AgEcon SEARCH
RESEARCH IN AGRICULTURAL & APPLIED ECONOMICS

The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

Efficiency Gains Arising from Dynamic Groundwater Markets

Todd Guilfoos
University of Rhode Island

Cloe Garnache
Michigan State University

Jordan Suter
Colorado State University

Nathaniel H. Merrill
United States Environmental Protection Agency

Abstract

We demonstrate the conditions for a dynamically efficient groundwater market that considers the optimal path of extraction of the resource, the value of a finite amount of water, and incorporates hydrologic conditions that allow for spatial variability. We then apply this theory of dynamic groundwater markets to empirical data from Kansas where groundwater depletion is of considerable importance. This model sheds light on the potential gains associated with more sophisticated markets that incorporate time into the trading ratios for temporary and permanent transfers of groundwater rights. We find that with exhaustion externalities and trading among areas with and without depletion concerns, using constant trading ratios can cause large welfare losses. Though with only pumping cost externalities, the use of constant trading ratios is a good approximation of the first best outcome assuming the total number of permits is estimated accurately.

Introduction

Groundwater management is critical to sustainable agricultural development, especially in parts of the world where groundwater extraction consistently exceeds natural recharge. For example, large portions of the Ogallala aquifer and the Central Valley of California in the United States, the North China Plains Aquifer (Glieck and Palaniappan 2010), and a series of shallow aquifers, including the Neogene and Dammam aquifers in eastern Saudi Arabia face documented challenges related to sustainability. These aquifers are in danger mainly because irrigation demand is much larger than the rates of groundwater recharge in these areas (Gleeson 2012). The cumulative extraction of groundwater for irrigation has resulted in considerable decreases in land values as depletion reduces future stocks and increases extraction costs (Hornbeck and Keskin 2011). Spatial variation within groundwater resources is also important; while total water supplies in a region may be large relative to aggregate demand, areas with concentrated irrigation may still face severe shortages because of slow lateral groundwater flows. Groundwater management can therefore be socially valuable given the externalities associated with groundwater use and the concern that groundwater depletion may jeopardize future irrigation opportunities.

Water markets, where rights to use water can be bought and sold, have received considerable attention in the economics literature as a groundwater management tool (Bauer 1997; Mukherji 2004; Brennan 2006; Brown 2006; Hadjigeorgalis 2009; Goemans and Prichett 2014). Policy experts have also called for expansion of water markets as an effective tool to deal with spatial inefficiencies in water use (Thompson et al. 2009). The Bren School of Environmental Science tracked transactions in both surface water and groundwater markets from 1987 to 2008 throughout the western United States, showing that the total number of transactions in the western US grew substantially from 1987 to 2008. Figure 1, illustrates this outcome along with the significant fluctuations in the water volume transferred depending on demand that is driven by variation in seasonal precipitation. Though water markets have grown over time, this growth is primarily due to increases in surface water markets. Many groundwater basins still lack strong water institutions or robust water markets even though they face rapidly declining resource stocks and increased demand for irrigation water.

Water markets specifically designed to transfer groundwater rights are a relatively new development, with considerable uncertainty around how specific market and hydrologic features influence economic outcomes. Palazzo and Brozovic (2014) find that groundwater trading could significantly reduce the costs to farmers associated with water use reductions. They also find that cost savings can vary greatly over space when trading restrictions are enforced. Wheeler et al. (2014) highlight the challenges and design considerations when implementing groundwater markets, such as strong and consistent institutions across and within basins.

Other important challenges remain for efficient groundwater markets such as accurate pricing of future use of the resource, transaction costs (McCann and Garrick 2014), the transfer of inactive rights to active users, and the absence of flexible mechanisms that deal with price and weather uncertainty. Some areas of the world have been reluctant to adopt markets for groundwater rights for these reasons and other constraints on trading (Easter and Huang 2014). Areas such as the High Plains Aquifer and Punjab area of India (Kaur et al. 2012) face depleting groundwater stocks due in part to the underpricing of groundwater. These areas are pressed to find solutions to deal with the resource scarcity, and accurate resource pricing could play a large roll in mitigating over extraction. The need for better groundwater management and accurate pricing is all the more imperative with climate change and greater uncertainty over future irrigation supplies (Rosegrant et al. 2014). Groundwater markets in practice and in theory generally rely on the assumption that lateral groundwater flows are instantaneous resulting in homogenous aquifer depletion over space (i.e., the bathtub model). Yet, this assumption rarely holds in practice. Research is needed to incorporate uneven depletion of the aquifer into market pricing or the optimal paths of depletion into trading ratios for different groundwater users. This is critical to determining the welfare impact of resource management, as the lack of access is likely to be more important than the marginal cost of extraction.

