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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.

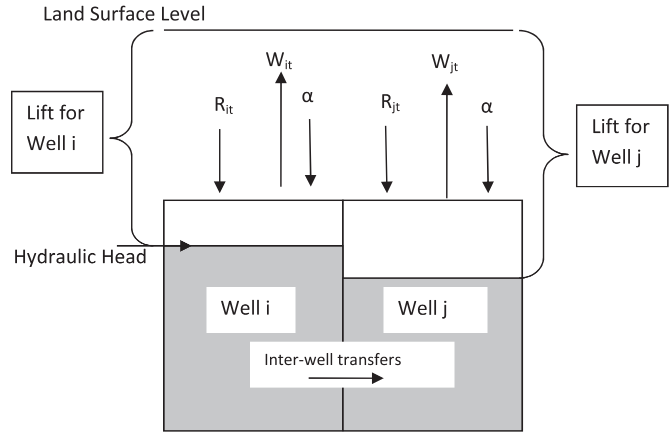

Fig. 1. A two cell aquifer.

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.

account changes in production, irrigation technology, and crop choice along the negatively sloped linear demand curve,

$$W_{it} = g_i + k_i P_{it} \tag{2}$$

where W_{it} is the water demanded at time t, $g_i > 0$ and $k_i < 0$ are demand parameters and P_{it} is the price of water for farmer i at time t and is determined by the farmer's pumping cost at their well. Pumping cost for farmer i, $\overline{P}_{it}$, is given by:

$$\overline{P}_{it} = C'_0 + C'_1 (S_L - H_{it}) \tag{3}$$

where $C'_0 \geq 0$ is a negligible fixed cost, and $C'_1 > 0$ is the marginal cost of pumping one acre foot[6] of water 1 ft vertically. The vertical distance that water needs to be pumped to reach the surface at time t is the lift, defined as $S_L - H_{it}$, where S_L is the surface level and H_{it} is the water level in well i at time t. Defining $C_0 = C'_0 + C'_1 S_L$ and $C_1 = -C'_1$ we express the cost function as

$$\overline{P}_{it} = C_0 + C_1 H_{it}. \tag{4}$$

This cost is the long run marginal cost to pump one acre foot of water given lift in the well and determines the price of water.

In our model the height of water is location specific and incorporates inter-well transfers via Darcy's Law (the middle term on the right hand side of Eq. (5)). The equation of motion is defined as

$$H_{i,t+1} - H_{it} = \frac{R_i}{A_i S} - \sum_{j \neq i}^{J} \left(\frac{K A_{0i} \left(H_{it} - H_{jt} \right)}{d_{ij} A_i S} \right) - \frac{(1-\alpha) W_{it}}{A_i S}. \tag{5}$$

We convert the volume of water being transferred between wells i and j into the corresponding change in height through dividing by storativity, S, or the volume of water a unit of soil can hold, and A_i, the surface area of the land that a farmer inhabits. J is the number of adjacent cells that share a side with cell i, every cell in the model need not contain a well. The main difference between our equation of motion (5) and the bathtub model is that in the bathtub model the instantaneous water flow ensures a uniform water height through the aquifer which depends only on the total water extracted from the aquifer and not the water extracted at any particular well.

2.2. Myopic Behavior

Under perfectly competitive myopic behavior each farmer i maximizes her private consumer surplus in each period separately. Consumer surplus per unit of time is given by Eq. (6), derived from Eqs. (2) and (4).

$$\mathit{Consumer\ Surplus}_{it} = \frac{{W_{it}}^2}{2k_i} - \frac{g_i W_{it}}{k_i} - (C_0 + C_1 H_{it}) W_{it}. \tag{6}$$

Taking water height in the well as given, each farmer extracts water to the point where the marginal benefit of extraction is equal to the marginal cost of extraction. Farmers operate in a common pool resource and do not expect to retain the gains in future periods from saving water in the current period. The natural recharge, water extraction, return from irrigation, and inter-well transfers change the water level from one period to the next. In the following period the farmer again takes the height of water as given and repeats the process which yields the time path of extraction under perfect competition. Welfare for the entire aquifer is the sum of farmers' consumer surpluses.[7] The aquifer does not have a bottom which ensures that it will reach a steady state with some positive volume of water.

2.3. Strategic Behavior

In a model with finite hydraulic conductivity, farmers may choose to act strategically as some of their water savings will stay in their own well. To model strategic farmer behavior we assume they have adaptive expectations about the inter-well flows which are unlikely to be known by any farmer. This expectation that all future inter-well flows are equal to the previous period inter-well flows is given by Eq. (7)

$$E\left(\sum_{j \neq i}^{J} \left[\frac{K A_{0i} \left(H_{it} - H_{jt} \right)}{d_{ij} A_i S} \right] \right) = \sum_{j \neq i}^{J} \left[\frac{K A_{0i} \left(H_{i,t-1} - H_{j,t-1} \right)}{d_{ij} A_i S} \right]. \tag{7}$$

The current value Hamiltonian for a farmer in continuous time is given by

$$\begin{aligned} \check{H}_i = {} & \frac{W(t)_i^2}{2k_i} - \frac{g_i W(t)_i}{k_i} - (C_0 + C_1 H(t)_i) W(t)_i \\ & + \mu(t)_i \left(\frac{R_i}{A_i S} - E\left(\sum_{j \neq i}^{J} \left[\frac{K A_{0i} \left(H(t)_i - H(t)_j \right)}{d_{ij} A_i S} \right] \right) - \frac{(1-\alpha) W(t)_i}{A_i S} \right). \end{aligned} \tag{8}$$

This assumption allows each farmer to solve for an optimal extraction path that maximizes her profit. The farmer updates her information about the height of her well water and information about inter-well transfers over time and recalculates her optimal extraction path. More details for this solution can be found in supplementary Appendix B (Guilfoos et al., 2013, Part E).

