decides to use only 5 in. of water for corn for a given season. Then, the model allows the farmer to apply 5 in. of water to half of the 50 acres, such that the 25 acres will be irrigated with 10 in. of water for corn while the other 25 acres remain unirrigated. This farmer behavior is also adopted by Palazzo and Brozović (2014) for a similar study of groundwater trading in our study area.

3.4. Agent-Based Economic Model Formulation

The agent-based economic model is described in the two sections below. In the first section, design of the "baseline" model (developed by Mulligan et al., 2014) in which agents maximize individual profits subject to fixed constraints on water usage (allocated groundwater quotas) is provided. In the second section, we describe the changes made to model design to introduce trading between agents.

3.4.1. Decentralized Optimization With Fixed Quotas

In the agent-based economic model, for each agent there is an objective function in which individual profits are maximized. The objective function shown in equation (1) below contains all revenues and costs faced by the agent. Table 1 provides definitions for the different variables. The total costs faced by each agent is the sum of energy costs for groundwater pumping, and fixed and operating costs. Total fixed and operating costs are obtained from the 2018 Nebraska Crop Budgets (Klein et al., 2017). The total revenue for each agent is a function of the amount of crop produced, determined through a linear crop production function and the crop price. For model runs in which agents are allowed to trade water allocations (groundwater market), the revenues/costs of trading allocations are added to the objective function. The constraint in equation (2) bounds the pumping to limits on available land area and crop irrigation requirements. The constraint in equation (4) limits pumping to the allocated groundwater quota.

Maximize

$$\sum_{c=1}^{N}\left\{\left[\frac{p_c y_{a,c} d}{w_{a,c}} - \frac{h_{a,s}\gamma_w p_e d}{e} - \frac{f_c d}{w_{a,c}}\right] Q_{a,c,s}\right\} \tag{1}$$

subject to

$$0 \le \sum_{c=1}^{N} Q_{a,c,s} \le Q_a^u \tag{2}$$

$$Q_a^u = \max_c \frac{A_a w_{a,c}}{d} \tag{3}$$

$$\frac{d\sum_{c=1}^{N} Q_{a,c,s}}{A_a} \le \text{CAP} \tag{4}$$

Each model run has a 50-year time period, with each agents decisions optimized each year. The optimization is carried out using the active-set optimization algorithm in the *R* programming language. For each agent, the decision variable that is optimized is the amount of groundwater to pump at the start of the cropping season subject to constraints on water allocated and land available. Based on groundwater use in the previous year, updated depth to groundwater for each agent is calculated at the beginning of each cropping season. The depth to groundwater determines the pumping costs for each year. Return flows are assumed to be

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20% of pumping volumes (Zeng & Cai, 2014), with a pumping efficiency of 80%. Values for the various model parameters are reported in the supporting information.

3.4.2. Groundwater Market Formulation

The differences in the marginal value product (MVP) of water for the different farmers is what drives trading in a groundwater market. In our model settings, each farmer has a unique MVP of water stemming from differences in productivity. To model a groundwater market that allows agents to trade allocated permits, we use the penalty-based decentralized optimization formulation proposed by Yang et al. (2012), represented by equation (5).

$$\max F_i(x_i, p_i|w_i) = \max[f_i(x_i) - p_i(x_i - w_i)] \tag{5}$$

where x_i represents the water used, p_i represents the water price, w_i represents the water use permit for the agent, and $f_i(x_i)$ represents the water use benefit. As in the formulation described previously, the model assumes that all agents maximize water use benefits. In the formulation described above, a positive (negative) difference between x_i and w_i, that is, $x_i > w_i$ ($x_i < w_i$) represents the amount of water an agent is willing to buy (sell) at the given price.

The algorithm for estimating the demand function for water is as follows:

1. For each level of groundwater quota (in terms of depth), the total volumetric allocation for each farmer based on their available irrigated land is determined. This represents the maximum possible water usage by each farmer (constrained by land use).
2. The sum of all volumetric allocations under a particular cap, A_c, is used to constrain the algorithm and ensure that the solution from the algorithm is feasible (i.e., system-wide water usage is less than or equal to the sum of water allocations).
3. The solution algorithm starts with $p_i = 0$ at which all the agents use all the water that they can possibly use because selling permits is not economically advantageous. However, this results in water usage greater than the allowable A_c. This situation, although unrealistic, allows the numerical search loop to find an initial solution through which the price of water can then be increased to reach an equilibrium between A_c and groundwater extracted.
4. The price of water is incrementally increased until equilibrium is reached.
5. The system reaches equilibrium, and the algorithm stops when the sum of the modeled water use approaches the sum of the water use permits (A_c, i.e., $\sum x_i = \sum w_i$).

