2009

Groundwater Pumping and Spatial Externalities in Agriculture

Lisa Pfeiffer
Department of Agriculture and Resource Economics
University of California, Davis
pfeiffer@primal.ucdavis.edu

C.-Y. Cynthia Lin
Department of Agriculture and Resource Economics
University of California, Davis
cclin@primal.ucdavis.edu

May 1, 2009

Water supply

Selected Paper prepared for presentation at the Agricultural and Applied Economics Association 2009 AAEA & ACCI Joint Annual Meeting, Milwaukee, Wisconsin, July 26-29, 2009

Working paper.

Abstract

The objective of this paper is to investigate the behavior of farmers who share a common pool resource; in this case, an underground aquifer. In the case where seepage may occur, this seepage renders the resource non-exclusive, giving rise to a spatial externality whereby pumping by one user affects the extraction cost and total amount that is available to other nearby users. Theoretically, these externalities are potentially important causes of welfare loss. Using a unique data set of groundwater users in western Kansas, augmented with spatial hydrological data, we are able to empirically measure the physical and behavioral effects of groundwater pumping by a farmer's neighbors. To address the endogeneity of neighbors' pumping, we use the neighbors' permitted water allocation as an instrument for their pumping. We find that one thousand acre-feet pumped by one's neighbors can lower the water table by about 1.5 feet, on average. We also find that one thousand acre-feet of pumping by one's neighbors will cause an increase in own pumping of about ten acre-feet. We estimate that about two percent of the total amount of groundwater extracted each year in western Kansas is over-extraction due to the effect of spatial externalities.

Introduction

The extraction of water and other natural resources by multiple agents should be modeled using a dynamic spatial model because of the externalities involved when each user only considers his own private benefits when deciding how much of the resource to extract. In the case of an aquifer or other shared resource where seepage (movement of the resource from the area owned by one individual to the area owned by another) may occur, this seepage renders the resource non-exclusive (Dasgupta and Heal 1979; Eswaran and Lewis 1984). This property gives rise to a spatial externality whereby pumping by one user affects the extraction cost and total amount that is available to other nearby users. The spatial externality has been disaggregated into different types of effects, including a pumping cost externality and a stock or strategic externality (Provencher and Burt 1993; Negri 1989). The pumping cost externality arises because withdrawal by one user lowers the water table and increases the pumping cost for all users. The strategic externality arises because the property rights on the water in an aquifer are generally undefined. What a farmer does not withdraw today will be withdrawn by other farmers, which undermines their incentive to forgo current for future pumping (Negri 1989). Theoretically, these externalities are potentially important causes of welfare loss (Dasgupta and Heal 1979; Eswaran and Lewis 1984; Negri 1989; Provencher and Burt 1993; Rubio and Casino 2003; Msangi 2004; Saak and Peterson 2007), but empirically we have little evidence to determine whether farmers react to these externalities or have an idea of their magnitude.

The objective of this paper is to investigate, theoretically and empirically, the behavior of farmers who share a common pool resource. A spatial dynamic physical-economic model is developed to characterize agricultural groundwater users' pumping behavior. We compare a social planner's optimal decisions with those of a group of profit maximizing individuals who have full property rights to the land, but their groundwater is an incomplete common good because they cannot fully capture the groundwater beneath their land.

Hypotheses from the models and data from western Kansas are used to econometrically determine if the pumping behavior of neighbors affects the pumping decision. The estimations are spatially explicit, taking advantage of detailed spatial data on groundwater pumping from the portion of western Kansas that overlies the High Plains Aquifer system. Measuring interactions between neighbors is challenging, however, because of simultaneity (individuals affect their neighbors and their neighbors simultaneously affect them) and spatial correlation in observable and unobservable characteristics (Manski 1993; Brock and Durlauf 2001; Conley and Topa 2002; Glaeser, Sacerdote, and Scheinkman 1996; Robalino and Pfaff 2005).

We use an instrumental variables approach to purge neighbors' decisions of the endogenous component. Groundwater users in Kansas extract water under the doctrine of prior appropriation, meaning that they are allotted a maximum amount to extract each year. This annual amount was determined when the user originally applied for the permit. Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981. The permit amount is a strong determinant of actual pumping, but is uncorrelated with the pumping of neighbors, which is determined by their own permit. Therefore, we use this permit amount as an instrument for neighbors' water pumping. In addition, the instrument is weighted by a function of the distance between each neighbor that takes into account the way in which water moves through an aquifer. Thus, the IV approach controls for errors that may be spatially autocorrelated as well as the simultaneity of neighbors' pumping decisions.

This is the first study to empirically measure economic relationships between groundwater users. If externalities in groundwater use are significant, it lends insight into the causes of resource over-exploitation. If they are not significant or are very small in magnitude, a simpler model of groundwater user behavior, where each user essentially owns their own stock, is sufficient. Both outcomes would give guidance to policymakers, although it is important to note that the results are highly dependent on the hydrological conditions of the aquifer under study.

Theory and Model

Groundwater extraction is not a purely economic problem. There are physical equations of motion that connect spatial areas and link consecutive time periods to one another. The use of a spatially explicit model is important because the aquifer and land is quite heterogeneous. This model has several advantages over the standard groundwater extraction model that assumes that an aquifer is like a bathtub. In the simple bathtub model, a decrease in the level of the aquifer caused by extraction by any individual is transmitted immediately and completely to all other users of the aquifer, and all users are heterogeneous (Burt 1964). In fact, aquifer systems do not adjust instantaneously to withdrawals, and the response can be complex and heterogeneous, even within a small geographic area (Heath 1983). Externalities present within a system would thus reflect the explicit spatial relationship between users, including the distance between them, and the physical and hydrological characteristics of the space that separates them.

The hydrological system

A physical equation of motion governs the change in water height from one period to the next, and from one spatial area to another. The equation of motion for groundwater stock is derived from simplified hydrological mass-balance equations, and assumes that the land owned by each farmer can be thought of as a "patch" with a uniform stock of water beneath each farm. Water flows between "patches" according to hydrological rules. This is obviously a simplification of the true physical nature of groundwater flows because height is a continuous function (Freeze and Cherry 1979; Brozovic, Sunding, and Zilberman 2002), but is a notable improvement on the "bathtub" aquifer model which has been used in previous theoretical work (Negri 1989; Provencher and Burt 1993). The "patch" framework captures the important characteristics of groundwater movement and allows for heterogeneous users, while avoiding the complications of a more sophisticated hydrological model (Janmaat 2005; Sanchirico and Wilen 2005). The equation of motion is:

$$\dot{s}_i = -w_i + g_i(w_i) + \sum_{j \in I} \theta_{ji}. \tag{1}$$

The change in groundwater stock s_i from one period to the next depends on the amount agent i is pumping, w_i, and the amount of recharge to patch i, $g_i(w_i)$. Recharge is a function of return flow (the proportion of the amount pumped that returns to the groundwater table) and precipitation, but the amount that actually soaks into the soil to recharge the aquifer depends on soil characteristics and topography. I assume $\frac{\partial g_i}{\partial w_i} \geq 0$.

