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Production Externalities and the Gains from Management in a Spatially-Explicit Aquifer

Dale T. Manning and Jordan F. Suter

Groundwater is a valuable input to agricultural production in many areas, but its use imposes external costs on nearby producers. Little attention has been given to externalities that directly affect groundwater productivity. We develop a dynamic, spatially-explicit model of groundwater use that allows changes in saturated thickness to affect both the pumping cost and productivity of nearby wells. We compare gains from coordinated, socially optimal groundwater use to those that result from a user pursuing unilateral optimization. For wells with average saturated thickness, both unilateral and coordinated optimization can moderately increase the net present value of resource rents.

Key words: Colorado, dynamic optimization, groundwater management, hydro-economic model, Republican River Basin, well capacity

Introduction

Groundwater resources provide a valuable input to agricultural production, particularly in arid and semi-arid regions. The value of groundwater resources in agricultural production is directly determined by the profitability of irrigation. Groundwater pumping, however, imposes external costs on nearby groundwater users, leading to inefficient use of the water resource. These external costs arise because groundwater use reduces the availability of water at nearby locations. While economists have identified several specific externalities associated with declines in saturated thickness (Provencher and Burt, 1993),[1] externalities that arise due to higher pumping cost have received the majority of the attention in hydro-economic modeling efforts (e.g., Gisser and Sánchez, 1980; Feinerman and Knapp, 1983; Rubio and Casino, 2001; Guilfoos et al., 2013; Guilfoos, Khanna, and Peterson, 2016). In this research, we analyze the impact of an additional externality—agricultural productivity losses resulting from reduced saturated thickness—that has received less attention in previous research (Foster, Brozović, and Butler, 2014, provide an exception). Although the production externality has parallels to externalities associated with groundwater exhaustion (Tsur and Zemel, 1995; Guilfoos, Khanna, and Peterson, 2016; Merrill and Guilfoos, 2018), production externalities are likely to be more pervasive across an aquifer since they apply to more than just groundwater wells with low saturated thickness. The nature and magnitude of these externalities have important implications for the net social benefit associated with groundwater management and how it varies as a function of aquifer characteristics.

We develop a spatially-explicit hydro-economic model of groundwater use that allows us to investigate how the relative gains to socially optimal (coordinated) groundwater management depend

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[1] Saturated thickness is the vertical thickness of the hydrogeologically defined aquifer unit in which the pore spaces are filled (saturated) with water (Kansas Geological Society, http://www.kgs.ku.edu/HighPlains/atlas/atpst.htm).

on the relationship between an aquifer's saturated thickness and agricultural productivity at a given location. We also explore how this relationship affects the gains to unilateral optimization at the well level. This second question provides feedback on the extent to which groundwater use that accounts for dynamic linkages can support higher net returns, even when it does not involve the full coordination of all users. Finally, to explore the likelihood of gains from groundwater management in practice, we use modeled production data from Colorado's Republican River Basin to estimate the responsiveness of production value to saturated thickness, accounting for changes in producer decisions as water levels fall. Using modeled data in the absence of observed resource use provides a novel way to overcome the data shortages typical of nonmarket resources.

We find that the gains from unilateral optimization and coordinated groundwater management depend critically on the sensitivity of crop production to the level of saturated thickness, what we term the production-saturated thickness elasticity. When declines in saturated thickness correspond to substantial output reductions, individual users stand to benefit from unilateral optimization relative to myopic behavior. We also show that as the relationship between agricultural production and saturated thickness becomes more inelastic, gains from reduced water use can only be achieved through the coordination of multiple users. This result suggests that, in some instances, local management efforts will only serve to enhance the value of scarce water resources if the spatial extent of management efforts can be expanded to cover a sufficient number of resource users.

Background

Our study contributes to three strands of the economics literature related to groundwater resources: The first is the large body of research that investigates Gisser and Sánchez's (1980) finding that groundwater management generates trivial increases in net social benefits. Investigating the robustness of this result, Allen and Gisser (1984) show that it does not depend on the assumption of linear water demand. Similarly, Feinerman and Knapp (1983) evaluate groundwater management in Kern County, CA, under a variety of assumptions related to demand parameters and aquifer characteristics and find that the returns to management are always less than 10%. Brill and Burness (1994) investigate a wide range of assumptions and conclude that management can enhance economic value when the discount rate is low, when demand grows over time, and when well capacity diminishes with lower aquifer levels.[2] More recent attention in the literature has focused on evaluating spatially-explicit models, where groundwater externalities are highest at the point of extraction and dissipate with distance from a well engaged in pumping. Under these more realistic conditions, Brozović, Sunding, and Zilberman (2010) show that management gains can be relatively large when wells are spaced closely together. In this same vein, Guilfoos et al. (2013) implement a simulation model involving a spatially-explicit aquifer in which external pumping effects concentrate in nearby farms and show that significant gains to management can exist.

A second strand of the literature explores the nature of groundwater pumping externalities. Most economic models of groundwater use represent pumping externalities as increasing pumping costs through lower aquifer levels (see Koundouri, 2004, for a review). Provencher and Burt (1993) identify two additional types of externalities that result from groundwater pumping: a stock externality as groundwater use in one period reduces the set of potential actions in future periods and a risk externality that arises when groundwater use reduces the ability of risk-averse agents to respond to stochastic events. Negri (1989) also identifies a strategic externality that exists as users compete to capture rents from limited water resources. Saak and Peterson (2007) evaluate dynamic externalities in a more realistic case with finite lateral groundwater flows governed by Darcy's Law and shows that user beliefs regarding the speed of these flows impact predicted behavior.

Previous research has also explored how changes in the rate at which wells are physically able to pump water (referred to as well capacity) influence economic outcomes. Well capacity

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[2] Low well capacity does not affect water productivity in their specification.

is determined largely by local hydrologic conditions such as saturated thickness and hydraulic conductivity. Groundwater use at one location reduces the saturated thickness at nearby locations, which leads to reduced well capacity at neighboring wells. Brill and Burness (1994) and Burness and Brill (2001) model declines in well capacity as nonlinearly increasing the costs of delivering a given volume of water due to increased pumping time. A more recent series of papers by Foster, Brozović, and Butler (2014, 2015a,b) points out that lower well capacity also limits an irrigator's ability to deliver water to crops when it creates the most value, thus directly reducing the productivity and profitability of water. This change in productivity affects optimal planting and irrigation decisions.

The production externality that we analyze occurs because of the direct relationship between reductions in saturated thickness and diminished well capacity, which in turn reduces groundwater productivity. Some previous literature has accounted for a potential exhaustion externality, which occurs when groundwater use increases the probability that saturated thickness at nearby locations will drop below a level at which groundwater irrigation remains economically viable. This exhaustion externality can be due to a certain (Athanassoglou et al., 2012; Guilfoos, Khanna, and Peterson, 2016; Merrill and Guilfoos, 2018) or uncertain (Tsur and Zemel, 1995) level of saturated thickness, below which the resource no longer supports profitable irrigated production. Compared to an exhaustion externality, which occurs because of a discrete change in the ability of groundwater to provide economic benefits, the production externality that we evaluate is a result of marginal decreases in the productivity of groundwater as saturated thickness declines. This implies that, although the magnitude may vary across space, production externalities are present at all locations within an aquifer. Exhaustion externalities, by comparison, are concentrated in portions of an aquifer with very low levels of saturated thickness, where further reductions may necessitate conversion to dryland production.

