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Analysis

Groundwater management: The effect of water flows on welfare gains

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ABSTRACT

We construct a spatially explicit groundwater model that has multiple cells and finite hydraulic conductivity to estimate the gains from groundwater management and the factors driving those gains. We calibrate an 246-cell model to the parameters and geography of Kern County, California, and find that the welfare gain from management for the entire aquifer is significantly higher in the multi-cell model (27%) than in the bathtub model (13%) and that individual farmer gains can vary from 7% to 39% depending of their location and relative size of demand for water. We also find that when all farmers in the aquifer simultaneously behave strategically the aggregate gains from management are significantly smaller. However, individual farmers do not have the incentive to behave strategically even with finite hydraulic conductivity when other farmers behave myopically.

1. Introduction

Groundwater plays an important role in agriculture in many semi-arid areas where open access and poorly defined property rights may cause over-extraction. There is a demonstrated concern about this issue from policy makers and advocates; for example, in an article entitled "Rising Calls to Regulate California Groundwater," Tony Rossmann, a lawyer specializing in water rights, referred to the need for a new solution to California's water scarcity when he stated, "The answer so far has been to drill deeper…This can't continue."[1] This concern is not confined to California, but is present in many aquifers around the world [China, India, Yemen, Australia, and Spain] where water extraction outstrips natural recharge (Giordano (2009)). But the current economic literature on groundwater (for example, Gisser and Sanchez (1980), Lee et al. (1981), Allen and Gisser (1984), Feinerman and Knapp (1983), Nieswiadomy (1985), Kim et al. (1989), Brill and Burness (1994), Knapp and Olson (1995), and Koundouri (2004)) generally finds a small welfare gain from management.[2]

Papers following Gisser and Sanchez (1980) tried to uncover the economic assumptions that lead to a small welfare gain without much success. Many previous studies use a hydrologic model referred to as the 'bathtub' model which assumes that groundwater flows instantaneously in the aquifer. By assuming an instantaneous lateral flow the bathtub model underestimates the pumping costs, therefore the impact of instituting management predicted by this model tends to be small. When we employ a more hydrologically realistic model with gradual lateral water flow, a relatively large welfare gain from groundwater management can exist.

There is a growing interest in groundwater management's spatial component and policy implications. Brozovic et al. (2010) find that the bathtub model will incorrectly estimate the groundwater pumping externality and yields the incorrect optimal extraction path of groundwater. Using a two cell differential game Athanassoglou et al. (2012) identify that a bathtub model may provide a damaging policy recommendation with adverse implications to welfare. These works advance the idea that space and the physics of groundwater flows are important elements to policy. While this growing literature incorporates the spatial components of groundwater, much of the analysis has been on a small scale, two cell model, and has not taken on the complexity of a larger and more complex aquifer system with many agents and interactions. The existing literature makes clear that the bathtub model is a poor modeling choice but there is no indication how badly bathtub models do compared to a complex aquifer in terms of welfare or the likely distribution of welfare gains among farmers. A small differential game cannot answer this question because there are many interactions between hundreds or possibly thousands of farmers in a large aquifer that affect welfare outcomes. We build upon the current literature by quantifying the gains from management in a complex multi-cell aquifer and the extent to which its magnitude depends on the physical location of the farmers and the crops that they grow. Our work strengthens our

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[1] Source: The New York Times, May 13, 2009.

[2] Koundouri (2004) finds that when an aquifer is damaged to the point of collapse there are large gains, this could be the case for coastal aquifers that may be damaged by salt water intrusion. Many aquifers don't face the particular externality studied in Koundouri (2004).

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understanding of the situations under which groundwater management might be an economically desirable policy goal.

Our main contributions are: (i) revealing the distribution of welfare gains from groundwater management in a large multiple cell aquifer, (ii) illustrating the effect on the welfare gains from spatial and demand heterogeneities, and (iii) measuring welfare gains from management when farmers in a large aquifer behave strategically. We numerically demonstrate these contributions with an application of the model to Kern County, California, using a detailed field map to identify well location and water demand heterogeneity. We find that under myopic behavioral assumptions the bathtub model greatly underestimates welfare gains for most farmers. We retrieve a 13% welfare gain from optimal management under the bathtub model in Kern County and up to 39% – as much as three times larger – for some farmers under the multiple cell model.

To isolate factors contributing to welfare gains from management we investigate abstract scenarios in which we carefully vary spatial and demand heterogeneities in a simplified setting. Keeping the total water demanded and the overall physical characterization of the aquifer constant and equal, we illustrate the effects on welfare driven by changes in location and demand concentrations. We find that the magnitude of the welfare gain from groundwater management is more sensitive to demand heterogeneity than to spatial heterogeneity, at both the aquifer and the individual farmer level.