$\dot{s}$ also depends on the net flow into i's land that is caused by physical height gradients or other hydrological factors that determine how water flows within an aquifer. θ_{ij} is defined as the share of the water in the aquifer that starts in patch i and disperses to patch j by the next period, so $\sum_{j \in I} \theta_{ji}$ is the net amount of water that flows into patch i from all other patches in the system. Groundwater flow is generally stock dependent; net flow is a function of the stocks of water in all the other patches, so $\theta_{ji}(s_1, s_2, ... s_I)$ and $\frac{\partial \theta_{ji}}{\partial s_i} \leq 0$. A simple while still hydrologically reasonable functional form assumption for net flow is derived from Darcy's Law for water movement through a porous material: the dispersal of water between patches depends on the physical gradients between patches, $\frac{s_i - s_j}{x_{ji}}$, the transmissivity of the material holding the water, commonly called k, and the cross-sectional area through which the fluid is moving, $\frac{s_i - s_j}{2}$ (Brutsaert 2005). In this simple model, the net flow into patch i is $k_j \cdot \frac{(s_i - s_j)^2}{2x_{ji}}$, where x_{ji} is the distance between plot i and j. θ_{ji} could also be more complicated and consider the effects of aquifer bed topology, continuous cones of depression from pumping, or saltwater intrusion, for example (Janmaat 2005).

In a long-run equilibrium without pumping and a homogeneous aquifer bed, $s_i = s_j, \forall i, j$; the groundwater stocks under all land patches will be equal.

The single owner/social welfare maximizer's problem

The socially optimal rate of extraction would be chosen by a single owner who has access to perfect and complete information about both the hydrological system and the economic variables that affect the profitability of groundwater pumping. To set that benchmark, consider a single owner who must make pumping decisions for an entire aquifer basin, upon which lie many "patches" or plots of land with groundwater pumps. Revenue earned on each plot i, $R_i(w_i)$, depends on how much water he extracts from the aquifer to irrigate crops, and cost C^w is dependent both on the amount extracted and the stock available, s_i. The smaller the stock, the greater the distance through which the water must be pumped to reach the surface, so $\frac{\partial \mathbf{C}_i^w(s_i)}{\partial s_i} < 0$. This planner would seek to maximize the present value of aggregate profit by planning for this aquifer basin (assuming there is no flow in or out of the aquifer):

$$\max_{\{w_i(t)\}_{i=1}^{I}} \int_0^{\infty} e^{-rt} \left[\sum_{i=1}^{I} \left(R_i(w_i) - C^w(s_i) w_i \right) \right] dt \tag{2}$$

where the owner chooses the set of pumping volumes on each plot of land in each time period, $\{w_i(t)\}$. The t subscripts have been omitted for simplicity of notation. The owner optimizes subject to the equation of motion for the water height under each plot $\dot{s}_i = -w_i + g_i(w_i) + \sum_{j\in I}\theta_{ji}$, $i = 1, ..., I$ and the transversality condition $\lim_{t\to\infty} e^{-rt}\lambda_{it}s_{it} = 0$, $i = 1, ..., I$.

In this formulation the single owner is pumping water from each plot for use on that plot's crops.[1] The owner will consider each farm's shadow value of a unit of groundwater stock when determining the optimal solution, so as to internalize any externality that could occur. The current value Hamiltonian for this problem is

$$H(w_1, ..., w_I, s_1, ..., s_I, \lambda_1, ..., \lambda_I) = \sum_{i=1}^{I}(R_i(w_i) - C^w(s_i)w_i) + \sum_{i=1}^{I}\lambda_i\left[-w_i + g_i(w_i) + \sum_{j\in I}\theta_{ji}\right]. \tag{3}$$

The first order conditions to the Hamiltonian are

$$\frac{\partial R_i}{\partial w_i} = C^w(s_i) + \lambda_i - \lambda_i\frac{\partial g_i}{\partial w_i} \tag{4}$$

$$r\lambda_i - \dot{\lambda}_i = -w_i\frac{\partial C_i^w(s_i)}{\partial s_i} + \lambda_i\sum_{j\in I}\frac{\partial\theta_{ji}}{\partial s_i} + \sum_{\substack{j\in I\\ j\neq i}}\lambda_j\frac{\partial\theta_{ij}}{\partial s_i} \tag{5}$$

$$\dot{s}_i = -w_i + g_i(w_i) + \sum_{j\in I}\theta_{ji},\ i = 1, ..., I \tag{6}$$

The owner will choose the crop-water combination such that the value marginal product of the water is equal to the marginal pumping cost plus the shadow value of water. The shadow value is a function of the flow onto and off of the farmer's plot. Clearly, the social optimum is a function of the water height on all the parcels of land under the owner's control, all of the interconnections between parcels, and all of the shadow values. It is possible, given heterogeneous costs or revenue across plots i, that interior solutions will not be optimal for all plots (i.e., optimal pumping may be zero in some plots).

This program is identical to the single owner problem normally analyzed using a bathtub aquifer model if we assume that transmissivity is infinite, the aquifer is parallel sided and flat bottomed, return flow is zero, and parcels are perfectly homogeneous (Negri 1989). It does not matter where the wells are located or how many there are, as long as water can be transported costlessly to the entire surface of the parcel. If we make these assumptions, the first order condition 5 can be summed over all the parcels, and collapses to $\dot{\lambda} = r\lambda + Nw\frac{\partial C^w(s)}{\partial s}$, where N is the total number of parcels the planner or single owner controls, and w is the total amount of water withdrawn per plot. By integrating, using the transversality condition, and combining the first order conditions, the marginal condition for an arbitrary $\bar{t}$ is obtained:

$$\frac{\partial R}{\partial w} = C^w(s) + N\int_t^\infty e^{-r(t-\bar{t})} w \frac{\partial C^w(s)}{\partial s} dt. \tag{7}$$

To be intertemporally efficient, a landowner will extract water until the marginal value product of water is equal to the marginal cost of extraction plus the value of the marginal unit of water as stock, which is the definition of the shadow price λ. The marginal unit left as stock has value because it reduces future pumping costs. This is the standard Hotelling solution, where the shadow value grows as a function of the rate of interest.

Individual, dynamically optimizing farmer

Now compare the social planner's solution to the solution of a group of individual landowners, each having property rights to one "patch", that partially share the water resource. The objective function faced by one of these farmers would be:

$$\max_{\mathbf{w}_i(t)} \int_0^{\infty} e^{-rt} \left[R_i(w_i) - C^w(s_i) w_i \right] dt, \tag{8}$$

with the equation of motion as in equation 1 and transversality condition $\lim_{t \to \infty} \lambda_{it} h_{it} = 0$. This problem is similar to that that posed in Janmaat (2005), but dissimilar to much of the previous literature on spatial fisheries, in that each parcel is owned by an individual with no claim on the profit earned in any other parcel.

The first order conditions are derived from the maximization of the Hamiltonian:

$$\frac{\partial R_i}{\partial w_i} = C^w(s_i) + \lambda_i - \lambda_i \frac{\partial g_i}{\partial w_i} \tag{9}$$

$$r\lambda_i - \dot{\lambda}_i \ = -w_i \tfrac{\partial C_i^w(s_i)}{\partial s_i} + \ \lambda_i \sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i}, \tag{10}$$

and equation 1.

Again, equation 9 shows that along the optimal extraction path, the individual will equate marginal revenue from pumping to marginal cost plus the resource rent or shadow value. Recharge decreases the value of the resource as stock. Equation 10 states that the resource rent must increase at the discount rate, adjusted for the effects of net flow and increasing extraction costs. Stock dependent net flow means that $\sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i} < 0$, which in effect increases the discount rate.