We propose a new framework that incorporates groundwater markets and a hydrologic model to investigate the above challenges to dynamically efficient groundwater markets. Recent studies on groundwater management incorporate spatially explicit relationships that account for the realities of physical resource dynamics (Guilfoos et al. 2013; Guilfoos et al. 2016; Kuwayama and Brozovic 2013). Our contribution is to provide a more explicit theory of dynamic groundwater extraction with groundwater flows than that proposed by Kuwayama and Brozovic (2013) who define a general theory for dynamic trading ratios for groundwater extraction and its effects on stream depletion. We build off their work to account for exhaustion concerns and provide estimates and logic as to when dynamic trading ratios affect economic efficiency for groundwater management. We adopt a spatially explicit hydro-economic model that is linked to a market for groundwater use rights. We then apply this model to a numerical estimation of the benefit of a dynamically efficient groundwater market when applied to Kansas, an area with depletion concerns.

We find that the paths of shadow prices are roughly proportional in many scenarios where only heterogeneity and pumping cost externalities are present, but no exhaustion externality exists. Constant trading ratios seem sufficient for these scenarios when loss of access to the aquifer is not of great concern. When exhaustion externalities are present the path of shadow prices diverge to a greater extent and welfare losses can be significant without dynamic trading ratios. This result is largely driven by how permits are allocated and trading across areas with and without exhaustion concerns.

Model

We formulate a model that incorporates uneven depletion across the aquifer, as this can be of large importance to the size of groundwater management benefits (Guilfoos et al. 2016) and the lateral flows of groundwater with spatial and time relationships between wells (Guilfoos et al. 2013, Kuwayama and Brozovic 2014). We will use Darcy's Law to define the spatial relationships between agents whom exist on a grid over the aquifer and own wells. The dynamic problem is given:

$$max \int_0^T e^{-\rho t} \sum_{i=1}^{I} f(w_i, x_i) dt \qquad s.t. \tag{1}$$

$$\dot{x_i} = \frac{R_i - (1-\propto) w_i}{A_i S} - \sum_{i \neq j}^{J} \frac{K_i C_i (x_i - x_j)}{A_i S d_{ij}} \qquad \forall\, i$$

$$\overline{x_i} \leq x_i \qquad \forall\, i$$

$$x_i(0) = x_{0i} \qquad \forall\, i$$

The net benefit function for an agent, indexed $i = 1,2,3, \ldots I$, is given by $f(w_i, x_i)$ and is a function of time, t, the choice variable, *w*, which is water taken from the aquifer, and the state variable *x*, the height of water (saturated thickness) at well *i*. The discount rate is given by ρ. The $\overline{x_i}$ parameter accounts for the minimum water height for viable production. This constraint is meant to account for direct impacts on the productivity of the groundwater resource as saturated thickness falls. In particular, the physical limit on the quantity of water that can be pumped over a finite period of time, referred to as well capacity or yield, becomes more binding as the level of saturated thickness falls. With limited capacity, a well may not be able to deliver adequate irrigation water during key points during the growing season, thus impeding agricultural productivity and profits (Foster et al. 2014; 2015). The model presented here captures an extreme case where saturated thickness declines to a point where limited capacity implies that irrigated production is no longer as profitable as dryland production. The equation of motion includes *R*, the volumetric natural recharge, *K*, the hydraulic conductivity, specific yield, *S*, is the volume of water a unit of soil can hold, α, the return coefficient, A, the surface area of the land that a farmer inhabits, C, the cross-sectional area through which water flows between the wells adjacent to agent *i's* well, and d_{ij}, the distance between agent i and j. J is the number of adjacent agents to agent i, which we refer to as neighbors.

This problem can be written as a Lagrangian augmented with a current-value Hamiltonian to incorporate the inequality constraint in program with a slight abuse of notation (1).

$$\mathcal{L} = \sum_{i=1}^{I} \left(f_i(w_i, x_i) + \mu_i \left[\frac{R_i - (1-\propto)w_i}{A_i S} - \sum_{i \neq j}^{J} \frac{K_i C_i (x_i - x_j)}{A_i S d_{ij}} \right] + \lambda_i (x_i - \overline{x_i}) \right) \qquad (2)$$

To simplify the analysis we begin with a two-agent model. We use subscripts to index well and time notation, and superscript to denote derivatives. First, starting with a single neighbor j for agent i we derive the solution for the shadow price of water. Solving for the μ multipliers provides us with the true value of water in the ground in a given time period that incorporates the shadow price of exhaustion, $\boldsymbol{\lambda}$, as well as the external effect on other wells through lateral flows on the depletion at a particular well. Defining the intermediate variable θ_i:

$$\theta_i = \frac{\frac{K_i C_i}{A_i S d_{ij}}}{\rho + \frac{K_i C_i}{A_i S d_{ij}}}, \qquad (3)$$

we can express μ_i as

$$\mu_i = \left[f_i^w(\cdot) + f_i^x(\cdot) + \lambda_i + \left[f_j^w(\cdot) + f_j^x(\cdot) + \lambda_j \right] / (\theta_j) \right] \left(\frac{1}{1 - \frac{K_i C_i}{A_i S d_{ij}} \theta_j} \right). \qquad (4)$$