This groundwater market setup assumes that all agents have equal access to buying groundwater permits (agents can trade across political boundaries); hence, all agents face a uniform equilibrium water price. While all agents face a uniform equilibrium water price, each agent will have a unique marginal value of water owing to the spatial heterogeneity in aquifer conditions. The use of the physically based groundwater model helps indirectly capture the effect of this heterogeneity on each agent's marginal value of water. Policies limiting pumping while controlling for spatial variability through the use of trading ratios exist for parts of the Ogallala aquifer. Using a simple two-well aquifer, Guilfoos et al. (2017) show that using constant trading ratios can help avoid welfare losses provided that total amount of groundwater permits are calculated correctly and no exhaustion externalities occur. The groundwater market setup we adopt thus does not intend to consider the overall sustainability of the Basin. One of the goals of our investigation is to quantify and highlight the effect of the absence of trading ratios on third-party impacts; thus, we do not include trading ratios in our groundwater market formulation.

3.5. Scenario Analysis

The coupled economic and groundwater model are driven with different combinations of water allocations, and temperature and precipitation changes to illustrate their respective impacts on the two groundwater management policy approaches. Six different groundwater allocations, in terms of inches per unit area (depth), indicating varying levels of water scarcity are used to compare the performance of water quotas and groundwater markets. The water allocations examined here vary from 10 to 15 in., in 1-in. increments. We assume that farmers are not limited by their well capacity to pump at the higher allocations and do not require extra investment when their allocation is increased to 15 in. Water allocations are assigned uniformly for all agents.

As part of this study, we perform a climate stress test, which systematically perturbs the climate inputs to test the sensitivity of the system to precipitation and temperature (Brown et al., 2011). In our modeling framework, changes in precipitation affect groundwater directly by altering the aquifer recharge and net irrigation requirements; it affects groundwater indirectly through changes in streamflow and thus baseflow. Changes in temperature affects the evaporation from shallow groundwater and crop evapotranspiration, ultimately affecting irrigation requirements.

The ranges for the climate perturbations, relative to historically observed climate, are informed by the range of changes projected for the study region in the Fifth Coupled Model Intercomparison Project (CMIP5) GCMs. Projections of future climate for this region suggest an increase in mean temperature and display significant uncertainty in precipitation changes. Precipitation is varied from −30% to 30% of historic average with 15% increments and temperature from 0 to 4 °C with 1° increments. Climate shifts are applied to the baseline precipitation and temperature assigned for grid cells in the modeling domain uniformly across space and time. The updated climate inputs are used to calculate the precipitation recharge and evapotranspiration values. Groundwater irrigation needed is also updated for the different changes in precipitation and precipitation.

In total, 3,000 model runs for the fixed groundwater allocation and groundwater market settings (1,500 each, 6 allocations × 5 precipitation × 5 temperature × 10 sets of agent characteristics), each 50 years long are conducted for this study.

4. Results and Discussion

This section begins with results comparing the economic and environmental performance of water quotas and groundwater markets under climate change. Next, uneven distributional impacts from groundwater trading are quantified. Finally, the impact of changes in climate on groundwater dynamics are explored and discussed.

Figure 2(a) shows how average annual system-wide profits change with the average annual groundwater pumping for different allocations and varying climate. Figure 2(b) shows the spatial distribution of the average annual groundwater pumping for each agent under trading with baseline climate and a given allocation. The solid line in Figure 2(a) shows the profits when agents are provided a uniform allocation and not allowed to exceed that (i.e., quotas on groundwater use); the dashed line represents the profits when the agents are allowed to trade their allocations. While the coupled model is run with several combinations of climate changes, the climate futures shown in this figure represent the bounds of changes. The black, green, and red lines represent climates that are baseline (historic), cooler and wetter (30% increase in precipitation and no warming), and warmer and drier (30% decrease in precipitation and 4 °C warming), respectively. The difference between the solid and dashed lines is the change in benefits when farmers are allowed to trade their groundwater allocations; we refer to these changes in benefits as the “gains from trading.” The gains from trading stem from two factors: water being directed to the most efficient users and the ability of farmers to sell their unused allocation allowing for greater system-wide groundwater use.

Figure 2(a) indicates that gains from trading depend on the groundwater allocation and the resulting price of water and are highest under “optimal” scarcity conditions. In the baseline and the cool and wet climate conditions, the gains are greatest at the lowest allocation of 10 in. and decrease as the allocations increase (and scarcity decreases). At the highest allocation of 15 in., the gains are smallest because the allocation is high enough to satisfy most farmers water requirements, and there is reduced incentive to trade. This is highlighted in Table 2, which shows that under baseline and cool and wet climate conditions, only 0.6% and 5.8% of farmers are limited by an allocation of 15 in. Figure 2(b) indicates that most of the pumping takes place in the central part of the Frenchman Basin in the Chase and Perkins counties in Nebraska. A comparison with Figure S6 in the supporting information that illustrates the spatial distribution of pumping under fixed allocations reveals that the spatial distribution does not change significantly. This is understandable given the reduced volume of trading at an allocation of 12 in.