To see the marginal condition another way, the first order conditions can be combined and then integrated to obtain the marginal condition for an arbitrary $\bar{t}$:

$$\frac{\partial R_i}{\partial w_i} = C^w(h_i) + \left(1 - \frac{\partial g_i}{\partial w_i}\right) \int_t^{\infty} e^{-\left(r - \sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i}\right)(t - \bar{t})} w_i \frac{\partial C_i^w(s_i)}{\partial s_i} dt. \tag{11}$$

The necessary condition for intertemporal optimization shows that water is extracted until marginal profits are equal to marginal extraction costs plus the present value of the shadow value of water. A unit of groundwater left in the aquifer has value only in proportion to the amount that he can capture in the future. The $\sum_{j \in I} \frac{\partial \theta_{ji}}{\partial s_i}$ term captures the extent to which the resource is common. As this term gets larger, less of the water left as stock can be captured by the owner of the land, decreasing the value of the marginal unit of stock. This would shift the extraction path towards the present.

Higher values of $\frac{\partial g_i}{\partial w_i}$, the function describing recharge and return flow, will decrease the value of the marginal unit of groundwater as stock, increasing present period pumping.

Using figure 1, some predictions about the sign of the effect that neighbors' pumping should have on the quantity of water extracted can be generated. In part (a), individual i faces a larger stock, or equivalently a shorter depth to the water table than does j. Due to the negative gravitational gradient, water will flow out of i's plot. To capture the water before it can flow out, i would pump more.

In part (b) of figure 1, the gravitational gradient is positive, causing water from j to flow to i. However, any additional pumping by j will decrease the gradient, causing less water to flow in. Individual i would pump more to maintain, or even increase, the gradient between the two plots. Thus, we expect the coefficient on neighbors' pumping to be positive regardless of the sign of the gradient, although the reason for interrelationship is slightly different. Anything that increases the gradient between patches will also increase present period pumping, including a greater hydroconductivity, a smaller distance between patches (neighbors closer together), and higher pumping by neighboring patch owners.

Finally, the solution to the individual's dynamic optimization problem leads to greater extraction than would occur under a single owner, as long as $\theta_{ii} \neq 1$. θ_{ii}

describes the proportion of water starting in patch i which stays in patch i the following period. If all of the water that starts in i stays in i, for all i, then there is no lateral flow in the aquifer and the derivatives $\frac{\partial\theta_{ji}}{\partial s_i}$ and $\frac{\partial\theta_{ij}}{\partial s_i}$ are zero. Consider first order conditions 5 and 10. In 10, the interest rate is decreased by the sum of the net flow derivatives $\sum\limits_{j\in I}\frac{\partial\theta_{ji}}{\partial s_i}$, and with stock dependent flow, this sum is negative, effectively increasing the interest rate. In the central planner's first order condition 5, the interest rate is further adjusted by the derivatives of flow going from i to j. Given stock dependent flow, $\frac{\partial\theta_{ij}}{\partial s_i} \geq 0$, or an increase in the stock level at i will cause more movement out of patch i to all other patches. Thus, as long as $\sum\limits_{\substack{j\in I\\ j\neq i}}\frac{\partial\theta_{ij}}{\partial s_i} > 0$, it will negate the effect of $\sum\limits_{j\in I}\frac{\partial\theta_{ji}}{\partial s_i}$ and the total amount of water withdrawn per period by the social planner will be less than the total amount of water withdrawn by all of the individuals.

This leads to the testable hypothesis that if a farmer owns multiple wells in adjoining parcels, he will manage them differently than if each well was owned by a different person. Specifically, any effect of pumping from his own wells (on water table height or pumping) will be less than the effect of pumping from wells owned by others.

Empirical analysis

Data

A unique data set allows the empirical exploration of many of the hypotheses that come from the theoretical model. Kansas has required the reporting of groundwater pumping by water rights holders since the 1940s, although only data from 1996 to the present are considered to be complete and reliable.[2] The data are available in an ArcView based GIS application called the Water Information Management and Analysis System (WIMAS).[3] It includes spatially referenced pumping data at the source (well or pump) level, and has the farmer, field, irrigation technology, amount pumped, and crops grown identified. It also contains industrial and municipal points of diversion. Also available are spatial datasets of recharge, water bodies, and other geographic information.

The United States Geological Survey's High Plains Water-Level Monitoring Study maintains a network of nearly 10,000 monitoring wells. Data from these wells have been used to estimate yearly water levels using a kriging interpolation procedure in ArcGIS. The USGS also has information on specific yield and transmissivity in shape file format, and rainfall data comes from the PRISM Group at Oregon State University.[4] Relevant information from the geographic files was captured at the points of diversion (well) level using ArcGIS. There are about 8,000 points of diversion for each of the 10 years from 1996 to 2005.

Summary statistics for the variables used in the analysis are presented in tables 1 and . The average number of acre-feet extracted per irrigation well per year is 136. Irrigators own an average of 2.8 wells, and pump an average of about 350 acre-feet in total. Each well irrigates an average of 143 acres, and each well owner irrigates an average of 308 acres. The average depth to groundwater is 114 feet, but ranges from 0.8 to over 350 feet. The average change in the depth to groundwater from one year to the next is one foot. Over the ten year period, each point of diversion got an average of 22.6 inches of precipitation per year. Recharge, hydroconductivity, and soil characteristics are not measure per year; they are estimated by the United States Geological Survey and evaluated at each point of diversion. Recharge to the Kansas portion of the High Plains Aquifer is low; the average amount of recharge is 1.4 inches, with a minimum of 0.3 and a maximum of 6 inches. The mean hydroconductivity is

6.58 feet/day.

Three measures of soil quality are used in the analysis. Irrigated capability class is a categorical variable describing the suitability of the soil for irrigated crops; the first category being the most suitable. 45% of the plots have soils in category 1, 37% in category 2, and 14% in category 3. Less than 4% of plots are in categories 4, 5, and 6. The average available water capacity is 0.18 cm/cm, and the mean slope (as a percent of distance) is 1.1%.

A variety of spatial neighborhood variables are constructed to investigate the effect of neighbors' pumping. Summary statistics are provided in table . A half mile, one, two, three, and four mile radius around each well is constructed and the average number of neighboring well and the number of acre-feet of groundwater extracted from those neighboring wells is included in the table. Weighted gradients, calculated as the difference in water table height between two wells, divided by the distance and multiplied by hydroconductivity, are used to weight the amount of water pumped by neighbors by the impact they should have. To obtain average marginal effects, the estimated coefficient must be multiplied by the average weight, so they are presented in table .

Empirical Estimation Strategy

Using the data from Kansas, we can directly estimate the equation of motion and test the effect of pumping on the change in groundwater stock from one year to the next. The stock or groundwater can be equivalently measured as lift height, or the distance from the ground surface to the top of the water table. Because our data contains information on static levels (the top of the groundwater table), we use this as a measure of stock. Given the assumptions of the equation of motion, the change in groundwater height should depend on the amount that is pumped at the location that height is measured (own pumping), the amount pumped by neighbors, the distance between the farms, the relative heights of the water tables, and the transmissivity of the aquifer at that location. Several models of the form

$$h_{it+1} - h_{it} = \beta_0 + \beta_1 w_{it} + \beta_2 w_{jt} + \beta_3' \mathbf{X_{it}} + \varepsilon_i. \tag{12}$$

are estimated, where $h_{it+1} - h_{it}$ is the change in lift height from one year to the next, w_{it} is own-well pumping, w_{jt} represents various forms of neighbor's pumping, and $\mathbf{X}$ is a vector of hydrological characteristics and interaction terms.

