Optimal groundwater management in response to the intensity of lateral flows

Kent F. Kovacs[1]
Tel: (479) 575-2323
kkovacs@uark.edu

Alvaro Durant-Morat[1]
Tel: (479) 575-6038
adurand@uark.edu

[1] University of Arkansas
Department of Agricultural Economics and Agribusiness
216 Agriculture Building
Fayetteville, AR 72701

Selected Paper (or Poster) prepared for presentation at the Southern Agricultural Economics Association SAEA) Annual Meeting, Jacksonville, Florida, 3-6 February 2018.

Abstract

Lateral flows of groundwater where there is instant movement from one location to another is the typical assumption in the models of the optimal management of a groundwater stock. We find optimal pumping is lower and economic returns are lower in models of finite lateral flow than models that suppose water can travel instantly through an aquifer. An abundant groundwater region earns 5% lower economic returns and pumps 20% less groundwater when lateral flow is finite. Depleted groundwater regions pump 25% less and earn 8% lower economic returns if there is limited lateral groundwater flow.

Introduction

The central control of groundwater eliminates the stock externalities that arise from the spillover effect of the use of groundwater on the pumping decision of other users (Provencher 1993). However, the assumption of instantaneous lateral flow of groundwater affects the optimal use of the groundwater stock even when there is central control of the resource (Brozovic et al. 2010). The difference in the optimal management because of the lateral flow of groundwater affects the rate of groundwater depletion and the potential returns from the irrigated landscape. The appropriate central control of the groundwater resource matters for identifying how much optimal pumping differs from the inefficient pumping that occurs in a competitive situation with common property resource use and intertemporal user cost externalities. Once the correct optimal pumping in the presence of finite lateral flows are known, then policies to align the decentralized use of the groundwater with the central management approach can be set properly.

We apply a mathematical programming model of groundwater use across two thousand sites over thirty periods to the Arkansas side of the Lower Mississippi River Basin (a farming region referred to as the Arkansas Delta). Using a central planner objective of economic returns maximization, the bathtub aquifer model tracks the infinite lateral flow of groundwater in response to well pumping, and extraction costs rise at every site on the landscape in response to pumping at one site. In the spatial aquifer model, the finite lateral flow means that pumping at one site causes extraction costs to rise only at sites that are in close proximity to the pumped well. The study region is well suited to the examination of how lateral flows influence management because there is ample spatial variability across the sites in the irrigation demand of the crops, well depth, saturated thickness of the aquifer, and rate of natural recharge. This provides a range of agronomic and aquifer site characteristics for the examining the influence of crop mix and groundwater use choices on economic returns. The use of the spatial variation to understand the economic consequence of groundwater policies has increased (Guilfoos et al. 2016; Kuwayama and Brozoivc 2013; Palazzo and Brozovic 2014), but the spatial variation in these models has not been used to examine the influence of lateral flow of the aquifer on central management.

Policies to curtail groundwater use remedy the problem of over extraction due to myopia and common pool resource externalities. However, even in a centrally planned system, regulation is necessary when the groundwater users do not take account of the full value of the groundwater. For instance, the value of groundwater to stabilize profit in unexpectedly dry years, known as buffer value, is one such value not taken into account by a central planner (Tsur 1990). Other social values of groundwater include the avoidance of subsidence, the provision of flows for riparian ecosystems, and the ability to dilute pollution in groundwater. A useful criterion for evaluating alternative regulations is cost-effectiveness. A regulation's ability to increase the aquifer in a centrally managed system cost-effectively depends on the modeling assumption for the degree of lateral groundwater flow.

Methods

The methods section describes the optimization problem of the central planner that include model components for the land cover decision and the associated irrigation of the chosen crops through groundwater pumping, which depends on the lateral flow of the groundwater. Spatial analyses consider the difference in management for the bathtub and spatial aquifer models by examining results for abundant and depleted groundwater regions.