The efficient dynamic trading ratio, which represents the number of units of water from agent j that can be traded for a unit of water under agent i's land at time t, can then be defined as

$$\frac{f_{it}^w(w,x)}{f_{jt}^w(w,x)} = \frac{\mu_{it}(w,x)}{\mu_{jt}(w,x)}. \qquad (5)$$

The more complex the network of neighbors the more complex is the solution to the multiplier μ_i. For sufficiently homogeneous agents and aquifer, this model can be simplified and dynamic trading ratios may be irrelevant. Given our interest in depletion we note that one key term here is the discounted effect that the multiplier, λ_j, has on agent *i* in equation (4). This term indicates the shadow price associated with depletion at each well. It is apparent that the multiplier μ_i is also a function of agent *j*'s constraint on depletion; the value of a spatially variable and dynamic market rests on the heterogeneity of μ across time and space.

To help understand the importance of the time path of shadow prices we introduce logical proofs of when dynamic trading ratios are unnecessary, or do not add to welfare gains. There are two main propositions that can be established for the condition in equation 6 to hold with the ratio of shadow prices equal to the same constant, τ, regardless of the time period in which the shadow prices are measured.

$$\frac{\mu_{it}(w,x)}{\mu_{jt}(w,x)} = \frac{\mu_i(w,x)}{\mu_j(w,x)} = \tau_{i,j} \quad \forall\, i,j \tag{6}$$

Proposition 1: Assuming $\mu_i \in (0,\infty] \wedge \mu_j \in (0,\infty]$ or that there is an interior solution. When $\dot{\mu}_i = 0$ and $\dot{\mu}_j = 0$ the ratio of shadow prices is equal to a constant $\tau_{i,j}$.

Proof: The ratio of any two real numbers that are constants is by definition a constant.■

This simple proposition intuitively represents shadow prices that have reached a steady state value such that there is no need for dynamic or spatially variable trading ratios. It is an empirical question whether a particular groundwater resource is sufficiently close to a steady state so as to negate the need for a dynamic market.

Proposition 2: Assuming $\mu_i \in (0,\infty] \wedge \mu_j \in (0,\infty]\ \forall\, t$ or that there is an interior solution. If $\frac{\dot{\mu}_i}{\mu_i} = \frac{\dot{\mu}_j}{\mu_j} \in \mathbb{R}\ \ \forall\, t$, then $\frac{\mu_i(w,x)}{\mu_j(w,x)} = \tau_{i,j}\ \forall\, t$.

Proof: The change in shadow prices for well i and j need to be proportional to maintain a constant ratio over time. Take the identity $\mu_{i,t+1} - \mu_{i,t} = \dot{\mu}_i$ and transform it to $\mu_{i,t+1} = \dot{\mu}_i + \mu_{i,t} \rightarrow \frac{\mu_{i,t+1}}{\mu_{i,t}} = \frac{\dot{\mu}_i}{\mu_{i,t}} + 1$. If $\frac{\dot{\mu}_i}{\mu_{i,t}} = \frac{\dot{\mu}_j}{\mu_{j,t}} \rightarrow \frac{\mu_{i,t+1}}{\mu_{i,t}} = \frac{\mu_{j,t+1}}{\mu_{j,t}}$ which shows that $\frac{\mu_{i,t}}{\mu_{j,t}} = \frac{\mu_{i,t+1}}{\mu_{j,t+1}}$.■

Proposition 2 states that we can tolerate a rate of change in the shadow price and use a constant trading ratio, but only when the rate of change is proportional between shadow prices for all time periods. This constrains wells to have shadow prices that change at the same proportional rate, otherwise they will diverge at some point in time and a constant trading ratio will not attain the first-best allocation of groundwater across time and space. Given the number of economic and hydrological parameters influencing the shadow price, it is *ex ante* unclear whether constant trading ratios will be associated with large inefficiencies.

Based on the theoretical framework and discussion we construct three hypotheses relevant to the efficiency of dynamic groundwater markets.

Hypothesis 1: In the presence of heterogeneous hydrological and/or economic conditions, dynamic trading ratios are welfare enhancing compared to constant trading ratios.

Hypothesis 2: Greater agent heterogeneity, without exhaustion, will result in greater benefits from adopting a dynamic groundwater market.

Hypothesis 3: The time path of the shadow prices are not proportional when there are exhaustion externalities present.