Equation 12 estimates the physical relationship between water pumped at various locations and changes in groundwater depths. To investigate the behavioral and economic relationship between neighboring groundwater users, a reduced form approach is used. However, neighbors' interactions can be difficult to estimate because of the simultaneity resulting from each observation being each other observation's neighbor. Additionally, neighbors may tend to be affected by the same unobservable characteristics, biasing estimates (Manski 1993; Moffitt 2001). The interaction of neighbors has been studied in oil extraction (Libecap and Wiggins 1984; Lin forthcoming). It has also been investigated in land use change (Irwin and Bockstael 2002; Robalino and Pfaff 2005) using physical attributes of neighboring parcels as instruments to identify the effect of the behavior of neighbors on an individual. We make use of the fact that in Kansas, groundwater is allocated under the doctrine of prior appropriation (Peck 1995). Each groundwater user has an appropriation contract which states the maximum amount that he is allowed to pump in one year. This appropriation is expected to be highly correlated with the quantity pumped of the respective appropriator, but uncorrelated with the pumping decision of the appropriator's neighbors.[5]

A series of simultaneous equations explain farmers' behavior, and can be modeled with a two-step estimation procedure. The first equation is used to predict neighbors' pumping as a function of exogenous individual characteristics. For each individual i, a neighborhood M is defined. M could potentially include all water users in the aquifer (N). The equation

$$\sum_{\substack{j=1 \\ j\neq i}}^{M} k_j \cdot \frac{h_{it} - h_{jt}}{x_j} \cdot w_{jt} = \alpha + \beta \sum_{\substack{j=1 \\ j\neq i}}^{M} k_j \cdot \frac{h_{it} - h_{jt}}{x_j} \cdot c_j + \varepsilon_{tj};\ M \in N \tag{13}$$

is the first stage regression, where the weights $k_j \cdot \frac{h_{it}-h_{jt}}{x_j}$ come from the equation for Darcy's Law describing the movement of a fluid through porous material. Again, $h_{it} - h_{jt}$ is the difference in lift height in a given time period, h_j is hydroconductivity, and x_j is the distance between i and j. These weights adjust the amount pumped by the effect that it should have. For example, if the distance between the two well is greater, the effect should be smaller. If the height gradient is larger, the effect should be greater. w_j is pumping, and c_j is the individual's appropriation contract, our exogenous instrumental variable.

In the second stage, predicted levels of pumping from 13 are used to estimate i's expected pumping:

$$w_{it} = X_{it}\beta + \gamma c_i + \eta \left(\sum_{\substack{j=1 \\ j\neq i}}^{M} k_j \cdot \frac{h_{it} - h_{jt}}{x_j} \cdot w_{jt} \right)^{*} + \mu_{it};\ M \in N. \tag{14}$$

X_{it} is a matrix of individual specific regressors that affect the pumping decision such as the number of acres irrigated, rainfall, and soil quality. c_i is the individual's appropriation contract, and the estimated coefficient η measures the effect of the spatial externality.

Methodologically, some assumptions are made to estimate the system. There are nearly 8000 observations for each year, and technically all could be included as neighbors. Alternatively, a maximum distance could be specified, beyond which interaction is not expected to occur, as Robalino and Pfaff (2005) assumed. Finally, a maximum number of neighbors M could be chosen. We construct several types of neighborhoods to check the robustness of the estimates.

Results and Discussion

Tables and shows the results from the estimation of equation 12, the basic relationship between acre-feet that are pumped from one's own well and surrounding wells and the change in water lift height. From table , regressions (1) through (5), one hundred acre-feet pumped in one year are associated with an increase in lift height of 0.21 to 0.49 feet the following year, depending on the model specification. Average pumping at a single well is 136 acre-feet, and the average change in lift height is 1.0 feet, so these estimates are quite reasonable.

Also included is the sum of the acre-feet pumped in increasing distances around i. As expected, the effect is significantly smaller than the effect of own-well pumping, and the effect of neighbor's pumping decreases as the distance from i increases. One thousand acre-feet of pumping within a half mile causes an increase in lift height of about 1.4 feet, while one thousand acre-feet pumped 2 miles away is associated with an increase in lift height of 0.8 feet. Figure 2 illustrates the decreasing effect; the effect nearly disappears when the distance increases to 3 or 4 miles. [6]

Regressions (6) through (9) in table use a slightly different construction of neighbors' pumping. In these regressions, pumping in the one-mile radius is used exclusive of pumping within a half mile; pumping in the two-mile radius is exclusive of pumping within one mile, and so on. We expect the estimates of neighbors' pumping to be smaller than in the previous (non-exclusive) cases, but the estimated coefficients are quite similar. The two trajectories are compared in figure 2. Column (10) presents the results when all of the concentric buffers are included in the same regression. The coefficients become less significant, we suspect because of serial correlation, but the basic result is still evident. Own pumping has the largest effect, but pumping from a neighbor up to two miles away can still reduce the water table at i's well.

In column (11) of table , measures of hydroconductivity are included. Hydroconductivity is a measure of how well water flows laterally through an aquifer. Thus, higher levels of hydroconductivity, when interacted with neighbor's pumping, may be associated with a greater increase in lift height. However, higher hydroconductivity may also result in higher flow through the aquifer in general, and higher levels of recovery from pumping. The results from the regression appear to support the second hypothesis. The hydroconductivity variable is significant and negative and interaction term is insignificant, indicating that in areas with higher hydroconductivity, the depth to the water table increases less from year to year, all else constant.

Recharge measures the potential for percolation into the aquifer; precipitation measures the amount of water (in addition to own pumping) that is available to recharge the aquifer. Both variables are expected to decrease the lift height. The estimated marginal effect of precipitation is negative as expected. The estimated effect of recharge is negative for slightly above average levels of precipitation.

From the theory, we would expect multiple wells owned by the same person to be managed differently than multiple wells owned by different people because of the various types of spatial externalities discussed in this paper and others. Just as the optimal extraction rate of a social planner would be lower than that of a group of individuals, the extraction rate of an individual who owns several wells would be lower than if different people owned each separate well. One way to test this hypothesis is to see if pumping from other wells owned by the same person has an effect on the height at location i. It is expected that a farmer would manage his wells such that the overall level of groundwater beneath his land decreases at whatever he has determined the optimal extraction path to be. He is more likely to substitute pumping from one well with pumping from another. Thus, we expect pumping from other wells owned by the same person as the well at location i to have a smaller effect than pumping from wells owned by neighbors, or even a negative effect, on the groundwater level at i. From the results presented in tables and , we can see that this is the case. The coefficient on acre-feet pumped from wells owned by the same person has an insignificant effect on the water table level at i. While the relationship contains behavioral implications which have not been explicitly estimated, it is evidence that a single owner manages his wells differently than would multiple owners, which is predicted from the theoretical model.

