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Water Resources Research



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Key Points:

- Economic value of groundwater conservation depends on initial aquifer conditions
- Optimal point to limit pumping is a function of local hydrology, climate, and economics
- Sustaining well yields increases productivity and maintains drought resilience

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Effects of initial aquifer conditions on economic benefits from groundwater conservation

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Abstract Worldwide, there is growing recognition of the need to reduce agricultural groundwater use in response to rapid rates of aquifer depletion. To date, however, few studies have evaluated how benefits of conservation vary along an aquifer's depletion pathway. To address this question, we develop an integrated modeling framework that couples an agro-economic model of farmers' field-level irrigation decision-making with a borehole-scale groundwater flow model. Unique to this framework is the explicit consideration of the dynamic reductions in well yields that occur as an aquifer is depleted, and how these changes in intraseasonal groundwater supply affect farmers' ability to manage production risks caused by climate variability and, in particular, drought. For an illustrative case study in the High Plains region of the U.S., we apply our model to analyze the value of groundwater conservation activities for different initial aquifer conditions. Our results demonstrate that there is a range of initial conditions for which reducing pumping will have long-term economic benefits for farmers by slowing reductions in well yields and prolonging the usable lifetime of an aquifer for high-value irrigated agriculture. In contrast, restrictions on pumping that are applied too early or too late will provide limited welfare benefits. We suggest, therefore, that there are "windows of opportunity" to implement groundwater conservation, which will depend on complex feedbacks between local hydrology, climate, crop growth, and economics.

1. Introduction

Extraction of groundwater for irrigation at rates in excess of natural recharge has led to significant depletion of groundwater resources in many countries [*Haacker et al.*, 2015; *Richey et al.*, 2015]. Aquifer depletion, in turn, has had negative impacts on agricultural production through increases in pumping costs, reductions in well yields, depletion of connected surface-waters, and, in some cases, irreversible loss of aquifer storage through salinization and compaction [*Aeschbach-Hertig and Gleeson*, 2012; *Steward et al.*, 2013; *Gorelick and Zheng*, 2015]. A major challenge for research, therefore, is to understand how groundwater should be managed to meet the food production demands of growing global populations.

Driven by widespread concern about the implications of ongoing aquifer depletion, a large body of research has attempted to quantify the economic value of groundwater conservation and management (for reviews, see *Koundouri* [2004]; *Qureshi et al.* [2012]). A common feature of the majority of existing analyses is the assumption of a fixed initial aquifer condition, usually based on predevelopment or present-day water levels. Studies therefore typically have not evaluated how initial aquifer conditions influence the returns to groundwater conservation. In real-world systems it is very difficult to implement and enforce regulations to restrict groundwater management policies in California in response to ongoing drought conditions [*Moran and Wendell*, 2012]. Given this, an important policy-relevant research question is: at what point along a depletion pathway is it optimal economically to restrict groundwater pumping for irrigation?

To understand how and why the timing of pumping reductions may affect the value of groundwater conservation, it is necessary to consider the feedbacks that occur between groundwater and agricultural production, and how these interactions presently are represented in integrated models used by researchers. The majority of existing hydro-economic research shares a common conceptual modeling framework, which assumes that aquifer depletion primarily affects farmers' income through changes in the energy required to pump groundwater. Based on this framework, drawdown of water tables caused by irrigation

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To date, few studies have examined the validity of this assumption that the economic impacts of depletion on agricultural production are linear with decreasing water levels. In reality, changes in pumping costs are not the only impact of groundwater drawdown for farmers. An additional consequence of aquifer depletion are physical reductions in borehole well yields, which occur because the reduced saturated thickness is no longer sufficient to sustain flows needed to support high pumping rates [Hecox et al., 2002; Boonstra and Soppe, 2006]. Recent research has demonstrated that these reductions in well yields will have large negative impacts on both the productivity and profitability of groundwater-fed irrigation as, below a certain threshold, well yield constrains farmers' ability to schedule irrigation optimally during the growing season leading to increased risks of crop failure especially during drought years [Foster et al., 2014, 2015a, 2015b; Collie, 2015]. Existing studies have not considered the dynamic hydrological response of well yields to drawdown, or the biophysical and economic impacts that changes in well yields have on agricultural production and farmers' water use decision-making. We suggest that this a significant limitation of current estimates of the value of groundwater conservation, and that, in reality, there may be large benefits to managing rates of aquifer depletion to avoid or limit the negative impacts of low well yields on irrigated agriculture. Furthermore, given the dependence of well yields on saturated thickness, we hypothesize that initial aquifer conditions may be an important factor governing the value of groundwater conservation, and that an optimal aquifer state may exist at which farmers should be incentivized to reduce future extraction.

To test this hypothesis, we develop an integrated modeling framework that couples an agro-economic model of farmers' field-level irrigation decision-making [*Foster et al.*, 2014, 2015a] with a physically-based model of a groundwater abstraction borehole [*Upton et al.*, 2013; *Upton*, 2014]. Unique to the developed model is the explicit representation of bi-directional feedbacks between aquifer hydrology and agricultural production through changes in both groundwater pumping costs and well yields. Subsequently, we apply this model to a hypothetical case study in the High Plains region of the U.S. to evaluate the variation in the economic benefits of groundwater pumping quotas as a function of initial saturated thickness.

The High Plains Aquifer is one of the most important groundwater systems in the world. The aquifer supports 30% of irrigated crop production in the U.S., providing water needed to grow over \$35 billion of crops annually and contributing significantly to global food security [Basso et al., 2013; Steward and Allen, 2016]. Across large parts of the aquifer, particularly in the southern and central High Plains, groundwater extraction has far outstripped natural rates of recharge over recent decades, leading to rapid declines in water tables and drying up of previously perennial streams. In these areas, it is estimated that usable groundwater resources may be exhausted fully within the century [Haacker et al., 2015]. Given the large current imbalance between pumping and recharge, the primary challenge for water managers and policymakers therefore is to limit further depletion and resultant negative impacts on agricultural production. This is distinct to management challenges elsewhere in the aquifer (e.g., in the Northern High Plains), where long-term depletion trends are less extreme and policy is focused more on addressing impacts of pumping on stream depletion. Nevertheless, the challenge of managing long-term aquifer depletion due to unsustainable agricultural pumping is by no means unique to parts of the High Plains. Efforts to prolong the usable lifetime of aquifers to support irrigated crop production are at the forefront of current policy debates in many other major groundwater systems worldwide, including the Central Valley of California, the North China Plain, the Indo-Gangetic Plain, the Middle East and North Africa [Richey et al., 2015].

Our findings demonstrate that, in aquifers experiencing chronic long-term depletion, a range of initial conditions exist for which reducing groundwater extraction may have long-term economic benefits for farmers by slowing the rate of well yield decline, and, as a result, prolonging the usable lifetime of an aquifer for irrigated production. Moreover, through sensitivity analyses, we demonstrate that the bounds of this range, and the size of potential welfare gains, are conditioned on local hydrogeological and biophysical properties that control the sensitivity of irrigated production to groundwater scarcity. Maintaining or, in the case of aquifers with limited recharge potential, extending the usable lifetime of groundwater for irrigated agriculture is a critical policy-relevant research question in the High Plains and other groundwater systems worldwide [Aeschbach-Hertig and Gleeson, 2012; Basso et al., 2013; Steward et al., 2013]. Our study is the first to provide insights and modeling tools that capture how changes in well yields affect returns to groundwater conservation through impacts on the future drought resilience of agricultural production. Consequently, we provide valuable new information that can be used to support inter-temporal policy and management of irrigation water use in order to maximize economic and food security benefits from limited groundwater resources.