The final strand of the economics literature relates to the benefits of strategic behavior and coordination in common-pool resource systems. This line of research has been motivated in large part by Ostrom's research investigating the circumstances under which groups effectively come together to manage common-pool resources (e.g., Gardner, Ostrom, and Walker, 1990; Ostrom, Walker, and Gardner, 1992; Ostrom, 1999). Walker, Gardner, and Ostrom (1990) extend this research to cooperative behavior related to groundwater use, and Ostrom (2010) assesses the challenges related to the polycentric governance of natural resources. Finally, Rubio and Casino (2001) evaluate the theoretical implications of strategic and cooperative behavior with respect to groundwater resources.

In this study, we use a model of groundwater use that represents the relationship between saturated thickness, well capacity, and productivity, which enables us to generate estimates of the magnitude of the gains from unilateral and coordinated groundwater management in the presence of an externality resulting from diminished productivity. Our research builds on the Peterson and Saak's (2018) framework, which uses a dynamic model to evaluate the importance of heterogeneity in the depth of the bottom of the aquifer on the divergence between myopic and socially optimal steady states, when reductions in saturated thickness impact groundwater productivity.

Hydro-Economic Model

We now describe the hydro-economic model used to investigate the role of production externalities in determining the gain to coordinated groundwater management. Solving numerically for wells in the Republican River Basin of Colorado allows us to demonstrate that returns to unilateral optimization and coordination across users depend on the elasticity of production with respect to groundwater levels. We model agricultural output at well i in year t as $y_{it} = \left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) x_{it}^{\eta}$, $i = 1, \ldots, n$, which can be sold for price, p. In the production function, w_{it} is the amount of water pumped, a_i, b_i are positive parameters, x_{it} is the saturated thickness of the aquifer at well i, and $\eta \geq 0$ is the elasticity of production with respect to saturated thickness. Production responses to saturated thickness are driven by the connections between saturated thickness, well capacity, and producer choices (including crop mix and irrigation volume). As well capacity falls, producers concentrate water on fewer irrigated acres. The lower capacity also affects producers' ability to deliver water to crops when it creates the most value (e.g., during a hot, dry period). The behavioral response to this constraint can lead to water applications at suboptimal times, resulting in lower water productivity (e.g., some low-capacity wells remain on throughout a growing season, even during precipitation events).

The impact of changes in capacity on productivity may depend on the saturated thickness at the well. If a given well has a large saturated thickness, marginal declines in capacity may produce little change in production. At the same time, if a well has very little water, further decreases cause minimal additional declines in profit, which is already at a low level. In a middle range, as a producer goes from unconstrained to constrained in the ability to deliver water when it is most needed, declines in capacity can lead to large changes in irrigation behavior driven by changes in crop mix and the ability to respond to precipitation events. As well capacity passes through this range, planting acres in water-intense crops becomes increasingly risky.

While well capacity is the driving force behind the changing productivity of water, we model it using saturated thickness because well capacity is determined by saturated thickness (conditional on hydraulic conductivity) at each well (Hrozencik et al., 2017). Therefore, to simplify notation, we express production as a function of pumping and saturated thickness at the well. The first term in parenthesis in the production function, consistent with linear water demand for a given level of saturated thickness, matches the functional form for production often assumed in the groundwater economics literature (e.g., Gisser and Sánchez, 1980; Guilfoos et al., 2013).

We assume uniform surface elevation and bedrock depth and that each well is drilled to the bottom of the aquifer. This means that changes in saturated thickness can be interpreted as changes in the vertical height that water must be pumped to the surface. It also means that producers do not have the option to drill deeper over time as saturated thickness falls. While, in general, both surface height and bedrock depth can vary significantly over a large aquifer, we focus on neighboring wells, which are more likely to have similar aquifer conditions.[3] Given these assumptions, the marginal cost of water extraction is $c_{0i} - c_{1i}x_{it}$, where $c_{0i}, c_{1i} > 0$. In this model, as saturated thickness falls, productivity decreases because of lower well capacity and marginal extraction costs increase as water must be lifted a greater vertical distance. These cost parameters could vary across wells to reflect differences in the efficiency of pumps or variation in surface elevation, though we assume these to be constant in the application considered here. Combining revenue and cost terms, per period profit becomes $p \times (a_i w_{it} - 1/2 b_i w_{it}^2) x_{it}^{\eta} - (c_{0i} - c_{1i}x_{it}) w_{it}$.

We model wells as cells situated along a linear array. The saturated thickness at well i adjusts according to Darcy's Law and depends on pumping rates from wells in the set of adjacent cells, j_a, as well as pumping at well i. Therefore, the change in saturated thickness at well i is

$$\dot{x}_{it} = \frac{R_i + (\alpha - 1) w_{it}}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i} (x_{it} - x_{jt})}{d_{ij} AS_i} \; \forall\, i \tag{1}$$

where R_i is the recharge into the cell of well i, α is the proportion of applied water that returns as recharge, d_{ij} is the distance from well i to well j, and A_{0i} is the cross-sectional area through which water flows, assumed constant across time. As the saturated layer of an aquifer falls, this cross-sectional area falls over time (Guilfoos, Khanna, and Peterson, 2016). In this case, assuming the parameter to be time-invariant will tend to overstate management impacts because external pumping costs fall with saturated thickness. AS_i is the surface area multiplied by aquifer storativity and k_i is the

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[3] To allow greater generalizability, we could specify depth to water and saturated thickness as separate, well-specific variables. To simplify notation, we assume a one-to-one mapping between saturated thickness and depth to water across all wells.

aquifer's hydraulic conductivity.[4] The second term on the right side of equation (1) is summed across all adjacent cells, j, belonging to the set, j_a. Importantly, in our study area, well spacing is regulated by law and no new wells can be drilled. This allows distance to be exogenous to the management policy that is put in place. In regions with unregulated well spacing, the distance between wells may be an important factor to consider when measuring policy impacts. Greater distance between wells means that external pumping impacts become smaller.

We consider three alternative behavioral scenarios: myopic pumping, unilateral optimization, and social optimization. As in Gisser and Sánchez (1980), we use the myopic pumping case as a benchmark for comparing gains to alternative management scenarios. When one well unilaterally optimizes by conserving water in the short run, this reflects the decision of a single user (or subset of users) to conserve water for future periods. When making this decision, an individual is assumed to account for the linkages across farms that are governed by Darcy's Law but not to account for the cost imposed on other users.

Myopic Pumping Behavior

To solve for the myopic pumping path, we assume that each individual well user sets the marginal benefit of pumping to the marginal cost of pumping in year t. Specifically, for user i,

$$px_{it}^{\eta}\left(a_i - b_i w_{it}\right) = c_{0i} - c_{1i}x_{it}. \tag{2}$$

With myopic behavior, individual pumpers observe saturated thickness and pump groundwater until the marginal net benefit of pumping in a given period is zero. Impacts on self and other pumpers over space and time are ignored.