Given that there is empirical evidence for significant lateral flow in the equation of motion, we expect groundwater users to adjust their behavior in response to the pumping of neighbors. The reduced-form behavioral model is estimated using equations 13 and 14, and the results are presented in tables through 8. Table 8 shows that the absolute value of neighbors' pumping, weighted by the gradient described in equation 13, is highly correlated with the absolute value of those neighbors' appropriation contracts, also weighted by the gradient, in all of the specifications used for tables , , and . The regressions in these tables are estimated with a simultaneous system of equations, using neighbors' appropriation contracts as instruments for neighbors' pumping. Controlling for authorized quantity, precipitation, and soil and hydrological characteristics, we find that the weighted sum of neighbors' pumping does have a significant effect on the quantity of water extracted. The average effect (presented at the bottom of the tables), which is the coefficient on neighbors' pumping multiplied by the average weight (provided in table), clearly increases as the neighborhood gets closer to i. Column (1) of table uses the weighted sum of the neighbors within 0.5 miles, column (2) all neighbors within 1 mile, column (3) all neighbors within 2 miles, column (4) all neighbors within 3 miles, and column (5) all neighbors within 4 miles. The average effect shows that, for example, 1000 acre-feet of additional pumping by neighbors within a half mile radius, at the margin and with the average gradient weight, would cause one to increase their own pumping by 15 acre-feet. One thousand acre-feet of pumping by ones' neighbors within a one mile radius is associated with an increase in pumping of about 10 acre-feet. Figure 3 shows that at two miles the effect decreases dramatically, nearing zero as the distance is increased to three and four miles. For robustness, we also estimate the effects of pumping exclusive of pumping in the smaller radius, and these estimates are presented in table . The estimated effect is only slightly smaller.

From table , the average amount of water pumped in a one mile radius is 239 acre-feet. Therefore, for the average groundwater extractor, pumping by all neighbors within one mile would cause him or her to increase their own pumping by an average of 2.5 of an acre-feet. Average pumping is 136 acre-feet, so the effect of neighbors' pumping accounts for about 2 percent of total pumping.

In regressions (11) and (12) of table , neighbors' pumping is divided among those with a negative weight (j's depth to groundwater is larger than i's) and those with a positive weight (i's depth to groundwater is larger than j's). We expect both of the coefficients to be non-negative, but for different reasons, as discussed in the previous section. We have no a priori prediction of the relative magnitudes of the effects. Again, we find a significant effect, concentrated in the effect of those neighbors with positive weights (a larger depth to groundwater, see figure 1). This may indicate that groundwater users are more concerned about maintaining a rate of inflow from neighbors (a beggar-thy-neighbor effect (Janmaat 2005)) than they are with losing water to their neighbors.

Conclusion

The inefficiencies resulting from the exploitation of common property resources are of continuing concern to economists, resource managers, and policymakers. In the case of groundwater or other resources where property rights exist, but may be incomplete because spatial movement of the resource makes it impossible to fully capture what is officially owned, the measurement of this spatial movement is important because it quantifies the resulting inefficiency. The externalities resulting from groundwater pumping from a common aquifer have been extensively discussed and their importance debated (Dasgupta and Heal 1979; Gisser and Sanchez 1980; Eswaran and Lewis 1984; Negri 1989; Provencher and Burt 1993; Rubio and Casino 2003; Msangi 2004; Saak and Peterson 2007), but they have never been empirically measured. This paper is the first to do so.

We find evidence of both a physical movement of groundwater between farms and a behavioral response to this movement in the agricultural region of western Kansas overlying the High Plains Aquifer. The movement of water in the aquifer is in response to physical height gradients caused by groundwater extraction, as well as other hydrological properties that affect groundwater flow. We find that 100 acre-feet of pumping is sufficient to lower the static level of the water table at one's own well by 0.21 to 0.49 feet, and 1000 acre-feet of pumping by neighbors within about a two-mile radius can reduce the static level at one's well by 0.8 to 1.5 feet the following year. At the average levels of pumping by an individual and his neighbors, this amounts to a reduction in the water table of 0.64 to 1.02 feet per year, about 0.8 percent of the mean depth to groundwater.[7] While we don't have sufficient information to estimate the increase in extraction costs due to own and neighbors' pumping, the finding that neighbors' pumping does affect own depth to groundwater makes further data collection and investigation of the nature of extraction costs important.

Spatial externalities resulting from the inability to completely capture the groundwater to which property rights are assigned cause some degree of overextraction in theoretical models. Using an instrumental variable and spatial weight matrices to overcome estimation difficulties resulting from simultaneity and spatial correlation, we find that on average, the spatial externality causes overextraction that accounts for about 2 percent of total pumping. More than one million acre-feet of groundwater are extracted from the Kansas portion of the High Plains Aquifer each year, and our results indicate that over 20,000 acre-feet of this quantity are extracted as a result of inefficiencies caused by spatial externalities.

Policy options available that would be reasonably easy to implement to reduce the inefficiency caused by the spatial movement of water in the aquifer are limited. Libecap and Wiggins (1984) argue that unitization and contracting between neighbors should occur naturally; landowners most affected by pumping from their neighbors would buy up neighboring land to reduce the movement out of their land. Our results indicate that this would be effective; in tables and we show that water pumped from wells owned by the same person does not have the same affect as an equal amount of water pumped by neighboring landowners. Indeed, Kansas has been experiencing a decline in the number of farms and an increase in the number of acres per farm, but it is not clear that it is because of the externalities caused by groundwater movement. Increasing returns to scale and size, the availability of off-farm income opportunities, and other structural changes within the American agricultural sector may be driving this change. Regardless of the cause, unitization will decrease the importance of spatial externalities. The formation of Groundwater Management Districts, a water bank, and the facilitation of leasing or selling back water rights to the state are some other measures that the state of Kansas has undertaken, but the fact that participation has been nearly nonexistent suggests that transaction costs are higher than the possible gains from these programs (Pfeiffer and Lin 2009).

Notes

[1]This is in contrast to the single owner/social planner depicted in Negri (1989) where the planner controls the entire swath of land, pumps from only one location, and then presumably distributes it to the spatial location where it is needed

[2]Personal communication with Dr. Jeffrey Peterson, Kansas State University, April 5, 2008.

[3]http://hercules.kgs.ku.edu/geohydro/wimas/

[4]PRISM (Parameter-elevation Regressions on Independent Slopes Model) data sets are recognized world-wide as the highest-quality spatial climate data sets currently available. http://www.prism.oregonstate.edu/

[5]The original allocations may be spatially correlated, but the time series nature of our data will provide variation over time. The appropriation contracts are constant over time, so are unlikely to be correlated with a neighbor's pumping decision in any one year.

[6]A lag of neighbors' pumping was included in these regressions; (Brozovic, Sunding, and Zilberman 2002) argue that it can take a significant amount of time for the effect of pumping in one location to be transmitted to another location. However, for these locations and hydrological conditions the two-year lag is insignificant, so the lags were dropped.

[7]Using the estimates of 0.21 to 0.49 feet/100 acre-feet of own pumping, 1.5 feet/1000 acre-feet of neighbors' pumping within a one mile radius, average own pumping of 136 acre-feet, average one mile radius pumping of 239 acre-feet, and average depth to groundwater of 114 feet.