Interestingly, in the warm and dry climate future, the gains from trading do not decrease as much with increasing allocations. These gains primarily stem from a greater demand for groundwater irrigation (due to higher crop water requirements and reduced precipitation) that encourages trading. For the low

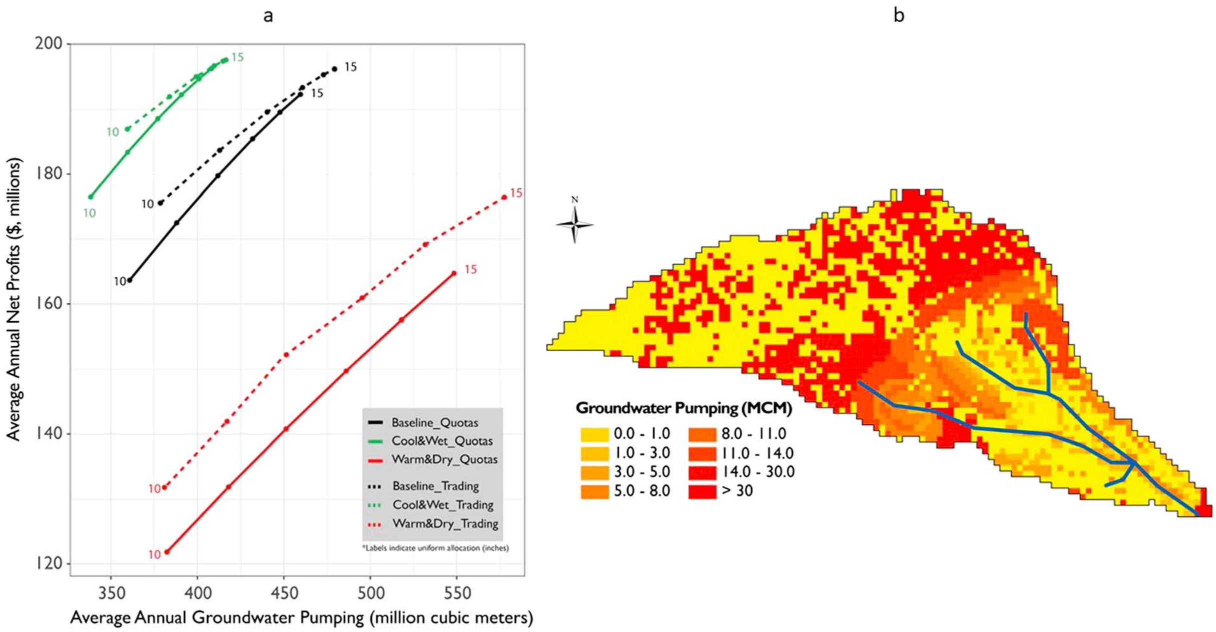

Figure 2. A Total annual average agent profits and groundwater pumping for different allocations and varying climates for a groundwater market and water quotas. The black line shows results for model runs under historic climate, while the red and green lines show results under warmer and drier (30% decrease in precipitation and 4 °C warming) and cooler and wetter (30% increase in precipitation and no warming) climates, respectively. B spatial distribution of average annual groundwater pumping (aggregated for each agent) under trading with baseline climate and an allocation of 12 in.

allocations under the warm and dry climate, groundwater pumping is similar for both the quotas and trading scenario; under this constrained groundwater availability, the resulting high groundwater price (shown in Figure 6) serves to discourage trading. With significantly increased pumping (much more than is seen in the model results), we may also expect costs of land subsidence and deteriorating water quality, which are not accounted for here, to become important. Benefits of trading allocations are highest when the allocations are adapted to the prevailing climate conditions to create the "optimal" level of scarcity and can increase revenues by up to $10 million (~8% of total revenues). A higher variation in crops and water usage than is observed in this region would be expected to lead to larger gains from trading (Zeff et al., 2016). It is pertinent to note here that transactions costs associated with permit trading are not included here and would likely reduce the economic gains from trading.

Figure 2(a) also shows how crop profits may be affected by possible changes in future climate. Cooler and wetter future climate conditions lead to slightly reduced groundwater pumping and increased crop profits (green curves shift up and to the left of the black curves). The warmer and drier future has a more pronounced negative impact on crop profits. Due to the increased groundwater irrigation needs in a warmer and drier future and a higher cost of groundwater pumping (shown in Figure 3(a)), crop profits for a given level of groundwater use are significantly lower in warmer and drier climate.

Table 2
Percentage of Farmers for Whom a Particular Allocation Binds Under Different Climates When No Trading Is Allowed (i.e., Quotas)

	Climate conditions		
Cap (in.)	Cool and wet	Baseline (historic)	Warm and dry
10.05	16.2	39	86
11.05	11.6	32.4	83.8
12.05	6.8	22.2	78.8
13.05	3	14	72.4
14.05	1.4	10	64.6
15.05	0.6	5.8	58.6

Figure 3(a) shows the cost of groundwater pumping under different climates and allocations. The figure shows, as expected, higher allocations leading to greater pumping and higher cost of pumping. Changes in groundwater recharge associated with the different climates are seen to influence cost of pumping where the costs vary for nearly identical groundwater pumping volumes. The figure also reveals that for the same allocation, groundwater pumped varies with climate. At low allocations, the differences between groundwater pumping across different climates are relatively small, since many of the farmers use most of their allocations. At higher allocations, the differences become much greater. In a warmer future, crop