Recent empirical work suggests myopic farmer behavior may be a reasonable assumption of economic behavior, but the evidence is mixed. Pfeifer and Lin (2012) and Huang et al. (2009) find some empirical evidence of strategic over-pumping in aquifers. Savage and Brozovic (2011) find that they cannot reject myopic behavior after controlling for endogeneity of well location. In a survey by Dixon (1989) Californian farmers confirm that they do to not take into consideration that they affect the level of water in the aquifer. On the other hand laboratory experiments run by Suter et al. (2012) show students save some water for future use when hydraulic conductivity is finite.

2.4. Optimal Control

In the optimal control scenario the social planner maximizes the sum of the present value of consumer surplus across all farmers subject to the equation of motion described in Eq. (5). The current value Hamiltonian in continuous time is given by

$$\begin{aligned} \check{H} = \sum_{i=1}^{I} \Bigg[& \frac{W(t)_i^2}{2k_i} - \frac{g_i W(t)_i}{k_i} - (C_0 + C_1 H(t)_i) W(t)_i \\ & + \mu(t)_i \left(\frac{R_i}{A_i S} - \sum_{j \neq i}^{J} \left[\frac{K A_{0i} (H(t)_i - H(t))}{d_{ij} A_i S} \right] - \frac{(1-\alpha) W(t)_i}{A_i S} \right) \Bigg]. \end{aligned} \tag{9}$$

The Hamiltonian, even in the simplest two cell aquifer, has a solution which is not fully identified, as shown in detail in Part C of supplementary Appendix B (Guilfoos et al. (2013)). The complication comes from the inter-well transfers defined by Darcy's Law; there are too many unknowns to fully identify an analytical solution. Because an analytical solution is intractable we solve the optimal control problem using numerical optimization techniques as detailed in Section 3.

[6] One acre foot of water is the volume of water in one acre of surface space one foot deep.

[7] The only relevant agents in the model are the farmers who demand water, and fixed costs are assumed to be zero (i.e. costs of farms are assumed to be sunk). Social welfare is equal to the area underneath the demand curves for farmers and above the flat marginal cost curve, their consumer surpluses, which in turn is equal to farmers' profits.

Table 1
Kern County parameter values for detailed map.

Symbol	Description	Homogeneous farmers[a]	Heterogeneous farmers[a]
I	Number of groups of farmers	99	99
N	Number of cells in aquifer	246	246
R_n	Natural recharge for each cell in aquifer (acre/ft per year)	888,000/246 = 3609.7	888,000/246 = 3609.7
AS_n	Surface area times storativity of each cell	129,000/246 = 524.3	129,000/246 = 524.3
K[b]	Hydraulic conductivity for each cell (ft/year)	800	800
A_0[c]	Cross sectional area of each cell (acres)	175.9	175.9
d[c]	Distance between adjacent cells (ft)	12,772	12,772
g_i	Demand intercept (acre/ft)	3,967,143/99 = 40,072	max = 71,172 min = 19,347
k_i	Decrease in demand for a $1 increase in price (acre/ft)	−57,143/99 = −577.2	max = −1025 min = −278
C_0	Cost of pumping water from surface to sea level ($/acre foot)	321	321
C_1	Cost increase of pumping from a one foot change in height ($/acre foot of lift)	−.09	−.09
α	Return coefficient	.20	.20
r	Rate of time preference	.05	.05
T	Time period length	90	90
H_0	Initial height of water (feet)	3352	3352

[a] Source: Aquifer totals are from Feinerman and Knapp (1983), unless otherwise noted. Lower case letter i refers to a farmer; lower case letter n refers to an aquifer cell.
[b] Estimated from the soil composition of the aquifer.
[c] Calculated from the size and number of cells in the aquifer.

3. Numerical Methodology for the Optimal Control Solution

The simplicity of the equation of motion in the bathtub model makes it possible to find an analytical solution. However, the analytical solution to the optimal control problem with Darcy's Law in a multi-cell setting is intractable. Therefore, we use a numerical global optimization routine[8] and agent-based modeling software to find the largest consumer surplus for the entire aquifer, which coincides with finding the optimal extraction paths for all farmers.

The numerical solution to the problem is calculated using Mathematica and NetLogo. NetLogo is an agent-based software program used to model the aquifer's multi-cell structure. The Mathematica optimizer operates like the social planner, running different water extraction scenarios reiteratively in NetLogo until a 'best' extraction scenario is found. The 'best' extraction scenario is one where the discounted welfare of the entire aquifer is maximized and optimal path of water extraction at each well is found. Instead of directly choosing agents' optimal extraction trajectories, we choose the optimal tax rate trajectories for each well. Given the structure of the model, the optimal tax rates coincide with the optimal extraction paths. The optimization process is illustrated in the Appendix in Fig. A.1.