Solving for the quantity of groundwater pumped by a myopic user in a given period,

$$w_{it} = \frac{a_i}{b_i} - \frac{c_{0i} - c_{1i}x_{it}}{pb_i x_{it}^{\eta}}. \tag{3}$$

Equation (3) can be plugged into equation (1) to determine how the aquifer saturated thickness at well i changes over time. Solving the resulting system of ordinary differential equations (ODEs) for N wells produces the myopic solution for saturated thickness, x_{it}^m, which we insert into equation (3) to obtain w_{it}^m. Finally, we plug x_{it}^m and w_{it}^m into the profit function to determine the net present value (NPV) of pumping at well i. Assuming discount rate, r, this becomes

$$NPV_i^m = \int_0^T \left(p\left(a_i w_{it}^m - \frac{1}{2} b_i w_{it}^{m2} \right) x_{it}^{m\eta} - \left(c_{0i} - c_{1i}x_{it}^m\right) w_{it}^m \right) e^{-rt}\, dt. \tag{4}$$

We then compare the myopic value of pumping at well i with the value generated from socially optimal groundwater management and from an individual user pursuing unilateral optimization.

Socially Optimal Solution

The socially optimal paths for pumping and saturated thickness represent the case in which wells coordinate and internalize all external pumping effects across space and time, including the increased costs and lower water productivity that result from decreasing aquifer levels. Under social optimization, each well balances the marginal benefit of pumping today with the dynamic marginal costs imposed on all other wells over time. Users consider both the increased pumping costs and

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[4] Hydraulic conductivity, fixed for a given well, describes the potential speed with which water can move laterally through the aquifer. As Edwards (2016) points out, higher hydraulic conductivity leads to higher connectedness between wells, leading to larger pumping externalities and gains to management.

lower productivity that occur because of changing water levels. Solving this model numerically allows us to estimate the gains to groundwater management as a function of η. In the socially optimal case, the planner's objective is to maximize the NPV of the rent earned from the water resource, or

$$\max_{w_{it}} \int_0^T \left(\sum_{i=1}^N p\left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) x_{it}^{\eta} - \left(c_{0i} - c_{1i} x_{it}\right) w_{it} \right) e^{-rt} dt \tag{5}$$

such that

$$\dot{x}_{it} = \frac{R_i + (\alpha - 1) w_{it}}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i} \left(x_{it} - x_{jt}\right)}{d_{ij} AS_i} \ \forall\, i, \tag{6}$$

with x_{i0} known. Defining λ_{it} as the costate variable associated with each of the N state variables, the current-value Hamiltonian for this problem becomes

$$\begin{aligned} H^{CV} = & \sum_{i=1}^N p\left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) x_{it}^{\eta} - \left(c_{0i} - c_{1i} x_{it}\right) w_{it} \\ & + \lambda_{it} \left(\frac{R_i + (\alpha - 1) w_{it}}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i} \left(x_{it} - x_{jt}\right)}{d_{ij} AS_i} \right). \end{aligned} \tag{7}$$

Assuming an interior solution, the Pontryagin conditions for this problem state that

$$p x_{it}^{\eta} \left(a_i - b_i w_{it}\right) - \left(c_{0i} - c_{1i} x_{it}\right) - \frac{\lambda_{it} (1 - \alpha)}{AS_i} = 0 \ \forall\, i, \tag{8}$$

$$\dot{\lambda}_{it} = r\lambda_{it} - \left[\eta x_{it}^{\eta - 1} p \left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) - c_{1i} w_{it} - \left(\sum_{j \in j_a} \frac{\lambda_{it} k_i A_{0i}}{d_{ij} AS_i} + \sum_{j \in j_a} \frac{\lambda_{jt} k_j A_{0j}}{d_{ij} AS_j} \right) \right] \ \forall\, i, \tag{9}$$

and

$$\dot{x}_{it} = \frac{R_i + (\alpha - 1) w_{it}}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i} \left(x_{it} - x_{jt}\right)}{d_{ij} AS_i} \ \forall\, i. \tag{10}$$

Equation (8) can be solved for w_{it} so that

$$w_{it} = \frac{a_i}{b_i} - \frac{c_{0i} - c_{1i} x_{it}}{p b_i x_{it}^{\eta}} + \frac{\lambda_{it} (\alpha - 1)}{p x_{it}^{\eta} b_i AS_i} \ \forall\, i. \tag{11}$$

Plugging equation (11) into equations (9) and (10) produces a system of nonlinear ODEs in λ_{it} and x_{it}. Assuming T is finite, $\lambda_{iT} = 0$. Combining with x_{i0} known, the system of ODEs can be solved numerically to produce the optimal state and costate paths, x_{it}^*, λ_{it}^*. Using the solution in equation (11) produces w_{it}^*. Finally, the optimal paths can be plugged into the objective function; separating the value from each well produces NPV_i^*. Because of the nonlinearity of the ODEs, the model does not have a closed-form solution (Guilfoos et al., 2013) and is solved numerically in the next section.

Unilateral Optimization

In addition to the extreme cases of myopic producers and socially optimal coordination, we investigate the impacts of one producer unilaterally choosing to conserve water in order to maximize the present value of rents from production over time. A producer optimizing unilaterally considers the impact of pumping today on future water availability, accounting for the behavior of neighboring wells over time. Instead of making pumping decisions conditional only on current groundwater levels, the dynamic optimizer weighs the private marginal benefit of pumping today against the private marginal cost of that pumping in all future periods. If a given well optimizes value over time without coordination across wells, the objective function becomes

$$\max_{w_{it}} \int_0^T \left(p\left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) x_{it}^{\eta} - (c_{0i} - c_{1i} x_{it}) w_{it}\right) e^{-rt} dt \tag{12}$$

such that

$$\dot{x}_{it} = \frac{R_i + (\alpha - 1) w_{it}}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i} (x_{it} - x_{jt})}{d_{ij} AS_i}. \tag{13}$$

The main difference between unilateral optimization and the social planner's objective described in equation (5) is that the individual user considers profit only at well i and accounts only for how saturated thickness changes at well i.[5] In this scenario, we assume that each individual optimizer knows other pumpers' decision strategies as well as aquifer conditions and initial saturated thickness. Each individual optimizer then determines a privately optimal pumping time path conditional on the time path of all other players. Given that individual optimizers are assumed to commit themselves to an entire temporal path of groundwater pumping conditional on the paths of neighboring users, the solution concept can be thought of as an open-loop Nash equilibrium (Rubio and Casino, 2001).

Following the same procedure as in the socially optimal scenario, the Pontryagin conditions for this dynamic optimization problem imply that

$$w_{it} = \frac{a_i}{b_i} - \frac{c_{0i} - c_{1i} x_{it}}{p b_i x_{it}^{\eta}} + \frac{\lambda_{it} (\alpha - 1)}{p x_{it}^{\eta} b_i AS_i} \equiv w_{it}^R \tag{14}$$

and

$$\dot{\lambda}_{it} = r\lambda_{it} - \left[\eta x_{it}^{\eta - 1} p \left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) - c_{1i} w_{it} - \left(\sum_{j \in j_a} \frac{\lambda_{it} k_i A_{0i}}{d_{ij} AS_i}\right)\right]. \tag{15}$$

Note the apparent equivalence of equation (14) to equation (11). Individual pumping decisions account for dynamic effects of pumping in both scenarios, but the size of those effects differs. In the socially optimal case, the decision accounts for dynamic costs not only to an individual well but to all wells in the model. In the unilateral optimization case, producers only consider dynamic effects at the same well.

