BEHAVIOR IN A SPATIALLY EXPLICIT GROUNDWATER RESOURCE: EVIDENCE FROM THE LAB

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This research uses laboratory experiments to examine how hydrogeologic properties of groundwater models influence decision making. The results reveal that pumping rates are highest when the underlying model is such that the future costs of groundwater use are broadcast evenly to all users, as a majority of participants behave myopically. There is less myopic behavior when the groundwater dynamics are governed by spatially explicit models, where the private cost of groundwater use is high relative to external costs. These results suggest that models used to simulate common-pool resource dynamics play an important role in determining both economic predictions and behavioral outcomes.

Key words: common-pool resources, groundwater, laboratory experiment, resource dynamics.

JEL codes: Q25, C91, C61.

Groundwater is the primary source of drinking water for more than half of the world's population and accounts for at least one quarter of all water withdrawals. As climate change alters the quantity and increases the variability of surface water flows, the stress on groundwater resources is likely to increase in many areas. This research examines the feedback between human decision making and dynamic groundwater systems through a combination of experimental economic techniques and simple hydrogeologic models.

Most economic research related to the use of groundwater resources has focused on optimization models that use theory to compare socially optimal and myopic[1] outcomes using simplistic groundwater models that ignore the spatial effects of groundwater pumping (e.g., Feinerman and Knapp 1983; Gisser and Sanchez 1980; Knapp and Olson 1995; see Koundouri 2004 for a summary). Brozovic, Sunding, and Zilberman (2010) incorporated spatially explicit groundwater models but continued to focus on predicted differences between myopic and optimal pumping behavior. The laboratory-based economics experiments that we report in this paper advance the groundwater literature by examining how differences in hydrogeologic models influence both predicted pumping rates and the actual behavior of resource users. To this end, we predict that more realistic spatially explicit groundwater models, in which groundwater resources take on more attributes of a private resource, will lead to less myopic behavior and higher observed social efficiency.

The experimental results confirm that differences in hydrogeologic models across treatments lead to significant differences in pumping rates, as predicted by theory, and to differences in the behavioral strategies used by individual participants in the experiment. In cases where the hydrogeologic model induces dynamics such that the future costs of groundwater use are evenly shared by all users, more than half of the participants in the experiment can be categorized as using the resource myopically. In the spatially explicit models, where the private costs of using groundwater increase relative to the external costs, participants are less likely to behave myopically. Both the observed pumping rates and the frequency of myopic behavior lead to significant variation

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[1] A number of authors refer to myopic decision making in a groundwater CPR as "competitive" behavior (e.g., Feinerman and Knapp 1983; Gisser and Sanchez 1980).

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in realized social efficiency outcomes across treatments.

This research complements a growing body of research in experimental economics that has investigated individual decision making with respect to *common-pool resources* (CPRs). The laboratory sessions extend the experimental CPR research by incorporating more realistic resource dynamics into experiments that introduce differential private and external costs associated with resource use. In this context, laboratory economics experiments are essential for understanding how differences in hydrogeologic models influence behavioral strategies. While observation of the properties of real-world groundwater resources is feasible, the investigation of behavioral strategies over time would require direct observation of firm-level pumping rates and the benefits and costs of this groundwater use. Collection of naturally occurring data of this sort is much less feasible.

The remainder of the paper is organized as follows. We present a review of the economics literature relevant to experiments on groundwater use, then provide a description of the theoretical predictions related to the intensity of groundwater resource use. We next describe the experimental protocol used to study individual behavior and analyze the results from the experimental sessions. Finally, we provide some concluding thoughts.

Relevant Literature

Beginning with the pioneering research by Gardner, Ostrom, and Walker (e.g., Gardner, Ostrom, and Walker 1990; Ostrom, Walker, and Gardner 1992; Walker, Gardner, and Ostrom 1990), challenges associated with CPR utilization have been examined extensively using a diverse array of laboratory experiments. The majority of these studies focus on static CPR problems in which the external cost of resource use does not extend across periods. In addition, most of the experiments implement scenarios in which the use of the CPR by one participant has an equally negative impact on all other participants and evaluate different types of institutions designed to ameliorate inefficiencies. Our experimental research builds on this work by implementing dynamic CPR scenarios as well as cases in which the cost of CPR use is spatially variable across participants.

While most CPR experiments rely on a static setting, a few notable studies use a dynamic framework. Mason and Phillips (1997), for example, evaluate the efficiency of CPR outcomes in both static and dynamic experimental treatments that vary the size of the group making appropriations. The treatments explore the tradeoffs associated with greater cooperation in small groups, which leads to both greater resource conservation (which increases efficiency) and prices that exceed competitive levels in the output market (which reduces efficiency). Research by Herr, Gardner, and Walker (1997) also evaluates CPR use in both static and dynamic settings and finds increased inefficiencies in the dynamic setting relative to the static one due to myopic behavior in the dynamic environment. Experiments by Moxnes (1998a, 1998b) explore the ability of participants to manage dynamic resources over which they have exclusive property rights. He finds that misperception of dynamic feedback can lead to overexploitation even when resources are not open access.

The experimental study most relevant to this research is by Gardner, Moore, and Walker (1997), which evaluates the effects of three types of institutional arrangements on groundwater use in a dynamic "bathtub"(or single-cell) model of the resource. The authors find that the behavior of experiment participants is significantly less efficient than anticipated by either optimal or subgame perfect predictions and that a system that allocates water use based on a quota system has the best potential to increase welfare. Although this is an important exploration into the relationship between institutions and the efficiency of groundwater use, the simplified dynamics of the groundwater resource, the known terminal period, and the lack of myopic predictions make it difficult to generalize the authors' findings.

More recent experimental studies evaluate appropriation behavior when a CPR is transferred across generations of users (Fischer, Irlenbusch, and Sadrieh 2004), when the benefits of resource use are heterogeneous across players (Margreiter, Sutter, and Dittrich 2005), when the informational feedback to players is a treatment variable (Apesteguia 2006), and when participants use the proceeds from CPR use to contribute to a public good (Solstad and Brekke 2011). Several recent experiments also implement scenarios in which resource use has a spatially specific effect on future outcomes. Schnier (2009) implements static CPR treatments that vary the direction of the externality associated with appropriations and finds that social efficiency is greater in cases where externalities are unidirectional compared with cases where they are bidirectional. The results suggest that a full understanding of the natural links between players is necessary to effectively predict CPR outcomes. Janssen and Ostrom (2008) implement a scenario involving a spatially explicit, dynamic CPR where participants make real-time appropriation decisions. The researchers show how different types of institutions emerge to manage a dynamic CPR through communication among participants. Janssen, Anderies, and Cardenas (2011) investigate a situation in which individual users have differential impacts on the future viability of a resource. They show that successful management of the CPR depends on the users that have the greatest impact on the group exercising restraint in the intensity of their resource use.

As with research related to behavior in CPR experiments, the number of theoretical and numerical studies in the economics literature that specifically evaluate optimal management of groundwater resources is extensive. Building on early research by Gisser and Sanchez (1980), most of these economic studies evaluate the relationship between optimal and myopic use (e.g., Burness and Brill 2001; Feinerman and Knapp 1983; Kim et al. 1989; Knapp and Olson 1995; Nieswiadomy 1985). Despite identification of several types of externalities associated with groundwater use (Provencher and Burt 1993), these studies typically find that the divergence between myopic and optimal behavior is relatively small in terms of social efficiency and that the costs associated with implementing institutional changes may outweigh any realized benefits.