Tables and Figures

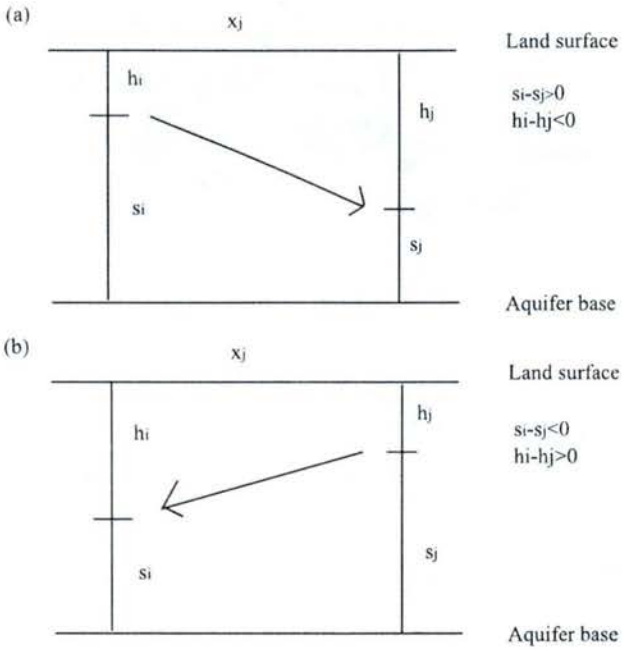

Figure 1: Relationship between i and j in terms of depth to groundwater

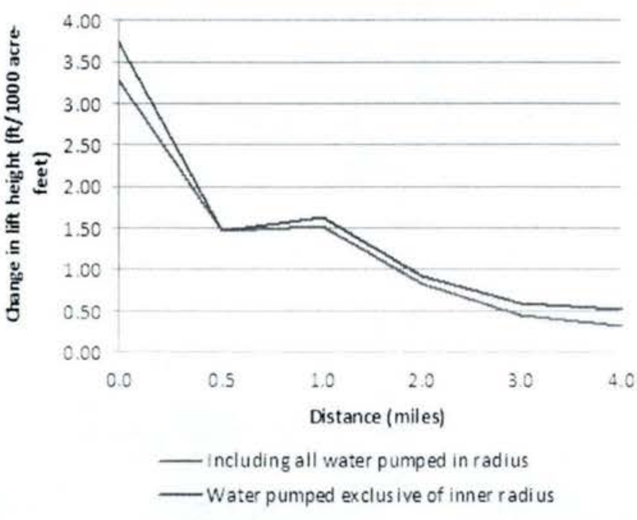

Figure 2: Effects of neighborhood pumping on the change in water table height

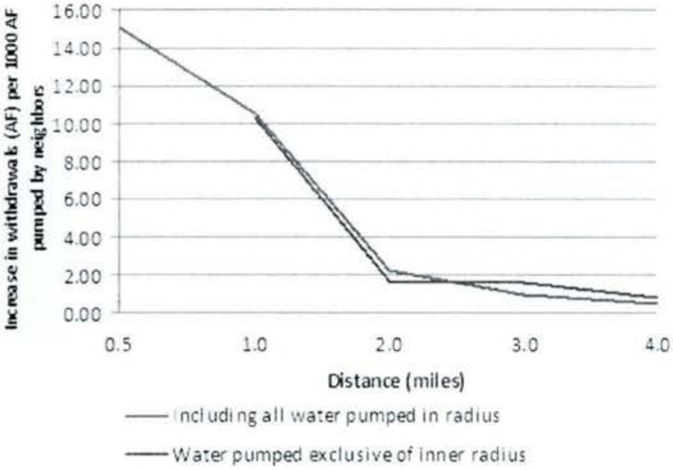

Figure 3: Effects of neighborhood pumping on the groundwater withdrawals

Table 1: Summary Statistics, 1996-2005

Individual-year level variables	N	Mean	Std. Dev.
Acre-feet pumped, single well	85813	136.08	127.24
Acre-feet pumped, single water rights owner	85813	350.33	731.81
Acres planted on irrigable land, single well	85813	143.58	93.66
Acres planted on irrigable land, single water rights owner	85813	308.34	539.09
Depth to groundwater (ft)	85813	114.31	76.07
Change in depth to groundwater (ft)	76812	1.17	14.63
Change in depth to groundwater, county average (ft)	459	1.00	8.18
Precipitation (in)	85813	22.36	5.79
Individual level variables			
Recharge (in)	9337	1.41	1.34
Hydroconductivity (ft/day)	9342	6.58	7.52
Slope (% of distance)	8957	1.10	0.94
Irrigated Capability Class	8740	1.80	0.90
Available water capacity (cm/cm)	8957	0.18	0.03
Distance to nearest neighbor (mi)	9337	0.70	0.51

Table 2: Summary Statistics of Spatial Neighborhood Variables

	Number of neighboring wells	Acre-feet pumped	Average gradient weight	Average gradient weight, exclusive of inner radius
0.5 mile cutoff	0.06	46.70	75.45	
	(0.24)	(103.75)	(148.09)	
1 mile cutoff	0.49	239.12	50.12	46.80
	(0.78)	(274.26)	(93.44)	(85.43)
2 mile cutoff	3.44	977.05	27.81	24.03
	(2.54)	(805.35)	(51.56)	(43.97)
3 mile cutoff	9.61	2118.09	20.16	15.89
	(5.72)	(1611.79)	(37.09)	(28.91)
4 mile cutoff	17.51	3520.91	17.55	14.37
	(9.16)	(2510.62)	(32.16)	(25.78)

Note: Standard deviations in parentheses.

Table 3: Equation of Motion. Dependent Variable: Change in the depth to groundwater from one year to the next (ft)

	(1)	(2)	(3)	(4)	(5)
	0.5-mile cutoff	1-mile cutoff	2-mile cutoff	3-mile cutoff	4-mile cutoff
Amount pumped (acre-feet)	0.00481	0.00410	0.00288	0.00252	0.00213
	(0.0007)***	(0.0007)***	(0.0007)***	(0.0007)***	(0.0008)**
Amount pumped at other	0.00028	0.00029	0.00028	0.00026	0.00025
wells owned by i (acre-feet)	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*
Acre-feet pumped by	0.00146	0.00151	0.00082	0.00044	0.00030
neighbors	(0.0008)	(0.0003)***	(0.0001)***	(0.0001)***	(0.0000)***
Precipitation (in)	-0.21190	-0.20781	-0.20342	-0.20304	-0.20167
	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***
Potential recharge (in)	1.95678	1.84501	1.64692	1.58049	1.50933
	(0.3678)***	(0.3685)***	(0.3701)***	(0.3710)***	(0.3719)***
Precipitation*recharge	-0.03830	-0.03544	-0.02999	-0.02797	-0.02581
	(0.0117)**	(0.0117)	(0.0118)*	(0.0118)*	(0.0118)*
Constant	2.93436	2.70519	2.42451	2.37472	2.28930
	(0.5430)***	(0.5450)***	(0.5470)***	(0.5476)***	(0.5486)***
N	64854	64854	64854	64854	64854
r^2	0.00474	0.00507	0.00555	0.00561	0.00569

Note: * p<0.05, ** p<0.01, *** p<0.001. Standard errors in parentheses.