2. Methodology

This section discusses the development of the integrated hydro-economic modeling framework that is presented in this paper. In section 2.1, a conceptual overview of the design of the proposed framework is provided, highlighting the important data exchanges that occur between modular components. Subsequently, sections 2.2–2.4 describe the calculations performed by the economic, agricultural, and groundwater model components, respectively.

2.1. Integrated Model Design

Figure 1 illustrates the design of the integrated model, which couples three modular components: an economic model, a crop model (AquaCrop), and a groundwater model (Simulating Pumping Boreholes with a Darcy-Forchheimer Regional-Radial Flow Model - SPIDERR). Components are linked using Matlab version 2015a [*Mathworks Inc.*, 2015]. A brief description of the simulation workflow is provided below, noting the resolution and data exchanges for each of the modular components.

Each integrated simulation begins on the planting day of the first simulation year. Before advancing in time, all individual submodels are initialized to set up model parameters and initial conditions. The economic model component is then executed to determine the optimal crop mix and irrigation strategy for the first growing season, conditional, in part, on current aquifer conditions (water level and well yield). Next, Aqua-Crop simulates crop growth and groundwater pumping for irrigation on the present day. Pumping decisions are dependent on the preseason choice of crop mix and irrigation strategy, observed weather conditions on the current day, current soil moisture level, and also consider restrictions imposed by well yield. Given simulated groundwater pumping, SPIDERR then is executed to update aquifer heads and well yields for the start of the next simulation day. AquaCrop and SPIDERR continue to perform daily time-steps and exchange data in an iterative manner until the start of the growing season in the following simulation year. This process is repeated until the end of the full simulation period is reached, enabling analysis of the dynamic coevolution of the coupled agricultural groundwater system over space and time.

2.2. Economic Model

The role of the economic submodel is to determine farmers' optimal field-level decisions about crop mix and irrigation strategy for the upcoming growing season. The model is executed once per year at the time



Figure 1. Design of the integrated modeling framework, highlighting the key feedbacks and data exchanges that occur between crop, economic, and groundwater model components.

of planting, and assumes that the farmer makes irrigation decisions myopically with no consideration of the effects that current water use decisions may have on aquifer conditions and profits in future periods. On the extensive margin, the farmer chooses what proportion of the field to plant with dryland and irrigated crops. A farmer's intensive margin decision is characterized by the selection of an intraseasonal irrigation strategy for the proportion of the field that is irrigated. We assume that a farmer's intraseasonal irrigation decisions can be represented by a soil moisture target strategy, which defines the level of soil moisture depletion at which irrigation is initiated in each of the four main crop growth stages (initial, development, midseason, late-season). The specification of the intensive margin decision in terms of a soil moisture target strategy provides a behaviorally realistic representation of farmers' irrigation scheduling heuristics, and captures the biophysical relationship between intraseasonal soil moisture dynamics and final crop yield [*Steduto et al.*, 2012].

The optimization approach used to determine a farmer's joint choice of extensive and intensive margin decisions is based on the model developed by *Foster et al.* [2014, 2015a]. For each joint decision, we run AquaCrop (section 2.3) using historic weather time series to presimulate distributions of crop yields and irrigation requirements that account for the impacts of interannual weather variability. A unique version of each distribution is also presimulated for different constraints on the maximum daily irrigation rate. Importantly, this enables the subsequent economic optimization to capture the effects of well yield on farmers' preseason production decisions. Low well yields, in particular, constrain significantly instantaneous irrigation capacity, and previous research has shown that this may create incentives for farmers to reduce irrigated area in order to mitigate resulting production risks [*Foster et al.*, 2014, 2015a, 2015b].

The presimulated estimates of crop yield and irrigation requirements, along with economic data describing input and output prices, are used to calculate expected distributions of total seasonal profits (equation (1)) and irrigation water use (equation (2)) for each possible joint production decision. These calculations consider two feedbacks with the modeled groundwater system. First, the current water table depth determines the energy required to pump groundwater and, therefore, the variable cost of irrigation. Second, well yield affects crop yield and irrigation requirements as described above. Well yield also has small effects on the variable cost of irrigation, as, for low well yields, each unit of irrigation takes longer to apply and, therefore, labor and maintenance costs are larger than for higher yielding wells. Equations detailing the impacts of well yield and water table depth on the variable cost of irrigation are reported in *Foster et al.* [2015a], and are based on relationships reported for crop budgets in the High Plains region [*Klein and Wilson*, 2015]. We do not consider the effects of changes in well yield or water table depth on pump energy efficiency, but incorporating these dynamic feedbacks would be an interesting extension to our economic model in future work.

$$\Pi_{j,k,m} = \Pi_{l_{j,k,m}} + \Pi_{D_{j,k}}$$

$$= [Y_l(S_m, \Theta_j | W) \cdot (p_{c_l} - c_{h_l}) - c_{f_l} - X_l(S_m, \Theta_j | W) \cdot c_{v_l}(W, Z)] \cdot A_k$$

$$+ [Y_D(\Theta_j) \cdot (p_{c_n} - c_{h_n}) - c_{f_n}] \cdot (A_{\max} - A_k)$$
(1)

$$V_{j,k,m} = X_I(S_m, \Theta_j | W) \cdot A_k$$
⁽²⁾

where Π is profit (\$), *Y* is crop yield (tonne ha⁻¹), *X* is total seasonal irrigation (cm), *V* is total seasonal volumetric irrigation (ha-cm), *W* is well yield (m³ d⁻¹), *Z* is total dynamic head (m) that the pump must generate to lift and pressurize groundwater for irrigation, *S* is the soil moisture target strategy, *A* is irrigated area (ha), A_{max} is the total field area (ha), Θ is a time-series of daily weather conditions for the growing season, p_c is the crop price (\$tonne⁻¹), c_f is the fixed production costs (\$ha⁻¹), c_h is the crop harvesting costs (\$tonne⁻¹), c_v is the variable irrigation cost (\$ha-cm⁻¹), subscript *I* denotes the irrigated crop, subscript *D* denotes the dryland crop, subscript *j* denotes the year of historic weather data, subscript *k* denotes the choice of irrigated area size, and subscript *m* denotes the choice of soil moisture target strategy.

Output distributions given by equation (1) subsequently are used to calculate the expectation, $\mathbb{E}(\Pi_{k,m})$, and variance, $\sigma_{\Pi_{k,m}}$, of profits for each joint extensive and intensive margin decision. Given these estimates, the joint decision is optimized using a certainty equivalent maximization approach (equation (3)). Equation (3) considers the impact of farmers' risk preferences using the Arrow-Pratt coefficient of relative risk aversion, γ , where a value equal to 0 represents a risk neutral farmer and values less/greater than 0 reflect increasingly

risk seeking/averse decision-making. Equation (3) also limits the range of potential joint strategies to account for restrictions on groundwater abstraction. Previously, *Foster et al.* [2015a] imposed abstraction quotas as binding restrictions on water use in each individual year. However, in equation (3) we assume only that expected volumetric pumping must be less than the specified abstraction limit in order to capture more realistically the way quotas are applied in real-world settings. For example, pumping restrictions often are enforced over multiyear windows to provide flexibility for farmers to increase water use in drought years whilst decreasing pumping in wetter years [*Palazzo and Brozović*, 2014].

$$[A^*, S^*] = \max_{\{k,m\}} \left[\mathbb{E}(\Pi_{k,m}) - 0.5 \cdot \frac{\sigma_{\Pi_{k,m}} \cdot \gamma}{\mathbb{E}(\Pi_{k,m})} \right]$$
(3)

subject to:

$$\mathbb{E}(V_{k,m}) \leq Q$$

where A^* and S^* are the optimal irrigated area (ha) and soil moisture target strategy, respectively, Π is the profit (\$), σ_{Π} is the variance in profits (\$), γ is the Arrow-Pratt coefficient of relative risk aversion, V is total volumetric irrigation use (m³ yr⁻¹), Q is the regulatory restriction on groundwater pumping (m³ yr⁻¹), subscript *k* denotes the choice of irrigated area, and subscript *m* denotes the choice of soil moisture target strategy.