To solve the model with unilateral optimization, we assume that the individual user correctly anticipates the behavior of others and chooses an optimal pumping path in response. As an illustration, if well i behaves dynamically while all other wells behave myopically, equation (3) is used to determine pumping at other wells and λ_{lt} with $l \neq i$ would equal 0. The resulting system

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[5] In this paper, we use "social planner," "management," and "fully coordinated" to refer to resource use over space and time that maximizes discounted profits.

of ODEs becomes

$$(16)\qquad \dot{x}_{it} = \frac{R_i + (\alpha - 1)\, w_{it}^R}{AS_i} - \sum_{j \in j_a} \frac{k_i A_{0i}\,(x_{it} - x_{jt})}{d_{ij} AS_i},$$

$$(17)\qquad \dot{x}_{lt} = \frac{R_l + (\alpha - 1)\, w_{lt}}{AS_l} - \sum_{j \in j_a} \frac{k_l A_{0l}\,(x_{lt} - x_{jt})}{d_{lj} AS_l} \text{ for } l \neq i,$$

$$(18)\qquad \dot{\lambda}_{it} = r\lambda_{it} - \left[\eta x_{it}^{\eta-1} p \left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) - c_{1i} w_{it} - \left(\sum_{j \in j_a} \frac{\lambda_{it} k_i A_{0i}}{d_{ij} AS_i}\right)\right],$$

where w_{it}^R comes from equation (14) and w_{lt} comes from equation (3). This system of ODEs can be solved for x_{it}^R, x_{lt}^R, and λ_{it}^R to obtain the solution to the case where one individual unilaterally optimizes while all others continue to behave myopically. Plugging this solution into $\int_0^T \left(p\left(a_i w_{it} - \frac{1}{2} b_i w_{it}^2\right) x_{it}^{\eta} - (c_{0i} - c_{1i} x_{it})\, w_{it}\right) e^{-rt} dt$ for all i allows us to calculate the NPV for each well in this scenario, NPV_i^R. Comparing NPV_i^R for the individual who unilaterally optimizes to NPV_i^m describes the incentive that exists for individuals to unilaterally conserve water, given that others continue to behave myopically. By varying η numerically, we investigate how the individual returns to unilateral optimization and coordination depend on the sensitivity of crop production to changes in saturated thickness and well capacity. We then provide an empirical estimate for η to explore the existence of incentives for groundwater conservation in practice.

Model Parameterization

The hydro-economic model is used to compare the value generated from groundwater under the three management scenarios described in the last section using three wells, indexed $i = 1, 2, 3$. Table 1 provides the parameters used to solve the three-well model, which were chosen to reflect aquifer and producer characteristics in the Republican River Basin of Colorado and to facilitate model comparison with previous literature. In particular, the marginal cost of pumping, $c_{1i} = 0.09$, return coefficient, $\alpha = 0.2$, and discount rate, $r = 5\%$, are taken from Guilfoos et al. (2013). Production parameters are derived from an assumption that the choke price for water is \$500/acre-foot and that the marginal product of water is zero at 525 acre-feet.[6] We chose c_{0i} to produce an initial demand for water in the myopic model that falls in the range of average water consumption in 2014, or 180 acre-feet (equivalent to 16.5 inches/acre on a full center-pivot circle of 130 acres). Hydrologic parameters were obtained based on regional averages, assuming 130 acres of irrigated land (with a storativity coefficient of 0.154). The recharge parameter was chosen to equal the regional average of approximately half of baseline pumping. Finally, T is assumed to be 100 years.

We focus on three wells in the region, assumed to be located along a linear array as depicted in Figure 1. While pumping by the well in cell 2 affects saturated thickness in both cells 1 and 3, there is no direct connection between saturated thickness in cells 1 and 3. An indirect linkage forms as pumping in cell 1 draws water from cell 2 in the following period, impacting the flow of water between cells 2 and 3 in subsequent periods. It should also be noted that the initial saturated thicknesses for each well (x_{10}, x_{20}, and x_{30}) are assumed to differ slightly to allow for heterogeneity in initial water availability. The model results, however, are qualitatively robust to variation in the assumed initial saturated thickness at each well.

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[6] The extensive margin is not necessarily held fixed. With more water, a producer could plant more irrigated acres or provide more water to existing acres planted. The choke price of \$500 is based on maximum average observed agricultural water transactions in Colorado of \$495/acre-foot/year (based on California Water Transfer Records, https://www.bren.ucsb.edu/news/water_transfers.htm). This assumes an annual discount rate of 6%. The x-axis intercept is chosen because pumping data in the basin indicate that 99% of well-years use less than 529 acre-feet.

Table 1. Economic and Hydrologic Parameter Values Used to Solve the Hydro-Economic Model

Economic Parameters	Parameter Value
p	\$1
η	0.08–1.5
a_i	chosen to obtain \$500 choke price for water
b_i	chosen to obtain x-intercept of 525 acre-ft
c_{0i}	\$200
c_{1i}	\$0.09/ft
r	0.05

Hydrologic Parameters	Parameter Value
x_{10}	195 ft
x_{20}	201 ft
x_{30}	205 ft
a	0.2
k_i	75 ft/day
A_{0i}	0.01 acres
AS_i	$130 \times 0.154 = 20$
d_{ij}	2,297 ft
R_i	75 acre-ft

Notes: Table indicates parameter values used to numerically solve the model.

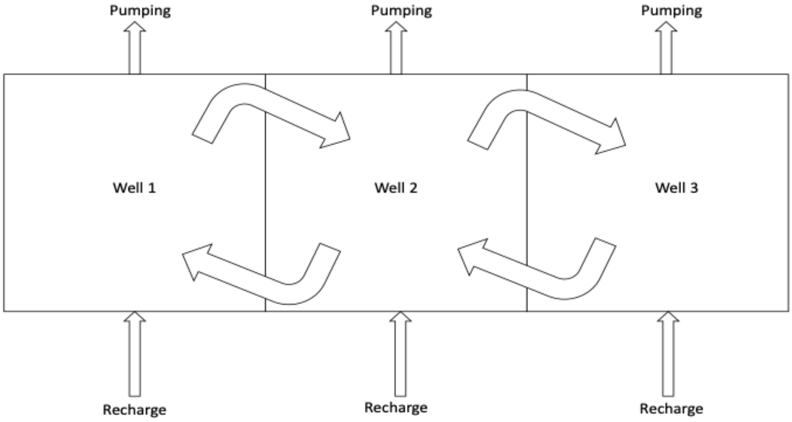

Figure 1. Representation of Three-Celled Aquifer with Lateral Flow Governed by Darcy's Law

The distance between each of the wells is assumed to be 2,297 feet (700 m). Figure 2 illustrates the cumulative distribution of the minimum distance between individual wells in three of the groundwater management districts in the region. Approximately 80% of wells are observed to have at least one additional well within 2,000–3,000 feet.