We posit in these hypotheses that there will be a significant difference in the welfare benefits associated with groundwater trading by adopting trading ratios that are defined dynamically rather than at a steady state. When omitting the transaction costs, dynamic trading ratios perform at least no worse than constant ratios by design since they take into account the optimal allocation of irrigation water across time, but the question is whether the efficiency gains are economically significant. This will help to address the question of whether the potential benefits of a dynamic market justify the higher potential costs of administering and governing it. The second hypothesis supposes that agent heterogeneity alone is enough to justify dynamic trading ratios, which is a more stringent test of the economic importance of dynamic markets since it takes away heterogeneity in exhaustion as a driver of the efficiency loss in the market. This is also an important distinction for the application of simpler markets since some groundwater basins have significant saturated thickness and loss of access is not of great concern. Therefore, this hypothesis highlights the applicability of a more complex market to different geographic areas. The third hypothesis posits that the importance of potential exhaustion on the path of shadow prices. This is posited for two intuitive reasons, we know that a depletable resource has an exponentially increasing shadow price through time by the Hotelling Rule, while a sustainable resource does not have an exponentially increasing shadow price which suggests contrasting areas with exhaustion externalities and areas without exhaustion externalities can generate very different trading ratios over time. The importance of this hypothesis is in the proportional change in shadow prices, shown in Proposition 2. If exhaustion externalities in a parts of a shared aquifer can cause similar time paths of shadow prices then dynamic trading ratios may not be needed since the ratio of shadow prices would be approximately constant.

The time path of the shadow price of groundwater is the primary variable of interest, since that defines the trading ratios defined by the shadow prices. The complex system and connection between farms through hydrology makes the solution to the optimal path of water extraction by farmers, and therefore the shadow prices, difficult to obtain. Intuition can be gained, however, by simple characterizations of the natural resource extraction problem. Farzin (1992) shows that the optimal time path of the shadow price for an exhaustible resource depends on how the marginal cost function changes overtime; when the marginal cost of extraction increases monotonically over time so does the shadow price. It is also shown that with a non-exhaustible resource the shadow price could have a much different time path; e.g., even with a monotonically increasing marginal extraction cost, the time path of shadow prices could be decreasing as in Gisser and Sanchez (1980). Therefore, wells that have depletion concerns could have a different path than ones that do not; and wells that have different time horizons to depletion could also have very different shadow prices at any point in time. The question of how big these differences are and how much they impair reaching a first-best policy outcome are empirical questions.

These hypotheses investigate when the differences in shadow prices are important based on heterogeneity, the time to exhaustion, or whether exhaustion will occur. To illustrate the changing shadow prices over time more concretely we simulate our problem under a variety of conditions to identify how much spatial and temporal variation matter to welfare in a dynamically defined groundwater market.

Simulations

We use numerical methods to solve for the optimal trading ratios with data from an application in Kansas, which lies over the Ogallala aquifer. We numerically solve the system of equations to find optimal shadow prices over time for each agent (irrigation well). To demonstrate the basic time paths of shadow prices, we posit a two-well aquifer and vary important factors that affect trading ratios. The two-well model in Figure 2 represents the most basic spatial aspects of changing shadow prices between wells. Two wells in this model exist in two adjacent cells which share a side and which groundwater can flow through. The amount of groundwater flow depends on the difference in groundwater heights in the wells, the size of the cross sectional area shared by the cells, hydraulic conductivity, and distance between wells.

Using this simple representation of wells we can investigate many different aspects of how shadow prices change when groundwater flows laterally. Intuitively the areas that deplete water faster and have a lower water height will be supplemented over time by lateral flows from neighboring cells. With an absolute bottom of a cell, depicted in Figure 1 for well i, the amount of natural recharge and lateral flows may not be enough to sustainably extract water and well i may reach the point of exhaustion, leading to a change of irrigation practices to dryland farming or an alternative land use. It also may be true that wells reach a steady-state before the point of exhaustion such that the marginal cost of pumping water becomes large enough to equate to the marginal benefit of irrigation. These parameters of water demand, lateral flows, and aquifer characteristics determine if the shadow price of depletion, λ, at a well is positive. Another important factor that may affect the time path of shadow prices is the local demand for irrigation water compared to the local availability. As irrigation demand increases the shadow price of water increases due to falling water heights and quicker exhaustion of depletable wells. Demand heterogeneity can be due to a number of factors, including soil, climate, and economic characteristics. Heterogeneity in aquifer characteristics may also play a role in the evolution of trading ratios, as hydrologic conductivity or the amount of recharge available can shape the path of shadow prices between wells.