2.3. Crop Model

We use the crop simulation model, AquaCrop-OS [*Foster et al.*, 2017], to simulate intraseasonal crop growth and irrigation use within our integrated framework. AquaCrop-OS is an open-source version of AquaCrop (available at http://www.aquacropos.com), a water-limited crop yield model originally developed by the Food and Agriculture Organization of the United Nations (FAO) [*Steduto et al.*, 2009]. AquaCrop has been applied successfully in many areas of the world to evaluate agricultural water management [*Vanuytrecht et al.*, 2014a], and, therefore, is ideally suited to address the types of research questions considered in this paper.

Given the optimized crop mix selected preseason by the economic model, AquaCrop runs on a daily timestep to simulate crop growth processes, such as root expansion and canopy cover development, based on specified phenological calendars and input weather time series (maximum temperature, minimum temperature, precipitation, and estimated reference evapotranspiration). Biomass accumulation on each day is calculated as a function of simulated daily crop transpiration and a crop-specific water productivity parameter [*Steduto et al.*, 2009]. Finally, AquaCrop estimates crop yield as a function of the simulated aboveground biomass and crop harvest index.

During the growing season, crop development in AquaCrop may be affected by both water and temperature stress. Water stress effects are determined as a function of root zone soil moisture depletion and the sensitivity of different biological processes to water deficits. AquaCrop updates soil moisture contents daily using a finite-difference solution that considers inflows and outflows from precipitation, irrigation, drainage, soil evaporation, and transpiration [*Raes et al.*, 2009]. In this study, we calculate the daily volume of applied irrigation dependent on the average root zone soil water content, and the farmers' preseason choice of a soil moisture target strategy and irrigated crop area. On days when irrigation is triggered, the applied water depth is equal to the current depletion of total available water (field capacity minus permanent wilting point) in the root zone. However, the volumetric rate of irrigation cannot exceed well yield, which is calculated by the groundwater model component (section 2.4).

2.4. Groundwater Model

A physically-based groundwater model, the Simulating Pumping Boreholes with a Darcy-Forchheimer Regional-Radial (SPIDERR) flow model [*Upton et al.*, 2013; *Upton*, 2014], is used to simulate changes in aquifer water levels and well yields in response to the daily irrigation pumping decisions made by AquaCrop (section 2.3). The factors motivating our choice of SPIDERR are discussed below, followed by a description of the approach used to model changes in well yields.

A common feature of many hydro-economic studies to date has been the use of single-cell groundwater models, which assume that an aquifer, much like a bathtub, will respond uniformly and instantaneously to



Figure 2. Relationship between saturated thickness and well yield for three different values of aquifer hydraulic conductivity. The simulated curves are conditioned on assumptions of constant pumping and recharge (30 mm yr⁻¹) over a period of 120 days, that the borehole penetrates the full thickness of the aquifer, and that aquifer properties are homogeneous and isotropic. Well yields are capped at a maximum value of 8000 m³ d⁻¹ to reflect constraints on flow capacity imposed by pump and irrigation system technology.

extraction. Real aquifers, however, are substantially more complex, and it has been shown that this assumption may lead to large errors in estimates of pumping externalities and the value of groundwater management [Brozović et al., 2010]. In response, a growing body of work has used spatiallydistributed groundwater models, such as MODFLOW [Harbaugh, 2005], to provide more realistic estimates of aquifer dynamics and the economics of groundwater use [e.g., Brozović et al., 2010; Mulligan et al., 2014; Castilla-Rho et al., 2015; Hu et al., 2015]. However, due to computational constraints, these models typically have only been applied at coarse spatial and temporal resolutions (e.g., km² and monthly) that are insufficient to capture the borehole-scale water table drawdown and changes in well yields that are experienced by individual farmers.

Hybrid radial-cartesian groundwater models, such as SPIDERR, provide a solution to this limitation, but have yet to be utilized in hydro-economic research. In SPIDERR, a radial flow model is used to simulate, at fine resolution, linear and nonlinear flow processes in the vicinity of an abstraction borehole. The radial flow model, in turn, is nested within a coarser-scale cartesian model grid that captures the response of the wider regional aquifer system to localized pumping decisions. Consequently, SPIDERR simulates efficiently and accurately changes in aquifer water levels from borehole to catchment scales, which would not be possible using either single-cell or spatially-distributed groundwater modeling approaches [*Upton et al.*, 2013].

For a detailed description of the calculations performed by SPIDERR, the reader is referred to the associated model documentation [*Upton et al.*, 2013; *Upton*, 2014]. Here, we describe the methodology to estimate changes in well yields as an aquifer is depleted, which have not been considered in any previous integrated analysis of groundwater management. In our model, we calculate the maximum well yield for each borehole as a function of the initial saturated thickness. This calculation is performed on the day of crop planting in each simulation year, and well yield subsequently is fixed until the start of the next growing season. The functional relationship between well yield and saturated thickness is presimulated by running SPIDERR iteratively to determine, for different initial aquifer conditions, the maximum daily pumping rate that can be sustained over the length of a typical growing season (e.g., 120–150 days for corn in the High Plains region) without causing the water table to fall below the base of the well. The simulated relationship between well yield and saturated in large part on local aquifer (e.g., hydraulic conductivity, specific yield/storage) and borehole properties (e.g., well depth and construction), which influence the size of the cone of depression that is formed for a given pumping rate [*Hecox et al.*, 2002]. For example, Figure 2 shows three curves simulated using SPIDERR that relate saturated thickness to well yield for different hydraulic conductivities.

3. Illustrative Model Application

We apply the modeling framework described in section 2 to a hypothetical case study to illustrate the ability of our model to capture the key feedbacks influencing the coevolution of coupled agricultural groundwater systems, and to evaluate how these feedbacks affect the value of groundwater conservation. This section begins with a brief description of the model parameterization (section 3.1). Following this, sections 3.2 and 3.3 summarize the integrated simulations that are conducted in this paper.

3.1. Model Parameterization

Our case study considers a scenario of an individual producer who farms a single field overlying an aquifer, which, in absence of limits on pumping, will be over-exploited. Crop and economic model parameters, as described below, are based on typical production conditions in the High Plains of the U.S., which is an area of intensive groundwater-fed irrigation. Groundwater model parameters are also consistent with conditions in the High Plains aquifer, but also are varied to enable analysis of the influence of initial aquifer conditions and hydrogeological properties on the value of groundwater conservation.