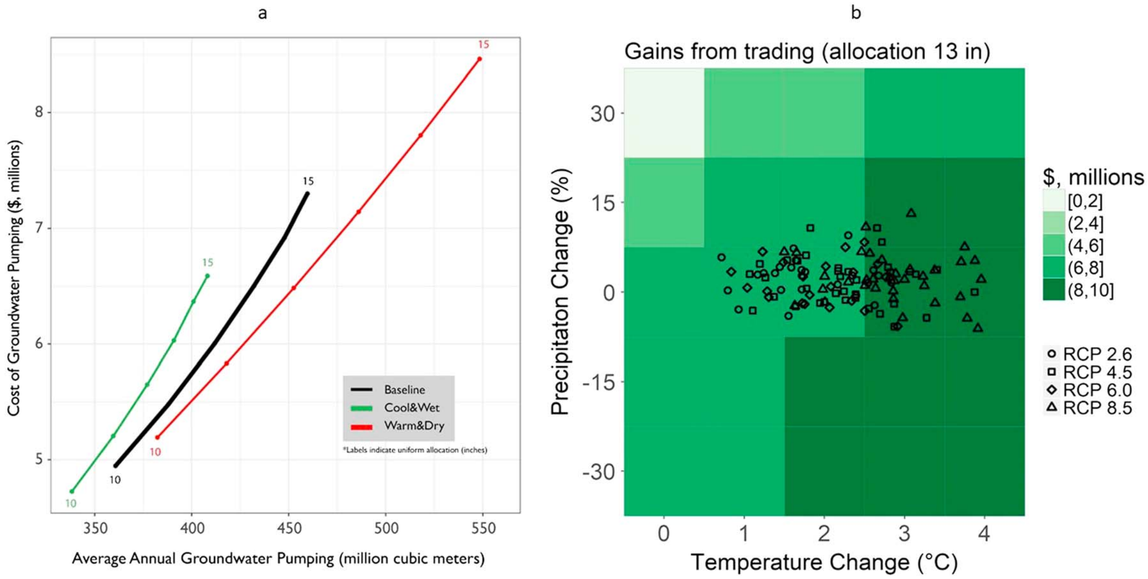

Figure 3. A cost of groundwater pumping ($, millions) for different groundwater allocations under various climate conditions. B sensitivity of gains from trading to changes in temperature and precipitation changes for an initial allocation of 13 in. Fifth coupled model Intercomparison project GCM projections for different emission scenarios are overlain.

water requirements increase and reduced precipitation leads to increased required groundwater irrigation. Consequently, farmers who may not have needed to use their entire allocation do so under the warmer and drier climate.

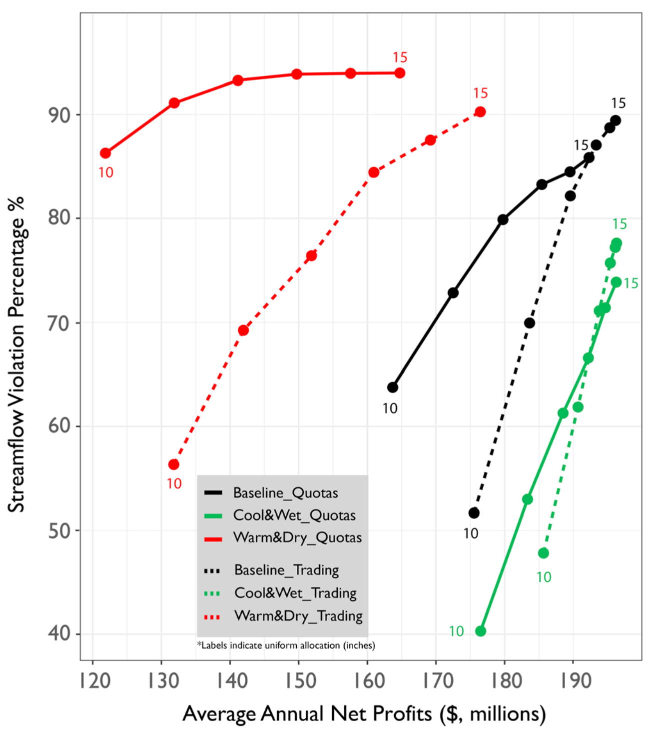

Figure 4. Average annual streamflow violations as a function of groundwater allocations for varying climates and management policies. The solid lines show results for the model runs where agents are assigned fixed quotas, while the dashed lines show results from models runs where agents can trade their allocated quotas.

The sensitivity of gains from trading to changes in temperature and precipitation is shown in Figure 3(b) in a climate response surface. The relative sensitivity to precipitation or temperature can be observed visually by comparing the changes in shading across rows (precipitation) and columns (temperature) in both the response surface. For an initial allocation of 13 in., the figure shows that gains from trading are sensitive to both changes in temperature and precipitation (with a higher sensitivity to temperature changes, especially under dry conditions). For higher temperatures, which lead to greater demand for groundwater, the gains are also the greatest. As precipitation increases and dependence on groundwater is reduced, the gains are seen to reduce (shift from darker to lighter shade). It should be noted that the range of change in precipitation we evaluate is greater than the projected changes based on CMIP5.