Using the parameterization described here, the model is solved numerically to explore the increase in resource rent earned through unilateral and social optimization of groundwater use relative to myopic behavior.[7]

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[7] We used Matlab's BVP4c function to obtain numerical solutions to the systems of ODEs described in this section. A finite time horizon means that we have an ending condition for every costate variable in the model. Combining this with aquifer (state variable) initial conditions allows the model to solve. Code is available from the authors upon request.

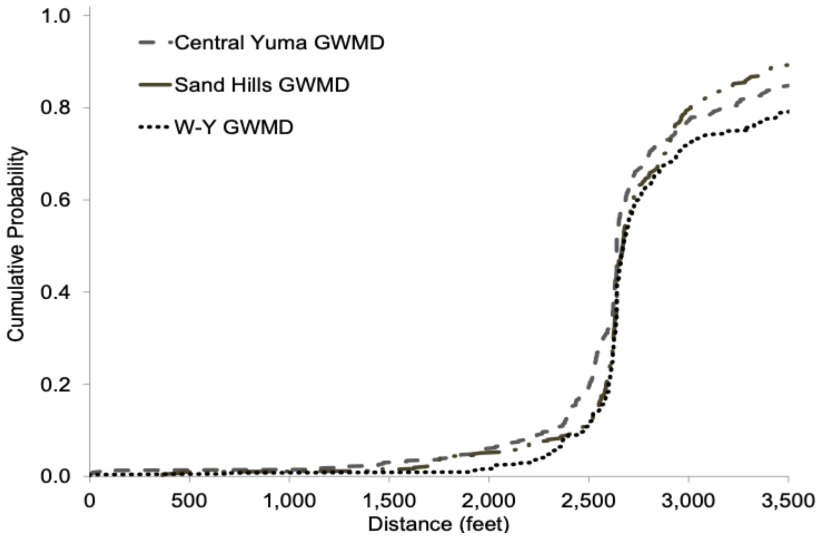

Figure 2. Cumulative Distribution of Distance to Nearest Well for Three Separate Groundwater Management Districts (GWMD) in Colorado's Republican River Basin

Numerical Model Results

To address our primary research questions, we generate results for the three separate management scenarios across a range of parameterizations for the elasticity between production and saturated thickness. We examine a range of elasticity values because the true value of this parameter has not been explored in the literature (in the empirical section of this paper, we provide an estimate of this value for a specific case). By comparing the NPV of profits associated with myopic behavior to socially optimal behavior under each parameterization, we observe how changes in the production elasticity impact the returns to coordinating groundwater use across wells. By comparing myopic behavior to unilateral optimization behavior, we observe both the private returns to dynamic management as well as the external benefits generated at other wells from unilateral optimization (see Online Supplement A for an example of model solutions over time).

The myopic management results presented in Table 2 highlight the importance of the production elasticity in influencing the NPV of profits when producers do not dynamically optimize. Higher values of the production elasticity lead to a lower NPV of profits. Given the setup of the model, higher production elasticities generate larger spatial and dynamic impacts of water pumping as saturated thickness falls, which lowers the value of production. As a result, profits decline more quickly as saturated thickness is reduced when η is large. The overall result is that the NPV is substantially higher when the elasticity is 0.1 compared to when it is 1.5.

The elasticity parameter also has a large impact on the gains to groundwater management. Table 3 demonstrates that increases in the elasticity between production and saturated thickness tend to increase the returns to social optimization relative to myopic behavior. For example, at an elasticity value of 1.5, all three producers achieve profits through optimal management that are more than 50% above myopic returns. By comparison, for a relatively low elasticity value (e.g., 0.1), the returns to coordination across wells are just 2%.

A similar relationship between the production-saturated thickness elasticity and returns to unilateral optimization is reflected in Table 3. Importantly, with a low production-saturated thickness elasticity, the incentive to unilaterally optimize is small, reaching less than 1% with $\eta \leq 0.1$. This increase is small compared to the socially optimal gains. Unilateral optimization behavior does generate external benefits to neighboring wells that are more than 50% of the gain to the individual engaging in the optimal behavior. These benefits increase as η increases, but at low elasticity values;

Table 2. Present Value of Profit Associated with Myopic Behavior

Production-Saturated Thickness Elasticity	Well 1	Well 2	Well 3
0.08	$478,265	$476,716	$476,086
0.1	$472,833	$470,788	$469,894
0.3	$424,969	$418,785	$415,826
0.5	$390,658	$381,584	$377,345
0.7	$364,308	$353,126	$348,070
0.9	$343,231	$330,479	$324,907
1.1	$325,906	$311,972	$306,093
1.3	$311,375	$296,551	$290,514
1.5	$298,995	$283,509	$277,423

Notes: Table indicates the present value of profit earned at each well for each production-saturated thickness elasticity indicated in the first column.

Table 3. Percentage Increase in Net Pesent Value of Profit with Unilateral Optimization by Well 2 and Social Optimization

	Well 2 Unilateral Optimization			Social Optimization		
Production-Saturated		% Increase			% Increase	
Thickness Elasticity	Well 1	Well 2	Well 3	Well 1	Well 2	Well 3
0.08	0.48	0.55	0.47	2.08	2.05	2.03
0.1	0.49	0.60	0.48	2.39	2.36	2.33
0.3	1.36	1.80	1.33	7.36	7.20	7.06
0.5	2.38	3.30	2.32	13.49	13.07	12.74
0.7	3.44	4.98	3.35	20.45	19.63	19.03
0.9	4.50	6.73	4.39	28.29	26.94	25.99
1.1	5.53	8.58	5.40	36.99	34.94	33.54
1.3	6.52	10.50	6.39	46.74	43.80	41.85
1.5	7.51	12.46	7.38	57.63	53.62	51.00

Notes: Well 2 Unilateral Optimization shows the percent gains in present value of profit at each well when wells 1 and 3 continue to behave myopically. Social Optimization shows the percent gains in present value of profit from optimal management. Both show gains relative to myopic behavior at all three wells.

gains from groundwater management, even of just 2%, require coordination across multiple wells. As η becomes large, gains to unilateral management exist but remain small compared to those from social optimization.[8]

These results suggest that if the production-saturated thickness elasticity is high in practice, producers face a unilateral incentive to increase the present value of rent earned from irrigated production. While coordination resulting in social optimization of rent generates the greatest return, incentives for unilateral optimization exist with a sufficiently elastic production response to saturated thickness. In practice, little observational data exist describing the empirical relationship between saturated thickness, well capacity, and production. Therefore, we turn to a basin-wide model of crop and irrigation decisions in Colorado to estimate the importance of changes in saturated thickness to agricultural production at a well.

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[8] As indicated in Foster, Brozović, and Butler (2017), gains to management also depend on initial conditions. In Online Supplement B, we present the results of a sensitivity analysis to assumed initial saturated thickness levels. Consistent with Foster et al., proportional gains to management (holding the production-saturated thickness elasticity fixed) increase with small decreases in initial saturated thickness below the saturated thickness value assumed in the model.