The economic model considers a single farmer who manages a typical guarter-section (52.5 ha) field using a center-pivot irrigation system. As described in section 2.2, the farmer's irrigation decision has two components in our model; an extensive margin choice of the land area that will be irrigated, and an intensive margin choice of the intensity of irrigation per unit area of irrigated land. On the extensive margin, the farmer may divide this field between irrigated corn and dryland sorghum crops in increments of 0.5 ha. Irrigated corn and dryland sorghum crops were chosen as they reflect typical irrigated and dryland crops grown in large parts of the High Plains region. For the area planted with irrigated corn, the intensive margin choice of a soil moisture target for each crop growth stage varies, in increments of 0.01, between 0 and 1, which equate to permanent wilting point and field capacity respectively. Input and output prices for both crop types are defined in Table 1 based on reported farm budgets averaged over the period 2010-2015 [Klein and Wilson, 2015], and it is assumed that crops are planted on 1 May each year. Finally, distributions of potential crop yields and irrigation requirements for corn are simulated with AquaCrop. These simulations use 34 years (1982–2015) of historic weather data (data available from: http://hprcc.unl.edu) recorded at Champion in Chase County, Nebraska, and consider constraints on maximum daily irrigation rates ranging from 0.1 mm to 15 mm in increments of 0.1 mm. Expected dryland sorghum yield is set equal to a fixed value (4.4 tonne ha⁻¹), based on average reported yields over the period 2010–2015 (data available from: https://www.nass.usda.gov/Quick_Stats), due to a lack of data to calibrate AquaCrop adequately for sorghum production in the region. This assumption is realistic because our economic model assumes that farmers make planting decisions based on expectations of crop yields given known weather variability. Actual reported sorghum yields therefore should be an accurate proxy for farmers' expectations of yields under current climate variability and management practices.

AquaCrop requires the definition of crop, soil, and weather input parameters. Crop growth parameters for corn are defined according to previous successful applications of AquaCrop in the High Plains region [*Heng et al.*, 2009; *Foster et al.*, 2015a], and, as discussed above, we assume a fixed dryland sorghum yield due to a lack of calibration data for this crop. Soil type is defined as a loamy soil, with soil water contents at permanent wilting point, field capacity, and saturation equal to $0.137 \text{ m}^3 \text{ m}^{-3}$, $0.280 \text{ m}^3 \text{ m}^{-3}$, and $0.459 \text{ m}^3 \text{ m}^{-3}$, respectively, and a saturated hydraulic conductivity of 372 mm d⁻¹. It is assumed that the soil initially is wetted to 80% of field capacity, and that irrigation efficiency is 90% indicative of a typical high-efficiency center-pivot system. Finally, a 50 year daily weather time series (minimum and maximum temperature, precipitation, reference evapotranspiration) is generated by sampling years at random from the 34 year historic record.

In SPIDERR, we define a localized unconfined aquifer with areal dimensions of 2 km by 2 km and a maximum thickness of 100 m. The aquifer has impermeable boundaries on all sides, with the exception of the upper

Table 1. Economic Model Parameters		
Parameter	Sorghum (Dryland)	Corn (Irrigated)
Crop price (\$tonne ⁻¹)	190	197
Fixed cost (\$ha ⁻¹)	660	1014
Harvest cost (\$tonne ⁻¹)	6.7	14.9
Irrigation energy cost (kwh ⁻¹)		0.1
Irrigation labor cost (\$h ⁻¹)		20
Irrigation system repair cost (\$h ⁻¹)		3.2

boundary where there is a constant recharge inflow of 30 mm yr⁻¹ (1,20,000 m³ yr⁻¹ over the entire domain). The constant annual recharge inflow is distributed evenly over both space and time across nodes in SPIDERR. This assumption, while a simplification of reality, is reasonable given that our analysis is focused primarily on situations where the water table is tens of meters below the ground surface, for which the thickness of the unsaturated zone would be expected to smooth out temporal variations in recharge due to climate. Additionally, we assume that there is no relationship between the rate of recharge and irrigation pumping decisions due to the high level of irrigation efficiency in our study region. These assumptions are also consistent with previous hydro-economic model analysis of groundwater management in the High Plains region [*Bulatewicz et al.*, 2010; *Mulligan et al.*, 2014]. Aquifer hydraulic conductivity and specific yield are set equal to 30 m d⁻¹ and 0.1, respectively, and both properties are assumed to be homogeneous. The irrigation borehole is located at the center of the modeled domain, and penetrates the full thickness of the aquifer. The irrigation system pressure is defined as 207 kPa (30 psi), and the maximum potential well yield is restricted to 8000 m³ d⁻¹ to account for technical limits imposed by pump technology. Finally, for the sake of computational simplicity, we ignore the effects of nonlinear well losses and non-Darcian flow effects in the simulations, which can be included in simulations performed by SPIDERR. In reality, these effects may lead to additional increases in drawdown during pumping events. However, for our hypothetical case, we choose to neglect these processes in order to simplify our analysis and focus attention on the critical feedbacks between well yield and the value of groundwater conservation, which are the primary concern of this paper.

3.2. Model Simulations

To test our hypothesis that initial aquifer conditions are an important determinant of returns to groundwater conservation, we run simulations for different combinations of initial saturated thickness and regulatory restrictions on annual groundwater pumping. Initial saturated thickness is varied from 10 m to 90 m in increments of 2 m, capturing aquifers that have already been highly overexploited through to those that have yet to experience significant depletion. Regulatory pumping restrictions are assumed to vary from 1,20,000 m³ yr⁻¹ to 3,00,000 m³ yr⁻¹ in increments of 20,000 m³ yr⁻¹ to cover a spectrum of potential quotas, ranging from a lower bound that is equal to average annual recharge to an upper bound that imposes no binding restrictions on pumping.

For each combination of initial saturated thickness and groundwater pumping quota, we run our integrated model over a 50 year period. Actual profits in each simulation year are calculated based on crop yields and irrigation water use simulated by AquaCrop, along with economic values for input and output prices used in the preseason economic model calculations (equation (1)). Given actual profits in each year, total economic benefits over the planning horizon are calculated using equation (4). We assume a discount rate of 3%, which is consistent with the social rate of time preference for consumption of natural resources such as groundwater [*Das et al.*, 2010; *Fenichel et al.*, 2016].

$$NPV = \sum_{t=1}^{50} \frac{\pi_t}{(1+d)^t}$$
(4)

where *NPV* is the net present value (\$), *t* is the integrated simulation year, π is the actual profit (\$), and *d* is the fractional discount rate.

Subsequently, the outputs from equation (4) are used to determine the groundwater pumping restriction that maximizes net economic benefits for each initial aquifer condition. Economic benefits under optimal pumping quotas are compared to those predicted by our model for unrestricted extraction to obtain estimates of the potential economic gains from groundwater conservation as a function of initial saturated thickness. Note that our model is focused on the benefits of groundwater conservation for a single hypothetical farmer, and does not consider interactions with neighboring producers or the broader regional groundwater system. Following the results of our analysis, we discuss these simplifications in detail in section 5 of the paper and highlight how our results can be scaled to more complex regional agricultural groundwater systems.

3.3. Sensitivity Analysis

The analyses in section 3.2 test the hypothesis that the returns to groundwater conservation are a function of initial aquifer conditions at the time pumping reductions are implemented. These analyses are conditioned, in part, on the specified nonlinear feedbacks between saturated thickness and the profitability of groundwater-fed irrigation, which occur via changes in well yields. As a result, it is important to assess how sensitive our findings are to possible variability in these relationships.

