# The management of groundwater: Irrigation efficiency, policy, institutions, and externalities[1]

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**Abstract**

The management of groundwater resources for use in agriculture is an issue that reaches far and wide; many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels. There is a socially optimal rate of extraction that can be modeled, measured, and achieved through policy and a complete definition of the property rights that govern groundwater. However, there are several factors that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. These include increases in irrigation efficiency, perverse incentives from policy, institutional incentives, and externalities.

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# 1. Introduction

The management of groundwater resources for use in agriculture is an issue that reaches far and wide; many of the world's most productive agricultural basins depend on groundwater and have experienced declines in water table levels. The food consumers eat, the farmers who produce that food, and the local economies supporting that production are all affected by the availability of groundwater.  Worldwide, about 60 percent of groundwater withdrawn is used agriculture, and in some countries, the percent of groundwater extracted for irrigation can be as high as 90 percent (National Groundwater Association, 2015).  Increasing competition for water from cities and environmental needs, as well as concerns about future climate variability and more frequent droughts, have caused policy makers look for ways to decrease the consumptive use of water.

There is a socially optimal rate of extraction that can be modeled, measured, and achieved through policy and a complete definition of the property rights that govern groundwater. Social optimality can incorporate environmental amenities that provide value to people, ecosystems, or environments. Complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource will induce the socially optimal rate of extraction in many cases. Where externalities occur, whether they are caused by the physical movement of water, by environmental damages or benefits, or by other causes, well thought-out policy can provide the incentives to move an individual's extraction path back to the socially optimal one.

There are two main reasons why the farmers may be overpumping relative to what would be the socially optimal water pumping.  First, owing to institutional reasons farmers may not be optimizing dynamically: they might not be considering the effects of current pumping on the amount of water that would be available to pump in the future. For example, as explained below, the prior appropriation doctrine is an institution that distorts the incentive to optimize dynamically over the life of the resource, because farmers are unable to bank any unused portions of the water allocation in a particular year for use in future years. A second reason farmers may be overextracting the resource is owing to a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects the amount of water they have available to pump.

There are several factors that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. These include increases in irrigation efficiency, perverse incentives from policy, institutional incentives, and externalities.

One factor that may lead farmers to overextract groundwater are increases in irrigation efficiency. It is possible for increases in irrigation efficiency to lead to increases in groundwater extraction. In particular, if demand is elastic enough, if the higher efficiency technology operates at a lower marginal cost, and if the higher efficiency technology increases revenue, then irrigation efficiency will increase groundwater extraction (Pfeiffer and Lin, 2014).

A second factor that may lead farmers to overextract groundwater are perverse incentives from policy. One such type of policy are voluntary, incentive-based water conservation programs for irrigated agriculture. These programs are often considered win-win policies; their objective is to reduce the consumptive use of water for agriculture, and they also often contribute to an increase in the earning potential of farms through the yield-increasing effect of efficient irrigation technology (Cox, 2013). For this reason, these programs are extremely popular and politically feasible, especially where the resource is considered scarce. However, when behavioral responses of the irrigator are ignored, such policies can have unintended or even perverse consequences. For example, programs that subsidize efficient irrigation technology cause farmers to respond by switching to more water intensive crops, thereby increasing, not decreasing, water extraction (Pfeiffer and Lin, 2014).

A third factor that may lead farmers to overextract groundwater are institutional incentives, and, in particular, how the prior appropriation doctrine affects dynamic optimality. Groundwater users extract water under an institutional setting that governs their property rights to the groundwater and affects constraints they face and the choices they make. The prior appropriation doctrine allots water rights based on historical use, with priority going to those who claimed their right first. Appropriation contracts are stated in terms of a maximum acre-feet of extraction per year with a "use it or lose it" clause. Farmers must use their allocation each year and are unable to bank any unused portions of the water allocation in a particular year for use in future years. However, since the groundwater is in part a nonrenewable resource, since the availability of water is stochastic, since demand for water is greater when it is less available, farmers could operate in a more dynamically efficient manner if the appropriator could use less water in some years and more in others.

A fourth factor that may lead farmers to overextract groundwater are externalities. For example, one reason farmers overextract water is due to a common pool resource problem: they share the aquifer with other farmers, and thus other farmers' pumping affects water availability. 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.