We parameterize this model with data from Northwest Kansas over the Ogallala, which has specific concerns about depletion in the near future. Baseline values for the simulations are provided in Table 1. Recharge, hydraulic conductivity, and storativity were provided from the Kansas Water Office and were taken as representative values for a farm in Groundwater Management District 4. The demand parameters are also representative of a farm in Groundwater Management District 4 as estimated in Guilfoos et al. (2016). We provide three scenarios and evaluate the time path of the shadow price, the difference in trading ratios from a set reference point, and discuss welfare implications.

The six scenarios we examine are 1) Homogeneous wells with no depletion concerns (baseline scenario) 2) Heterogeneous wells with no depletion concern (well 1 has twice as many irrigated acres as well) 3) Homogeneous wells with a binding constraint on depletion in one well (depletion scenario) 4) Heterogeneous wells with lower hydraulic conductivity (low K scenario) 5) Heterogeneous wells with lower hydraulic conductivity (low K scenario) 6) Heterogeneous wells with no depletion concern (well 1 has twice the demand intercept of well 2). The first scenario uses the values from Table 1 and simulates both wells. The second scenario illustrates the effect of exhaustion on one well by defining the bottom of the well to 2970 ft of elevation. The third scenario generates demand heterogeneity by doubling the parameters of irrigation water demand in one well, but defines the bottom of the aquifer as sufficiently deep so as not to cause exhaustion.

Simulations are run for forty periods and only the first twenty periods are shown to minimize end period effects. These simplified scenarios with two wells are helpful to control for the increasingly complex network of connections between a large aquifer with hundreds to thousands of wells, and contribute to understanding the casual effects of changes to the groundwater environments.

Results

The time path of shadow prices for the simulations are shown in Figure 3. We demonstrate the different scenarios in six panels. In Figure 3, Panel (a) is the baseline case of two homogeneous wells with no exhaustion; Panel (b) is the case where well 1 has twice the demand for water at the same water height, and exhaustion is not a binding constraint for either well; Panel (c) is the case where well 1 has a binding constraint on exhaustion and well 2 does not, but well 1 and well 2 are homogeneous; Panel (d) is the case where well 1 has twice the demand for water at the same water height while hydraulic conductivity is half that of panel (b); Panel (e) is the case where well 1 has twice the demand for water at the same water height while initial groundwater elevation is set to 3070 for both wells; Panel (f) is the case where well 1 has a intercept for groundwater that is twice that of well 2, but both have the same slope for demand. Two striking characteristics of these graphs are that all the panels with demand and aquifer heterogeneities appear to have similar time paths for the shadow price, but the panel with an exhaustion externality has a very different time path of shadow prices. It is also apparent that in Panel (c) wells do not follow proportional time paths of shadow prices, or that Proposition 2 does not hold. In the other panels the time paths of shadow prices appear approximately proportional.

Table 2 shows estimates of welfare effects when using a constant trading ratio across twenty periods across scenarios. We assume that the total number of permits are determined with accuracy but inefficiency is driven by 20% of the stock of permits being traded at an inaccurate constant trading ratio and then compare the discounted welfare for both wells to the first best discounted welfare using optimal trading ratios in all periods. In most cases we find very small effects on welfare of using a constant trading ratio. In the case of exhaustion we find a small effect because 20% of permits trading in each period does not cause premature extinction of well 1 within 20 periods. An important assumption to the first best outcomes and these 'second best' constant trading ratios is that they both get the total amount of permits correct and inefficiency is driven by suboptimal trading ratios. These suboptimal trading ratios don't have strong affects in the near future, or 20 periods. We evaluate an additional scenario in which we posit trading across the region, with the four wells from panel (b) and panel (c). Here a misallocation of permits can cause greater damage as the ratio of shadow prices changes more and the mispricing of permits can lead to over-pumping in the well with exhaustion concerns.

In relation to our hypotheses we can make some determination under what conditions dynamic trading ratios are beneficial. It appears that we can reject Hypothesis 1 as heterogeneity of demand and aquifer properties by themselves does not provide a necessary condition for dynamic trading ratios, which means that dynamic trading ratios will not be welfare enhancing for all situations. We can also reject Hypothesis 2, as the lack of difference in time paths of, excluding exhaustion, demonstrate that dynamic trading ratios are likely of little importance., The similarity in many of the panels can attest to the how insensitive the paths of shadow prices to various changes in demand or parameters of the aquifer, other than the distance to the bottom. Hypothesis 3 we cannot reject, as the time path of shadow prices diverge even with wells that are close to each other, and take on different first derivatives with or without exhaustion. This hypothesis highlights when and where we might find the most appropriate use of dynamic trading ratios, when exhaustion is an externality or when there well productivity is affected by drawdown of the water table.

These results indicate that exhaustion of one well will create different time paths for the shadow prices for connected wells, and vastly different time paths than a system of wells farther away that does not have exhaustion concerns.