Table 2. Crop Water Stress Parameter Sets						
Parameter	Stress Type	Threshold	Set 1	Set 2	Set 3	
$p_{\rm exp}$	Leaf expansion	Upper	0.10	0.14	0.30	
		Lower	0.55	0.72	0.80	
p _{sto}	Stomatal conductance	Upper	0.50	0.69	0.80	
		Lower	1.0	1.0	1.0	
p _{sen}	Canopy senescence	Upper	0.60	0.69	0.85	
		Lower	1.0	1.0	1.0	
$p_{\rm pol}$	Crop pollination	Upper	0.7	0.8	0.95	
		Lower	1.0	1.0	1.0	

First, we analyze how sensitive estimates of the value of groundwater management are to the rate of natural recharge to the groundwater system. Recharge rates will have a strong influence on the trajectory of aquifer depletion, and also will determine the level of irrigation pumping that is sustainable in the long-term. Consequently, recharge rates may be an important determinant of both the magnitude and timing of economic benefits from groundwater conservation. We repeat the simulations described in section 3.2 with recharge values

decreased to 10 mm d⁻¹ and increased to 50 mm d⁻¹. Results are compared to those obtained in previous simulations (section 3.2) for a base recharge rate of 30 mm d⁻¹.

Second, we evaluate how our results may be affected by variability in the relationship between saturated thickness and well yield. As noted in section 2.4, this relationship is conditioned on the hydrogeological properties of the aquifer, such as hydraulic conductivity, which control the amount of drawdown that occurs within a borehole for a specific rate and duration of pumping. Figure 2 demonstrates that in low conductivity aquifers, a greater initial saturated thickness is required to sustain well yields as drawdown is concentrated in the vicinity of the borehole. In contrast, in high conductivity aquifers, larger well yields can be maintained as drawdown is distributed across a wider area. We examine how these differences affect our estimates of the value of groundwater conservation by repeating the analyses described in section 3.2 for each of the three curves shown in Figure 2.

Finally, we examine how our estimates of the value of groundwater conservation are affected by the sensitivity of agricultural production to reductions in well yields. In AquaCrop, intraseasonal soil moisture deficits affect a range of simulated growth processes, including leaf expansion, stomatal conductance, canopy senescence, and pollination. Water stress begins to limit each process when root zone soil moisture depletion exceeds a specified upper threshold, and fully inhibits the process when depletion is equal to our greater than a specified lower threshold [Raes et al., 2009]. Both upper and lower thresholds are expressed as proportions of total available water, defined as the water held between field capacity and permanent wilting point within the root zone. We construct three parameter sets that represent the plausible range of upper and lower water stress thresholds for corn (Table 2) based on parameter bounds reported by Vanuytrecht et al. [2014b]. Parameter set 1 is indicative of a corn variety that has high sensitivity to soil moisture deficits (i.e., crop growth processes are inhibited at low levels of moisture stress), whereas parameter set 3 represents a corn variety that has low sensitivity to soil moisture deficits (i.e., crop growth will only be inhibited for higher levels of soil moisture depletion). Parameter set 2 matches the calibrated parameter values used in the simulations in section 3.2. For each parameter set, we presimulate distributions of crop yields and irrigation requirements as described in sections 2.3 and 3.1, and, using these data, we repeat the simulations in section 3.2. Comparison of model outputs for each parameter set highlights how our previous estimates of the value of groundwater management may be influenced by sensitivity of irrigated crops to reductions in groundwater supply.

4. Results

4.1. Initial Conditions and the Value of Conservation

Our results demonstrate that the value of restricting agricultural groundwater use is a highly nonmonotonic function of initial aquifer conditions, with value increasing and then decreasing as initial saturated thickness is reduced. Figure 3a illustrates the change in net present value from groundwater pumping restrictions, relative to under conditions of unrestricted abstraction, over a 50 year simulation period for different initial aquifer conditions. When initial saturated thickness is large (greater than 42 m), it is demonstrated that pumping restrictions have little positive impact on farmers' discounted economic benefits over the simulated planning horizon. Similarly, the economic gains from imposing pumping quotas also are negligible



Figure 3. (a) The change in net present value (%) and total irrigated crop production (%) under an optimal pumping quota, relative to a scenario of unrestricted groundwater abstraction, for different levels of initial saturated thickness. For each initial saturated thickness, (b) the economically optimal groundwater pumping quota ($1000 \text{ m}^3 \text{ yr}^{-1}$) that is selected by the model. Note, results for initial saturated thickness above 60 m are not displayed as no benefits are observed in this range. The optimal pumping quota is also not displayed for saturated thickness values of less than 12 m or greater 42 m, as, for these initial conditions, our model finds that it is not optimal economically to restrict groundwater pumping.

when the aquifer already has been heavily depleted (initial saturated thickness less than 12 m). However, within these upper and lower bounds, Figure 3a shows that there is potential to generate large economic gains by restricting levels of groundwater abstraction. The peak in economic gains occurs for an initial saturated thickness of 22 m, for which optimal regulation of pumping increases discounted economic benefits by 15.4% over the 50 year planning period. The specific pumping quota that maximizes economic benefits is decreasing within this range of initial aquifer conditions (Figure 3b), reflecting the need for increasingly stringent pumping reductions as the prior level of depletion increases. Contrastingly, for low or high initial saturated thickness, the optimal pumping quota is equal to a rate that effectively matches unrestricted rates of abstraction (i.e., no pumping quota increases farmers' economic benefits). It is interesting to note that a number of areas of the High Plains aquifer, in particular in parts of Kansas and Texas where depletion trends are significant, currently have saturated thickness between 12 m and 42 m [*McGuire et al.*, 2012]. This finding indicates that farmers in such areas may benefit economically from implementing groundwater conservation to limit future depletion. However, it should be noted that the magnitude specific local benefits will be influenced by local biophysical, behavioral, and economic factors, and, therefore, further site-specific analysis would be need to make predictions for specific locations across the aquifer.

To explain the impacts of prior depletion on the value of groundwater management that are observed in Figure 3, it is necessary to consider the feedbacks between saturated thickness and well yield in our integrated modeling framework. Imposing pumping quotas leads to reductions in the annual volume of groundwater that is abstracted, and, consequently, slows the reduction in aquifer water levels over the 50 year simulation period. When initial saturated thickness is large, drawdown of water tables has no effect on borehole well yields as water levels remain sufficiently high throughout the simulation period to maintain well yields at their upper limit. However, when initial aquifer water levels are lower, further drawdown during the planning period may result in large reductions in borehole well yields. Figure 4 illustrates this effect for the model simulations conducted with an initial saturated thickness of 22 m (where the peak in economic benefits from regulation occurs), demonstrating that pumping lifts (panel a) are consistently lower, and well yields (panel b) higher, when an optimal groundwater pumping quota (1,80,000 $\text{m}^3 \text{ yr}^{-1}$) is imposed relative to when abstraction is unrestricted. Note that in both unrestricted and optimal pumping simulations, water levels appear to be effectively converging to the same steady-state condition. This is because, as well yields are reduced, annual groundwater pumping also decreases due to reductions in irrigated area. A steady-state well yield thus exists, at which it is not optimal economically or possible physically to pump more than the natural rate of recharge. This well yield is associated with a specific saturated thickness and pumping lift (Figure 2), and, as a result, water levels stabilize at this point. The impact of conserving groundwater is simply to modify the pathway and time to reach this steady-state condition. It is important to highlight that this result emerges, in part, because we assume in our model that farmers can not drill additional



Figure 4. Change in: (a) total pumping lift (m); and (b) well yield $(m^3 d^{-1})$ over the 50 year simulation period for an initial saturated thickness of 22 m. Results are shown for model runs where abstraction is unrestricted (black lines) and where an economically optimal pumping quota (1,80,000 m³ yr⁻¹) is imposed (red dashed lines).

wells to increase total pumping capacity. We discuss this simplification in detail in section 5.2, but also note that, in many regions experiencing chronic aquifer depletion, there are moratoriums in place that limit new well drilling for irrigation.