Land covers in an agricultural region

The initial land availability equals the sum of the land covers chosen for site *i* at any time *t* (Eq. 1).

$$\sum_{j}^{n} L_{ijt} = \sum_{j}^{n} L_{ij0} \text{, for } j = \text{crops, government easement} \quad (1)$$

Irrigation in the infinite lateral flow aquifer versus the finite lateral flow aquifer

We suppose irrigation water for producers comes from groundwater pumping from wells, GW_{it}. The water used for irrigation must be less than the water available from wells (Eq. 2).

$$\sum_{j=1}^{n} wd_j L_{ijt} \le GW_{it} \quad (2)$$

For the bathtub aquifer, the aquifer depletion occurs uniformly over space in response to the collective groundwater extraction of the producers. The volume of the aquifer AQ_t is not variable across space since the degree of lateral flow is infinite and the aquifer moves down at the same rate for every site. The sum of the site specific natural recharge, nr_i, is the total recharge of the aquifer for the landscape that occurs from precipitation, streams, and underlying aquifers each period (Eq. 3). The depletion of the bathtub aquifer volume, $AQ_0 - AQ_t$, divided by the area of the landscape, $\sum_{i}^{m} \sum_{j}^{n} L_{ij0}$, indicates how much the depth to the aquifer increases at all sites. Capital costs per acre-foot to account for new well drilling in response to the aquifer decline is c^c (Eq. 4).

$$AQ_t = AQ_{t-1} - \sum_{i}^{m} GW_{it} + \sum_{i}^{m} nr_i \quad (3)$$

$$GC_{it} = c^c + c^p \left(dp_i + \frac{\left(AQ_0 - AQ_t \right)}{\sum_{i}^{m} \sum_{j}^{n} L_{ij0}} \right) \quad (4)$$

For the spatial aquifer, the variable intensity of well pumping across the landscape creates uneven aquifer depletion and cones of depression. The groundwater stored in the flat-bottomed aquifer beneath site *i* at the end of the period *t* is AQ_{it}. The underground flow into the aquifer at site *i* and out of site *k* when an acre-foot is pumped from a well at site *i* depends on the distance and the lateral speed of underground water movement based on the soil profiles and hydraulic gradient observed between sites. Jenkins (1968) quantifies the groundwater flow out of site *k* into site *i* according to the hydraulic diffusivity, which is hydraulic conductivity multiplied by difference in saturated thickness between the two sites of the aquifer, divided by the square of the shortest distance between the pumped well at site *i* and the nearby site *k*. The groundwater flow out of site *k* into site *i* divided by the sum of all groundwater flow into site *i* is the proportion p_{ik} (Eq. 5).

$$p_{ik} = \begin{cases} \dfrac{\dfrac{K_{ik}\left(T_{k0}-T_{i0}\right)}{d_{ik}^2 S}}{\sum_{k=1}^{n}\dfrac{K_{ik}\left(T_{k0}-T_{i0}\right)}{d_{ik}^2 S}} = \dfrac{\dfrac{K_{ik}\left(T_{k0}-T_{i0}\right)}{d_{ik}^2}}{\sum_{k=1}^{n}\dfrac{K_{ik}\left(T_{k0}-T_{i0}\right)}{d_{ik}^2}} & \text{if } T_{k0} > T_{i0} \\ 0 & \text{if } T_{k0} \le T_{i0} \end{cases} \qquad (5)$$

where K_{ik} is the average hydraulic conductivity between sites *i* and *k*, $\left(T_{k0}-T_{i0}\right)$ is the difference of the initial saturated thickness between sites *k* and *i*, and d_{ik} is the distance between sites *i* and *k*. The unitless specific yield *S* is constant for an unconfined aquifer, and this does not influence the proportion p_{ik}. The initial formulation of Equation 5 used a temporally variable saturated thickness that changes in response to well pumping and natural recharge, but the temporally variable saturated thickness is found to have little influence on the results and the solve time increases markedly.

The groundwater that leaves site i in response to pumping across the landscape is $\sum_k^m p_{ik} GW_{kt}$.