Thus, increases in irrigation efficiency, perverse incentives from policy, institutional incentives, and externalities can affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. I now discuss each of these factors in turn.

## 2. Increases in irrigation efficiency

Increases in irrigation efficiency may be one factor that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. Irrigation efficiency is defined as the proportion of consumed water (also called "consumptive use") that is beneficially used by a crop ("effective water") and is given by (Burt et al., 1997; Pfeiffer and Lin, 2014):

$$\text{irrigation efficiency} = \frac{\text{effective water}}{\text{consumptive use of water}}. \tag{1}$$

More efficient irrigation systems increase this proportion, allowing less water to be applied for a given yield. In many watersheds, some portion of the irrigation water applied flows downstream as runoff, or recharges the aquifer via percolation. In these cases, the "consumptive use of water" is equal to applied water minus this return flow, and the spatial unit of irrigation efficiency must be defined because irrigation efficiency at the basin level would diverge from that at the field level by the amount of water that is reused (Huffaker, 2008; Ward and Pulido-Velazquez, 2008; Huffaker and Whittlesey, 2000).

True water conservation occurs only with a decrease in individual consumptive use. Changes in irrigation efficiency may change a farmer's profit maximization problem, and can result in behavioral changes that affect individual consumptive use.

A limited amount of theoretical research has attempted to determine the conditions under which an increase in irrigation efficiency would result in a decrease in consumptive use. Caswell and Zilberman (1983) focuses on how irrigation efficiency improves the "effectiveness" of variable inputs, which are combined with heterogeneous land qualities, for crop production. Land-augmenting technologies such as more efficient irrigation increase the ability of lower quality soils to provide water and nutrients to crops (Caswell and Zilberman, 1986). Caswell and Zilberman (1983) show that land quality variation affects the extent of technology adoption. They also show that effective water and yields will always increase when a more efficient irrigation technology is adopted, but the change in actual irrigation application depends on the elasticity of the marginal productivity of water, which can also be interpreted as the elasticity of demand for irrigation water, as they are equal at the optimal solution. When demand is inelastic (corresponding to the section of the production function nearing full irrigation, where the marginal yield response is relatively weak), an increase in irrigation efficiency results in a decrease in irrigation. When water demand is elastic (corresponding to a strong marginal yield response), increases in irrigation efficiency will increase irrigation. Huffaker and Whittlesey (2003) develop a similar model incorporating the possibility of return flows.

Empirical estimates of the elasticity of demand for irrigation water are limited, but of those that exist, they suggest that the demand for irrigation water is inelastic (Hendricks and Peterson, 2012; Moore, Gollehon and Carey, 1994; Schoengold, Sunding and Moreno, 2006; Scheierling, Loomis and Young, 2006), meaning that an increase in irrigation efficiency would reduce groundwater extraction.

However, a larger body of research has focused on the development of data-calibrated simulation models to predict the effects of increasing irrigation efficiency on irrigation. Ellis, Lacewell and Reneau (1985) develop a model to analyze the adoption of limited tillage and dropped nozzles in the high plains region of Texas. They find that because dropped nozzles improve delivery efficiency and reduce the variable cost of irrigation, producers would apply more water per acre to increase yields, plant more water intensive crops, and increase irrigated acreage. However, total water use over the 40-year horizon considered remained essentially constant because in their model, water withdrawals were limited by annual pumping limits.

Huffaker and Whittlesey (2000) model private investment in a more efficient irrigation technology and its effect on conservation. They find that investment was only cost-effective when consumptive use was below the yield maximizing level with the status quo technology because of some constraint, like a low precipitation year. The investment in irrigation efficiency would be used to increase yields, and consumptive use would increase.

Scheierling, Young and Cardon (2006) incorporate an agronomic simulation model with an economic linear programming model to study the effects of an irrigation efficiency subsidy. They find that consumptive use never decreased as a result of the subsidy; the number of irrigations increased when acreage was fixed, and the number of irrigated acres of the most water intensive crop (corn) increased when acreage was not fixed.

Ward and Pulido-Velazquez (2008) analyze the effect of subsidies for the adoption of drip irrigation in New Mexico’s Rio Grande Basin on crop yields, irrigated acreage, income, and total water depletion over a 20-year time horizon. They find that yields and net farm income increased under the subsidy, but total water depletion was always greater than the case with no subsidy for irrigation technology. When total irrigated acreage was allowed to increase in the model, water depletion increased even more.