Table 4: Equation of Motion, Using Concentric Radii of Neighbors. Dependent Variable: Change in the depth to groundwater from one year to the next (ft)

	(6)	(7)	(8)	(9)	(10)	(11)
	1-mile cutoff	2-mile cutoff	3-mile cutoff	4-mile cutoff	Concentric buffers	1-mile cutoff
Amount pumped (acre-feet)	0.00414	0.00311	0.00313	0.00296	0.00211	0.00401
	(0.0007)***	(0.0007)***	(0.0007)***	(0.0007)***	(0.0008)**	(0.0007)***
Amount pumped at other	0.00028	0.00027	0.00025	0.00024	0.00026	0.00027
wells owned by i (acre-feet)	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*	(0.0001)*
Acre-feet pumped by neighbors,	0.00163				0.00071	0.00135
exclusive of pumping in half mile	(0.0003)***				(0.0003)*	(0.0004)***
Acre-feet pumped by neighbors,		0.00093			0.00051	
exclusive of pumping in one mile		(0.0001)***			(0.0002)**	
Acre-feet pumped by neighbors,			0.00059		0.00015	
exclusive of pumping in two mile			(0.0001)***		(0.0001)	
Acre-feet pumped by neighbors,				0.00052	0.00026	
exclusive of pumping in three mile				(0.0001)***	(0.0001)**	
Precipitation (in)	-0.20864	-0.20537	-0.20642	-0.20533	-0.20079	-0.22978
	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0229)***	(0.0232)***
Potential recharge (in)	1.85376	1.68370	1.67688	1.64140	1.50967	1.44528
	(0.3685)***	(0.3699)***	(0.3705)***	(0.3712)***	(0.3720)***	(0.3746)***
Precipitation*recharge	-0.03558	-0.03084	-0.03044	-0.02924	-0.02598	-0.02312
	(0.0117)**	(0.0118)**	(0.0118)**	(0.0118)*	(0.0118)*	(0.0119)
Hydroconductivity (ft/day)						-0.06578
						(0.0145)***
Hydroconductivity*Acre-feet						-0.00000
pumped by neighbors, 1-mile radius						(0.0000)
Constant	2.75866	2.53294	2.56919	2.52101	2.24895	3.79175
	(0.5441)***	(0.5457)***	(0.5459)***	(0.5467)***	(0.5492)***	(0.5820)***
r^2	0.00504	0.00543	0.00531	0.00533	0.00576	0.00560

Note: * p<0.05, ** p<0.01, *** p<0.001. Standard errors in parentheses.

Table 5: IV Regressions of Acre-feet Pumped

	(1)	(2)	(3)	(4)	(5)
	0.5-mile cutoff	1-mile cutoff	2-mile cutoff	3-mile cutoff	4-mile cutoff
Neighbors' pumping	0.00020	0.00021	0.00008	0.00005	0.00003
	(0.0001)***	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***
Acres planted on	0.80188	0.79913	0.79726	0.79667	0.79645
irrigatable land	(0.0047)***	(0.0047)***	(0.0047)***	(0.0047)***	(0.0047)***
Appropriation contract	0.09217	0.09153	0.09094	0.09079	0.09061
	(0.0023)***	(0.0023)***	(0.0023)***	(0.0023)***	(0.0023)***
Precipitation (in)	-3.77834	-3.74417	-3.72503	-3.71435	-3.70726
	(0.0816)***	(0.0815)***	(0.0816)***	(0.0817)***	(0.0818)***
Potential recharge (in)	4.24137	4.29666	4.30617	4.30866	4.31787
	(0.3714)***	(0.3706)***	(0.3703)***	(0.3704)***	(0.3704)***
Mean slope	-2.46893	-2.55841	-2.59765	-2.60656	-2.62497
	(0.4090)***	(0.4081)***	(0.4079)***	(0.4080)***	(0.4081)***
Irrigated capability class	6.11471	6.02273	5.94045	5.91479	5.94918
=2	(0.8042)***	(0.8024)***	(0.8019)***	(0.8022)***	(0.8021)***
Irrigated capability class	-3.67411	-3.05122	-2.83875	-2.78663	-2.71070
=3	(1.3928)**	(1.3913)*	(1.3921)*	(1.3931)*	(1.3940)
Irrigated capability class	22.08771	22.90146	23.40200	23.54916	23.63303
=4	(2.6863)***	(2.6816)***	(2.6826)***	(2.6844)***	(2.6855)***
Irrigated capability class	24.75862	26.12020	25.94862	26.10584	26.28738
=5	(5.8976)***	(5.8859)***	(5.8811)***	(5.8830)***	(5.8839)***
Irrigated capability class	41.46339	42.64508	42.70547	42.64843	42.78908
=6	(3.7169)***	(3.7105)***	(3.7084)***	(3.7090)***	(3.7100)***
Available water capacity	-4.45e+02	-4.39e+02	-4.38e+02	-4.38e+02	-4.37e+02
	(16.5489)***	(16.5224)***	(16.5171)***	(16.5198)***	(16.5286)***
Constant	178.93640	176.78933	176.12149	175.84160	175.44016
	(3.8134)***	(3.8114)***	(3.8158)***	(3.8204)***	(3.8263)***
N	65284	65284	65284	65284	65284
r^2	0.5309	0.5330	0.5337	0.5336	0.5335
partial r^2 (first stage)	0.3910	0.5769	0.7007	0.7836	0.8195
Average effect	**0.01509**	**0.01052**	**0.00222**	**0.00101**	**0.00053**

Note: * $p<0.05$, ** $p<0.01$, *** $p<0.001$. Neighbors' pumping is a weighted sum, absolute value of the weights. Standard errors in parentheses. Average effect=beta on neighbors' pumping*average weight.

Table 6: IV Regressions of Acre-feet Pumped, Using the Amount Pumped Exclusive of Inner Radius

	(6) 1-mile cutoff	(7) 2-mile cutoff	(8) 3-mile cutoff	(9) 4-mile cutoff
Neighbors' pumping	0.00022	0.00007	0.00010	0.00006
	(0.0000)***	(0.0000)***	(0.0000)***	(0.0000)***
Acres planted on irrigatable land	0.79897	0.79877	0.79660	0.79790
	(0.0047)***	(0.0047)***	(0.0047)***	(0.0047)***
Appropriation contract	0.09167	0.09139	0.09080	0.09092
	(0.0023)***	(0.0023)***	(0.0023)***	(0.0023)***
Precipitation (in)	-3.74161	-3.74310	-3.70951	-3.72027
	(0.0815)***	(0.0817)***	(0.0821)***	(0.0819)***
Potential recharge (in)	4.27663	4.26826	4.30063	4.29854
	(0.3706)***	(0.3708)***	(0.3708)***	(0.3709)***
Mean slope	-2.58794	-2.56209	-2.60318	-2.60740
	(0.4083)***	(0.4085)***	(0.4085)***	(0.4086)***
Irrigated capability class =2	6.01878	5.99397	5.90909	6.04846
	(0.8026)***	(0.8031)***	(0.8032)***	(0.8028)***
Irrigated capability class =3	-3.07169	-3.18339	-2.84012	-2.93417
	(1.3917)*	(1.3937)*	(1.3967)*	(1.3957)*
Irrigated capability class =4	22.88105	22.92909	23.53638	23.23122
	(2.6825)***	(2.6865)***	(2.6911)***	(2.6881)***
Irrigated capability class =5	26.10240	25.28065	26.11514	26.01200
	(5.8878)***	(5.8888)***	(5.8904)***	(5.8910)***
Irrigated capability class =6	42.63485	42.10414	42.42749	42.52944
	(3.7118)***	(3.7128)***	(3.7131)***	(3.7146)***
Available water capacity	-4.38e+02	-4.41e+02	-4.39e+02	-4.38e+02
	(16.5309)***	(16.5369)***	(16.5385)***	(16.5551)***
Constant	176.75127	177.25204	175.89942	176.04547
	(3.8132)***	(3.8196)***	(3.8359)***	(3.8340)***
N	65284	65284	65284	65284
r^2	0.5327	0.5324	0.5327	0.5325
partial r^2 (first stage)	0.6152	0.6995	0.4180	0.7781
Average effect	**0.01030**	**0.00168**	**0.00159**	**0.00086**

Note: * p<0.05, ** p<0.01, *** p<0.001. Neighbors' pumping is a weighted sum, absolute value of the weights, exclusive of pumping in the smaller radius, i.e., 1-mile cutoff is exclusive of pumping in half-mile radius, 2-mile cutoff is exclusive of pumping in 1-mile raduis. Standard errors in parentheses. Average effect is beta on neighbors' pumping times the average weight.