The effect of pumping restrictions on the trajectory of aquifer depletion and well yields, has important implications for agricultural productivity and profitability. For large initial saturated thickness that buffer well yields fully, economic benefits from pumping restrictions are derived from reductions in irrigation pumping costs because less groundwater is abstracted from shallower depths. These economic gains are counteracted though by small declines in irrigated corn yields due to the farmer adopting deficit irrigation practices to reduce total water use, meaning that the net benefits from reducing groundwater abstraction are negligible (Figure 3a). Contrastingly, when initial saturated thickness is small, well yields are constrained significantly irrespective of any conservation efforts. In this situation, there are minimal benefits from restricting pumping as the farmer already has been forced to reduce irrigated area and groundwater significantly due to the production risks posed by low well yields [Foster et al., 2014, 2015b]. Between these upper and lower bounds, however, limiting groundwater pumping can have positive impacts on both irrigated crop production and farm profits. Slowing or limiting the interannual decline in well yields (Figure 4) enables the farmer to maintain higher irrigated production areas, minimize risks of drought-induced crop failure, and slow the transition to lower value dryland production (Figure 5). Reductions in production and profits in early years are more than offset by gains in later years, with cumulative profits in the optimal quota scenario increasing above those in the unrestricted pumping scenario beyond year 16 of the 50 year planning period (for an initial saturated thickness of 22 m). Figure 3a demonstrates that these economic



Figure 5. Change in: (a) irrigated corn area (ha); and (b) dryland sorghum area (ha) over the 50 year simulation period for an initial saturated thickness of 22 m. Results are shown for model runs where abstraction is unrestricted (black lines) and where an economically optimal pumping quota (1,80,000 m³ yr⁻¹) is imposed (red dashed lines).



Figure 6. Change in net present value (%) under an optimal pumping quota, relative to a scenario of unrestricted groundwater abstraction, for different levels of initial saturated thickness. Results are shown for simulations conducted with recharge rates of 10 mm yr⁻¹, 30 mm yr⁻¹, and 50 mm yr⁻¹. Note, results for initial saturated thickness above 60 m are not displayed as no benefits are observed in this range.

gains from regulation are correlated strongly with increases in total irrigation corn production, which are achieved because pumping restrictions limit declines in irrigated area over the planning horizon.

4.2. Sensitivity Analysis 4.2.1. Recharge Rate

Figure 6 shows the change in net present value from imposing an optimal pumping quota, relative to unrestricted abstraction, for different initial aquifer conditions and recharge rates. For each recharge condition, Figure 6 demonstrates that the value of groundwater conservation remains strongly dependent on initial saturated thickness. However, important differences can be observed in the economic gains from restricting abstraction. In particular, as recharge rates are decreased, the range of initial conditions over which restricting abstraction

will improve farmers' net economic returns expands. For the low recharge scenario (10 mm d⁻¹) restricting abstraction will have a positive economic impact when initial saturated thickness is between 10 m and 50 m, whereas for the high recharge scenario (50 mm d⁻¹) the range is significantly narrower (12 m to 32 m).

These differences reflect the important effects that recharge rates have on the trajectory of aquifer depletion. For low recharge rates, the interannual decrease in water levels is large (approximately 0.6 m yr⁻¹ on average for unrestricted abstraction), and greater initial saturated thickness is needed to buffer well yields throughout the 50 year simulation in the absence of groundwater pumping restrictions. In contrast, for higher recharge rates, interannual water table declines are smaller (approximately 0.2 m yr⁻¹ on average for unrestricted abstraction), and well yields will only be significantly impacted during the simulation period if extensive prior depletion already has occurred. The range of initial aquifer conditions for which irrigated production is negatively impacted during the planning horizon, and for which it is beneficial therefore to restrict abstraction, is smaller in systems that have higher recharge rates. Moreover, in these systems, the long-term gains from regulation are expected to be greater due to the fact that water levels and well yields potentially can be stabilized with modest reductions in annual extraction, which would not be practical economically in aquifers with lower rates of recharge.

4.2.2. Well Yield Response to Hydraulic Conductivity

The effects on the estimated value of groundwater conservation of varying the relationship between saturated thickness and well yield are shown in Figure 7. Aquifer hydraulic conductivity impacts the magnitude of economic benefits from restricting groundwater pumping, and also the optimal time for regulation. As hydraulic conductivity is increased, Figure 7 demonstrates that economic gains from limiting groundwater abstraction are constrained to a lower range of initial aquifer conditions (10 m to 36 m when conductivity is equal to 50 m d⁻¹). Contrastingly, for less conductive aquifers, benefits from regulation are distributed over a wider range of initial aquifer conductivity is equal to 10 m d⁻¹).

Inspection of the relationship between saturated thickness and well yield for different hydraulic conductivities (Figure 2) provides insights to explain the results observed in Figure 7. Aquifers with higher hydraulic conductivity, such as those composed of unconsolidated sands and gravels, can provide large well yields for small levels of saturated thickness because drawdown from pumping is distributed over a wide radius around the borehole. In these aquifers, there may be only minimal economic benefits from restricting pumping before significant depletion has occurred. Beyond this point, however, there may be large value in



Figure 7. Change in net present value (%) under an optimal pumping quota, relative to a scenario of unrestricted groundwater abstraction, for different levels of initial saturated thickness. Results are shown for simulations conducted with aquifer hydraulic conductivity uniformly equal to 10 m d⁻¹, 30 m d⁻¹, and 50 m d⁻¹. Note, results for initial saturated thickness above 60 m are not displayed as no benefits are observed in this range.

restricting pumping to avoid rapid reductions in well yields and associated impacts on irrigated production areas. In contrast, low conductivity aquifers (e.g., minimally fractured hard-rock systems) experience reductions in well yields for much smaller levels of depletion as water table drawdown is concentrated in the vicinity of the borehole itself. Pumping restrictions will be required earlier along the depletion pathway in these aquifers, and economic gains will decline to zero long before aquifer storage can be fully exhausted hydrologically.

4.2.3. Crop Tolerance to Water Stress

Figure 8 shows the impacts on returns to groundwater conservation of varying the soil moisture depletion thresholds at which water stress is initiated in AquaCrop. Decreasing crop toler-

ance to soil moisture deficits (parameter set 1 in Table 2) dampens the potential value of conservation. Positive benefits from conservation are found for slightly larger initial saturated thickness, and returns to conservation decline to zero earlier. In contrast, increasing crop tolerance to soil moisture deficits (parameter set 3 in Table 2) has markedly less impact on the value of conservation relative to the base case simulation (parameter set 2 in Table 2). Indeed, the main effect of increasing tolerance to water stress is a small shift in the optimal window to restrict abstraction.