Next, we evaluate the tradeoff between economic gains and environmental performance for the different groundwater management policies. Streamflow depletion caused by excessive groundwater pumping is one of the primary drivers of groundwater management in the region. We gauge environmental performance by *streamflow violation percentage*, which is the percentage of occurrence when modeled streamflow is less than the streamflow targets at 17 stream cell locations across the basin. Streamflow violations occur when modeled flow is less than 75% of the 1990–2000 average flow determined from the RRCA MODFLOW model output. These targets are unrelated to actual targets outlined in the Republican River Compact.

Figure 4 shows the impact of groundwater trading and changes in climate on average streamflow violations. As expected, violations for a given water allocation increase significantly under a warmer and drier future. The data points in the top right quadrant of Figure 4 show the economic and environmental outcomes under the highest allocation of groundwater (15 in.). Not surprisingly, this least constrained groundwater pumping, where environmental externalities are not penalized, results in the highest economic benefits and the least environmentally sustainable outcome. In the absence of groundwater management, farmers act in their own interests to maximize their profits. The "costs" of environmental degradation are spread across all users. Since farmers do not directly experience these costs, there is no incentive to use groundwater "sustainably" if there are no regulations on groundwater use. Increasing streamflow violations indicate a falling groundwater table resulting in higher cost of pumping groundwater. However, a combination of ample recharge and favorable aquifer characteristics (high transmissivities) means that the pumping costs (shown in Figure 3(a)) is low relative to the benefits of pumping, and thus, declining groundwater levels do not change the pumping behavior of the farmers and slow down groundwater depletion.

Streamflow depletion is a function of the location of groundwater pumping. Trading groundwater leads to changing the location of groundwater pumping. If the more productive water users are closer to streams, in the absence of restrictions on trading (e.g., trading ratios), trading can lead to higher streamflow depletion. To prevent one set of agent productivity parameters and their associated locations of groundwater pumping from unduly influencing results, model runs are performed with 10 different sets of randomized agent characteristics (crop yield and crop water requirements) as used by Mulligan et al. (2014).

In theory, allowing trading between agents should lead to a lower streamflow violation for a given level of system-wide profits because as the price of groundwater increases, less efficient farmers reduce their water usage and sell their permits to the more efficient farmers. Since a greater proportion of water is used by the more productive water users, crop production per unit of water used increases. We see this improved environmental performance due to trading in the warm and dry climate scenario, and for some allocations under the baseline climate. However, under the cool and wet climate and higher allocations under the baseline climate, trading leads to higher streamflow violations. This is because trading allows farmers who had excess groundwater allocated (i.e., those agents who are constrained by their land) to sell the excess groundwater, leading to overall higher system-wide pumping and consequently greater streamflow depletion. Thus, in some cases, the increase in overall pumping negates the environmental benefits of higher water productivity. This highlights the importance of allocating groundwater permits while accounting for each users need to prevent the creation excess permits (slack) that can lead to overabstraction.

Improperly designed water markets where water trading does not account for the spatially heterogeneous hydrogeologic conditions can lead to uneven distributional impacts that may make an economically advantageous groundwater market politically infeasible. Figure 5 illustrates the uneven distributional impacts, in terms of difference in per unit pumping costs, resulting from trading between agents for a single allocation (14 in.), emphasizing the presence of winners and losers in the market. The difference in per unit pumping costs for each agent caused by groundwater trading is calculated using equation (6).

$$\%\text{difference in per unit pumping costs} = \left(\frac{PC_{\text{trade}} - PC_{\text{no trade}}}{PC_{\text{no trade}}}\right) - \left(\frac{PV_{\text{trade}} - PV_{\text{no trade}}}{PV_{\text{no trade}}}\right) \tag{6}$$

where PC represents the annual average pumping costs and PV represents the annual average pumping volume. Some agents enjoy a decrease in per unit pumping costs due to reduced groundwater pumping from adjoining neighbors (winners). Negative impacts are experienced by agents whose per unit pumping costs increase (losers). On the one hand, the figure suggests that the third party *economic* effect of trading is not large. Even though per unit pumping costs change by up to 8%, pumping costs are small relative to other costs and crop profits. Figure 5(b) suggests that for this particular groundwater allocation and agent productivity set, farmers closer to the stream tend to generally sell their allocations to farmers farther away from the streams. Resultantly, per unit pumping costs decrease closer to the stream.

Figure 6 shows the equilibrium groundwater price versus annual groundwater pumping for different allocations of groundwater, under various future climates averaged over the 50-year simulation. The figure represents the farmers willingness to pay (or alternatively, the demand function) for groundwater. Under all climate scenarios, as allocation increases, groundwater scarcity decreases and leads to reduced groundwater price. The figure shows a noticeable increase in the price elasticity of groundwater demand (calculated from the demand function) that varies from −0.1 under current climate conditions to around −1.2 under low