Empirical Estimates of Response to Saturated Thickness

To understand the importance of the production-saturated thickness elasticity in practice, we use the results of a well-level dynamic model of planting, irrigation, and production in Colorado's Republican River Basin (see Hrozencik et al., 2017, for a detailed description of the empirical model). Importantly, the model allows for changing saturated thickness, depth to water, and well capacity over time. The model assumes that each of the 3,006 wells in the basin is operated independently and that producers choose the number of acres to plant in irrigated and dryland corn and wheat. Prior to planting, each myopic producer knows the well capacity and makes a planting decision to maximize expected profits in that year, given a known water and crop yield production function generated using the agronomic model AquaCrop (Steduto et al., 2009). At the time of planting, well capacity for that year is exogenous to the producer. Therefore, the data provide information assuming myopic producers, but the water-yield production functions do not depend on management regime. The social planner or manager may reduce the optimal volume of water applied at each well, but this should not affect the fundamental relationship among water applied, yield, and revenue.

As water availability declines over time, producers in the model switch from water-intense to less water-intense crops (i.e., from corn to wheat). The weather distribution is also known as of planting and includes the possibility of wet, normal, and dry years. In each year of the simulation, weather is realized from the known distribution and groundwater use decisions are made, generating irrigated yields, output, revenue, and profit at each well. Specifically, the simulation has annual weather realizations of normal, dry, normal, wet, normal, dry, normal, wet, etc. Finally, technology is held constant across the simulation.

Using the model, we simulate a 50-year period and obtain model output reporting saturated thickness (x_{it}), water applied (w_{it}), and revenue earned (v_{it}) at well i in year t. To aggregate production value across multiple crops, we sum the dollar value of output, assuming constant output prices. This allows the observed revenue produced from water to adjust to both intensive and extensive decisions that affect the use and value of water. Saturated thickness averages 141 feet (s.d. = 72), while wells pump an average of 248 acre-feet (s.d. = 48) and earn average revenue of \$126,000/well (s.d. = 30,000).[9] Importantly, our data on water use and revenue over time come from the output of this behavioral model. All variables in the statistical model (with the exception of initial saturated thickness) come from this model. Key variation comes from changes in saturated thickness, water use, and revenue over time. These changes are driven by changing well capacity at each well over time. Therefore, parameter estimates are conditional on the myopic but profit-maximizing behavior described by the model, which has the benefit of a known data-generating process, allowing us to control for all confounding factors. If, however, producers respond to changing water availability in systematically different ways, the modeled data omit this behavior and parameter estimates may not capture true elasticities.

Initial measurements of saturated thickness for each well are obtained from the U.S. Geological Survey (Flynn, Arnold, and Paschke, 2009), while saturated thickness in future periods is the result of modeled pumping and groundwater flows across space and time. The simulation model links production and irrigation decisions to the Republican River Compact Administration's MODFLOW model, which produces the updated saturated thickness information. Figure 2 provides a map of the basin that includes information related to current saturated thickness and the spatial location of irrigation wells. Saturated thickness and the density of wells tend to be highest in the northeastern portion of the basin, with saturated thickness reaching over 200 feet in some areas. Wells in the southern portion of the basin tend to have fewer than 100 feet of saturated thickness.

The modeled data create a panel of 3,006 wells, each operating for 50 years. These data are then used to estimate an econometric model in which revenue is regressed on saturated thickness and the

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[9] Modeled water use is higher on average than the 2014 water consumption used to parameterize the dynamic model. Numerical results are qualitatively robust to the water volume used for parameterization.

volume of groundwater applied. To control for time-invariant factors that influence revenue, such as soil type and aquifer hydraulic conductivity, the model includes well-level fixed effects. This is important because both hydraulic conductivity and saturated thickness contribute to well capacity. Here, we examine the impact of changes in saturated thickness on behavior through the capacity channel.

The production-saturated thickness elasticity may vary across different levels of initial saturated thickness. This occurs as very deep saturated thickness can fall by a large amount and still provide sufficient water to maintain relatively high well capacity and water productivity. At the other extreme, if saturated thickness is low, the crop yield is also low and further depletions have only a small impact on productivity. In a middle range, falling saturated thickness can have meaningful impacts on well capacity and water productivity (Foster, Brozović, and Butler, 2017). To allow for a nonconstant relationship between revenue and saturated thickness, we estimate our empirical model using a split sample in which separate coefficients are estimated for wells with more than and less than 100 feet of saturated thickness. We choose 100 feet of saturated thickness as the cutoff because it represents the 25th percentile of initial saturated thickness in the sample. We further estimate separate models using saturated thickness bins of 50 feet from 0 to 250. Let s indicate the saturated thickness bin used to estimate the model. Our model of revenue at well i in year t becomes

$$v_{it}^{s} = \alpha_{i}^{s} + \eta^{s} x_{it}^{s} + \beta_{1}^{s} w_{it}^{s} + \varepsilon_{it}^{s}. \tag{19}$$

Revenue, groundwater applied, and saturated thickness in equation (19) are expressed in logs. Therefore, the estimates of η^s represent the production-saturated thickness elasticity in the basin, accounting for the ability to switch crops.[10] This is the relevant parameter because crop switching is an important margin along which producers respond to changing water availability (Pfeiffer and Lin, 2014). Importantly, changes in revenue that occur as the crop mix changes should be accounted for in the estimate of η. Therefore, we do not condition on the crops planted. These estimates, combined with the results presented in the previous section, illustrate the potential gains to coordination and unilateral optimization for wells in the region.

Econometric Results

Table 4 presents the coefficient estimates for equation (19). The model is estimated for the overall sample and separately for high and low saturated thickness well-year observations.[11] The first column suggests that the average production elasticity is around 0.05, which implies that, on average, gains to coordination and unilateral optimization are likely small in the basin. When the sample is split, however, it becomes clear that some well-year observations demonstrate a more elastic production-saturated thickness relationship. In particular, production elasticity climbs to 0.23 for wells with more than 100 feet of saturated thickness, consistent with larger gains to optimization.

To further explore the magnitude of η for different ranges of saturated thickness, Figure 3 presents the estimated values for η^s, assuming saturated thickness bins of 50 feet. Figure 3 also includes a cumulative distribution function for current saturated thickness across the basin. The production-saturated thickness elasticity is largest in the bins between 100 and 200 feet of saturated thickness, with an estimated elasticity of 0.3. Nearly 40% of all wells in the basin fall within this range. Referring back to Table 3, this estimated elasticity suggests that regions of wells with saturated thickness of 100–200 feet are the most likely to gain from unilateral and social optimization of groundwater use. On average, 100 feet of saturated thickness corresponds to roughly 600 gallons/minute of well capacity in our data. At this well capacity, anecdotal evidence suggests

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[10] See Online Supplement C for a precise description of the relationship between η^s and η described in the theoretical model section. They both describe the proportional change in revenue in response to a proportional change in saturated thickness.

[11] The number of wells in each of the two models estimated using a subsample does not sum to the total of 3,006. This occurs because some wells have observations that fall in both the >100-foot and the <100-foot bins.

Table 4. Estimation Results Investigating the Sensitivity of Revenue to Production-Saturated Thickness Elasticity

		Saturated Thickness Bin	
Variable	**Overall**	**>100 ft**	**<100 ft**
Saturated thickness (log)	0.0523***	0.226***	0.0309***
	−0.00182	−0.00525	−0.00211
Water volume (log)	0.467***	0.508***	0.298***
	−0.00204	−0.00239	−0.004
Fixed effects	Well	Well	Well
No. of obs.	150,300	100,563	49,737
R^2	0.277	0.36	0.112
No. of wells	3,006	2,429	1,328

Notes: Dependent variable is the natural log of revenue. Triple asterisks (***) indicate significance at the 1% level. Standard errors, clustered at the well, are indicated in parenthesis. We estimate the model using all well-year observations, then separately for well-year observations with saturated thickness above and below 100 feet. Data used for estimation are as modeled in Hrozencik et al. (2017).