Contor and Taylor (2013) show that in general it is the case that total consumptive use increases when efficiency improves, due to rational producer behavior in equating the marginal cost of a production input (irrigation water) with its marginal benefit.

In contrast, Peterson and Ding (2005) find that conversion from flood irrigation to center pivots could reduce overall irrigation water use for corn in Western Kansas. However, they do not consider the possibility of changes in cropping patterns or the expansion of irrigated acreage, and their results rely on the assumption that flood systems can irrigate all 160 acres of a 160 acre field, while center pivots can irrigate only 126 of the 160 acres. In reality, the remaining corners may be irrigated with various types of corner irrigation systems.

These studies expose what seems to be a disconnect between the theoretical literature, which posits that the demand for irrigation water must be elastic for an increase in irrigation efficiency to result in an increase in consumptive use, and data-calibrated simulations models, which under reasonable assumptions often find that an increase in irrigation efficiency increases consumptive use. Caswell and Zilberman's (1983) and Huffaker and Whittlesey's (2000) models focus on land conversion. They use single crop, single year models that do not allow for the possibility that the technology may affect crop revenue and cost functions as well.

Most of these assumptions are unreasonable for a modern crop production system. The relevant time horizon is longer than one season; the use of crop rotation patterns and fallow cycles is ubiquitous, so over the planning horizon a farmer would likely be irrigating at less than full irrigation. The long-term demand for irrigation water is likely to be more elastic than the short-term demand (Hendricks and Peterson, 2012).

In addition, efficient irrigation technologies such as dropped nozzles are known to affect the revenue and cost functions directly. The higher efficiency and directed spray pattern of dropped nozzles aid with the inter-seasonal timing of irrigation, allowing farmers to better fulfill a crop’s water requirements during peak water demand days and critical growth stages (New and Fipps, 1990; Peterson and Ding, 2005). Experimental station research has shown that corn yields under dropped nozzles can be up to 13 percent higher than yields under conventional center pivots, and that the yield benefit is greatest under irrigation deficit situations such as drought or cases in which a farmer's pumping limit is insufficient for full irrigation (New and Fipps, 1990, Howell et al., 1995; Schneider and Howell, 1998; O'Brien et al., 2001). Dropped nozzle systems require significantly less pressure than conventional center pivots to operate, which would decrease the energy cost of groundwater extraction and application (Rogers. Alam and Shaw, 2008).

Pfeiffer and Lin (2014) incorporate these revenue and cost effects into the basic structure of Caswell and Zilberman's (1983) model. In their model, $f(x,k)$ denotes the revenue earned from the use of a productive input *x*, where *x* is derived from an input *q* that is acquired and then transformed at some rate *k*. Here, *q* is applied water $k \in [0,1]$ is irrigation efficiency, and *x* is effective water. Irrigation efficiency affects the revenue function through the transformation of applied water into effective water, as well as directly, by allowing farmers to better fulfill the crop's water requirements during critical growth stages. The farmer solves the following optimization problem:

$$\begin{aligned} &\max_x \; f(x,k) - c(k)q \\ &\text{s.t.} \;\; x = kq \end{aligned} , \tag{2}$$

where $c(k)$ is the marginal cost of water extraction and application. This yields the following first-order condition:

$$\frac{\partial f(x,k)}{\partial x} = c(k)/k , \tag{3}$$

which can also be written as the demand function $X(\cdot)$ for effective water:

$$x = X(c(k)/k, k) = \tilde{f}^{-1}(c(k)/k; k) , \tag{4}$$

where $\tilde{f}^{-1}(\cdot;k)$ denotes the inverse of the partial derivative of $f(\cdot)$ with respect to $x$ (i.e., the inverse of the left-hand-side of equation (3)). Then, denoting $\tilde{c} = c(k)/k$, the price of effective water, and substituting $x = kq$ into equation (4), the demand function for applied water is:

$$q = X(c(k)/k, k)/k \ , \tag{5}$$

and the effect of a change in irrigation efficiency on the demand for applied water is:

$$\frac{\partial q}{\partial k} = k^{-1}\left( \frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)k^{-1} - \frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c(k)k^{-2} + \frac{\partial X(\tilde{c},k)}{\partial k} - X(\tilde{c},k)k^{-1} \right). \tag{6}$$