4. Model Parameters for Kern County, CA

The parameter values listed in Table 1, calibrated to a two hundred and forty six cell aquifer, are from Feinerman and Knapp (1983) for Kern County, CA. Ninety nine cells have farms that use groundwater for irrigation and an additional one hundred and forty seven cells are empty, land that goes unfarmed, and all two hundred and forty six cells receive recharge. This calibration is used to obtain the main results in Section 5.2 using the detailed map of Kern County, CA. The parameters are aquifer specific estimates of water demand and physical estimates of the recharge, size, and capacity. The storativity and hydraulic conductivity parameters are consistent with Kern County, an unconfined aquifer that is made up of sand and gravel. The distance and cross sectional area are calculated with wells at the center of the cell and water flows through shared sides of the cells according to Darcy's Law. All the cells in the aquifer are equal in size, making the distance between wells equal to the length of one side of a cell, and the cross sectional area equal to the length of one side of a cell multiplied by the thickness of the aquifer. The thickness is estimated to be on average 600 ft deep and is kept uniform and constant across cells for simplicity.

We allow the model to run for 90 periods, each period representing a year. The discounted social welfare becomes insignificant past ninety periods using a 5% discount rate, which is used by Feinerman and Knapp (1983). When all cells contain homogeneous farmers we verify the planner's numerical solution is equal to the planner's analytical solution (see Guilfoos et al., 2013, Part E).

5. Results

5.1. Overview

We present four sets of results: First, in Section 5.2 we use a detailed map of Kern County, CA, to estimate the welfare gain from management assuming myopic behavior. In Sections 5.3 and 5.4 we use abstract scenarios to identify the sensitivity of the welfare gain to variations in the spatial and demand heterogeneity. In Section 5.5 we investigate the results of management under the assumption that farmers behave strategically in the detailed aquifer of Kern County, CA. To add robustness, in the abstract scenarios we also analyze the Pecos Basin, TX, aquifer used by Gisser and Sanchez (1980) in their seminal study.

We compare multi-cell model results to the bathtub model results for the same parameters to establish the difference in the welfare gains under finite hydraulic conductivity. In fact, the bathtub model results match the published results in Gisser and Sanchez (1980) and Feinerman and Knapp (1983). That is, when using the bathtub model and assuming myopic behavior, we retrieve welfare gains from optimal management of 13% and 0.01% for Kern County and the Pecos Basin, respectively. This is true for all farmers in the aquifer, as they each benefit equally under the bathtub model.[9]

[8] The function we use in Mathematica is NMinimize to optimize the negative of discounted consumer surplus. This function uses the method of Nelder–Mead, but if Nelder–Mead does poorly, it switches to differential evolution. These are global optimization functions that search a large space of parameters and look for the global minimum. We limit the search space in general to positive tax rates which are the search variables in this case. Since this is a numerical optimization we cannot be 100% sure that we are at the global optimum and instead we may be in a local optimum. But through iterations of searching simple formulations of the model given different starting points and different methods we converged on the same answer. We also verify our method can replicate a known solution, in our appendix we show that we can replicate the optimal path of extraction from a bathtub model specification. These steps give us confidence that we are likely at a global optimum in our solutions.

[9] Using the parameters for the aquifer provided by Feinerman and Knapp (1983) we find the results given in the text. As a sensitivity check we calculate the area of the aquifer in GIS (2,684,470 acres) which we find to be larger than the parameter that Feinerman and Knapp use (1,290,000 acres). The estimate of total discounted consumer surplus is higher in all scenarios and the percentage welfare gain from management is smaller in all scenarios but the difference between the multi-cell model and the bathtub model are all the same. The results are qualitatively the same using either area to estimate the model results. We choose to use the Feinerman and Knapp results for consistency with the literature and to be able tie back to their results. The additional results are in the supplementary appendix G.