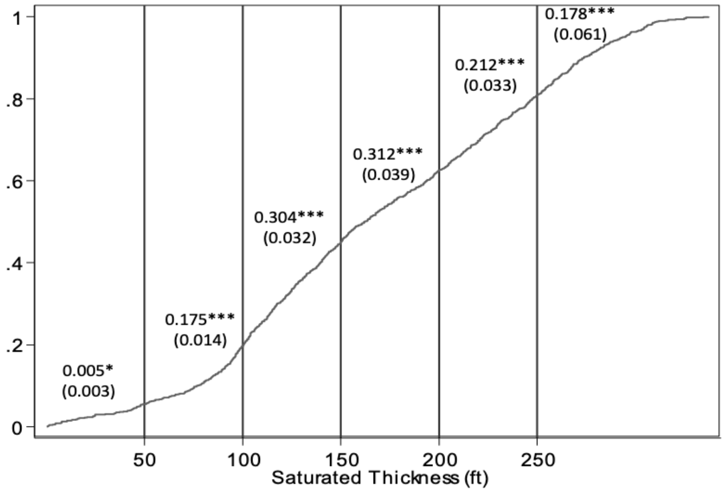

Figure 3. Production-Saturated Thickness Elasticity by Initial Saturated Thickness Bin

Notes: Single and triple asterisks (*, ***) indicate significance at the 10% and 1% level. Standard errors, clustered at the well, are indicated in parenthesis. Production response to saturated thickness differs by saturated thickness level.

that producers must begin making adjustments to irrigation management to account for lower capacity. Adjustments include planting fewer acres, changing crops, and preseason watering. These adjustments likely cause a relatively fast decrease in revenues associated with a given volume of water applied.

Recall that when $\eta = 0.3$, unilateral optimization increases returns to pumping by 1.8% for well 2, while coordination increases the NPV of rents by an average of 7% across the three wells. This result suggests that coordinating water conservation efforts can substantially increase value beyond a unilateral optimization effort, though the gains remain moderate. It may also be the case that the higher gains to unilateral management incentivize more producers to make intertemporal tradeoffs when making irrigation decisions when saturated thickness falls within ranges with higher elasticities. With saturated thickness less than 100 feet or more than 200 feet, the elasticity begins to fall, leading to smaller gains to management.

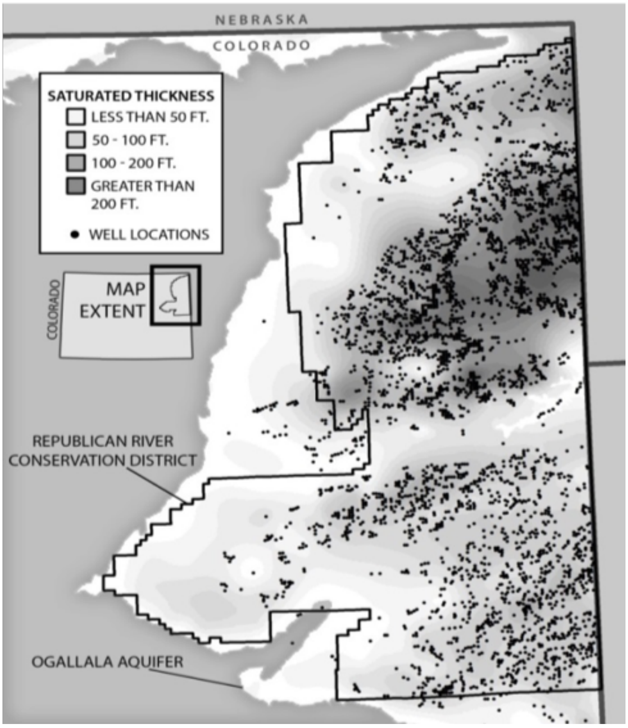

Figure 4. Well Locations and Saturated Thickness in Colorado's Republican River Basin

Discussion and Conclusion

The numerical and empirical results presented here demonstrate a critical connection between the production-saturated thickness elasticity, η, and the gains to dynamic and coordinated groundwater management across time and space. Specifically, as elasticity increases, the external and private future costs associated with pumping at a given well also grow. As a result, both gains to unilateral dynamic decision making and gains to coordination increase with η.

In practice, it appears that η is quite inelastic on average (<0.1) in our study area, but there are ranges of saturated thickness where η exceeds 0.3. This suggests that there may be subregions within the Republican River Basin that would benefit more substantially from coordinated groundwater management efforts. Regions of high (in the north) and low (in the south) saturated thickness likely have relatively low average production elasticities (Figure 4). In these regions, coordinated management has small returns and the incentive to unilaterally optimize is also small. Between these extremes, in regions of saturated thickness in the 100–200 foot range, coordinated management could produce meaningful gains in the present value of rents earned from the scarce water resource. The highest gains are not in the regions with the least water but instead can occur in regions where current stocks are currently at healthy levels but may soon experience low levels.

The model presented here abstracts away from some important features of groundwater use in practice. First, it focuses only on three wells and assumes that the connected portion of the aquifer covers just the three cells in which the wells are located. In practice, many wells could be connected hydrologically in complex ways that increase or decrease the gains from conservation.

Our modeling efforts do not account for the potential for converting from irrigated to dryland production. This assumption tends to increase the gains to groundwater management since it increases the economic cost associated with declines in the productivity of irrigated land (Merrill and Guilfoos, 2018), which may be more profitable in dryland production. Our modeling also holds the distance between wells constant. As the distance between wells increases, however, the external effects of pumping decrease, creating greater incentives for an individual to optimize unilaterally but reducing the gains from coordination across wells. We also do not account for the possibility that well owners frequently operate more than one well and occasionally operate many nearby wells. In these cases, our model clearly shows the incentives that an individual well owner has to consider the dynamic linkages associated with groundwater use across multiple wells. We leave it to future work to evaluate specific areas where well spacing is such that dynamic behavior may be particularly attractive for an individual well owner and how ownership of multiple wells varies across the study area. Also, elasticity estimates provided here rely on modeled production data. Future work should build on this by using observational data on saturated thickness, well capacity, and agricultural production outcomes.

Importantly, the gains to management here result from higher water levels over time. This leads to higher well capacity and lower pumping costs, holding all else equal. In practice, water use may change (e.g., from agricultural to municipal), or other parameters of the model may change over time. For example, as water levels fall, hydraulic conductivity may change, resulting in different gains to management. Additionally, the gains to management for a given level of saturated thickness could vary across space for different rates of hydraulic conductivity.

Another promising area for future research concerns the separate identification of the pumping cost and production externalities described in the introduction. Our modeling efforts allow us to identify how profits change as a function of the elasticity between saturated thickness and production. This outcome, however, reflects the combined impact of productivity changes and changes in pumping costs. As η approaches 0, this reduces the production externality and begins to isolate the pumping cost externality. Future work comparing the relative magnitudes of these separate external costs would represent a valuable contribution to the literature.