These results capture the complex effects of intraseasonal and seasonal groundwater supply restrictions on crop production. The sensitivity of simulated crop production to water supply restrictions is affected by the



Figure 8. Change in net present value (%) under an optimal pumping quota, relative to a scenario of unrestricted groundwater abstraction, for different levels of initial saturated thickness. Results are shown for simulations conducted with three different parameter sets describing different levels of crop sensitivity to soil moisture deficits during the growing season (Table 2). Note, results for initial saturated thickness above 60 m are not displayed as no benefits are observed in this range.

parameters in Table 2, which describe the degree of soil moisture deficit a crop can tolerate before growth processes are inhibited and yields begin to be reduced. Parameter set 1 is characteristic of a corn variety that is highly sensitive to soil moisture deficits. For parameter set 1, the farmer may benefit from conserving groundwater to maintain higher well yields and limit intraseasonal irrigation constraints. However, the costs of conserving groundwater are high because, for parameter set 1, the crop is also highly sensitive to reductions in total seasonal irrigation. The economic and biophysical benefits of restricting abstraction to slow declines in well yields therefore are more limited for crops that have low tolerance to soil moisture deficits. In contrast, parameter set 3 represents a crop that has high tolerance to soil moisture deficits during the growing season. Nevertheless, our model still finds significant value in conserving groundwater to limit reductions in well yields for this parameter set. This is because low well yields lead to the build up of severe persistent soil moisture deficits over a growing season, which will have negative impacts on yields even for more drought tolerant corn varieties. Indeed, the effects of initial aquifer conditions on the value of groundwater conservation show only limited differences between parameter sets 2 and 3. These findings highlight the complex effects that differences in crop tolerance to water stress (e.g., between crop varieties/ types or farmers) may have on the spatial and temporal value of groundwater conservation. It is important to note that we assume changes in water stress thresholds for different crop growth processes are not independent. In reality, different varieties may have greater/lesser drought tolerance for specific aspects of development (e.g., canopy expansion, pollination), and this will also influence the potential benefits of groundwater conservation.

5. Discussion

5.1. Implications for Groundwater Management and Hydro-Economic Modeling

The results presented in section 4 highlight that initial aquifer conditions are an important, but previously unappreciated, factor governing welfare benefits from groundwater conservation. We demonstrate that a range of initial conditions exist for which reducing extraction, either through regulatory intervention or behavioral change, can extend the usable lifetime of an aguifer for irrigated crop production, and maximize the economic benefits from limited groundwater resources. In contrast, efforts to reduce groundwater pumping too early will constrain unnecessarily groundwater-fed irrigation. Similarly, conservation that is introduced after extensive depletion has occurred will be unable to limit the loss of drought resilience or the negative economic impacts of the transition from high value irrigated agriculture to low value dryland production. Our model provides useful insights for policymakers about where and when to target groundwater conservation efforts to have the greatest positive impacts on productivity and profits. This information is especially valuable given that groundwater management is politically challenging, time consuming, and expensive to implement and enforce [OECD, 2015]. For example, our findings suggest that some of the potential benefits from conservation may have been lost in parts of the High Plains aquifer that have already experienced extensive depletion (e.g., Texas, SW Kansas), with urgent reductions in water use required in other areas given projected depletion trends [Scanlon et al., 2012; Steward et al., 2013; Haacker et al., 2015].

Our analysis in this paper is field-level in scale. However, our results also provide valuable insights that can help to guide and inform regional groundwater management and policy analysis. Aquifer depletion will have differing effects on well yields for individual farmers. Variability in well yields, and their relative impacts on crop yields and profits, will arise due to heterogeneity in aquifer properties, soil types, climate, crop varieties, well depths, and economic costs between producers. The effects of drawdown on well yields thus adds an additional dimension to common-pool externalities of groundwater pumping, which previous economic studies have assumed are related solely to changes in pumping costs. Our findings indicate that there will be large spatial and temporal heterogeneity in the value of groundwater conservation, due to the distributional effects of depletion on farm profits that occur via changes in well yields. Moreover, we suggest that targeting groundwater management to producers whose well yields are most sensitive to further depletion is likely to result in greater welfare benefits than policies that are applied uniformly. Existing hydro-economic models of groundwater management [e.g., Brozović et al., 2010; Bulatewicz et al., 2010; Athanassoglou et al., 2012; Peterson and Saak, 2013; Steward et al., 2013; Medellín-Azuara et al., 2015] do not capture adequately these important feedbacks between aquifer depletion, well yields, and agricultural productivity. We suggest that such models therefore will be unable to provide reliable insights about the distributional impacts of depletion, or about how policies to control groundwater use should be implemented spatially and temporally to maximize welfare benefits from limited groundwater resources.

An important area for future development of our work is to extend our model to a more complex, regional aquifer in order to quantify the benefits from policies that target explicitly the distributional effects of well yields on crop productivity and profits. Scaling to a regional case study is likely to require simplification of some aspects of our model framework. Specifically, the total run-time of our integrated model (9 min per 50 year simulation) is dominated by the groundwater model subcomponent (85% of run-time). For a

regional analysis, it may be necessary therefore to simplify the groundwater component of the model. Computational overheads of spatially distributed hydrologic models are a common issue for hydro-economic research [*Harou et al.*, 2009]. One approach to address this challenge is to pregenerate response function matrices, which act as a surrogate for the full groundwater model. Response function matrices relate pumping stresses to changes in water levels at different locations, and are a useful approach for integrating hydrologic dynamics within multidisciplinary policy models in a computationally efficient manner [*Gorelick*, 1983; *Harou and Lund*, 2008; *Ahlfeld et al.*, 2009]. This approach has been used in a number of hydroeconomic studies of groundwater management [*Peña-Haro et al.*, 2009; *Mulligan et al.*, 2014; *Mulligan and Ahlfeld*, 2016], and could be adopted to limit computational demands when scaling our analysis to larger systems.

Finally, our focus in this study is on an aquifer that is experiencing chronic long-term depletion, and where significant water use reductions are needed to stabilize groundwater levels. This example is typical of major groundwater systems worldwide, including large parts of the High Plains and Central Valley Aquifers in the U.S. [Scanlon et al., 2012; Haacker et al., 2015], the Indo-Gangetic Plain [Rodell et al., 2009], the North China Plain [Feng et al., 2013], and aquifers in the Middle East and North Africa [Voss et al., 2013]. Nevertheless, there are other regions, including parts of the Northern High Plains [Kuwayama and Brozović, 2013; Mulligan et al., 2014; Palazzo and Brozović, 2014], where the main policy driver is streamflow depletion caused by drawdown of aquifer water tables. These cases are not the focus of this study. However, it is relevant to discuss briefly how connectivity between surface water and groundwater may affect the relationship between initial aquifer conditions and benefits from groundwater conservation. We hypothesize that a plot of the benefits of conservation as a function of initial saturated thickness (e.g., Figure 3) in these systems would display two distinct peaks. The first, for large saturated thickness, would represent the benefit of conserving groundwater to maintain connectivity with surface water systems, which have benefits for both the environment and surface water irrigation. The second peak, for lower saturated thickness, would capture the benefits of minimizing well yield reductions when surface water discharges have been captured fully. We suggest testing this hypothesis as an interesting area for future work in areas where streamflow depletion is the more important driver for groundwater conservation.

5.2. Model Limitations and Future Extensions

It is important to highlight that the simulations presented in this paper are conditioned on a number of assumptions, and discuss how these may influence our findings and inform directions for future research.

First, the economic component of our integrated modeling framework (section 2.2) assumes that a farmer makes myopic annual decisions about crop choice and irrigation strategy based on observed preseason aquifer conditions. In the absence of pumping restrictions, the farmer does not account for the impacts of extraction on the future availability and cost of groundwater beyond the end of the upcoming growing season. In the real-world, some farmers may not act myopically, and, alternatively, may behave in a manner that it is dynamically optimal by either conserving groundwater for future periods or increasing extraction rates to avoid future capture of common-pool groundwater by neighboring irrigators [Pfeiffer and Lin, 2012; Suter et al., 2012; Guilfoos et al., 2013]. We do not consider interactions between multiple farmers in this study, but it is likely that the private and social benefits of groundwater conservation would be even larger than predicted in sections 4.1-4.2 if strategic over-extraction leads to additional drawdown in the absence of regulations. Contrastingly, benefits from management are likely to be smaller in the case of strategic conservation behavior, as the farmer would act independently to preserve groundwater to support irrigated production in future periods. Importantly, this latter point highlights that incentivizing farmers to behave nonmyopically could have similar benefits to external regulations, such as pumping quotas, in terms of managing inter-annual changes in well yields and their impacts on irrigated agriculture. Supporting changes in behavior toward long-term conservation may also be more successful than an external regulator imposing restrictions on farmers, which would entail large economic and political costs for monitoring and enforcement, and should be analyzed in future work. Furthermore, where data exist, an interesting empirical extension of our work would be to use real-world data on saturated thickness and irrigated area from a depleting aquifer (e.g., parts of the southern and central High Plains) to explore to what extent farmers decision-making is consistent with the myopic decisions predicted by our model.