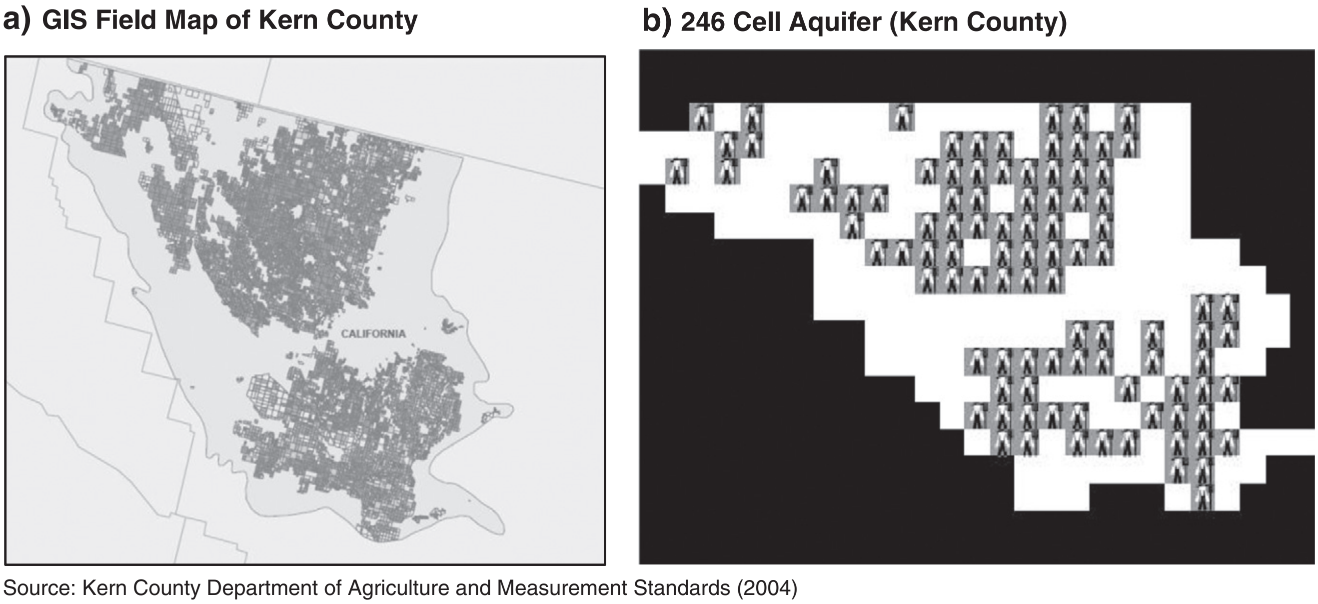

Fig. 2. a: GIS field map of Kern County Fig. 2b: 246 cell aquifer (Kern County). Source: Kern County Department of Agriculture and Measurement Standards (2004).

5.2. Detailed Map of Kern County, California

We investigate the welfare gains from optimal groundwater management under a detailed depiction of the Kern County aquifer. We use the total water demand and total physical properties (size, recharge, and storativity) for Kern County from Feinerman and Knapp (1983). Crop information and field location are obtained from field maps maintained by the Kern County Department of Agriculture and Measurement Standards, California (2004). The Department of Water Resources in California publishes estimated water usage by crop which we use to estimate the concentration of demand for each group of farmers (California Department of Water Resources (2001)). The concentration of demand is a distribution of the total market demand, a percentage of the market slope and market intercept values, across the wells in the aquifer.[10]

Fig. 2a shows a detailed GIS field map of Kern County. Fig. 2b shows an imported GIS map in our model, transformed into square cells using raster calculations in GIS. We use Fig. 2b, a 246 cell aquifer, to make a detailed water model of Kern County and apply the parameters from Table 1 to estimate the welfare gain from groundwater management.[11] A cell with an agent on it represents a group of farmers that use groundwater for irrigation. The white squares represent land above the aquifer that is not irrigated but receives recharge each period.

When farmers are heterogeneous the demand parameters are distributed according to type of crop.[12] Water use for the various crops in Kern County is reported in Table A.1 in the Appendix A.

[10] If we were to add the individual demand curves together the summation would equate to the market demand curve at every price and quantity combination.

[11] In the 246 cell aquifer the computational demands make finding individual tax rates difficult. Based on the analytical solution for the bathtub model, we employ an exponential functional form on tax rates to reduce the computational demands and verify that this assumption works in a 9 cell aquifer. The functional form for each farmer is given as TaxRate$_{it} = A_i + B_i * \exp(t * C_i)$ where A_i, B_i, and C_i are the variables that are chosen to find the optimal tax rate for farmer i. Code is provided at https://sites.google.com/site/toddguilfoos/ for replication.

[12] We add up the acre feet of water used per acre across the aquifer, determined by values from Table A.1, for each group of farmers who grow crops and allocate a percentage of the market demand intercept g and market demand slope k in the same proportion. For example, suppose there are two farmers in the aquifer. Let farmer 1's acre feet used = 2 and farmer 2's acre feet used = 3 then the relative concentration of demands would be calculated as; farmer 1 = 2/5 (40%) and farmer 2 = 3/5 (60%) of the market demand parameters g and k. This provides a rough estimate of the relative differences between farmer's demands in Kern County and holds the market demand constant and equal to the bathtub model result.

Summary statistics and the distribution of the welfare gains from management can be seen in Table 2 and Fig. 3, respectively.

When farmers are heterogeneous the overall welfare gain for Kern County is 26.7%. The welfare gains for individual farmers are spread out and highly correlated with their concentration of demand. The correlation coefficient between the gain for the heterogeneous farmers and their concentration of demand is 0.89. The maximum welfare gain is obtained by farmers towards the middle of the aquifer with high water demand crops, while the minimum welfare gain is obtained by the farmers in the outskirts of the aquifer with low water demand crops. With welfare gains of 26–38% for most farmers there may be a case for implementation of groundwater management policies. This contrasts the existing literature and the bathtub model that predicts a 13% gain for this aquifer with the same market demand.

Table 3 lists the gains by crop for the case that farmers are heterogeneous. We find that there is an increase in welfare gains by crop as the acre feet of water per acre increases, and that the ordering of crop categories by size of welfare gains is consistent with the ordering by the amount of acre feet of water per acre used by crop given in Table A.1 in Appendix A. This fact is what causes the high correlation between the welfare gains of heterogeneous farmer and their concentration of demand, which is determined by crop type.

To identify whether location or concentration of demand is the driving force behind the welfare gain for individual farmers, we also estimate the welfare gain from groundwater management in Kern County under the counterfactual that farmers have homogeneous water demand, assuming that their locations are as shown in Fig. 2b. When farmers are homogeneous crop choice is incorporated into the long run demand curve implicitly, as well as irrigation technology and

Table 2
Detailed map results.