Despite its simplifications, the model presented here highlights the relationship between production externalities and the gains to management in groundwater systems. Our empirical results suggest that the response of production and revenue to saturated thickness is quite inelastic on average but that there exist saturated thickness ranges within which the response becomes more elastic. Future research should investigate whether this result holds in other arid regions of the world. For example, in eastern Colorado the ability to produce dryland crops may mitigate some of the negative financial impact of low well capacity, but this may not be an option in drier regions of the world. The importance of the production-saturated thickness elasticity in influencing the economic gains to unilateral and coordinated groundwater management suggests that targeting conservation in areas with high production responses to decreases in saturated thickness can result in the largest increase in value generated from scarce groundwater resources.

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Online Supplement A: Model Solution Paths for Parameterized Elasticity Value

In this Online Supplement (OS), we provide an example of model solution paths, assuming a production-saturated thickness elasticity of 0.3, reflecting the empirical estimate of the elasticity when saturated thickness falls between 100 and 200 feet. Figure S1 shows the quantity of water used under the three management scenarios described in the theoretical model. At all three wells, coordination results in much less water used across the planning horizon of 100 years. It is not until 75 years in the future that farms begin to use more water under the socially optimal trajectory than under myopic behavior.

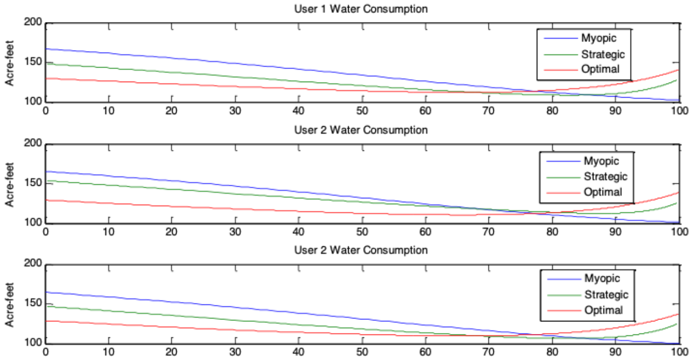

Figure S1. Comparison of Water Use at Three Wells Under Alternative Groundwater Use Scenarios

Although less water is used in early periods under coordination, higher levels of saturated thickness mean that profits do not fall by as much over time. Figure S2 demonstrates that profits with management exceed myopic profits after less than 20 years. While Well 2 acting alone has very little effect on water use by Wells 1 and 3, Well 2 does generate a benefit that spills over into Wells 1 and 3. This benefit does not become large until several decades have passed. Nevertheless, this illustrates the spillover effect that was seen under higher elasticities in Table 3.

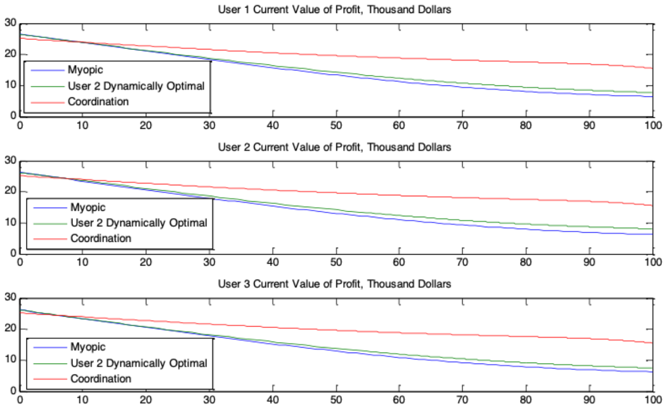

Figure S2. Comparison of Profits at Three Wells under Alternative Groundwater Use Scenarios

Online Supplement B: Impact of Initial Saturated Thickness on Gains to Management

In order to explore the importance of initial saturated thickness for gains to management, holding the production-saturated thickness elasticity fixed, we vary the initial saturated thickness levels from 80% to 120% of base values. Table S1 demonstrates that as initial groundwater availability falls, the gains to both unilateral and social optimization increase. For this exercise, we assume $\eta = 0.3$ but the qualitative result is similar for all elasticity values presented in Tables 2 and 3 of the paper. Since gains to unilateral management also rise as saturated thickness falls, we may expect more producers to behave dynamically as groundwater supplies are reduced even if η remains constant. In practice, both η and initial saturated thickness impact the gains to management. Since a higher η and lower initial saturated thickness have the same qualitative effect, further reductions in saturated thickness may magnify individual returns to management.

Table S1. The Impact of Initial Saturated Thickness on Gains to Groundwater Management Holding Elasticity Parameter Fixed

Initial Saturated Thickness	Well 2 Unilateral Optimization % Increase			Social Optimization % Increase		
(% of Base)	Well 1	Well 2	Well 3	Well 1	Well 2	Well 3
80%	2.03	2.76	1.98	10.75	10.48	10.27
85%	1.82	2.46	1.78	9.71	9.48	9.28
90%	1.64	2.20	1.61	8.82	8.61	8.44
95%	1.50	1.99	1.46	8.04	7.85	7.70
100%	1.36	1.80	1.33	7.36	7.20	7.06
105%	1.24	1.63	1.21	6.76	6.61	6.49
110%	1.14	1.49	1.11	6.24	6.10	5.99
115%	1.05	1.37	1.03	5.78	5.65	5.55

Notes: Saturated thickness elasticity is assumed equal to 0.3 for this sensitivity exercise.

Online Supplement C: Relating η^S to η

Revenue from irrigated agricultural production is:

(S1)
$$Rev = pf(w_{it})x_{it}^{\eta}.$$

Differentiating w.r.t. x_{it},

(S2)
$$\frac{dRev}{dx_{it}} = \eta pf(w_{it})x_{it}^{\eta-1}.$$

The revenue elasticity w.r.t. x_{it} is then:

(S3)
$$\frac{dRev}{dx_{it}}\frac{x_{it}}{Rev} = \eta pf(w_{it})x_{it}^{\eta-1} * \frac{x_{it}}{pf(w_{it})x_{it}^{\eta}} = \eta.$$

In equation 19, η^s is $\frac{dln(Rev)}{dln(x_{it})}$, which is $\frac{dRev}{dx_{it}}\frac{x_{it}}{Rev}$. Therefore, they are both equal to the revenue-saturated thickness elasticity.

Between the theoretical model and empirical specification, there is a difference in the functional form for $f(w_{it})$.

In the theoretical model, $f(w_{it}) = a_i w_{it} - \frac{1}{2}b_i w_{it}^2$. To estimate a constant elasticity, we assume C-D production in equation (19) such that

(S4)
$$Rev = p\alpha x^{\eta} w^{\beta}\varepsilon.$$

Therefore, $f(w_{it}) = \alpha w_{it}^{\beta}$. Both production functions are increasing in the range of water considered here and at a decreasing rate.

For the current analysis, the empirical objective was to condition on water availability to estimate the elasticity of revenue w.r.t. saturated thickness. Future work should explore the sensitivity of management gains to functional form. In addition, better empirical exploration of the relationship between water, saturated thickness, well capacity, and revenue could help to further elucidate how producer decisions and the returns to management depend on these parameters.