Although many studies claim relatively small efficiency gains from optimal management, there are at least three reasons to assess the broader applicability of these results. First, the studies typically focus exclusively on pumping decisions for established wells and ignore decisions on well spacing, installation, and technology. Incorporating entry and positioning of new wells leads to greater potential for suboptimal outcomes. Second, previous studies have utilized primarily bathtub models to describe aquifer dynamics, where pumping decisions by one firm have an identical impact on all other CPR users. Although this simplification facilitates optimal control modeling, it obfuscates the realities of groundwater dynamics—realities that generate spatially explicit effects on users based on their physical proximity to the site where the groundwater pumping occurs. Only recently have economists (Brozovic, Sunding, and Zilberman 2010) incorporated more realistic, spatially explicit groundwater models to assess how the externalities of groundwater use vary over space depending on specific hydrogeologic properties. Finally, given that obtaining access to data on actual pumping decisions is difficult, the overwhelming majority of past economic studies on the efficiency of groundwater use have relied on theoretical predictions of behavior. By ignoring the possibility that user behavior diverges from theoretical predictions in the face of (*a*) specific groundwater dynamics, (*b*) the timing of pumping, and (*c*) user experience, these models may mischaracterize the nature of predicted resource use.

Our experiments build on previous analyses of dynamic CPRs by incorporating more realistic, spatially explicit dynamic groundwater models that are similar to those analyzed theoretically by Brozovic, Sunding, and Zilberman (2010). In a divergence from previous work, we show that differences in the hydrogeologic models introduce differences not only in groundwater dynamics, but also in the nature of resource use. In cases where the private costs of groundwater use increase relative to external costs, myopic behavior tends to decrease.

Theory

We consider a theoretical model with n users sharing a common groundwater resource. As a reference for the reader, table 1 defines the variables and parameters used in the models presented.

Groundwater users choose pumping rates over an indefinite number of periods. In each period, the benefits to users are a concave function of the quantity of groundwater pumped, and the costs are a function of the quantity of pumping and the distance over which groundwater must be pumped (depth of the water table below the land surface). Specifically, the benefits associated with pumping by user i in period t are $\alpha q_{it} - \frac{\gamma}{2} q_{it}^2$ and the costs are $\phi d_i q_{it}$.[2]

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[2] The quadratic benefit and linear cost functions are chosen primarily for consistency with past groundwater research in the economics literature (e.g., Feinerman and Knapp 1983; Gardner, Moore, and Walker 1997; Rubio and Casino 2001). Although it is unlikely that a farmer would ever choose to irrigate beyond

Table 1. Variable and Parameter Definitions

Symbol	Label	Value	Units
Variables			
q.	Quantity of groundwater pumped	–	100,000 ft^3
d.	Depth to groundwater	–	ft
λ	Costate variable	–	\$
Parameters			
α.	Intercept of demand curve	240	\$
γ.	Slope of demand curve	4	\$
ϕ.	Cost parameter	1	\$
n.	Number of users	6	–
r.	Recharge rate	84	100,000 ft^3
A.	Area of aquifer	15,000	acres
S.	Storativity	0.001 and 0.004	–
T	Transmissivity	250,000 and Infinite	ft^2/yr
d_0.	Initial depth to water	100	ft
ρ.	Discount factor	0.85	–
δ.	Discount rate	0.1765	–

We consider two models of the underlying groundwater dynamics, which are conveyed through changes in the depth-to-water variable, d_t, over time. The first model, which is referred to as a "bathtub" model, assumes that pumping by one user increases the depth to water equally for all users in the next period. The second model we present captures spatially explicit effects on the depth-to-water variable over time. Both models assume a fixed number of users.

Bathtub Model

For the bathtub model we begin by setting up the social planner's problem and then explore behavior under both rational and myopic decision making. The social planner's objective is to maximize the sum of the discounted profits for all n users:

$$(1)\qquad Max \sum_{i=1}^{n}\left(\sum_{t=0}^{\infty}\rho^{t}(\alpha q_{it}-\frac{\gamma}{2}q_{it}^{2}-\phi d_{t}q_{it})\right)$$

$$s.t.\ d_{t+1}=d_{t}+\frac{\sum_{i=1}^{n}q_{it}-r}{AS}.$$

The difference function in the constraint represents the dynamics of the depth to groundwater in the bathtub model. In each period, the depth to water is simply a function of the depth to water in the previous period, plus the difference between the total quantity of water pumped by the n users in the previous period and the quantity of recharge, scaled by the area times the storativity of the aquifer.

Socially optimal individual decision making requires pumping decisions that correspond to the first-order conditions of the social planner's problem, which are provided in the supplementary appendix online. Explicitly solving for the optimal pumping decision in any given time period is challenging, since calculating the user cost requires knowledge of future optimal pumping decisions. To calculate the optimal decision in each period, we implement a simple approximation following Feinerman and Knapp (1983). The approximation assumes that the costate variable, λ is stationary, which implicitly assumes that future pumping is equal to current pumping.[3] With $\lambda_t=\lambda_{t+1}=\lambda$ the first-order conditions yield $\lambda=\frac{n\phi q_t}{\rho-1}$ After substitution, solving for q_t yields the optimal quantity of pumping in period k given by

$$(2)\qquad q_{k}^{O}=\frac{\alpha-\phi d_{k}}{\gamma-\frac{n\phi}{\delta AS}}.$$

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the point of positive marginal benefits, the downward sloping portion of the benefit function corresponds to excessive use of the groundwater resource leading to lower crop yields in a given period.

[3] An alternative approximation assumes that current pumping is equal to the steady-state optimum. Feinerman and Knapp (1983) show that this assumption tends to underestimate user cost, while the assumption that we utilize tends to overestimate user cost. While actual pumping rates in the experiment vary over the course of the trial, the simplifying assumption that future pumping rates equal current pumping rates generates predictions that closely approximate the numerically derived optimal trajectory. In addition, the social efficiency difference between the predicted optimal and true optimal trajectory is less than 1% in the bathtub case.

The optimal quantity of pumping in each period can therefore be solved as a function of the current depth to water and a set of parameters.

Users that behave rationally rather than optimally realize that groundwater pumping in time t increases their own costs in the future, but they ignore the costs that their pumping imposes on other users. The first-order conditions that guide behavior by the rational user are nearly identical to those in the social planner's problem, with the exception that the marginal cost of increased depth to water in this case is not multiplied by n. The approximation described for optimal decision making can also be applied to the rational user case. The λ term is simply replaced by the discounted private cost associated with a marginal increase in current-period pumping. Solving for the quantity pumped by a user following a rational strategy yields

$$(3) \qquad q_k^R = \frac{\alpha - \phi d_k}{\gamma - \frac{\phi}{\delta AS}}.$$

Given that the discounted external cost is strictly greater than the discounted private cost (by a factor of n), the optimal pumping decision will be lower than the rational pumping decision for all values of the depth-to-water variable.

Behavior of myopic users diverges from that of optimal and rational users because myopic users ignore the future private and external costs associated with pumping in the current period. Under myopic decision making, users simply pump the quantity of water that equates their marginal benefit and cost in that time period. Solving for q yields the explicit myopic pumping decision:

$$(4) \qquad q_k^M = \frac{\alpha - \phi d_k}{\gamma}.$$

Comparison of equations (2) and (4) reveals that myopic decision makers ignore the marginal social cost associated with each unit pumped that is given in the second term in the denominator of equation (2).

Spatially Explicit Dynamics

Most economic studies that incorporate groundwater dynamics rely on a simple bathtub model such as the one outlined above. In reality, water pumped at one point does not equally affect the subsequent depth to water for other resource users, as is assumed in a bathtub model. Instead, the specific hydrogeologic characteristics of the aquifer determine how pumping influences the depth to water at neighboring points in future periods. More specifically, the effect of pumping on the depth to water at nearby wells is at least a function of the transmissivity and storativity of the aquifer, time, and the distance between wells.

Spatially explicit models based on aquifer physics can be used to simulate the spatial and temporal response of hydraulic head (or depth to water) in response to pumping. Numerical groundwater models can incorporate complex aquifer characteristics of real aquifer systems. In this study, however, we consider a simple, homogeneous, rectangular, confined aquifer bounded on all sides so that we can compare behavior under a spatially explicit model with behavior in the bathtub model. This enables us to use an analytical solution of the groundwater response function (Theis 1935) that allows the depth to water to vary within the aquifer in response to changing pumping conditions at explicit locations within the model domain.