The common yardstick in the groundwater literature is to compare myopic farmers with a social planner's solution and measure the gap between welfare outcomes. We use this same yardstick to establish our central results. However, because of finite hydraulic conductivity in our model it is reasonable to expect that farmers may behave strategically: they may increase their own profits by saving some water for the future and lowering their future pumping costs. When we model strategic behavior we assume that farmers recognize there is finite hydraulic conductivity and use adaptive expectations about the lateral flows of water at their well to compute an optimal extraction path which is continuously updated. There are other definitions of strategic behavior that have been used in the literature (Negri (1989), Saak and Peterson (2007), and Rubio and Casino (2003)) all suggesting overpumping to various degrees. We find that when all farmers behave strategically the gains from management are indeed much smaller. However, individual farmers enjoy lower welfare when behaving strategically rather than myopically when other farmers behave myopically.

We expect the welfare gains from conservation will be greater in our model because farmers still have the incentive to over extract but face higher costs in the future as water takes time to flow in from neighboring sections of the aquifer. The behavioral assumption is predicated on the fact that each farmer still represents a small part of the aquifer and that water flows laterally into or out of wells, just not instantaneously as the bathtub model specifies.

We explicitly model water flows using Darcy's Law, an equation in hydrology that defines the lateral flow of water. Because water flows gradually to where it has been pumped our model allows well location and demand heterogeneity to gain importance. In a bathtub model well location is immaterial because water flows instantaneously and all farmers face the same water height in each period. As expected, the computational difficulty increases as we go from evaluating a one cell aquifer to evaluating an aquifer with many cells. We use agent-based modeling software coupled with global optimization techniques to make a new economic/hydrologic model, which allows us to look at the complex interactions between farmers and the water levels in an aquifer with spatial and demand heterogeneities.

There are existing computational models used by water managers that model gradual water flow using a multi-cell groundwater model.[3] While these models realistically model the physics of water flow, they suffer from an unsophisticated view of human behavior. This limitation manifests in three ways. (1) Objective functions must be linear, which may not be appropriate for a social welfare function. (2) The objective functions in the models cannot currently contain a state variable, while in our case including the state variable, well height, in the objective function is essential to modeling the problem from an economic point of view. (3) Agents are not economically interesting agents: for example, the price of water (cost) often has no effect on water demand. Our model improves existing models in economics by adding better hydrology and improves existing models in hydrology by adding better economics.

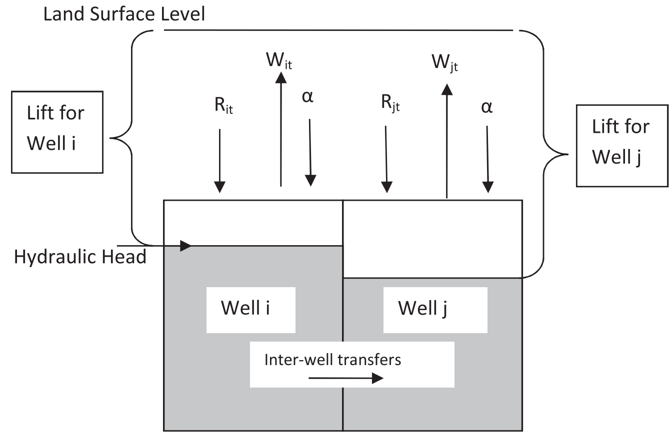

Fig. 1. A two cell aquifer.

2. Model

2.1. General Description

Our model builds on the economic and hydrologic setting introduced by Gisser and Sanchez (1980) and augments it with a multi-cell aquifer in which groundwater flows are governed by Darcy's Law. Fig. 1 demonstrates a simple version of our model for two adjacent cells in an aquifer. W_{it} and W_{jt} are the amounts of water farmers extract at time t to irrigate crops. R_{it} is the recharge that replenishes well i and R_{jt} is the recharge that replenishes well j. We assume that recharge is the same across all cells in the aquifer so that $R_{it} = R_{jt}$ for all i, j, and t. A fraction of irrigation water is returned to the aquifer via the return coefficient α, which we assume is also uniform throughout the aquifer. The height of water, or lift, determines the extraction cost faced by the farmer.

Well i has a larger hydraulic head which causes water to flow from well i to well j.[4] The total volume of water flowing from well i to well j at time t, Q_{ijt}, is determined via Darcy's Law and expressed as follows

$$Q_{ijt} = \frac{KA_{0i}\left(H_{it} - H_{jt}\right)}{d_{ij}} \tag{1}$$

where $(H_{it} - H_{jt})$ is the difference in hydraulic head[5]; d_{ij} is the distance along the flow path, A_{0i} is the cross sectional area through which water flows, and K, hydraulic conductivity, is a constant that depends on the composition of the soil (e.g. porous rock, clay, sand, gravel) which we assume is the same across the aquifer.The market for groundwater consists of farmers who pump water for irrigation. Farmers can use water only on the land overlying the aquifer and start with the same height of water, to make the comparison with the bathtub model consistent. The farmers face a long run demand curve that implicitly take into

[3] MODFLOW, MFP2005-FMP2, MODOPTIM, Source: http://water.usgs.gov/software/lists/groundwater/.

[4] The return flows and natural recharge are not subject to lateral flows in the initial period they occur but are subject to lateral flows after they have been added to the groundwater stock in all future periods.

[5] Hydraulic head is interpreted as the height of the water level at a given well.