This implies the following necessary and sufficient condition for increased irrigation efficiency to increase applied water:

$$\frac{\partial q}{\partial k} > 0 \Leftrightarrow \tag{7}$$

$$|\eta_x| > 1 - \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} c'(k)}{X(\tilde{c},k)} - \frac{\frac{\partial X(\tilde{c},k)}{\partial k} k}{X(\tilde{c},k)}, \tag{8}$$

where $\eta_x = \frac{\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} \tilde{c}(k)}{X(\tilde{c},k)}$ is the elasticity of demand for effective water. Since demand is downward sloping, $\frac{\partial X(\tilde{c},k)}{\partial \tilde{c}} < 0$, which means the first fraction on the right-hand-side of the inequality in equation (8) for the elasticity is positive if there is a negative cost effect $c'(k) < 0$ (the higher efficiency technology operates at a lower marginal cost); and the second fraction is positive if there is a positive revenue effect $\frac{\partial X(\tilde{c},k)}{\partial k} > 0$ (the higher efficiency technology increases revenue).

Thus, if demand is elastic enough, the higher efficiency technology operates at a lower marginal cost, and the higher efficiency technology increases revenue, then irrigation efficiency will increase applied water (Pfeiffer and Lin, 2014). Pfeiffer and Lin (2014) provide back-of-the-envelope calculations for the elasticity of demand, revenue, and cost effects in western Kansas, showing that it is plausible for the inequality in equation (8) to hold, thus making it possible that increases irrigation efficiency may increase groundwater extraction.

## 3. Perverse incentives from policy

Perverse incentives from policy may be a second factor that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. An example of perverse incentives from policy is the behavioral response to conservation programs.

In many places, policymakers have attempted to decrease rates of extraction through incentive-based water conservation programs. Between 1998 and 2005, the state of Kansas spent nearly $6 million on incentive programs, such as the Irrigation Water Conservation Fund and the Environmental Quality Incentives Program, to fund the adoption of more efficient irrigation systems. Such programs paid up to 75% of the cost of purchasing and installing new or upgraded irrigation technology, and much of the money was used for conversions to dropped nozzle systems (NRCS, 2004). These policies were implemented under the auspices of groundwater conservation, in response to declining aquifer levels occurring in some portions of the state due to extensive groundwater pumping for irrigation (Committee, 2001).

Voluntary, incentive-based water conservation programs for irrigated agriculture are often billed as policies where everyone gains. Their objective is to reduce the consumptive use of water for agriculture, and they also often contribute to an increase in the earning potential of farms through the yield-increasing effect of efficient irrigation technology (Cox, 2013).

Moreover, farmers are able to install or upgrade their irrigation systems at a reduced cost, resulting in substantial increases in profits; less groundwater is "wasted" through runoff, evaporation, or drift; marginal lands can be profitably retired; and farmers can choose whether to participate. For these reasons, these programs are extremely popular and politically feasible, especially where the resource is considered scarce. However, when behavioral responses of the irrigator are ignored, such policies can have unintended or even perverse consequences.

Pfeiffer and Lin (2014) find that policies that encourage the adoption of more efficient irrigation technology may not have the intended effect. Irrigation is said to be "productivity enhancing"; it allows the production of higher value crops on previously marginal land. Thus, a policy of subsidizing more efficient irrigation technology can induce a shift away from dry-land crops to irrigated crops. They may also induce the planting of more water-intensive crops on already irrigated land, as by definition, more efficient irrigation increases the amount of water the crop receives per unit extracted.

Similarly, land and water conservation and retirement programs may not necessarily reduce groundwater extraction, although they are billed as such. An example of a land retirement program is the Conservation Reserve Program created by the federal government in 1985 to provide technical and financial assistance to eligible farmers and ranchers to address soil, water, and related natural resource concerns on their lands in an environmentally beneficial and cost-effective manner (USDA, 2014). These programs include payments to landowners to retire, leave fallow, or plant non-irrigated crops on their land. Such programs operate on an offer-based contract between the landowner and the coordinating government agency. The contractual relationship is subject to asymmetric information, and adverse selection may arise because the landowner has better information about the opportunity cost of supplying the environmental amenity than does the conservation agent. There is substantial evidence that farmers enroll their least productive, least intensively farmed lands in the programs while receiving payments higher than their opportunity costs, thus accruing rents. It is quite unlikely that an irrigated parcel, which requires considerable investment in a system of irrigation (which, in turn, enhances the productivity of the parcel), will be among a farmer's plots with the lowest opportunity cost and thus enrolled in the program. Instead, farmers may opt to enroll non-irrigated plots in the Conservation Reserve Program, which does not have any effect on the amount of irrigation water extracted.