To generate a spatially explicit model that is directly comparable with the bathtub model, we assume that the aquifer is fully bounded. The boundaries are imposed by including a series of "image" wells that replicate the pumping decisions of users accessing the aquifer (e.g., Ferris et al. 1962). Theoretically, with an aquifer that is bounded on all four sides, one would need to include an infinite number of image wells to accurately estimate changes in depth to water over time. In this study, we found that including eight image wells per real well provided satisfactory results[4] and allowed calculations to be made in a reasonable amount of time (<30 sec) for use in the experiments.[5]

The modeling for the spatially explicit case follows Brozovic, Sunding, and Zilberman (2010), who compare myopic and optimal pumping in a dynamic spatial model. The benefits of pumping groundwater in a given period are identical to those described for the bathtub model; however, the depth-to-water variable has a different

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[4] To ensure that the accuracy of the depth calculation is never off by more than 5%, we multiply the well function by a small correction factor that is increasing in the number of time periods after pumping occurs.

[5] In this model, pumping from the image wells is treated as identical to withdrawals from the wells inside the boundaries of the aquifer, but the distance is greater for the image wells, implying that the well function is smaller.

functional form. The social planner's problem in the spatially explicit case is given by

$$(5)\quad Max \sum_{i=1}^{n} \left(\sum_{t=0}^{\infty} \rho^{t} (\alpha q_{it} - \frac{\gamma}{2} q_{it}^{2} - \phi d_{t} q_{it}) \right)$$

$$s.t.\ d_{it+1} = \sum_{k=1}^{t} \sum_{j=1}^{n} \frac{q_{jk} - q_{jk-1}}{4\pi T} \times w(t-k+1, v(i,j)) - \frac{(t+1)r}{AS},$$

where $v(i,j)$ is the radial distance between well i and well j, and $w(t,v) = \int_{(v^2 S/4Tt)}^{\infty} \frac{e^{-z}}{z} dz$ is known as the well function that translates pumping from well j at distance v into a level of drawdown at well i. The last term on the right-hand side of equation (5) accounts for recharge of r units of water into the aquifer in each period, which serves to uniformly reduce the depth to water for all firms, similar to the bathtub case.

The key difference in the spatially explicit model relative to the bathtub model is that the depth-to-water variable is location specific and is a function of both the distance and the sequence of pumping that occurs in all previous periods. Brozovic, Sunding, and Zilberman (2010) show that the impact of pumping at well i on the depth to water at well j is inversely related to the distance between well i and well j. An important corollary is that the drawdown associated with pumping that occurs at any specific well has the greatest impact on the future depth to water at that well. This implies that the future private cost associated with pumping in a spatially explicit model will always be higher than the future private cost calculated using an analogous bathtub model. In other words, the groundwater resource is more "private" in the spatially explicit case because the impact of pumping is greatest at the location where the pumping occurs. Behaviorally, this implies that myopic behavior is less likely with a spatially explicit model, since users have a greater incentive to take into account the effects that pumping has on their own future outcomes.

The magnitude of the total *external* cost associated with pumping an additional unit in the spatially explicit model is a function of the spacing of the wells in the aquifer. This implies that predicted social efficiency relative to the bathtub model is also a function of well spacing. In instances where wells are tightly clustered relative to the areal extent of the aquifer, the total external cost can exceed that of the bathtub case. Observed social efficiency is ultimately determined by the actual behavior of groundwater users in the two models, which we explore through the use of the controlled experiments described in this paper.

A second important difference between the spatially explicit model and the bathtub model is the "memory" of the system. The impact of groundwater pumping at well i on the subsequent depth to water at well j depends critically on the time interval as well as the distance between wells i and j. Pumping at well i in time period t may have very little impact on well j in period $t+1$ but may have a larger impact in later periods.

The first-order conditions to the social planner's problem in the spatially explicit case, provided in the supplementary appendix online, yield the following social optimality condition in any given period

$$(6)\quad k\alpha - \gamma q_{ik} - \phi d_{ik} = - \sum_{t=0}^{\infty} \sum_{i=1}^{n} \frac{\rho^{t+1} \phi q_{it+k+1}}{4\pi T} \times [w(t+1, v(i,j)) - w(t, v(i,j))].$$

The optimality condition simply equates the marginal net benefits of pumping for an individual user in a given round to the sum of the marginal social costs across all future periods associated with pumping an additional unit.[6] The impact across all future time periods of a marginal increase in pumping by user i on the depth to water faced by user j is given by the expression $\sum_{t=0}^{\infty} \frac{[w(t+1,v(i,j)) - w(t,v(i,j))]}{4\pi T}$. Multiplying this expression prior to summation by the discount factor times the marginal increase in the cost of pumping associated with a marginal change in depth to water provides the marginal cost imposed on user j associated with an additional unit of pumping by user i. The marginal social cost is then derived through summation of the marginal costs imposed on all n users.

Using the simplifying assumption, similar to that employed in the bathtub case, that future pumping is equal to current pumping allows for the derivation of the optimal trajectory of pumping in the spatially explicit model. This assumption involves replacing q_{it+k+1} in equation (6) with q_{ik} and bringing it outside of

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[6] In both the optimal and the rational strategy cases, we define $v(i,i) = 1$ to obtain a solution. To account for the fact that the aquifer is bounded, the summation also includes the image wells.

the summation. The optimal quantity of pumping by user i in period k is then derived as,

$$(7)\qquad q_{ik}^{O} = \frac{\alpha - \phi d_{ik}}{\gamma - \sum_{t=0}^{\infty}\sum_{i=1}^{n} \frac{\rho^{t+1}\phi}{4\pi T} \times [w(t+1, v(i,j)) - w(t, v(i,j))]}.$$

The second term in the denominator of the right-hand side of equation (7) is analogous to the term provided in the same location of the equation defining optimal pumping in the bathtub model (equation (2)). This expression represents the discounted marginal social cost imposed by pumping an additional unit in the current period. A convenient feature of the optimal pumping equation is that it is again only a function of the current depth to water and a set of parameters (which includes the spatial configuration of users).

The social optimality condition can be adjusted to generate the rational strategy in which users each equate their marginal benefit of pumping to their discounted marginal *private* cost across all rounds. Again using the simplifying assumption that future pumping rates are equal to current pumping, the decision-making rule for a rational user in period k in the spatially explicit model is given by

$$(8)\qquad q_{ik}^{R} = \frac{\alpha - \phi d_{ik}}{\gamma - \sum_{t=0}^{\infty} \frac{\rho^{t+1}\phi}{4\pi T} \times [w(t+1, v(i,i)) - w(t, v(i,i))]}.$$

The myopic decision predicted in the spatially explicit case is identical to that derived for the bathtub case and is provided in equation (4). Since myopic decision makers ignore all future costs, the dynamics of the system do not enter into their decision-making criteria.

The influence of the transmissivity, T, and storativity, S, parameters on predicted behavior in the spatially explicit model deserves specific attention given that these parameters help to define the experimental design, to be described next. The transmissivity value essentially serves to determine the magnitude (how much) and the timing (when) with which pumping at one well influences the future depth to water at other wells. Pumping at well i has the biggest effect on the depth to water in the next period at well i, and the effect on depth decreases with distance from well i. The resulting effect is known as the "cone of depression" that surrounds a well engaged in pumping groundwater. Higher values of T result in shallower, broader cones of depression. As T approaches infinity, the spatially explicit model converges to the bathtub model. In addition, if pumping at well i stops, the cone of depression becomes broader and shallower over time until the groundwater level is spatially uniform, regardless of the value of T. Thus, spatially explicit effects of pumping in the current period are reduced over time; eventually the amount pumped affects all users equally.

Brozovic, Sunding, and Zilberman (2010) show that the impact of marginal changes in the transmissivity parameter on social costs in steady state is ambiguous, with the result being dependent on the density of wells. In situations where wells are densely clustered, a marginal increase in the transmissivity parameter tends to reduce costs to the group. The intuition is that the effects of pumping at a particular well are transferred more quickly across a larger area, thus reducing the relative impact on locations in close proximity to where the pumping occurs.