% Gain from optimal management over perfect competition		
	Heterogeneous farmers	Homogeneous farmers
Total gain	26.7%	26.1%
Average gain	26.2%	26.3%
Min	7.7%	17.5%
Max	38.5%	28.5%
Total gain ratio[a]	2.05	2.01
Max gain ratio[a]	2.96	2.19

[a] These ratios are the total or maximum gain divided by the bathtub model gain of 13%.

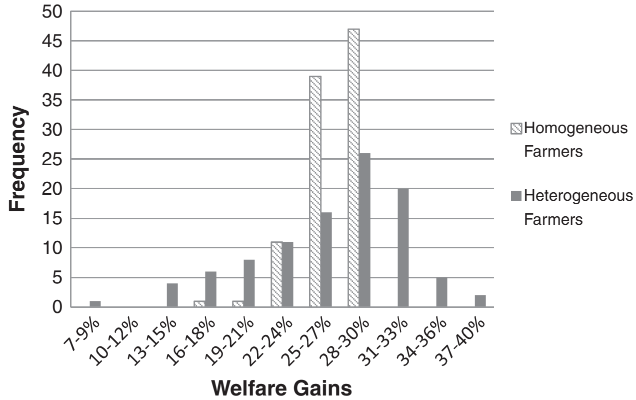

Fig. 3. Histogram of welfare gains from detailed map of Kern County, CA.

crop production. Most homogeneous farmers, 86 of 99, have gains between 25% and 28.5%. While the overall welfare gain from management remains the same at approximately 26%, the correlation between the gain when farmers are homogeneous and when farmers are heterogeneous in the same location is low, at 0.32. Compared to the high correlation between gains and the concentration of demand, this suggests that individual welfare gains are determined more by crop type than location.

5.3. Spatial Heterogeneity

To further analyze the contributions to the welfare gain, we evaluate simple abstract scenarios where we separately vary location and demand concentration. This is different from the detailed map results because we vary the location of a farmer in a controlled experiment and observe the change in the welfare gain from management. To assess the robustness of our results, we include an analysis of the Pecos Basin, TX, aquifer using the aquifer-level parameters provided in Gisser and Sanchez (1980). Table 4 lists the calibrated parameters of a nine cell aquifer of Kern County, CA, and Pecos Basin, TX. We keep the sum of individual demand constant across all scenarios and equal to the total market demand given by Eq. (2) in combination with the parameters reported in Table 4.

In Fig. 4 we examine different configurations of an aquifer varying the location of farmers on a nine cell map of an aquifer. We isolate a change in location, different positions in Fig. 4, from a change in concentration of demand, a change in the percentage of the market demand parameters assigned to a given group of farmers. There are nine cells in the aquifer with three being irrigated with groundwater; each picture of a farmer represents groups of farmers numbered to correspond to the results listed in Tables 5 and 6.

Table 3
Percent welfare gains by crop.

	% Welfare gains
Wheat, barley, oats, miscellaneous grain and hay, and mixed grain and hay	16.7%
Artichokes, asparagus, beans (green), carrots, and miscellaneous vegetables	20.5%
Potatoes	24.6%
Table grapes, wine grapes and raisin grapes	26.7%
Cotton, flax, hops, grain sorghum, and sudan	26.8%
Tomatoes for processing	28.3%
Beans (dry)	28.4%
Grapefruit, lemons, oranges, dates, and miscellaneous subtropical fruit	29.7%
Apples, apricots, cherries, peaches, and miscellaneous deciduous	29.9%
Corn (field and sweet)	29.8%
Almonds and pistachios	31.9%
Onions and garlic	24.5%
Alfalfa and alfalfa mixtures	37.6%
Total percent gains for the aquifer	26.2%

Table 4
Abstract scenario parameter values.

Symbol	Description	Pecos Basin, TX[a]	Kern County, CA[b]
N	Number of cells in aquifer	9	9
R_n	Natural recharge for each cell in aquifer (acre/ft per year)	173,000/9 = 19,222	888,000/9 = 98,666
AS_n	Surface area times storativity of each cell	135,000/9 = 15,000	129,000/9 = 14,333
K[c]	Hydraulic conductivity for each cell (ft/year)	800	800
A_0[d]	Cross sectional area of each cell (acres)	941	920
d[d]	Distance between adjacent cells (ft)	68,316	66,781
g	Market demand intercept (acre/ft)	470,365	3,967,143
k	Decrease in market demand for a $1 increase in price (acre/ft)	−3259	−57,143
C_0	Cost of pumping water from surface to sea level ($/acre foot)	125	321
C_1	Cost increase of pumping from a one foot change in height ($/acre foot of lift)	−0.035	−0.09
α	Return coefficient	0.27	0.20
r	Rate of time preference	0.05	0.05
T	Time period length	90	90
H_0	Initial height of water	3400	3352

Lower case letter *i* refers to a farmer; lower case letter *n* refers to an aquifer cell.
[a] Source: aquifer totals from Gisser and Sanchez (1980), unless otherwise noted.
[b] Source: aquifer totals from Feinerman and Knapp (1983), unless otherwise noted.
[c] Estimated from the soil composition of the aquifer.
[d] Calculated from the size and number of cells in the aquifer.

We identify the effect of spatial heterogeneity by assuming that the total land irrigated and demand concentration for each group of farmers is held constant and explore how the location of farmers affects the magnitude of the welfare gain. For example, in Table 5, compare Group 1 at Positions 1, 2 and 3 to see how much a change in location affects the welfare gain when Group 1's demand is held constant at 33% of market demand. It is apparent that when farmers are homogenous, all farmers are relatively insensitive to their relative location in the aquifer.