Pfeiffer and Lin's (2014) study, which has been cited in the New York Times (Wines, 2013) and the Washington Post (Howitt and Lund, 2014), focuses on incentive-based groundwater conservation policies in Kansas and finds that measures taken by the state of Kansas to subsidize a shift toward more efficient irrigation systems have not been effective in reducing groundwater extraction. The subsidized shift toward more efficient irrigation systems has in fact increased extraction through a shift in cropping patterns. Better irrigation systems allow more water-intensive crops to be produced at a higher marginal profit. The farmer has an incentive to both increase irrigated acreage and produce more water-intensive crops.

Pfeiffer and Lin (2014) find similar results in their analysis of the effects of land and water conservation and retirement programs on groundwater extraction. Theory predicts that because the programs are offer-based, farmers will enroll their least productive land. Pfeiffer and Lin's (2014) empirical results support this conclusion; they find essentially no effect of land conservation programs on groundwater pumping, which occurs, by definition, on irrigated, and thus, very productive land.

## 4. Institutional incentives

A third factor that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater are  institutional reasons that distort farmers' incentives to optimize dynamically so that they might not be considering the effects of current pumping on the amount of water that would be available to pump in the future.

Groundwater users extract water under an institutional setting that governs their property rights to the groundwater and affects constraints they face and the choices they make. A variety of property rights doctrines and institutions governing groundwater have evolved in the western United States. Many more institutions, both formal and informal, are in place in other locations around the world.

The hydrological characteristics of an aquifer affect the way that property rights over its water should be defined. For example, if water flows easily in an aquifer, the inefficiencies associated with the exploitation of common property resources are more likely (Dasgupta and Heal, 1979; Eswaran and Lewis, 1984). Additionally, the amount of recharge that an aquifer receives helps determine the economically efficient extraction path. If an aquifer receives very little recharge, it is least partially a nonrenewable resource and its social welfare maximizing extraction path can be described by a Hotelling-like model (Hotelling, 1931).

Current water rights in Kansas follow the prior appropriation doctrine. Before 1945, Kansas applied the common law of absolute ownership doctrine to groundwater. Water rights were not quantified in any way (Peck, 2007). In 1945, following multiple conflicts between water users and several major water cases that reached the Kansas Supreme Court, the "Arid Region Doctrine of Appropriation" was adopted, which permitted water extraction based on the principle of "first in time, first in right" (Peck, 1995).

The earliest appropriators of water maintain the first rights to continue to use water in times of shortage or conflict. The water right comes with an abandonment clause; if the water is not used for beneficial purposes for longer than the prescribed time period, then it is subject to revocation (Peck, 2003). To obtain a new water right, an application stating the location of the proposed point of diversion, the maximum flow rate, the quantity desired, the intended use, and the intended place of use must be submitted to and approved by the Department of Water Resources (Kansas Handbook of Water Rights, n.d.). Since 1945, Kansas has issued more than 40,000 groundwater appropriation permits (Peck, 1995).[2] The permits specify an amount of water that can be extracted each year and are constant over time.

Through the 1970s, the period of intensive agricultural development in Kansas, groundwater pumping permits were granted to nearly anyone who requested them. Some permits are as old as 1945, but the majority (about 75 percent) were allocated between 1963 and 1981 (Lin and Pfeiffer, 2015; Lin Lawell, 2015).

In the early 1970s, it was recognized that Kansas's groundwater resources were being depleted at a rapid rate in some locations. By 2008, in parts of southwestern Kansas, the water table has declined by over 150 feet since predevelopment.[3] This area was the first to be intensively developed, and continues to have the highest average extraction per square mile (Wilson et al., 2002).