Marginal increases in the transmissivity parameter tend to lower the ratio of discounted private costs to external costs; however, this result is also a function of the density of nearby wells (as well as the storativity and the baseline level of transmissivity). Higher transmissivity values act to distribute the effects of pumping across a greater area. Therefore, an increase in transmissivity tends to decrease the effects of pumping near the well where the pumping occurs. This always leads to lower private future costs at the well where pumping occurs and typically leads to higher costs at other wells. If, however, wells are very densely clustered, then increased transmissivity may have a larger aggregate impact on reducing costs for nearby wells relative to the location where the pumping occurs.

The storativity parameter scales the relationship between pumping and its effect on future depth to water. Higher storativity values imply that a greater amount of pumping is required to decrease the depth to water by one unit. This is easy to observe in the bathtub scenario, where $d_{t+1} - d_t = \frac{\sum_{i=1}^{n} q_{it} - r}{AS}$. As the product of A and S increases, a greater level of pumping by the group is required to increase the depth in the next period by one unit. In the spatially explicit case, storativity works in a similar fashion. Higher storativity values reduce the effect of current-period pumping on future changes in the depth to water for all users. Therefore, a marginal increase in storativity implies a decrease in the social cost of groundwater pumping.

Higher storativity values reduce the overall effect of pumping on the future depth to water; however, their effect on the ratio of private to external costs is ambiguous. Whether an increase in the storativity parameter increases or decreases the ratio of private to external costs depends on the density of wells and the transmissivity value. In situations where wells are tightly clustered (or the transmissivity value is relatively high), increases in storativity tend to decrease the ratio of private to external costs. When wells are more evenly spaced (or transmissivity is low), higher storativity values increase the ratio of private to external costs.

Experimental Design

In the experiment, each participant represents one of six groundwater users that share a common groundwater resource. In each round, participants make anonymous individual pumping decisions. In the model that underlies the experiment, each participant operates one well located in the middle of a 2,500-acre plot. The plots of the six participants are arranged in a 2 × 3 lattice pattern. The areal extent of the aquifer is 15,000 acres and exactly matches the land area covered by the six plots. In the experimental sessions, participants are provided with a diagrammatic depiction of the six wells overlaid on the groundwater resource (see figure 1). Following the theoretical framework we have described, net private benefits are a function of the quantity of water that participants choose to pump as well as the depth to water, which evolves over time based on the decisions of the participants. Specification of this dynamic process forms the basis of the four treatment conditions.

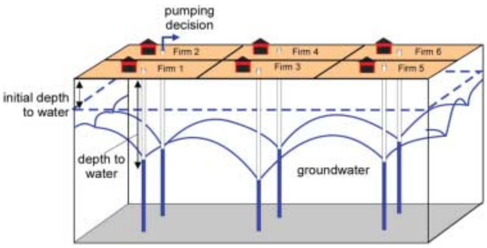

Figure 1. Example of six wells overlying the common groundwater resource in the spatially explicit treatments. A model appropriate to the particular treatment was shown to participants in the instructions.

The treatment parameters are defined in table 2. The first treatment represents a common bathtub model and, as we have noted, is a special case of the spatially explicit model where the transmissivity value, T, is infinite. In the second and third treatments, which we label Spatial 1 and Spatial 2, the depth to water is spatially variable and evolves based on a series of analytical Theis equations in which $T = 250{,}000\ \mathrm{ft}^2/\mathrm{yr}$. In Spatial 1, the storativity value is equivalent to that in the bathtub treatment ($S = 0.001$) while in Spatial 2, storativity is increased to $S = 0.004$. A higher storativity value reduces the drawdown associated with all levels of pumping and in this case increases the ratio of private to external costs. In both of the spatially explicit treatments, the ratio of private to external costs is higher than in the bathtub treatment.

The fourth treatment, labeled the *individual bathtub*, implements a setting in which the future costs of pumping are entirely private. This treatment represents an extreme scenario where there is no interaction between participants—in effect, groundwater becomes a private resource, which allows us to observe participant behavior related to solving the complex dynamic optimization problem. In this fourth treatment, the parameters are identical to the bathtub treatment except that the relevant area of each aquifer is one-sixth of the area used in that treatment.

The parameters that define the aquifer dynamics, namely the transmissivity and storativity values, were chosen so as to represent plausible real-world cases. For example, Brozovic, Sunding, and Zilberman (2010) provide storativity values of between 0.0001 and 0.005 for the Roswell Basin in New Mexico and the Crow Creek Valley in Montana, which bound the storativity values of 0.001 and 0.004 used in the experiments. For these same aquifers, the transmissivity ranges from 8,000 to 50,000 square feet per day, which is somewhat smaller than the 250,000 square feet per day used in the experiments. The size of the model aquifer that we utilize (15,000 acres) is smaller than either the Roswell Basin (790,000 acres) or the Crow Creek Valley (60,000 acres). The smaller aquifer size makes changes in the depth to water in the bathtub case somewhat more responsive to changes in pumping rates. The well density that we utilize of one well per

Table 2. Treatment Conditions

	Label	Storativity	Transmissivity (ft^2/yr)	Aquifer Area (acres)	Private Cost	Social Cost
Treatment 1	Bathtub	0.001	Infinite	15,000	0.87	5.20
Treatment 2	Spatial 1	0.001	250,000	15,000	1.45	5.75
Treatment 3	Spatial 2	0.004	250,000	15,000	0.78	1.76
Treatment 4	Individual Bathtub	0.001	Infinite	2,500	5.20	5.20

2,500 acres is representative of well spacings in a number of western states.[7]

Based on the parameterization used in the experiments, we begin by calculating the discounted future costs in each treatment associated with one participant pumping one additional unit. The final two columns of table 2 show the increase in discounted private and social costs across all future rounds associated with pumping an additional unit in the current period. These costs correspond to the second term in the denominator of equations (2) and (3), respectively, for the bathtub case and of equations (7) and (8) in the spatially explicit case. A discount factor of $\rho = 0.85$ is used in the calculations, which is consistent with the experimental protocol we will describe. The private and external costs in the spatially explicit case are calculated numerically. The costs faced by the third and fourth users are slightly different from those incurred by the other four users in each group, given their location in the model aquifer, but the differences are too small to appreciably influence the costs presented in table 2.

The table reveals that the social cost in Bathtub is equal to the private and social cost in Individual Bathtub, which implies that while the myopic prediction is the same in the two treatments, the rational prediction in Individual Bathtub is equal to the optimal prediction in Bathtub. In the spatially explicit treatments, a higher percentage of the social cost is private compared with Bathtub. In addition, although both the private and social costs are higher in the Spatial 1 than in the Spatial 2 treatment, the ratio of private to social costs is higher in Spatial 2. Thus, altering the storativity of the model aquifer across treatments allows us to test the effect of increasing the magnitude of the private costs of pumping, which should result in lower pumping rates, and of decreasing the ratio of private costs versus external costs of pumping, which should increase myopic behavior.

The predicted myopic, rational, and optimal trajectories for both pumping rates and depth to water are presented in figure 2 for the first seven periods. Predictions for the rational and optimal paths are calculated using the private and social costs associated with pumping in each period.

Predictions

The objective of the experimental treatments is to measure the extent to which differences in the hydrogeologic model used to represent the groundwater resource influence observed pumping rates, behavioral strategies, and social efficiency outcomes. To that end, we provide three primary predictions to be tested in the experimental sessions. For each prediction, we then specify several subpredictions and provide explanations for each.

Prediction 1: Differences in the hydrogeologic model across treatments lead to differences in pumping rates.

> P1a: Pumping rates are higher in Bathtub than in Spatial 1 and Individual Bathtub.
>
> P1b: Pumping rates are higher in Spatial 2 than in Spatial 1.

In formulating prediction 1 and related subpredictions, we focus on differences in predicted myopic and rational pumping rates. A visual depiction of predicted pumping rates under each strategy is provided in figure 2, while numerical predictions for the myopic and rational strategies are provided in table 3. The numerical predictions are made by regressing the predicted pumping rates in each round on treatment-specific indicator variables as well as

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[7] Dividing the agricultural acreage by the number of active wells reported in the 2008 Farm and Ranch Irrigation Survey reveals densities of one well per 1,392 acres in Arizona, 3,039 acres in Nevada, and 1,541 acres in New Mexico. Well densities are somewhat higher in California, Nebraska, and Texas, which average one well per 250 acres, and somewhat lower in Montana, Wyoming, and Utah, at an average of one well per 20,000 acres (USDA 2008).