The aquifer volume at site i in the previous period less the spatially weighted proportion of water pumped from the surrounding sites plus natural recharge equals the present aquifer volume (Eq. 6). The depletion of the aquifer volume, $AQ_{i0} - AQ_{it}$, divided by the area of the site, $\sum_j^n L_{ij0}$, indicates how much the depth to the aquifer changes for each site (Eq. 7).

$$AQ_{it} = AQ_{i(t-1)} - \sum_k^m p_{ik} GW_{kt} + nr_i \tag{6}$$

$$GC_{it} = c^c + c^p \left(dp_i + \frac{\left(AQ_{i0} - AQ_{it}\right)}{\sum_j^n L_{ij0}} \right) \tag{7}$$

Economic returns objective

Equation 8 indicates the economic objective to maximize the present value of farm net returns for the landscape over the fixed horizon T by changing the amount of land in each crop or government easement, and groundwater use, namely L_{ijt} and GW_{it}. The initial condition of the state variables, $L_{ij0} = L_0^{ij}, AQ_{i0} = AQ_0^i$, and the non-negativity constraints on land, water use, and the aquifer appear in the Equation 9.

$$\max_{L_{ijt}, GW_{it}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \left(pr_j y_{ij} - ca_{jk} \right) L_{ijt} - GC_{it} GW_{it} \right) \tag{8}$$

subject to:

$$L_{ij0} = L_0^{ij}, AQ_{i0} = AQ_0^i, L_{ijt} \geq 0, GW_{it} \geq 0, AQ_{it} \geq 0. \tag{9}$$

and the spatial dynamics of land and irrigation (Eqs. 1-4) for the bathtub aquifer model and (Eqs. 1,2,5-7) for the spatial aquifer model. The non-linear programming solver CONOPT from AKRI Consulting and Development performs the optimization in the Generalized Algebraic Modeling System (GAMS) 24.5.6 (GAMS Development Corporation 2016).

Policy options

The groundwater conservation policies we consider include a cap on groundwater pumping, a tax on groundwater pumping costs, and a subsidy to increase the rental payment of the government easement. A cap on groundwater use limits groundwater use for each site and period to 75% of the initial groundwater pumping. A tax on groundwater pumping costs (40% for the bathtub model and 10% for the spatial) and a subsidy on CRP rental payments (120% for the bathtub model and 90% for the spatial) achieve groundwater conservation similar to the cap on groundwater pumping.

Data

Three eight-digit hydrodologic unit code (HUC) watersheds comprise the study area where unsustainable groundwater use is occuring in the Arkansas Delta (Figure 1). Table 1 has the average acreage of each crop initially by site based on the 2015 Cropland Data Layer (Johnson and Mueller, 2010) for the entire landscape and for the rice and soybean intensive landscapes. With a 30yr Treasury Bond yield over the last decade of 5% (US Department of the Treasury, 2015) less a long-run expectation for inflation of 3%, the analysis uses a 2% real discount rate.

Farm production

The farm production parameters are in Table 2. The Division of Agriculture (2015) has the 2015 Crop Cost of Production estimates used for the costs of production by crop excluding irrigation costs. The Division of Agriculture (2015) has the average irrigation over the course of the growing season excluding natural rainfall. The crop prices come from the five-year average of December futures prices for harvest time contracts for all crops (GPTC, 2015). A 100 foot well requires about 13 gallons of diesel per acre-foot, and a 200 foot well requires about 26 gallons of diesel per acre-foot (Hogan et al., 2007).

Groundwater use and recharge

The depth to the water table and initial saturated thickness of the alluvial aquifer shown in Table 2 comes from the Arkansas Natural Resources Commission (ANRC 2015). Reed (2003) use a calibrated model of recharge for the period 1994 to 1998 associated with precipitation and flow to or from surface streams to determine the natural recharge (nr_i) of the Alluvial aquifer. The distance from the pump (d_{ik}) and the hydraulic diffusivity of the aquifer determines this underground flow of water. The ratio of the transmissivity and the specific yield (S) of the unconfined alluvial aquifer is the hydraulic diffusivity (Barow and Leake 2012). We use spatially coarse pilot points from Clark, Westerman and Fugitt (2013) to estimate the hydraulic conductivity.