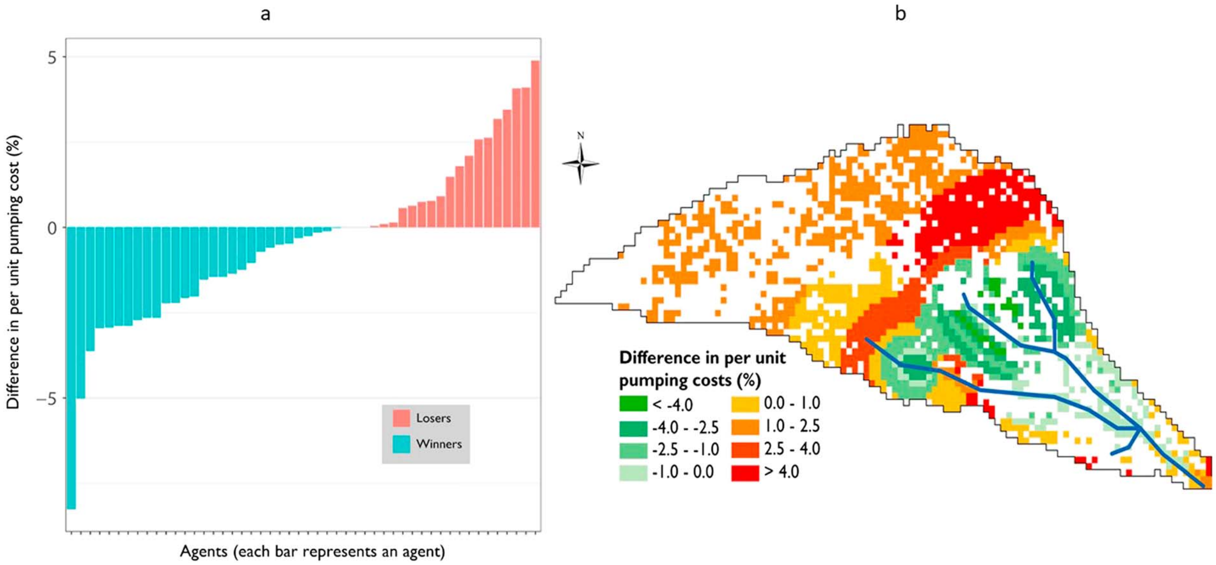

Figure 5. Distributional impacts of groundwater trading for a given water allocation and agent productivity set. A the difference in pumping costs experienced by agents due to modified pumping by neighboring agents; b the spatial distribution of change in per unit pumping costs.

allocations in a warmer and drier climate. This sensitivity to groundwater price manifests itself in the number of farmers who leave their farms fallow. In a warmer and drier climate, almost half of the farmers leave their farms fallow for an allocation of 10 in., whereas only 26% and 17% do so under baseline and cool and wet climate, respectively. Under higher allocations, the associated groundwater price and groundwater pumped in the warmer and drier climate future is significantly higher because of increased groundwater irrigation requirements and thus greater competition for the resource (scarcity).

For a cooler and wetter (green line) climate, while the price elasticity does not change significantly compared to baseline climate, the price of groundwater is always lower. This is primarily due to a lower demand for groundwater (due to increased) rainfall. This difference in price is greatest for the lowest allocation (because the demand is comparatively greater). At higher allocations (14 and 15 in.), the demand for, and hence price of, groundwater is low to begin with and so additional (rain) water availability does not have the same impact that it does when water scarcity and demand is comparatively higher.

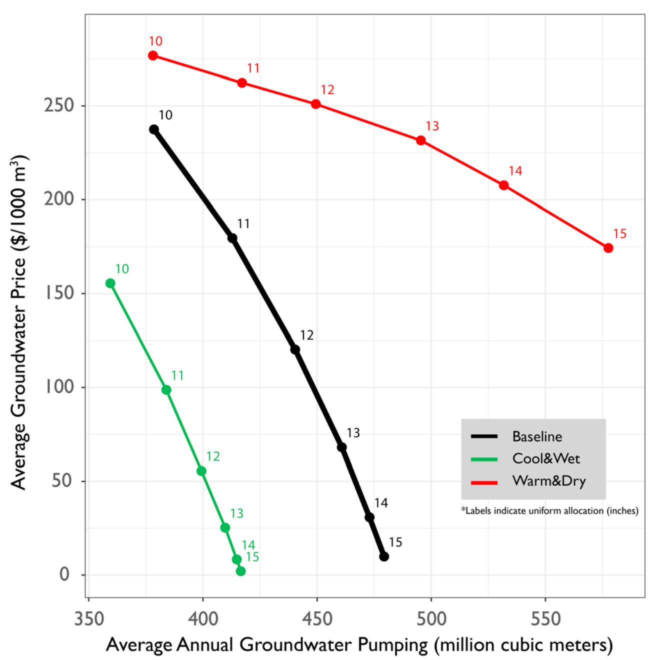

Figure 6. Average annual groundwater price and groundwater pumping for different allocations and varying climates in the groundwater market setup.

An alternative to a cap-and-trade system for groundwater management is directly pricing its use on a per volume basis (tax or tariffs). The respective merits for managing a natural resource by controlling its price (taxes) or quantity (permit trading) have been discussed extensively in the environmental economics literature (Weitzman, 1974). Figure 6 allows for a comparison of the outcomes associated with these two different approaches under climate change.