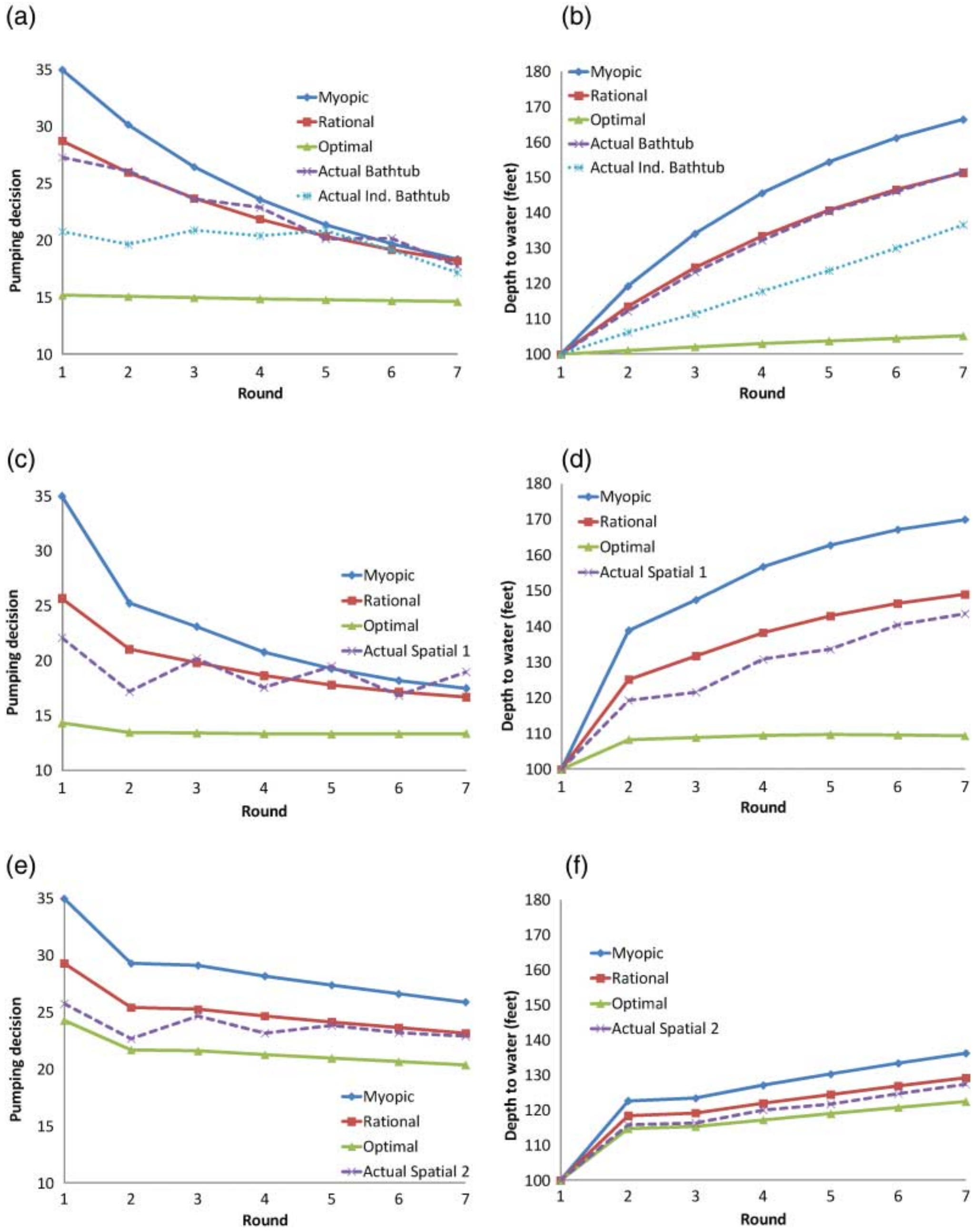

Figure 2. Predicted and actual trajectory of depth to water and pumping decisions by treatment: (a) and (b) Bathtub and Individul Bathtub; (c) and (d) Spatial 1; (e) and (f) Spatial 2[8]

on the treatment indicators interacted with the round number.

Pumping rates are predicted to be higher in Bathtub than in Spatial 1 under both the myopic and rational strategies. In addition, predicted pumping rates are higher in Bathtub relative to Individual Bathtub under the rational strategy, although the myopic prediction is the same. Predicted pumping rates are also higher for Spatial 2 relative to Spatial 1

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[8] Recall that the behavioral prediction is a function of current depth. Therefore, in looking at the pumping results, it can sometimes appear as if users are pumping at higher than the myopic rate in a particular round; however, the prediction is based on a scenario where users have been utilizing myopic behavior for the entire trial and have therefore increased the depth to water substantially.

Table 3. Analysis of Pumping Rates by Treatment

	Actual		Predicted			
	Pumping Rate	Round	Myopic Pumping	Rational Pumping	Myopic Round	Rational Round
Bathtub	28.52^{***}	-1.42^{***}	$34.4^{\dagger}$	28.8	$-2.29^{\dagger}$	−1.50
	(1.63)	(0.16)				
Spatial 1	20.84^{***}	-0.51^{***}	$31.1^{\dagger}$	$24.1^{\dagger}$	$-2.00^{\dagger}$	$-1.08^{\dagger}$
	(1.57)	(0.14)				
Spatial 2	25.00^{***}	-0.31^{*}	$33.2^{\dagger}$	$28.1^{\dagger}$	$-1.07^{\dagger}$	$-0.72^{\dagger}$
	(1.47)	(0.17)				
Individual Bathtub	20.07^{***}	−0.07	$34.4^{\dagger}$	$15.3^{\dagger}$	$-2.20^{\dagger}$	−0.09
	(1.73)	(0.29)				
N	2688					
R^2	0.877					
$F_{8,95}$	530.33					

Note: The values in the two "Actual" columns are parameters estimated by regressing the observed pumping rate in a particular round on treatment indicator variables and treatment indicators interacted with the round number. Robust SEs clustered at the participant level are in parentheses.

The values in the four "Predicted" columns are derived by regressing the predicted pumping rates under both myopic and rational decision making on a constant and the round number.

$^{***}, ^{**}, ^{*}$indicate coefficients that are significantly different from zero at the 0.01, 0.05, and 0.10 levels of confidence, respectively.

†indicates where the actual pumping rate or round coefficient is significantly different from the predicted value at the 0.05 level of confidence.

under both myopic and rational behavior. The higher storativity value in Spatial 2 means that groundwater pumping has a smaller effect on changes in depth to water in future periods. The smaller depth-to-water value translates into lower costs and higher net benefits of pumping groundwater in Spatial 2 relative to Spatial 1.

Prediction 2: Differences in the hydrogeologic model across treatments lead to differences in the pumping strategy types used by participants.

> P2a: Bathtub has the highest frequency of myopic users.
>
> P2b: The number of myopic users is higher in Spatial 1 compared with Spatial 2.
>
> P2c: Individual Bathtub has the fewest myopic users.

The predictions related to the frequency of myopic behavior are based on the relationship between private and social costs. In treatments where the private costs are high relative to the social costs, we predict less myopic play, since the incentives to consider the future effects of contemporaneous pumping are higher. Subpredictions P2a, P2b, and P2c are based on the fact that in Bathtub, only one-sixth (∼16.7%) of the costs are borne privately, whereas the proportion of private costs rises to >25% and nearly 50% in Spatial 1 and Spatial 2, respectively, and to 100% in Individual Bathtub. Motivations for myopic play are clearly lowest in Individual Bathtub, where all future costs associated with groundwater pumping accrue to the individual doing the pumping.

Prediction 3: Differences in the hydrogeologic model across treatments lead to differences in observed social efficiency.