In 1972, owing to concerns that the aquifer was over-appropriated, Kansas created five groundwater management districts (GMDs). The GMDs regulate well spacing and prohibit new water extraction within a designated radius of existing wells, which varies by GMD. The adoption of the prior appropriation doctrine, together with the development of GMDs to regulate

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[2] In the 2007 Census, there were 65,531 farms in all of Kansas, of which approximately 29,039 were located in regions that roughly overlie the aquifer (USDA, 2011).

[3] "Predevelopment" is defined as the water level in about 1960, when the first measurements were made.

new appropriations of water rights, arguably eliminated uncontrolled entry and the resulting over-exploitation commonly associated with common property resources (Lin and Pfeiffer, 2015; Lin Lawell, 2015).

The prior appropriation doctrine allots water rights based on historical use, with priority going to those who claimed their right first. Appropriation contracts are stated in terms of a maximum acre-feet of extraction per year with a “use it or lose it” clause. Farmers must use their allocation each year and are unable to bank any unused portions of the water allocation in a particular year for use in future years (Lin and Pfeiffer, 2015; Lin Lawell, 2015). Appropriation contracts therefore distort the incentive to optimize dynamically over the life of the resource, because the farmer is essentially guaranteed his appropriated amount of water until the resource becomes so scarce that it is no longer economical to pump. Since the groundwater is in part a nonrenewable resource, since the availability of water is stochastic, since demand for water is greater when it is less available, farmers could operate in a more dynamically efficient manner if the appropriator could use less water in some years and more in others.

Lin Lawell (2015) develops an empirical model to test whether groundwater users faced with the prior appropriation doctrine are behaving in a manner consistent with a dynamic model of nonrenewable resource extraction. In particular, do groundwater managers (individual farmers, in this case) consider the scarcity rent or shadow value of their resource when making extraction decisions? Or are they more myopic in their water extraction behavior, perhaps due to the incentives they face from the prior appropriation doctrine? This is one of the first studies to empirically test the hypotheses of the theoretical groundwater management literature.

Lin Lawell (2015) finds that despite the incentives given to groundwater users to pump their maximum allowable amount in each year by the prior appropriation doctrine, farmers extract water consistent with a dynamic model of resource extraction. While producers are allotted a time-invariant maximum amount that they can extract each year, they still consider their remaining stock of water, pumping by nearby neighbors, and projections of future commodities prices when making crop choice and pumping decisions. Her results therefore provide evidence that farmers recognize the nonrenewable nature of the resource that they manage, even though their property rights do not.

## 5. Externalities

A fourth factor that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater are externalities.

One example of an externality that arises in groundwater are spatial externalities. Spatial externalities arise because groundwater users face a common pool resource problem: because farmers are sharing the aquifer with other farmers, other farmers' pumping affects their extraction cost and the amount of water they have available to pump. 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; Brozovic, Sunding and Zilberman, 2002; Rubio and Casino, 2003; Msangi, 2004; Saak and Peterson, 2007).

Pfeiffer and Lin (2012) investigate the behavior of farmers who share a common pool resource. They develop a spatial dynamic physical-economic model to characterize agricultural groundwater users' pumping behavior. They 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 whose groundwater is an incomplete common good because they cannot fully capture the groundwater beneath their land.

Pfeiffer and Lin (2012) then empirically examine whether the amount of water one farmer extracts depends on how much water his neighbor extracts. In particular, they use data from western Kansas to econometrically determine if the pumping behavior of neighbors affects the groundwater extraction 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. Their results provide evidence of a spatial externality that causes farmers to overextract water.

Measuring interactions between neighbors is challenging 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, 2012; Moffitt, 2001). The interaction of neighbors has been studied in oil extraction (Libecap and Wiggins, 1984; Lin, 2009). It has also been investigated in land use change using physical attributes of neighboring parcels as instruments to identify the effect of the behavior of neighbors on an individual (Irwin and Bockstael, 2002; Robalino and Pfaff, 2012).

Pfeiffer and Lin (2012) 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. The permit amount for one's neighbors is a strong determinant of the actual pumping by one's neighbors, but is uncorrelated with one's own actual pumping, except through the effect of neighbors' pumping on one's own pumping. They therefore use the permit amount of one's neighbors as an instrument for neighbors' water pumping.