Conclusion

Intertemporal, or dynamic, trading ratios should be considered for groundwater management areas that have exhaustion externalities, but may not be appropriate for areas without exhaustion concerns. A variety of heterogeneous scenarios are explored and demonstrate relatively similar paths of shadow prices which suggest that constant trading ratios will do a good job of achieving a first best outcome. This result relies on two important assumptions; that the total amount of groundwater permits are calculated correctly and that there are no exhaustion externalities present. Exhaustion externalities are representative of a more continuous well capacity restrictions that can limit the ability of wells to produce as saturated thickness decreases.

The policy implications of these findings are important, the least cost of groundwater pumping abatement can be achieved in sustainable aquifers with an estimate of steady state shadow prices because constant trading ratios are sufficient. This drastically simplifies calculating and implementing a groundwater market to achieve welfare improvements. The exceptions to this policy can be encompassed in other similar externalities to exhaustion, such as salt water intrusion. This also suggests that quota policies would be attractive way of dealing with heterogeneity because differentiated prices may be difficult to estimate rather than relative shadow prices. The onus on calculating differentiated prices to implement optimal taxes is higher because it requires the absolute value of the externality to be known while trading ratios require the relative externalities to be known.

Dynamic trading ratios can be sensitive to welfare losses with exhaustion externalities care must be taken with groundwater markets are designed for local regions with these externalities. These externalities can be addressed with other mechanism designs, such as area level restrictions on trading. Future work can tease out the relative effectiveness on such policies on dynamic considerations.

References:

Bauer, C. J. (1997). Bringing water markets down to earth: The political economy of water rights in Chile, 1976–1995. *World development*, *25*(5), 639-656.

Brewer, J., Glennon, R., Ker, A., & Libecap, G. (2008). 2006 Presidential address water markets in the West: prices, trading, and contractual forms. *Economic Inquiry*, *46*(2), 91-112.

Brennan, D. (2006). Water policy reform in Australia: lessons from the Victorian seasonal water market. *Australian Journal of Agricultural and Resource Economics*, *50*(3), 403-423.

Brozović, N., Sunding, D. L., & Zilberman, D. (2010). On the spatial nature of the groundwater pumping externality. *Resource and Energy Economics*,*32*(2), 154-164.

Brozović, N., & Young, R. (2014). Design and implementation of markets for groundwater pumping rights. In *Water Markets for the 21st Century* (pp. 283-303). Springer Netherlands.

Easter, K. W., & Huang, Q. (Eds.). (2014). *Water Markets for the 21st Century: What Have We Learned?* (Vol. 11). Springer.

Farzin, Y. H. (1992). The time path of scarcity rent in the theory of exhaustible resources. *The Economic Journal*, *102*(413), 813-830.

Foster, T., N. Brozović, and A. P. Butler (2014), Modeling irrigation behavior in groundwater systems, *Water Resources Research,* 50.8, 6370-6389.

Foster, T., N. Brozović, and A. P. Butler (2015), Why well yield matters for managing agricultural drought risk, *Weather and Climate Extremes,* 10, 11-19.

Gleeson, T., Wada, Y., Bierkens, M. F., & van Beek, L. P. (2012). Water balance of global aquifers revealed by groundwater footprint. *Nature*,*488*(7410), 197-200.

Gleick, P. H., & Palaniappan, M. (2010). Peak water limits to freshwater withdrawal and use. *Proceedings of the National Academy of Sciences*,*107*(25), 11155-11162.

Goemans, C., & Pritchett, J. (2014). Western water markets: Effectiveness and efficiency. In *Water markets for the 21st century* (pp. 305-330). Springer Netherlands.

Guilfoos, T., Pape, A. D., Khanna, N., & Salvage, K. (2013). Groundwater management: The effect of water flows on welfare gains. *Ecological Economics*, *95*, 31-40.

Guilfoos, T., Khanna, N., & Peterson, J. (2016). Efficiency of Viable Groundwater Management Policies. *Land Economics*, *Forthcoming*

Hadjigeorgalis, E. (2009). A place for water markets: performance and challenges. *Applied Economic Perspectives and Policy*, *31*(1), 50-67.

Hornbeck, R., & Keskin, P. (2011). *The evolving impact of the Ogallala Aquifer: Agricultural adaptation to groundwater and climate* (No. w17625). National Bureau of Economic Research.

Kaur, B., Singh, S., Garg, B. R., Singh, J. M., & Singh, J. (2012). Enhancing water productivity through on-farm resource conservation technology in Punjab agriculture. *Agricultural Economics Research Review*, *25*(1), 79-85.

Kuwayama, Y., & Brozović, N. (2013). The regulation of a spatially heterogeneous externality: Tradable groundwater permits to protect streams. *Journal of Environmental Economics and Management*, *66*(2), 364-382.