> P3a: Social efficiency is lowest in Bathtub.
>
> P3b: Social efficiency is higher in Spatial 2 than in Spatial 1.
>
> P3c: Social efficiency is highest in Individual Bathtub.

The social efficiency measure is calculated as the difference between the observed net social benefits from pumping groundwater and the optimal net social benefits from groundwater use. Given that pumping rates and myopic behavior are predicted to be highest in Bathtub, rates of social efficiency should be lower in Bathtub than in the other three treatments. Since the social costs of pumping groundwater are lowest in Spatial 2, we expect that social efficiency will be higher in Spatial 2 relative to Spatial 1. Finally, since there are no external costs associated with groundwater use in Individual Bathtub, we expect the highest rates of social efficiency in that treatment.

Implementation

The experimental sessions were undertaken in spring 2011 at Oberlin College. All decisions were made via networked computers outfitted with a privacy shield, and the experiment was programmed and conducted with the *z*-Tree software (Fischbacher 2007). The subject pool comprised ninety-six undergraduate students recruited from the general student population. Twelve participants took part in each session and there were two sessions conducted per treatment. In each session, participants read a set of written instructions (provided in the supplementary appendix online), answered several comprehension questions, and then listened to a brief oral presentation of the instructions. The instructions provided participants with a groundwater context in which they were asked to make pumping decisions. The instructions were intentionally vague with respect to the exact nature of the underlying groundwater dynamics. This design element was meant to correspond to a typical scenario where the groundwater user does not expertly understand the hydrology of the underlying groundwater system.

In Bathtub, the instructions indicated that "the depth to the groundwater is determined equally by the quantity of water that you and the other five members of your group have pumped in previous rounds. This implies that your pumping decision has an equal impact on determining the depth to water for you and the other five players in your group." In the spatially explicit treatments, the instructions stated that "the depth to the groundwater is determined mostly by the quantity of water that you have pumped in previous rounds. To a lesser extent the depth will be determined by the quantity of water that is pumped by other members of your group." In Individual Bathtub, where there was no interaction among participants, the instructions stated that "the depth to the groundwater is determined by the quantity of water that you have pumped in previous rounds. Your pumping decision has no impact on determining the depth to water for anyone else in the experiment."

After reading and listening to the instructions, participants then completed one practice trial and four actual trials of a single treatment condition. The groups of six were randomly reshuffled after each trial, and the length of each trial was determined by a 15% termination probability (85% continuation probability). In other words, each round was the last round of the trial with a 15% probability, which translated to an expectation of $\frac{1}{0.15} = 6.67$ rounds per trial. To maintain comparability, the number of rounds in each trial was held constant across treatments, though the participants were not aware of the number of rounds *a priori*. Implementing identical trial lengths eliminates variation across treatments that might result from participants facing a very short or long trial early in the session and also facilitates empirical analysis. The actual lengths of the four trials were six, ten, five, and seven rounds, respectively. The stochastic termination rule induces an indefinitely repeated game, which reflects the reality faced by most groundwater users and is an advance over earlier groundwater experiments (Gardner, Moore, and Walker 1997) that used a fixed number of rounds. Implementing multiple trials within a session allowed participants to gain experience with the dynamic environment and researchers to observe any learning effects across trials.

Results

We now highlight the outcomes from the experimental sessions. The presentation of the results is organized by the three primary predictions we have formulated. Prior to directly evaluating the predictions, however, we present and discuss simple graphical depictions that illustrate the evolution of average pumping rates and depth to water over time in each treatment. The average pumping rate and depth to water for the first seven rounds of each treatment (averaged across the four trials) are depicted, along with the myopic, rational, and optimal predictions in figure 2. The graphs illustrate that in each treatment, actual pumping rates decline while depth to water increases over time, with the decline in pumping rates being most pronounced in Bathtub. Average pumping and depth in Bathtub closely track the rational predictions. We explore this result further in the formal analysis of the results. The changes in pumping rates and depth to water vary least in Spatial 2, where the high storativity coefficient reduces the impact of pumping decisions on groundwater levels. The sawtooth pattern of pumping rates in both of the spatially explicit treatments is also noteworthy. An explanation for this pattern is that the effects of an individual player's pumping decision on the depth to water at her own well is most significant in the round immediately following pumping. Therefore, depth to water increases rapidly after the first round, which in turn causes many players to cut back on pumping in the following round. This restraint in the second round allows the depth to water to recover somewhat for the third round, which again induces higher pumping rates in that round, and so on.

Analysis of Pumping Rates

To address the first prediction related to differences in pumping rates across treatments, we estimate an econometric model, with the pumping decision serving as the dependent variable. The independent variables are treatment indicators interacted with the round number. To account for the fact that individual participants make pumping decisions over a series of rounds, the standard errors in the model are clustered at the participant level.[9] Based on the estimation results presented in table 3, we find support for the prediction that pumping rates vary significantly based on the specification of the hydrogeologic model. In addition to exhibiting significant differences in the coefficients of the treatment indicators (F-test of equality, $p = 0.012$), we observe significant differences in the changes in pumping rates across rounds ($p < 0.01$).

Looking at the specific subpredictions, the data support P1a, as the observed pumping rate is approximately 40% higher in Bathtub than in both Spatial 1 and Individual Bathtub ($p < 0.01$ for each). The degradation in pumping rates is also significantly higher in Bathtub, resulting from the fact that the depth to water increases rapidly due to the high initial pumping rates.

The results reported in table 3 also support the prediction that pumping rates are higher in Spatial 2 relative to Spatial 1 ($p = 0.056$). This outcome is attributable primarily to the more limited effect that pumping has on changes in groundwater depth given the higher storativity parameter in Spatial 2. The effect is maintained over time, as the degradation in pumping rates is not significantly different across the two treatments ($p = 0.362$).

Analysis of Myopic Behavior

To evaluate the second primary prediction that differences in the hydrogeologic model influence behavioral strategies, we begin by measuring the prevalence of myopic behavior. A player adopts a myopic strategy by choosing the pumping rate at which the marginal benefit equals the marginal cost in that round. The marginal benefit in the experiment is $240 - 4q_{it}$, while the marginal cost is simply equal to the depth to groundwater, d_{it}. This implies that a myopic player will choose to pump $q_{it} = \frac{240-d_{it}}{4}$ in round t.

To measure the extent to which participants adopt myopic behavior on average, we regress the pumping rate on $\frac{240-d_{it}}{4}$ interacted with treatment indicator variables, where d_{it} is the actual depth to water faced by participant i in round t, and the standard errors are again clustered at the participant level.

If participants utilize primarily myopic strategies, the coefficients for each treatment in table 4 should be equal to unity. Instead, the estimated coefficients are significantly different and less than one in each case. This suggests that on average, participants behave as if they observe the future costs associated with current-round pumping decisions. Participants behave closer to the myopic prediction in Bathtub than in Individual Bathtub, as evidenced by the coefficient in the former, which is significantly higher ($p < 0.01$).

Although the coefficient for Spatial 1 is significantly less than the coefficients for both Bathtub and Spatial 2, participants in Spatial 1 are not necessarily more forward-looking because the private and social costs of pumping vary across treatments. To measure the extent to which the mean pumping decisions reflect rational or optimal behavior, we refer back to the future costs provided in table 2. A participant who takes future costs into account will make a pumping decision according to $q_{it} = \frac{240-d_{it}}{4+z}$ where z is the discounted future cost. As an example, if a participant in Bathtub is playing rationally and therefore taking into consideration the discounted private costs that she will incur from pumping an extra unit in the current round, then z will be equal to 0.87. If she is playing optimally, by considering the discounted social cost, then z will be equal to 5.20.

To derive the implicit future cost realized by the average participant in each treatment, we calculate $z_k = \frac{4*(1-\beta_k)}{\beta_k}$, where β_k is the estimated regression coefficient for treatment

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[9] The model was also estimated with participant and round specific fixed effects. The resulting parameter estimates and standard errors are nearly identical to those presented in table 4, and all implications remain the same.