Under the warmer and drier climate (red line), the range in groundwater price is significantly reduced while the range of corresponding pumping is increased relative to that under baseline climate. This potential variation in groundwater pumping and price due to changing climate can be manipulated with different groundwater policies. The extent of the variations influences which policy is most suitable. For instance, assuming that policy makers wish to constrain total system-wide groundwater pumping to 400 million cubic meters (MCM), a tax on groundwater (equal to the agents willingness to pay) of $200/1,000 m^3 would be needed under current climate. However, in the warmer and drier future climate scenario, the agents willingness to pay for groundwater changes. Under the tax of

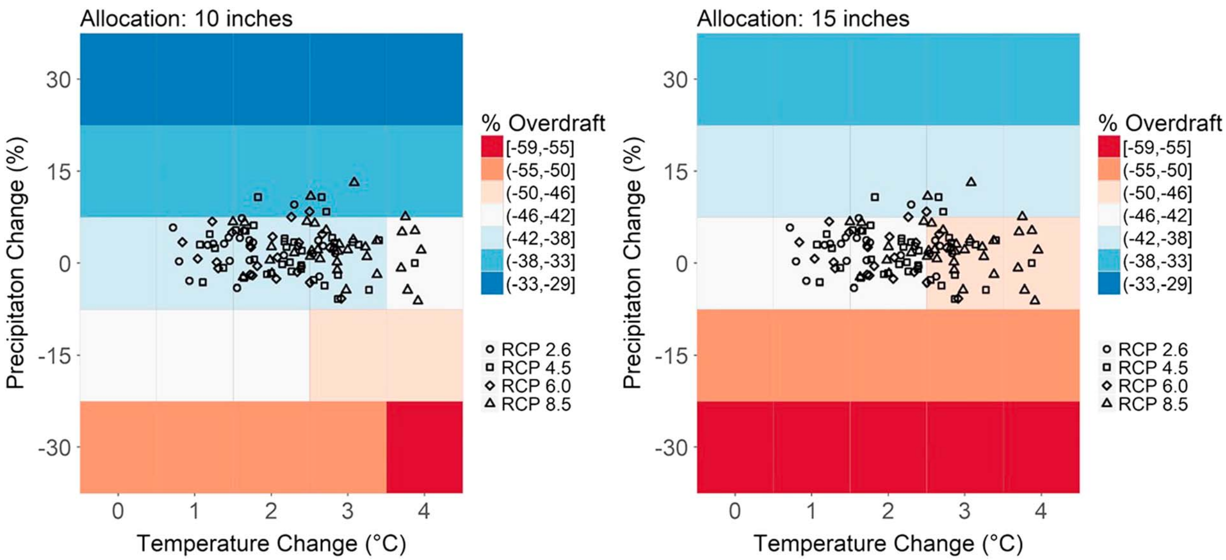

Figure 7. Sensitivity of groundwater overdraft (overdraft = evapotranspiration + groundwater pumping − recharge) to changes in precipitation and temperature for two different groundwater allocations (10 and 15 in.). Fifth coupled model Intercomparison project GCM projections for different emission scenarios are overlain.

\$200/1,000 m^3, the agents are projected to cumulatively pump around 535×10^6 m^3, almost 135×10^6 m^3 more than the desired limit. If the decision maker places a high importance on reducing variation in pumping (ensuring sustainable groundwater pumping levels), then implementing taxes may not be the most suitable policy; a cap and trade system would be more suitable. However, in that case the resulting reduction in potential variation in groundwater pumping would come at the cost of increased possible variation in groundwater prices (\$60/1,000 m^3 to \$270/1,000 m^3). A compromise between the two policies may be to set up a trading market with price controls (Roberts & Spence, 1976; Stranlund & Son, 2018). Such a system would work by allocating a total number of marketable groundwater permits and a price ceiling for exceeding the allocations. If the future climate is warmer and drier, the price ceiling provides an escape valve for farmers and prevents the agents from being priced out of using groundwater. In this study, we do not account for nonagricultural land uses in our objective function, that is, what happens with the portion of the field that is not planted. It is possible that this fallow land will have nonzero value.

Next, we illustrate how a range of changes in climate affects the level of groundwater overdraft. Currently, the rate of groundwater pumping exceeds the recharge in many parts of the Ogallala Aquifer resulting in declining groundwater tables. Changes in temperature and precipitation could stress the aquifer even more. Climate response surfaces in Figure 7 show how groundwater overdraft changes with climate and how these impacts manifest themselves for different water allocations. Groundwater overdraft is calculated as the difference between recharge into the aquifer and the sum of evaporation and groundwater pumping, normalized based on the recharge. Thus, it is presented here as a percent of recharge. We calculate the groundwater overdraft from the water balance for the last year of the 50-year model run.

Figure 7 indicates that groundwater overdraft is sensitive to changes in *both* precipitation and temperature, with a higher sensitivity to changes in precipitation. For a given temperature change, groundwater overdraft varies more with changes in precipitation than it does for changes in temperature for a given precipitation change. A comparison of the climate response surface between the two allocations suggests that the change in groundwater overdraft from historic climate conditions is similar for both allocations. GCM projections from CMIP5 for different emission scenarios are overlain. While there is significant variability in the future projections of precipitation, all projections indicate warming.