McCann, L., & Garrick, D. (2014). Transaction costs and policy design for water markets. In *Water markets for the 21st century* (pp. 11-34). Springer Netherlands.

Mukherji, A. (2004). Groundwater markets in Ganga-Meghna-Brahmaputra basin: theory and evidence. *Economic and political Weekly*, 3514-3520.

Palazzo, A., & Brozović, N. (2014). The role of groundwater trading in spatial water management. *Agricultural Water Management*, *145*, 50-60.

Rosegrant, M. W., Ringler, C., & Zhu, T. (2014). Water markets as an adaptive response to climate change. In *Water markets for the 21st century*(pp. 35-55). Springer Netherlands.

Thompson, C. L., Supalla, R. J., Martin, D. L. and McMullen, B. P. (2009), Evidence Supporting Cap and Trade as a Groundwater Policy Option for Reducing Irrigation Consumptive Use.

JAWRA Journal of the American Water Resources Association, 45: 1508–1518. doi: 10.1111/j.1752-1688.2009.00384.x

Wheeler, S., Loch, A., Zuo, A., & Bjornlund, H. (2014). Reviewing the adoption and impact of water markets in the Murray–Darling Basin, Australia.*Journal of Hydrology*, *518*, 28-41.

Tables and Figures

Figure 1 – U.S. Water Market Transactions

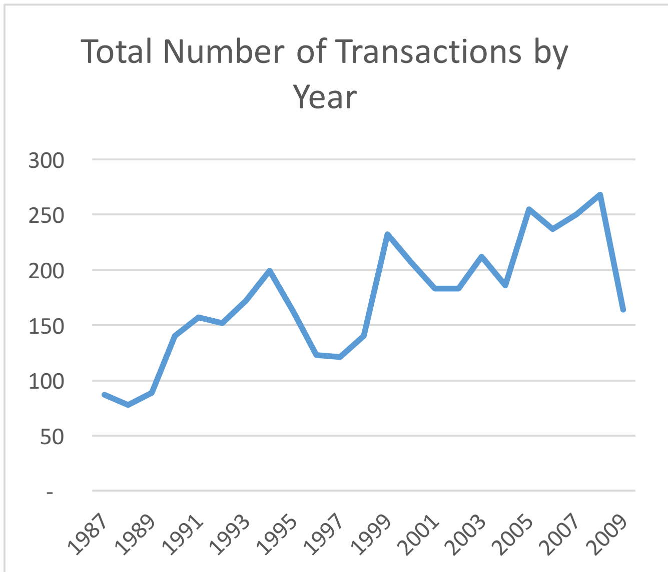


Figure 2 - A Two Well Aquifer

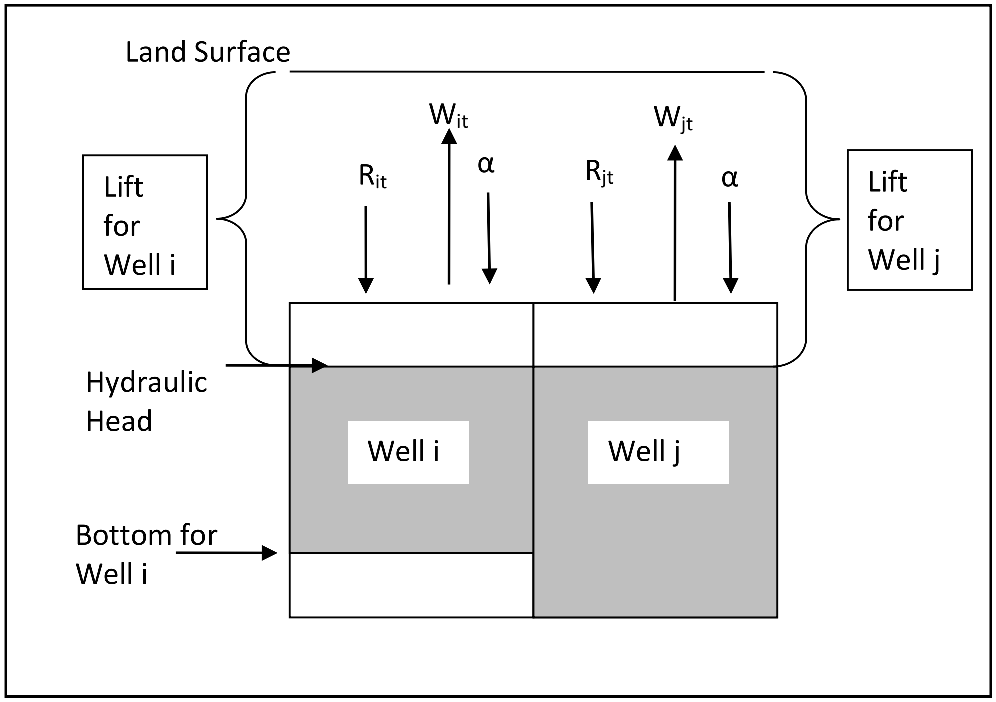
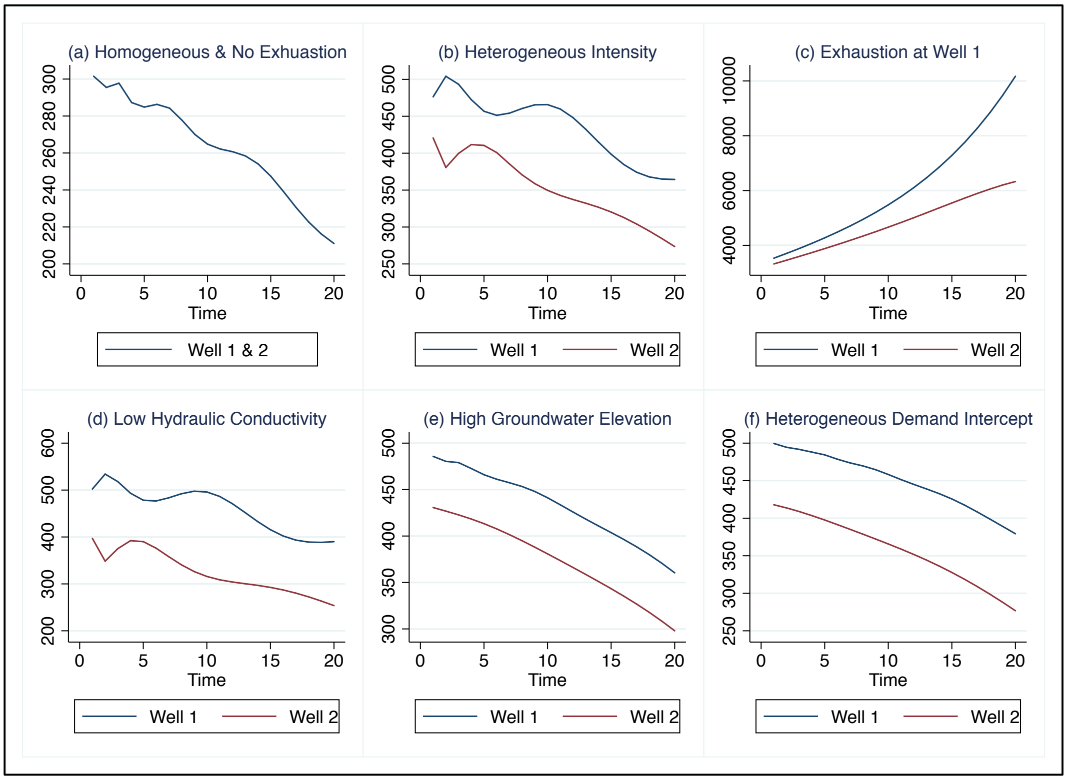


Figure 3 – Path of Shadow Prices