However, location plays a larger role when heterogeneity in demand is present. For example, in Table 6, the welfare gain for Group 2 (50% concentration of demand) in Kern County varies from 47.6% to 40.6% when field location changes.

We conclude that keeping the demand parameters constant and moving the location of the farmers closer together creates a larger welfare gain for the farmer with a relatively high demand for groundwater. Farmers with greater water demand face higher prices and become more sensitive to the lateral water flow from neighboring cells. For example, a farmer that grows alfalfa, a high water demand crop, is more sensitive to other farmers growing crops close to her farm than the farmer that grows safflower, a low water demand crop.

5.4. Demand Heterogeneity

The concentration of water demand may vary due to differences in crop choice or the amount of acreage irrigated by farmers. We evaluate the impact of demand heterogeneity on the gain from groundwater management by changing the concentration of demand while holding location and total market demand constant. Compare a particular farmer in the same location in different Tables; for example, compare Group 1 at Position 1 in Table 5 with 33% of the total demand with Group 1 in Table 6 at Position 1 with 25% of demand to see that a decrease of 8% in concentration of demand results in the welfare gain from management declining from 33.6% to 27.7%. Similarly, when Group 2 increases the

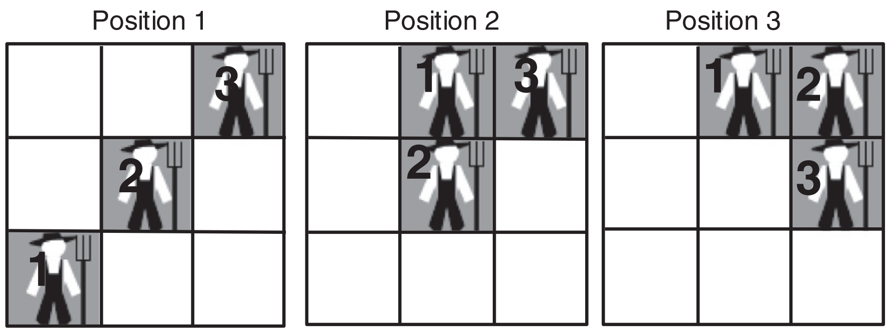

Fig. 4. Abstract scenarios.

Table 5
Abstract scenarios with homogeneous farmers.

% Gain from optimal management over perfect competition								
		Kern County, CA			Pecos Basin, TX		
		Position 1	Position 2	Position 3	Position 1	Position 2	Position 3
Concentration of demand	Group 1 — 33% of total demand	33.6%	33.5%	33.6%	.11%	.11%	.11%
	Group 2 — 33% of total demand	33.8%	33.7%	33.3%	.10%	.10%	.11%
	Group 3 — 33% of total demand	33.6%	33.5%	33.6%	.11%	.11%	.11%
	Aquifer total	33.7%	33.6%	33.5%	.10%	.10%	.11%

concentration of demand from 33% (Table 4) to 50% (Table 6) welfare gains increase from 33% to over 40%. In other words the proportional change in welfare gains is highly correlated with the proportional change in demand concentration.

While the welfare gain for the entire Kern County aquifer is roughly 33%–34%, and therefore much higher than the 13% predicted by the bathtub model, we find that the welfare gain for each group in Kern County depends critically on the concentration of demand. This reinforces the findings from the detailed map results.

In the Pecos Basin, the aquifer used by Gisser and Sanchez (1980) study, the welfare gain from optimal management is quite small even in a multi-cell setting, on the order of 0.1%. This difference to Kern County is driven by two reasons. First the amount of water demanded in the Pecos Basin is much smaller than in Kern County even though the two aquifers are of similar size. This is a function of the amount of irrigated acreage being much less in the Pecos Basin than in Kern County and also a function of crop choice. The other difference comes from a higher cost of extraction on average in Kern County, which is remnant of different energy prices and an assumption that Feinermann and Knapp made to incorporate inefficiency of pumping which Gisser and Sanchez did not make. So even though there are very different average gains for farmers in these aquifers there may be individual farmers with much to gain from management in the Pecos Basin who have a deep well, a crop with high water demand, and is in a cluster of other irrigating farmers. It is also several times the welfare gain in the bathtub model, as much as 6 to 23 times greater than the value reported in Gisser and Sanchez (1980). And similar to the Kern County results the heterogeneity of demand seems to drive the welfare gains from management more than the location of the wells.

5.5. Strategic Behavior

When farmers behave strategically in the presence of finite hydraulic conductivity and maximize the present value of surplus from their individual wells, discounted profits may be larger than under the assumption of myopic behavior. As a result, we may expect that the gains from management will be correspondingly smaller. One concern when using the assumption of strategic behavior is that the scale of the aquifer, how many cells there are, becomes important because any one cell may contain multiple farmers that implicitly work together to maximize their joint profits. Therefore a model with very low resolution and few cells would overestimate the profits from strategic behavior and therefore underestimate the welfare gains from management. But, to calculate the optimal control solution is computationally expensive and grows exponentially in difficulty as cells are added to the model and the resolution is increased. To overcome this problem we use a very detailed model with the same total properties and parameters for Kern County, CA but with 2134 farmers and 5644 cells (each cell is roughly 160 acres), Fig. 5, to calculate the perfect competition and strategic behavior profits and we infer the optimal control profits based on the results presented in Table 2.[13] Using the detailed aquifer from Fig. 5, the parameters from Table 1 appropriately adjusted for a 5644 cell aquifer, and the framework from Section 2.3 we find results for the entire aquifer, presented in Table 7.