Results

Table 3 indicates for the end of the study period the proportion of acreage in the crops, groundwater pumping per acre, the level of the aquifer per acre for the study area, and the 30-year farm net returns. The cones of depression that occur in the spatial aquifer result in more transition out of rice into soybeans, non-irrigated sorghum, and CRP across the entire landscape. At the rice intensive sites, the proportion of rice is 0.24 in the bathtub aquifer and 0.15 in the spatial aquifer, and the proportion of land in soybeans, is 0.40 in the bathtub and 0.48 in the spatial versions of the aquifer. The proportion of non-irrigated land is higher at the rice intensive sites than the soybean intensive sites. At the soybean intensive sites, there is a proportion of 0.72 for soybeans in the bathtub aquifer and 0.74 in the spatial aquifer, and the proportion of sorghum and CRP is 0.05 in the bathtub aquifer and 0.11 in the spatial aquifer.

The groundwater pumping and the aquifer volume reduction is greater in the bathtub aquifer. The less irrigation intensive use of cropland with the spatial aquifer makes the average aquifer thickness 67 feet in the final period while the bathtub aquifer is a smaller 61 feet. Groundwater use is lower at the rice intensive sites, where the aquifer is most scarce, compared to the whole landscape and the soybean intensive sites. The greater production of profitable irrigation intensive rice with the bathtub aquifer makes 30-year net returns $2,528 per acre while the net returns with the spatial aquifer are $2,377 per acre. The profitability of the average acre at the soybean intensive sites is greater because groundwater pumping cost are lower than elsewhere on the landscape.

Table 4 indicates there are on average 33 percent more rice acres with the bathtub aquifer compared to the spatial aquifer across all sites, although there is a large standard deviation of 73 percent. There is 50 percent less non-irrigated sorghum acres for the bathtub aquifer compared to the spatial aquifer. Over the study period, there is 12 percent greater groundwater use and 7 percent greater farm net returns for the bathtub aquifer than the spatial aquifer. For the rice intensive sites, the bathtub aquifer has 41 percent more rice acres and 15 percent more groundwater pumping while the soybean intensive sites has 16 percent more rice acres and 1 percent more groundwater pumping.

We compare the cost-effectiveness (in $ per acre-foot of groundwater conserved) of policies to conserve groundwater across the bathtub and spatial aquifers in Table 5. The cost-effectiveness of a policy is the social cost of the policy, which is the subtraction of the farm net returns plus government revenue with the policy from the farm net returns without the policy, and divided by the change in the aquifer level with and without the policy. For all the policies, the groundwater conservation cost is greater with the spatial aquifer than the bathtub aquifer. In the bathtub model, there is instant access across the landscape to all of the groundwater resource, and this allows crop patterns to change more easily to minimize economic harm in response to a policy than is possible with the spatial aquifer. The magnitude of the tax or subsidy to achieve the same conservation is larger in the bathtub aquifer than the spatial aquifer. Groundwater pumping is more sensitive to the policies in the spatial aquifer because groundwater does not flow easily to other parts of the landscape to alleviate the constraints of regulation.

Discussion and Conclusion

The optimal use of groundwater is greater at the regional scale with a bathtub aquifer than a spatial aquifer, and empirical estimates suggest how much more this use of the aquifer could be. Comparing regions of the landscape with initially abundant groundwater (soybean intensive) or depleted groundwater (rice intensive), producers in the bathtub aquifer model use 20% and 25% more groundwater over 30 years, respectively, than in the spatial aquifer model. At the site level, the abundant and depleted groundwater regions use on average 15% and 1% greater groundwater with the bathtub aquifer, but the standard deviation in these percent differences across sites is substantial at 37% and 54%, respectively.