Table 4. Observed Myopic Behavior

	Coefficient	SE	z	SE	Private Cost	Social Cost
Bathtub	0.817	0.042	0.897	0.252	0.87	5.20
Spatial 1	0.652	0.047	2.131	0.442	1.45	5.75
Spatial 2	0.774	0.037	1.166	0.244	0.76	1.76
Individual Bathtub	0.623	0.033	2.417	0.335	5.20	5.20
N	2688					
R^2	0.861					
$F_{4,95}$	345.751					

Note: The coefficients are generated by regressing the observed pumping rates on the predicted myopic pumping rate, calculated for each participant in each period as $(240 - depth_{it})/4$. The reported SEs are clustered at the participant level. The column of z values are calculated using the formula $z_k = 4(1 - \beta_k)/\beta_k$ where β_k the reported coefficient value for treatment k. The SEs for the z values are calculated using the delta method. The final two columns on the right provide the discounted private and social costs associated with a user pumping one additional unit.

k, shown in table 4. The calculated z values and associated standard errors[10] are listed in the third and fourth columns of table 4, along with future private and social costs in the fifth and sixth columns. In Bathtub, the implicit future cost suggests that the behavior of the average participant is not significantly different from the rational prediction ($p = 0.91$). Additionally, the implicit cost is significantly different and less than the expectation if participants adopted optimal behavior ($p < 0.01$). In the spatially explicit treatments, a joint test reveals that the implicit future costs are higher than would be expected with rational behavior ($p = 0.03$). A test of the individual z values reveals that in isolation, the coefficients approach statistically significant differences from the rational expectation at conventional levels $p = 0.13$ (for Spatial 1 and $p = 0.10$ for Spatial 2). The implicit costs in the spatially explicit treatments are significantly lower than the expectation for participants behaving optimally (joint test $p < 0.01$). In Individual Bathtub, the implicit future cost is less than the rational (and optimal) expectation ($p < 0.01$).

These results provide support for prediction 2, that dynamically strategic behavior varies across treatments based on groundwater dynamics. Rational behavior best describes *average* decision making in Bathtub, where future costs are shared equally across all users. In the two treatments with spatially explicit costs, behavior falls between the rational and optimal predictions. In other words, participants in these treatments actually reduce pumping by more than what would be expected if they were solely attempting to maximize their individual benefits in a noncooperative setting. Finally, in Individual Bathtub, in which a participant is solely responsible for influencing her own future cost, users pump less than the myopic prediction but significantly more than the rate that would maximize discounted net benefits.

Treatment-level averages potentially mask the distribution of individual pumping decisions, which may vary widely from the mean observation. For example, although rational behavior may best fit the average observed pumping rate in Bathtub, it could be that most participants use myopic behavior and that conservation by a few participants lowers the average observed pumping rate.

To explore individual behavior in more detail, we measure the percentage of participants exhibiting myopic behavior by treatment. To identify myopic participants, we regress the individual pumping rate in each round on $\frac{240-d_{it}}{4}$ for each of the ninety-six participants while suppressing the constant term. To control for the repeated nature of the decision-making process, we allow the error to take on an autoregressive-1 process and estimate the model using feasible generalized least squares with the Prais–Winsten procedure. If the parameter estimate of this regression is not significantly different from one, then a participant is classified as myopic. We then regress the binary identification of myopic players onto a set of indicator variables for each of the four treatments, clustering the standard errors at the group level. The results from this linear probability model are provided in table 5 as a measure of the percentage of players utilizing a myopic strategy in each treatment.

The results provided in table 5 reveal that 54% of the participants in Bathtub adopted a myopic strategy, which is significantly higher than in any of the other treatments. We therefore find support for prediction P2a, that

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[10] The standard errors are estimated using Stata's *nlcom* command, which employs the delta method. All tests of the z values are executed using Stata's *testnl* command.

Table 5. Myopic Strategy Identification Model

	Coefficient	SE
Bathtub	0.542	0.129
Spatial 1	0.167	0.151
Spatial 2	0.250	0.098
Individual Bathtub	0.125	0.073
	N	96
	R^2	0.369
	$F_{4,15}$	7.06

Note: The coefficients are generated by regressing binary identifiers for players classified as myopic on treatment indicator variables. They therefore represent the proportion of myopic decision makers in that treatment. The SEs are clustered by group.

rates of myopic behavior are highest in Bathtub. Although participants in Bathtub appear, on average, to follow rational behavior, the individual results reveal that the majority of them actually use a myopic decision-making heuristic. In other words, many participants behave myopically, but the minority of participants, who use less groundwater than the myopic prediction, significantly reduce the average pumping rate. The lowest frequency of myopic behavior is found in Spatial 1 and Individual Bathtub, in which participants faced the highest private costs of pumping. The fact that fewer than 20% of participants follow myopic behavior in these treatments suggests that using myopic play as a benchmark expectation is likely to provide inaccurate predictions. The difference in the proportion of myopic players between Spatial 1 and Spatial 2 is not significant ($p = 0.65$), and therefore we do not find support for prediction P2b, that myopic behavior will be higher in Spatial 1 relative to Spatial 2.

Ideally, it would also be useful to identify participants who follow rational and optimal behavior in each treatment in a similar fashion. This analysis is made difficult, however, by the fact that the gaps among myopic, rational, and optimal behavior vary by treatment. This means that in some treatments, it is more likely that behavior will not fit into any of the three behavioral types. For example, in Bathtub and Spatial 1, the gap between myopic and optimal behavior is significantly larger than it is in Spatial 2, making the identification of one of the three possible strategy types more likely in the latter treatment. Although we do not pursue identifying individual strategies beyond myopic behavior, we note that only four participants across all of the treatments can be identified as both myopic and rational (two in Individual Bathtub and one in each of the spatially explicit treatments).

Our analysis attributes variation in behavioral strategies across treatments to differences in private relative to external costs. It should also be noted that both strategic uncertainty and returns to other-regarding behavior vary across treatments and could also influence decision making. The strategic uncertainty associated with resource use is highest in Bathtub relative to the spatially explicit treatments and Individual Bathtub, given the higher degree of social interaction in Bathtub. If experiment participants are generally averse to strategic uncertainty, this should serve to reinforce the prediction of higher myopic play in Bathtub as participants pump more water early in the trial not knowing how the behavior of other group members will influence depth to water in future rounds. While we cannot rule out strategic uncertainty as a motivating behavioral factor, we note that we do not see dramatic changes across trials in pumping behavior, as discussed later in this section. If strategic uncertainty were to play a dramatic role, one might expect to see differences across trials as some of the strategic uncertainty is reduced with repeated play.

If participants are motivated primarily by pure altruism, where one behaves in a way aimed at improving the monetary payoffs of other participants, we would expect to see lower rates of myopic play in Bathtub, all else equal. This is due to the fact that conservation has the highest impact on reducing costs for other players in this treatment. We also cannot rule out pure altruism, but if it influenced decision making it should serve to reduce the treatment effects on myopic behavior that we observe.

Analysis of Social Efficiency

The third primary prediction is that differences in groundwater dynamics influence social efficiency outcomes. To measure social efficiency, we calculate individual net benefits by inserting the actual pumping decisions and depth to water into the net benefit equation, $\alpha q_{it} - \frac{\gamma}{2} q_{it}^2 - \phi d_{it} q_{it}$ for each individual. We then sum the individual net benefits across all participants in a group and sum across all of the rounds in each of the four trials. The efficiency measure is then calculated as (*observed net benefits*)/(*net benefits from optimal behavior*); the results reported in table 6 provide the average observed social efficiency for each trial of each treatment. The standard errors are generated from variation across the four groups of participants in each treatment. In addition, we include as a benchmark the measure of social efficiency that would result if all participants behaved myopically.