To take into account the way in which water moves through an aquifer, Pfeiffer and Lin (2012) weight their instrument by a function of the distance between each neighbor and the difference in lift height between neighbors that takes into account the way in which water moves through an aquifer. These weights adjust the amount pumped by the effect that it should have. If the distance between two wells is greater, the effect should be smaller. If the height gradient is larger, the effect should be greater.

Pfeiffer and Lin's (2012) study 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 his 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.

According to their results, Pfeiffer and Lin (2012) find evidence of a behavioral response to this movement in the agricultural region of western Kansas overlying the High Plains Aquifer. Spatial externalities resulting from the inability to completely capture the groundwater to which property rights are assigned cause some degree of over-extraction in theoretical models. Using an instrumental variable and spatial weight matrices to overcome estimation difficulties resulting from simultaneity and spatial correlation, they find that on average, the spatial externality causes over-extraction that accounts for about 2.5 percent of total pumping. Kansas farmers would apply 2.5 percent less water in the absence of spatial externalities (if, as an unrealistic example, each farmer had an impenetrable tank of water that held his or her portion of the aquifer).

Strengthening the evidence of the behavioral response to the spatial externalities caused by the movement of groundwater is Pfeiffer and Lin's (2012) additional empirical result that when a farmer owns multiple wells, he does not respond to pumping at his own wells in the same manner as he responds to pumping at neighboring wells owned by others. In fact, the response to pumping at his own wells is to marginally decrease pumping, thus trading off the decrease in water levels between spatial areas and internalizing the externality that exists between his own wells.

Aquifer heterogeneity can affect the extent of the spatial externality. Aquifers vary in rock composition, which determines the extent to which the water resource is shared. Portions of an aquifer where water moves rapidly, those with high hydraulic conductivity, as well as those that receive less yearly recharge, face a more costly common-pool problem and therefore receive higher benefits from coordinated management (Edwards, forthcoming). Edwards (forthcoming) uses the introduction of management districts in Kansas to test the effect of underlying aquifer heterogeneity on changes in agricultural land value, farm size, and crop choice. A landowner in a county with hydraulic conductivity one standard deviation higher sees a relative land value increase of 5-8% when coordinated management is implemented. Counties with lower recharge also see relative increases in land value. Changes in farm size and percentage of cropland in corn are also consistent with the proposition that the effect of coordinated management is unequal and depends on properties of the physical system.

In addition to the spatial externality, another externality that arises with groundwater extraction is that groundwater pumping from aquifers can reduce the flow of surface water in nearby streams through a process known as stream depletion. In the United States, recent awareness of this externality has led to intra- and inter-state conflict and rapidly-changing water management policies and institutions. Although the marginal damage of groundwater use on stream flows depends crucially on the location of pumping relative to streams, current regulations are generally uniform over space (Kuwayama and Brozovic, 2013). Kuwayama and Brozovic (2013) use a population data set of irrigation wells in the Nebraska portion of the Republican River Basin to analyze whether adopting spatially differentiated groundwater pumping regulations leads to significant reductions in farmer abatement costs and costs from damage to streams. They find that regulators can generate most of the potential savings in total social costs without accounting for spatial heterogeneity. However, if regulators need to increase the protection of streams significantly from current levels, spatially differentiated policies will yield sizable cost savings.

## 6. Conclusion

There are several factors that may affect farmers' groundwater use decisions and behavior and may lead them to overextract groundwater. The factors discussed in this paper include increases in irrigation efficiency, perverse incentives from policy, institutional incentives, and externalities.

Complete, measured, enforceable, and enforced property rights that consider the physical properties of the resource have the possibility of inducing the socially optimal rate of extraction in many cases. Where externalities occur, whether they are caused by the physical movement of water, by environmental damages or benefits, or by other causes, well thought-out policy can provide the incentives to move an individual's extraction path back to the socially optimal one. However, in practice, not all policies induce the socially optimal rate of extraction. Incentive-based groundwater conservation programs are a prime example of a well-intentioned policy that may have perverse consequences, for they may actually increase rather than decrease groundwater extraction. Similarly, property rights regimes such as prior appropriation may adversely impact the dynamic optimality of water extraction. When designing policies and regulation, policy-makers need to be wary of any potential perverse consequences of their policies, and also be aware of the implications of their policies.

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