5. Limitations and Future Work

Groundwater is a common resource property, meaning that one agents use can affect other groundwater users. When the location of pumping is changed as a result of trading, the distribution and magnitude of the impact of that pumping change. Results presented herein highlight the uneven distributional impacts when one-to-one trading of permits is allowed. This one-to-one trading does not account for the nonuniform impacts of groundwater pumping that is caused by the spatially heterogeneous aquifer conditions. To account for these differences, trading coefficients between agents that are based on the ratio of accrued marginal impacts need to be defined. These trading ratios will in effect create a spatially varying price for groundwater. In addition, environmental violations are tracked but not penalized in the current modeling framework. The benefits of markets compared to the system with water quotas would be greater were there a price on environmental violations.

While this analysis did not address the choice of groundwater allocation mechanism, it is nevertheless an important policy decision. The allocation of permits determines the spatial distribution of financial impact on stakeholders and resultantly their willingness to participate. Unsustainable allocations where the water is overallocated also lead to environmental degradation as discussed previously. In this analysis, although groundwater permits are allocated uniformly across all users, socioeconomic and political factors may make nonuniform allocation more suitable. A promising next step would be to explore different methods of allocating permits to assess their economic impact on users and basin-wide environmental outcomes. Additionally, we determine groundwater allocations based on land owned by farmers. This could result in excess "unnecessary" permits in the market and encourage. To minimize slack in the market, permits could be more carefully assigned based on historic use by farmers.

Results of this analysis should be viewed in context of some key limitations, including uncertainties associated with the groundwater model for a heterogeneous aquifer (Pulido-Velazquez et al., 2011), agent-based model parameters that remain constant during a single model run but vary across the different model runs (productivity, farmer operating costs, and crop prices) and assuming a linear relationship between stream depletion and groundwater pumping. In the modeling setup, the MVP of water for each farmer is constant. An interesting extension of this work would be to employ a variable MVP of water, associated with a nonlinear crop production function, and investigate differences in market outcomes.

In the farmer decision model, it is assumed that farmers know their respective crop irrigation requirements with certainty at the start of each time step that allows them to make decisions regarding trading. A future line of questioning could explore decision-making under stochastic climate conditions to more comprehensively understand the true value of trading, especially in regions where conjunctive use of surface water and groundwater takes place. Changes in future climate will affect not only magnitude of precipitation, as was investigated in this work, but also temporal variability that can affect aquifer recharge. In addition, while crop water requirements are assumed to change linearly with temperature for this analysis, recent studies have shown nonlinear relationships between crop water requirements and temperature (Fischer et al., 2007). While we acknowledge these shortcomings, we believe that they do not significantly undermine the key findings. Future endeavors addressing these limitations, especially those making use of nonlinear crop production functions, will further strengthen the outcomes from this analysis and provide valuable insight.

6. Conclusion

Increasing population and climate variability are stressing groundwater resources in many parts of the world, prompting calls for better management of groundwater. Incentives-based policies, such as a groundwater market, have been identified as promising solutions to manage groundwater; however, quantitative evaluations of the performance of these markets under uncertain climate are rarely performed. Using a calibrated physically based groundwater model with an agent based farmer decision model, this work compares the respective performances of a groundwater market and water quotas accounting for spatial and temporal variability in the Frenchman River subbasin overlying the High Plains aquifer. The use of a physically based groundwater model allows us to evaluate streamflow depletion impacts of excessive groundwater pumping that has been the primary driver of groundwater management in the Republican River Basin. The study quantifies the uneven distributional impacts of groundwater trading and shows how changes in climate affect groundwater market dynamics.

Results of this analysis suggests that changes in climate significantly influence farmers willingness to pay for groundwater, affecting the amount of groundwater pumping with the impact varying under different allocations. The study also finds that allowing users to trade groundwater allocations leads to modest improvements in economic performance. For a given level of water use, a groundwater trading system can result in fewer environmental violations (measured in terms of impact on streamflow); however, these environmental benefits can be negated if the groundwater allocation mechanism creates excess groundwater permits. The results show that economic gains from trading are unequally distributed across the users, with some users worse off due to third party impacts.

This work provides policy insights for regions considering groundwater markets as an instrument to sustainably manage groundwater. We illustrate how varying climatic conditions can alter groundwater and market dynamics and show that if management policies do not adapt dynamically to changing climate, suboptimal outcomes are obtained. A thorough assessment of impact of changes in future climate on market dynamics ought to be performed to determine the appropriate policy features (e.g., price or quantity controls). Not accounting for variable hydrogeologic conditions in a groundwater market leads to uneven spatial distributional impacts; this becomes especially important with when environmental impacts (e.g., stream depletion) are a concern, as in the study area. These impacts should be mitigated in a market design by adopting stream depleting factors (or trading ratios) that adjust water transfers between users by accounting for soil types, proximity to streams, flow zones, etc. While groundwater markets offer a promising alternative to traditional command and control management of groundwater, region-specific assessments are needed to determine whether the benefits promised by these markets are worth the potentially considerable administrative costs incurred in setting them up.

Acknowledgments
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