Table 6 provides support for the prediction that differences in groundwater dynamics influence social efficiency. Reinforcing our analysis of myopic behavior, the results reveal that social efficiency tends to be lower in Bathtub than in the other treatments, where the future private costs of current pumping are greater. We therefore find support for P3a, that social efficiency is lowest in Bathtub. We do not find strong support, however, for P3b, which predicts that social efficiency will be higher in Spatial 2 relative to Spatial 1. Although social efficiency is significantly different and higher in Spatial 2 in trials 2 and 4, on average the difference is not significantly different from zero ($p = 0.18$) across all four trials. It should also be noted that in Individual Bathtub, where individuals are responsible for managing their own private aquifer, the average social efficiency is highest at 94.4%, but users are unable to reap 100% of the benefits from the aquifer. This result is similar to the findings of Moxnes (1998a, 1998b), where participant misperception of dynamic feedback led to overexploitation of private resources, although the 5% efficiency loss in our case is less dramatic.

Observed social efficiency is significantly different from and higher than the myopic prediction in every case. The social efficiency predicted by myopic behavior is 50–80%, while the observed efficiency is always at least 80%. Although a number of individual participants used myopic strategies in each treatment, the participants who chose pumping rates that were less than the myopic prediction increased the social efficiency for the group. This outcome lends some credence to claims that the efficiency gains associated with managing pumping rates may not be great enough to offset the cost of implementing such policies. In addition, both the predicted myopic efficiencies and the observed efficiencies are inversely related to the number of rounds in the trial. The intuition for this result is that the optimal decisions are based on the 15% termination probability, which implies an expected number of rounds in each trial of 6.67. When pumping is higher than optimal and a trial involves fewer than seven rounds, the efficiency outcomes will be higher than if participants had utilized optimal pumping rates. In fact, it is possible for efficiency to exceed 100%, as it did in the third trial of Individual Bathtub, which included only five rounds.

Analysis of Learning Effects

Given that participants faced the same treatment condition in each trial, it is important to investigate the extent to which learning effects may generate differences in observed behavior across trials. To test for learning effects, we focus on differences in the depth-to-water variable across trials, which reflect cumulative differences in pumping rates over time. Specifically, we use the depth to water in the fifth round (the highest round reached in each of the four trials) as the dependent variable, which is regressed on indicator variables for the trials 2–4. The model is estimated separately for each of the four treatments, and standard errors are clustered at the participant level. We also estimated the model using pumping rates from the

Table 6. Observed Social Efficiency by Treatment

		Bathtub		Spatial 1		Spatial 2		Individual Bathtub	
	Rounds	Actual	Myopic	Actual	Myopic	Actual	Myopic	Actual	Myopic
Trial 1	6	90.6 (1.8)	63.6	94.1 (2.3)	56.9	93.5 (1.5)	74.6	97.1 (1.9)	63.6
Trial 2	10	77.6 (1.8)	53.8	80.0 (4.3)	50.9	92.6 (2.3)	77.6	84.3 (1.2)	53.8
Trial 3	5	99.1 (1.3)	66.3	95.4 (6.3)	58.7	90.9 (2.7)	72.2	100.8 (2.0)	66.3
Trial 4	7	88.3 (2.4)	60.9	89.5 (2.7)	55.2	94.3 (1.4)	76.0	95.2 (0.9)	60.9
Average		88.9 (2.2)	61.1	89.7 (2.4)	55.4	92.8 (1.0)	75.1	94.4 (1.7)	61.1

Note: For each treatment, the values provided in the "Actual" column are the mean observed social efficiencies across the four groups in each trial, with the SEs in parentheses. The values in the "Myopic" columns indicate the social efficiencies if all participants utilize myopic decision making.

Table 7. Learning Effects Models

	Bathtub	SE	Spatial 1	SE	Spatial 2	SE	Ind. Bath.	SE
Intercept	147.60***	1.62	143.67***	2.58	125.39***	1.16	129.65***	4.75
Trial 2	−2.60	1.91	−4.72*	2.52	−0.62	1.09	1.45	4.00
Trial 3	−1.26	1.64	−7.80*	4.07	−3.12**	1.39	−7.12*	4.20
Trial 4	−0.61	1.88	−0.45	2.95	1.15	1.52	−3.37	3.85
N	96		96		96		96	
R^2	0.014		0.054		0.090		0.022	
$F_{3,23}$	0.97		3.42		3.86		2.68	

Note: For each treatment, the coefficient results are reported from a regression of the depth to water in the fifth round on a constant and indicator variables for trials 2, 3, and 4. SEs are clustered at the participant level.
***,**,*indicate coefficients that are significantly different from zero at the 0.01, 0.05, and 0.10 levels of confidence, respectively.

first round as the dependent variable, and the results are qualitatively very similar.

The results from the treatment-specific models reported in table 7 are not suggestive of robust learning effects. The depth to water in the fifth round does not consistently increase or decrease across trials in any of the four treatments. In Individual Bathtub, there is no significant difference in the depth to water in the fifth round across the four trials. In the spatially explicit treatments and Individual Bathtub, the depth to water is lower or not significantly different in trials 2–4 than it is in trial 1. Especially in Individual Bathtub, one might expect participants to better understand the benefits of conservation in later trials. Evidence in this regard is weak, however, as even in trial 4 the average depth to water in the fifth round was not significantly different from trial 1. The most consistent result that we observe is that participants appear to reduce pumping rates in trial 3 relative to the other trials. One likely explanation for this outcome is that participants choose their pumping rate in part based on the outcome of the previous trial. Since the number of rounds is stochastic, it is plausible that participants update their priors regarding the number of rounds they expect to play based most heavily on the last trial. The ten rounds in trial 2 are the highest of any of the treatments, and there are greater returns to conservation as the number of rounds increase. Therefore, participants conserved more in the early rounds of trial 3, expecting there again to be a high number of rounds in this trial.

Discussion

Groundwater management is a key priority as policymakers around the world endeavor to maintain clean drinking water and functional irrigation sources. Individual groundwater resources, however, involve case-specific resource dynamics that generate differing incentives for individual users. This research uses experiments to examine behavior in four specific dynamic groundwater models, including two models that capture the spatially explicit costs associated with groundwater use.

Our results reveal not only that pumping outcomes vary widely according to the specific properties of the groundwater models that are implemented but also that differences in the groundwater models affect the behavioral strategies of users. In cases where the future costs of pumping are evenly shared by all users, average behavior is best described by rational behavior, and more than half of the participants can be characterized as myopic. In situations where a higher percentage of the future costs of current-period pumping are private, participants pump less than is individually rational on average and are significantly less likely to behave myopically.

The experiments described here are a first attempt to understand the relationship between resource use and differences in spatially explicit groundwater dynamics. As always, care must be taken in translating decisions made by undergraduates in a laboratory environment to real-world settings. The use of a student participant pool, however, does not preclude some general observations to be made that could be instructive to policymakers. One important implication of our research is the importance of understanding the hydrogeologic characteristics of specific groundwater resources. Our results suggest that the use of realistic, spatially explicit models of groundwater dynamics is likely to alter not only predicted myopic pumping rates, but also the frequency with which users adopt myopic behavior. On a related note, the experiments also imply that public attempts to improve the efficiency of groundwater use should likely focus on groundwater systems where there is a high degree of groundwater interaction among users and where pumping has a large impact on the future depth to water. In the model that we constructed, this occurred in situations with lower storativity and higher transmissivity values. Groundwater resources with these characteristics are more likely to experience inefficient use due to the fact that pumping by one individual has a larger negative external impact on other resource users.

Overall, observed efficiency in each of the treatments is relatively high. While other studies have shown only relatively small benefits associated with management even when users behave myopically, we find that observed efficiency is considerably higher than it is under purely myopic play. This result arises because many participants use less groundwater than the myopic prediction. While that is generally good news for efficient and sustainable groundwater use, several management concerns remain. First, in this experiment and in most theoretical studies, the number of wells is assumed to be fixed. If the number and location of wells are choice variables, the potential for inefficient outcomes increases. Second, we have focused on changes in the quantity of groundwater in the system. If water quality concerns are added, such as the risk of seawater intrusion when groundwater levels fall, there is again a greater potential for inefficiency. Finally, our analysis does not include external effects of groundwater pumping associated with changes in surface water, which could influence downstream users and environmental outcomes. These potential sources of inefficiency and management options to improve the observed outcomes are fruitful areas for future research.

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