Table 7: IV Regressions of Acre-feet Pumped, Differentiating Between Positive and Negative Weights

	(10) 1-mile cutoff	(11) 2-mile cutoff
Neighbors' pumping	0.00027	0.00013
(positive weights)	(0.0000)***	(0.0000)***
Neighbors' pumping	0.00015	0.00003
(negative weights)	(0.0000)***	(0.0000)*
Acres planted on	0.79911	0.79728
irrigatable land	(0.0047)***	(0.0047)***
Appropriation contract (acre-feet)	0.09154	0.09098
	(0.0023)***	(0.0023)***
Precipitation (in)	-3.74439	-3.72594
	(0.0815)***	(0.0816)***
Potential recharge (in)	4.29551	4.30709
	(0.3705)***	(0.3703)***
Mean slope	-2.55733	-2.59943
	(0.4081)***	(0.4078)***
Irrigated capability class	6.02494	5.93020
=2	(0.8024)***	(0.8019)***
Irrigated capability class	-3.04101	-2.87533
=3	(1.3912)*	(1.3920)*
Irrigated capability class	22.89804	23.39979
=4	(2.6816)***	(2.6823)***
Irrigated capability class	26.13146	26.24546
=5	(5.8858)***	(5.8809)***
Irrigated capability class	42.65085	42.68350
=6	(3.7105)***	(3.7080)***
Available water capacity	-4.39e+02	-4.38e+02
	(16.5223)***	(16.5157)***
Constant	176.77195	176.19490
	(3.8114)***	(3.8155)***
N	65284	65284
r^2	0.53306	0.53388
Average effect, positive weights	**0.01353**	**0.00362**
Average effect, negative weights	**0.00752**	**0.00060**

Note: * p<0.05, ** p<0.01, *** p<0.001. Neighbors' pumping is a weighted sum, absolute value of the weights. Standard errors in parentheses. Average effect is beta on neighbors' pumping times the average weight.

Table 8: First Stage Relationship Between Neighbors' Pumping and Neighbors' Appropriation Contracts. Dependent Variable: Absolute Value of Neighbors' Pumping

		Estimated coefficients	Constant	r^2
Independent variable:	Neighbors' contracts	Neighbors' contracts, exclusive		
0.5-mile cutoff	0.3601***		162.44***	0.4144
1-mile cutoff	0.4655***		534.47***	0.5764
2-mile cutoff	0.4657***		1514.10***	0.7041
3-mile cutoff	0.4734***		2478.76***	0.7878
4-mile cutoff	0.4716***		3955.75***	0.8251
1-mile cutoff		0.4910***	332.53***	0.6085
2-mile cutoff		0.4443***	1497.01***	0.6986
3-mile cutoff		0 .4569***	1766.55***	0.7674
4-mile cutoff		0.4556***	1983.75***	0.7886

Note: * p<0.05, ** p<0.01, *** p<0.001

References

Brock, W.A., and S.N. Durlauf. 2001. "Discrete Choice with Social Interactions." *Review of Economic Studies* 68:235–260.

Brozovic, N., D.L. Sunding, and D. Zilberman. 2002. "Optimal Management of Groundwater Over Space and Time." *Frontiers in Water Resource Economics* 29:109–135.

Brutsaert, W. 2005. *Hydrology: An Introduction*. Cambridge University Press.

Burt, O.R. 1964. "Optimal Resource Use Over Time with an Application to Ground Water." *Management Science* 11:80–93.

Conley, T.G., and G. Topa. 2002. "Socio-Economic Distance and Spatial Patterns in Unemployment." *Journal of Applied Econometrics* 17:303–327.

Dasgupta, P., and G.M. Heal. 1979. *Economic theory and exhaustible resources*. Cambridge, England: Cambridge University Press.

Eswaran, M., and T. Lewis. 1984. "Appropriability and the Extraction of a Common Property Resource." *Economica* 51:393–400.

Freeze, R.A., and J.A. Cherry. 1979. *Groundwater*. Prentice-Hall.

Gisser, M., and D.A. Sanchez. 1980. "Competition Versus Optimal Control in Groundwater Pumping." *Water Resources Research* 16:638–642.

Glaeser, E.L., B. Sacerdote, and J.A. Scheinkman. 1996. "Crime and Socail Interactions." *The Quarterly Journal of Econmics* 111:507–548.

Heath, R.C. 1983. "Basic Ground-water Hydrology." U.S. Geological Survey Water-Supply Paper No. 2220, U.S.G.S.

Irwin, E.G., and N.E. Bockstael. 2002. "Interacting agents, spatial externalities and the evolution of residential land use patterns." *Journal of Economic Geography* 2:31–54.

Janmaat, J.A. 2005. "Sharing Clams: Tragedy of an Incomplete Commons." *Journal of Environmental Economics and Management* 49:26–51.

Libecap, G.D., and S.N. Wiggins. 1984. "Contractual Responses to the Common Pool: Prorationing of Crude Oil Production." *The American Economic Review* 74:87–98.

Lin, C.Y.C. forthcoming. "Estimating Strategic Interactions in Petroleum Exploration." *Energy Economics*, pp. .

Manski, C.F. 1993. "Identification of Endogenous Social Effects: The Reflection Problem." *The Review of Economic Studies* 60:531–542.

Moffitt, R.A. 2001. *Social Dynamics*, Brookings Institution and MIT Press, chap. Policy Interventions, Low-Level Equilibria, and Social Interactions. pp. 45–82.

Msangi, S. 2004. "Managing Groundwater in the Presence of Asymmetry: Three Essays." PhD dissertation, University of California, Davis.

Negri, D.H. 1989. "Common Property Aquifer as a Differential Game." *Water Resources Research* 25:9–15.

Peck, J.C. 1995. "The Kansas Water Appropriation Act: A Fifty-Year Perspective." *Kansas Law Review* 43:735–756.

Pfeiffer, L., and C.Y.C. Lin. 2009. "Property Rights and Groundwater Extration in Kansas's High Plains Aquifer." Unpublished, Working paper.

Provencher, B., and O. Burt. 1993. "The Externalities Associated with the Common Property Exploitation of Groundwater." *Journal of Environmental Economics and Management* 24(2):139–158.

Robalino, J.A., and A. Pfaff. 2005. "Contagious Development: Neighbors' Interactions in Deforestation." Unpublished, Columbia University Working Paper.

Rubio, S.J., and B. Casino. 2003. "Strategic Behavior and Efficiency in the Common Property Extraction of Groundwater." *Environmental and Resource Economics* 26:73–87.

Saak, A.E., and J.M. Peterson. 2007. "Groundwater Use Under Incomplete Information." *Journal of Environmental Economics and Management* 54:214–228.

Sanchirico, J.N., and J.E. Wilen. 2005. "Optimal Spatial Management of Renewable Resources: Matching Policy Scope to Ecosystem Scale." *Journal of Environmental Economics and Management* 50:23–46.