The large site level variation in the difference in groundwater use according to the model of the aquifer reflects the variation of the initial conditions at those sites. The initial conditions that most explain the differences in groundwater use between the two types of aquifer at the rice intensive sites are the net returns to rice before irrigation costs, the initial depth, the initial aquifer volume, and the net returns to soybeans before irrigation costs. For the soybean intensive sites, the strongest determinants of the difference in groundwater use between the bathtub and spatial aquifers are the net returns to rice before irrigation costs, the initial depth, and the initial aquifer volume. In general, the initial conditions that explain differences in the groundwater use between the two models of lateral flows are the same for regions with abundant and depleted aquifers, but a region with a depleted aquifer is also sensitive to the net returns of a less irrigation intensive crop such as soybeans.

All the policies to encourage groundwater conservation are more cost-effective in a bathtub aquifer model than a spatial aquifer model. A high degree of lateral flow in the bathtub aquifer allows flexible adjustment to well pumping and crop mix across the landscape in response to a policy. A tax on groundwater use is the most cost-effective policy in the bathtub aquifer because the tax generates government revenue in groundwater abundant areas while lowering farm net returns only slightly. In the spatial aquifer model, the farm net returns fall more with the tax because groundwater cannot flow easily to the depleted aquifer region most harmed by the tax. The subsidy on CRP is the most cost-effective policy for the spatial aquifer model, but large government transfers are necessary to achieve the groundwater conservation goal. The CRP subsidy is effective in the spatial aquifer because this promotes land retirement in the places most likely to convert to a non-irrigated land use where well pumping costs are high and aquifer volumes low. The cap on groundwater is the least cost-effective policy in both the bathtub and spatial aquifer models.

References

Arkansas Natural Resources Commission (ANRC). “Arkansas Groundwater Protection and Management Report for 2011.” Little Rock, AR. 2015.

Barlow, P.M., S.A. Leake. “Streamflow Depletion by Wells-Understanding and Managing the Effects of Groundwater Pumping on Streamflow.” U.S. Geological Survey Circular 1376, 84 p. 2012.

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

California Department of Water Resources (CA DWR). “Groundwater Management.” Sacramento, CA. 2016.
http://www.water.ca.gov/groundwater/groundwater_management/index.cfm

Clark, B.R., D.A. Westerman, D.T. Fugitt. “Enhancements to the Mississippi Embayment Regional Aquifer Study (MERAS) groundwater-flow model and simulations of sustainable water-level scenarios.” U.S. Geological Survey Scientific Investigations Report 2013–5161, 29 p. 2013.

Division of Agriculture, University of Arkansas. “2015 Crop and Enterprise Budgets.” Little Rock, AR: AG-1272. 2015. https://www.uaex.edu/farm-ranch/economics-marketing/farm-planning/budgets/Budget_Text_2015.pdf

Edwards, E. 2016. “What Lies Beneath? Aquifer Heterogeneity and the Economics of Groundwater Management.” *Journal of the Association of Environmental and Resource Economists*. 3(2): 453-491.

Energy Information Administration (EIA), US Department of Energy. “Gasoline and Diesel Fuel Update.” November 2015. http://www.eia.gov/petroleum/gasdiesel/

General Algebraic Modeling System (GAMS) Development Corporation. “GAMS – A User’s Guide”. September 2016. Washington, D.C., USA. https://www.gams.com/help/index.jsp

Great Pacific Trading Company (GPTC). ‘‘Charts and Quotes.’’ November 2015. http://www.gptc.com/quotes.html.

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

Guilfoos, T., N. Khanna, J. Peterson. 2016. “Efficiency of Viable Groundwater Management Policies.” *Land Economics.* 92(4): 618-640.

Hogan, R., S. Stiles, P. Tacker, E. Vories, and K. J. Bryant. 2007. “Estimating irrigation costs.” Little Rock, AR: Arkansas Cooperative Extension Service. FSA28-PD-6-07RV.

Jenkins, C.T. “Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations”, Book 4, Chap. D1, 17 p. 1968.