These results suggest that strategic behavior does much better than perfect competition and that gains from management are approximately 10–12% for the entire aquifer, rather than 26–27% if myopic behavior is assumed. This result is contingent on two important facts: that the other farmers in the aquifer also act in a strategic manner and that the adaptive expectations are fairly close to future inter-well transfers. This first point can be intuitively understood as follows: If a farmer saves water for future use and her neighbors don't, she loses more water to (or gains less water from) her neighbors through lateral flows. The theoretical literature on strategic pumping suggests increased pumping is optimal following the same basic logic (Saak and Peterson, 2007). Numerically we confirm in our model that farmers will do better by behaving myopically rather than strategically if the other farmers

[13] The overall magnitude of welfare gains under optimal control is unlikely to be very sensitive to the number of cells in the aquifer and we assume that it is no different than the magnitude obtained with 246 cells.

Table 6
Abstract scenarios with heterogeneous farmers.

% Gain from optimal management over perfect competition							
		Kern County, CA			Pecos Basin, TX		
		Position 1	Position 2	Position 3	Position 1	Position 2	Position 3
Concentration of demand	Group 1 — 25% of total Demand	27.7%	27.8%	27.8%	.06%	.07%	.07%
	Group 2 — 50% of total demand	41.9%	47.6%	40.6%	.21%	.22%	.23%
	Group 3 — 25% of total demand	27.7%	27.7%	27.8%	.06%	.06%	.07%
	Aquifer total	32.8%	34.7%	32.3%	.14%	.14%	.14%

Fig. 5. 5644 cell aquifer (Kern County).

behave myopically.[14] Only when all farmers behave in the strategic way described here do we retrieve the results in Table 7. Essentially, farmers are in a bad Nash Equilibrium in which they have an incentive to pump more water to increase the lateral flows into their well and behave myopically, even with finite hydraulic conductivity. Second, to the extent that farmers are wrong about future lateral flows they choose the wrong extraction path. Situations that increase the size of errors in expectations make this type of strategic behavior unattractive, such as unpredictable variation in recharge or changes in water extraction by neighbors over time. Conditions that make this strategy attractive are when the size of the inter-well transfer is small or unlikely to change much by the actions of the farmer.

6. Conclusion

Hydrologists know that groundwater typically flows gradually through an aquifer and that the rate of lateral flows is important to groundwater management. On the other hand, until very recently, economists have assumed that groundwater flows instantaneously, rendering heterogeneity in well location and in the demand for water immaterial. Yet, there are increased calls for regulation of aquifers that face rapidly declining groundwater levels, such as in California, and the expectation that there could be large benefits from adopting groundwater management strategies. And while the literature provides us with the knowledge that the bathtub model will provide inaccurate estimates, it has not provided evidence of how inaccurate those estimates may be in a large aquifer. We bridge the gap between hydrologists, economists and policy makers by explicitly incorporating the slow movement of groundwater in a detailed multi-cell model of a large aquifer and quantify the welfare gains from optimal management.

Overall, we find that the welfare gain from groundwater management can be significant in Kern County at 26.7% when using a spatially detailed description of field location and concentration of water demand. Demand heterogeneities are important and highly correlated with individual farmers' welfare gains. Some farmers in high demand areas with high water demand could gain up to 39% which is roughly three times larger than implied by the bathtub model for the same aquifer. Our results are also contingent on the behavior of farmers. We show that if all farmers behave strategically then the welfare gain from optimal management is substantially smaller. But, it is also to the benefit of each farmer to behave myopically when they believe that other farmers behave myopically.

Our results imply that there may be large gains from management when farmers behave myopically. And policies that make it more likely for farmers to adopt behavior that strategically saves water may substantially increase welfare, such as well spacing requirements. We also show that getting the physics of groundwater correct is important when evaluating groundwater policy questions. This does not imply that all aquifers will benefit significantly from management –our results show that the Pecos Basin is likely to have small gains – but that a closer look at individual aquifers is in order to determine the size of welfare gains.

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Table 7
Gains from optimal management when farmers behave strategically.

	Heterogeneous farmers	Homogeneous farmers
(1) Total discounted profit: Perfect competition	$654,297,552	$662,188,141
(2) Total discounted profit: strategic behavior	$741,599,943	$756,267,077
(3) Estimated total discounted profit: optimal control[a]	$828,994,999	$834,357,058
% Gain from optimal control over strategic behavior: [(3) − (2)] / (2) [a] 100	11.8%	10.3%

[a] Calculated using gains of 26.7% and 26.0% from Table 2 respectively, multiplied by total discounted profits from perfect competition in row (1).

[14] In the model with 2134 farmers and 5644 cells we confirmed that total discounted profits for an individual farmer that behaves in a strategic way when all of the other farmers behave myopically are less than if she had instead behaved myopically. This test was run on 10 different farmers in various locations of the aquifer. We recognize there may be other ways in which farmers act strategically and possibly gain welfare; this example provides evidence that when comparing these two behaviors (strategic and myopic) with finite hydraulic conductivity it is not obvious that farmers will benefit from trying to save water as their welfare gains from doing so are tied to the actions of many other farmers. An alternative way to approach the problem is to find the best reaction of all the farmers to each other, but it is infeasible to calculate with this model.