Our integrated model assumes that all nonsimulated parameters, such as those describing crop growth in AquaCrop, are stationary throughout each 50 year simulation. In reality, this may not be the case, and the value of groundwater conservation may be influenced by how changes in natural and human system dynamics alter the marginal benefits and costs of conserving an additional unit of groundwater stock. For example, future increases in irrigated crop yield potential as a result of improved breeding or development of new crop varieties could increase the value of conserving groundwater resources to support higher levels of production in future years [Grassini et al., 2013; Steward et al., 2013]. Similarly, as indicated by the analysis in 4.2, breeding for improved traits (e.g., drought tolerance) may have complex impacts on the future value of water in crop production. Any future gains from groundwater conservation today also will depend upon the uncertain impacts of concurrent changes in crop irrigation water requirements due to climate change [Konzmann et al., 2013; Wada et al., 2013; Elliott et al., 2014], and variability in crop and input prices that will determine the economic value of any additional future production. Addressing the impacts on the value of aquifer management of these and other system nonstationarities is beyond the scope of this paper. However, there is great need for research to develop new methodologies to assess how these dynamic changes in the future value of natural capital stocks may influence the effectiveness of groundwater conservation strategies [Fenichel et al., 2016].

We estimate the value of groundwater conservation on the basis of a 50 year planning horizon. While a 50 year planning period is consistent with existing analyses of groundwater management [e.g., Das et al., 2010; Madani and Dinar, 2012; Mulligan et al., 2014], this assumption means that potential agricultural production beyond year 50 has no economic value. Where policymakers or stakeholders care about maintaining irrigated agriculture and other beneficial uses of groundwater for longer periods, it may be optimal to restrict pumping earlier and more stringently in order to ensure sustainable long-term groundwater use. Additionally, our analyses also assume that pumping quotas are applied as a constant constraint over each 50 year simulation period. This assumption reflects the fact that it is politically challenging to implement regulations in the real-world, and once regulations are introduced they are often hard to adjust over time [OECD, 2015]. However, in a dynamically optimal setting, it is likely that additional benefits could be obtained from implementing variable guotas that are a function of aquifer saturated thickness, and our results therefore inherently represent a second-best policy option. The work of Esteban and Dinar [2013] provides some support for this assertion, showing that sequential application of groundwater policies outperforms the application of single policies in isolation. Updating pumping restrictions over time would also support flexible aquifer management in the face of uncertainty about the future trajectory of both depletion and the marginal value of groundwater.

Our model analyses assume that farmers are subject to an external restriction on groundwater pumping, which they can adapt to by either reducing irrigated area or increasing deficit irrigation. In practice, however, a wider range of adaptation mechanisms and policies may exist to incentivize groundwater conservation, and the choice of policy or response may influence returns to conservation. Future work should seek to compare how the benefits from groundwater conservation vary for different types of policy that could be used to reduce groundwater pumping, such as taxes, energy quotas, water rights buyouts, artificial recharge, or water trading. These analyses should evaluate the distributional effects that alternative policies may have across regional-scale groundwater systems where well yield effects on crop production are spatially and temporally heterogeneous, and assess how effective different policies are at maximizing regional welfare benefits from groundwater conservation. Furthermore, future analysis should also consider farmers' individual ability to mitigate costs of groundwater conservation through improved field-level management practices that enable irrigation to be reduced with less impacts on crop yields and profits than predicted currently by our model. For example, farmers may be able to offset some costs of conservation by adopting techniques to reduce nonconsumptive irrigation losses to soil evaporation (e.g., soil mulching), or switching to crops that have higher economic value per unit of applied water (e.g., switching from corn to high-value vegetables).

Finally, in our model we assume that well yield is only limited by available saturated thickness. Saturated thickness is an optimistic measure of when well yields will be affected by depletion, and, in practice, farmers' may experience reductions in pumping capacity long before this point depending on the depth of their well and choice of pump [*Boonstra and Soppe*, 2006]. Pump head-capacity curves can be used to model changes in well yields as a function of borehole water levels for a given pumping system design [*Konikow*,

2010]. Future research therefore should seek to extend our approach to modeling well yields (section 2.4) to incorporate explicitly pump head-capacity curves. In addition, this work should also consider the economic costs and heuristics of farmers' decisions about when to upgrade their pump or drill a deeper well in response to reductions in pumping capacity. No existing study of groundwater economics has considered adequately the costs of well drilling and pump replacement as an aquifer is depleted. However, in the majority of aquifers around the world, these costs are likely to represent a significant impact of long-term depletion for producers, which may enhance the economic and societal value of conserving groundwater stocks.

6. Conclusions

In this paper, we extend the literature on the economics of groundwater by analyzing how the value of groundwater conservation is influenced by initial aquifer conditions at the time pumping reductions are implemented. We develop an integrated modeling framework that accounts explicitly for reductions in well yields as an aquifer is depleted, and the nonlinear impacts that these changes have on farmers' ability to buffer production against climate variability. Through a case study in the High Plains Aquifer, we demonstrate that the value of groundwater management is affected strongly by initial aquifer conditions. Our results show that there are "windows of opportunity" when it is optimal economically to restrict pumping in order to minimize future declines in well yields and maximize the long-term capacity of groundwater stocks to support irrigated agriculture. Finally, sensitivity analyses are used to illustrate how the impacts of initial aquifer conditions on returns to conservation are influenced by local properties of both the hydrological system and agricultural production.

Our findings have important implications for research and policy related to groundwater management. We suggest that, in a depleting aquifer, efforts to reduce groundwater use should be targeted spatially and temporally to minimize future reductions in well yields and resultant negative impacts on agricultural productivity and resilience to drought. In contrast, conservation policies that are implemented in areas that have experienced limited depletion to date, or conversely in regions which the aquifer already is close to exhaustion, are unlikely to be welfare-increasing for agriculture. This paper also highlights that existing hydro-economic models will underestimate the true economic benefits for farmers from groundwater conservation. Current models assume that depletion impacts agriculture through changes in marginal pumping costs that are linear with depth. However, our findings demonstrate that the nonlinear effects of well yield reductions on the long-term productivity of groundwater creates a large additional incentive for producers to limit groundwater depletion, which has not previously been considered in integrated model analysis of aquifer management.

Future work should seek to extend the analyses and model developed in this paper to provide a comprehensive methodology for estimating the long-term value of groundwater management in more complex, regional settings. In particular, research should evaluate the distributional affects of aquifer depletion on farmers, and identify which groundwater management policies are most effective at managing the heterogeneous impacts of intraseasonal groundwater supply reductions. Future work should also consider how the value of conserving groundwater may be affected by uncertainty about future crop yields and irrigation requirements due to climate change and crop breeding, and the impacts of costs for pump upgrades and well deepening in response to declining well yields that have not been captured in economic assessments of aquifer depletion to date. Results from these analyses would provide deep insights about how limited groundwater resources can be used efficiently and sustainably to meet food security needs of growing global populations in the face of climate change.

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