Note: Panel (a) contains two homogeneous wells with no exhaustion; Panel (b) contains well 1 with double the intercept and slope of well 2; Panel (c) contains homogeneous wells but well 1 has a binding constraint on exhaustion; Panel (d) contains the demand characteristics of panel (b) but with a lower hydraulic conductivity; Panel (e) contains the demand characteristics of panel (b) but with higher starting groundwater elevations in both wells; Panel (f) well 1 has double the demand intercept but the same demand slope as well 2.

Table 1. Parameter Values for baseline Two Well

Parameter	Description	Baseline Well Value
C_1	Cost of pumping	\$0.1044 acre-ft/ft
R	Natural recharge	35 acre ft
g	Demand intercept	178 acre ft
k	Demand slope	-0.66 acre ft
d	Distance between wells	5,200 ft
K	Hydraulic Conductivity	4,000 ft/year
A	Aquifer area	625 acres
x_s	Land surface	3,094 ft above sea level
$\bar{x}$	Lower aquifer bound	2,900 ft above sea level
x_0	Initial water height	3,010 ft above sea level
S	Storativity	.17
α	Irrigation water return	20%
ρ	Discount rate	5%

Table 2. Welfare Estimates

Scenario	Constant Trading Ratio	Welfare Difference
Panel (b) Heterogeneous	1.2543	0.02%
Panel (c) Exhaustion	1.2094	0.15%
Panel (d) Low Conductivity	1.4231	0.17%
Panel (e) High Groundwater	1.1601	0.03%
Panel (f) Heterogeneous Intercepts	1.2689	0.04%
Inter-basin Trade with Exhaustion	10.2456	5.57%