Appendix A

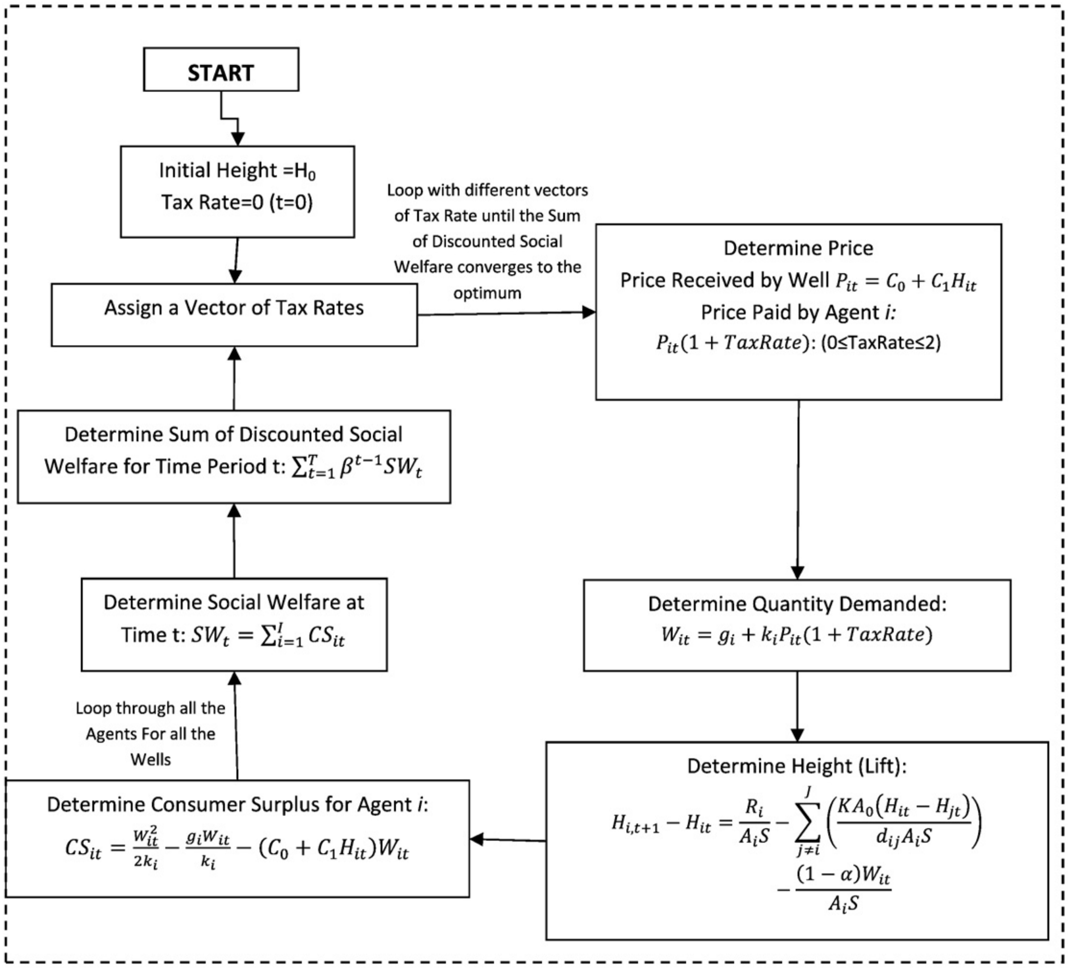

Fig. A.1. Numerical methodology for the optimal control problem.

Table A.1
Acre feet of water applied per acre.

Acre feet per acre	Crops
1.4	Wheat, barley, oats, miscellaneous grain and hay, and mixed grain and hay
3.1	Cotton
2.45	Sugar beets
3.68	Corn (field and sweet)
3.43	Beans (dry)
1.71	Safflower
3.1	Flax, hops, grain sorghum, sudan, castor beans, miscellaneous fields, sunflowers, hybrid sorghum/sudan, millet and sugar cane
5.15	Alfalfa and alfalfa mixtures
4.89	Clover, mixed pasture, native pastures, induced high water table native pasture, miscellaneous grasses, turf farms, bermuda grass, rye grass and klein grass
3.31	Tomatoes for processing
2.83	Tomatoes for market
2.78	Melons, squash and cucumbers
3.85	Onions and garlic
2.36	Potatoes
1.69	Artichokes, asparagus, beans (green), carrots, celery, lettuce, peas, spinach, flowers nursery and tree farms, bush berries, strawberries, peppers, broccoli, cabbage, cauliflower and brussel sprouts
3.84	Almonds and pistachios
3.64	Apples, apricots, cherries, peaches, nectarines, pears, plums, prunes, figs, walnuts and miscellaneous deciduous
3.60	Grapefruit, lemons, oranges, dates, avocados, olives, kiwis, jojoba, eucalyptus and miscellaneous subtropical fruit
2.74	Table grapes, wine grapes and raisin grapes

Source: California Department of Water Resources, 2001.

Appendix B. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ecolecon.2013.07.013.

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