Johnson, D.M., R. Mueller. “The 2009 Cropland Data Layer.” *Photogrammetric Engineering and Remote Sensing*. November (2010): 1201-1205.

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

Moore, M., N. Gollehon, M. Carey. 1994. “Multi-crop production decisions in western irrigated agriculture: the role of water price.” *American Journal of Agricultural Economics*. 76(4): 859-874.

National Agricultural Statistics Service (NASS), US Department of Agriculture (USDA), Arkansas Field Office. “Soybean Irrigated and Non-Irrigated.” November 2015. http://www.nass.usda.gov/Statistics_by_State/Arkansas/Publications/County_Estimates/

Palazzo, A., N. Brozovic. 2014. “The role of groundwater trading in spatial water management.” *Agricultural Water Management*. 145: 50-60.

Pfeiffer, L., C.-Y. C. Lin. 2012. “Groundwater pumping and spatial externalities in agriculture.” *Journal of Environmental Economics and Management.* 64(1): 16-30.

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

Provencher, B., O. Burt. 1994. “A Private Property Rights Regime for the Commons: The Case for Groundwater.” *American Journal of Agricultural Economics*. 76(4): 875-888.

Reed, T.B. “Recalibration of a Groundwater Flow Model of the Mississippi River Valley Alluvial Aquifer of Northeastern Arkansas, 1918-1998, with Simulations of Water Levels caused by Projected Groundwater Withdrawls Through 2049.” U.S. Geological Survey Water Resources Investigations Report 03-4109, 58 p. 2003.

Tsur, Y. 1990. “The Stabilization Role of Groundwater When Surface Water Supplies are Uncertain: The Implications for Groundwater Development.” *Water Resources Research* 26: 811-18.

U.S. Department of Agriculture (USDA) -- Farm Service Agency (FSA). “Conservation Reserve Program Statistics.” Internet site: http://www.fsa.usda.gov/programs-and-services/conservation-programs/reports-and-statistics/conservation-reserve-program-statistics/index (Accessed June 2016).

U.S. Department of the Treasury. “Interest Rate Statistics.” http://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/default.aspx. December 2015.

Wang, C., and E. Segarra. "The Economics of Commonly Owned Groundwater When User Demand Is Perfectly Inelastic." *Journal of Agricultural and Resource Economics* 36(2011): 95-120.

White, H. L., Jr. 1980. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica* 48: 817–838.

Table 1. Descriptive statistics of the spatial data across the sites of the study area

Variable	Definition	All sites	Rice intensive sites	Soybean intensive sites
			Mean values	
$L_{i,rice}$	Initial hectares of rice	46	126	14
$L_{i,isoy}$	Initial hectares of irrigated soybean	117	74	147
$L_{i,dsorg}$	Initial hectares of dry land sorghum	28	5	16
$y_{i,rice}$	Annual rice yield (kg per hectare)	6849	6849	6737
$y_{i,isoy}$	Annual irrigated soybean (kg per hectare)[1]	2493	2358	2762
$y_{i,dsorg}$	Annual dry land sorghum (kg per hectare)[1]	4275	4275	4401
dp_i	Depth to water (meters)	19	26	16
AQ_i	Initial volume of the aquifer (cubic meters)	48,925,984	38,722,638	51,565,631
K	Hydraulic conductivity (meters per day)	69	68	69
nr_i	Annual natural recharge of the aquifer per hectare (cubic-meters)	1,374	1,496	1,374

Note: Number of all sites is 2,000; number of rice intensive sites is 259, and number of soybean intensive sites is 737. [1] The mean and the standard deviation of the county yields come from the 11 counties in the study area.

Table 2. Value of economic and irrigation model parameters.

Parameter	Definition	Value
pr_{rice}	Price of rice ($/kg)	0.306
pr_{soy}	Price of soybeans ($/kg)	0.434
pr_{sorg}	Price of sorghum ($/kg)	0.165
pr_{crp}	Government payment per hectare for CRP	172.03
ca_{rice}	Annual production cost of rice ($/hectare)	1599.01
ca_{isoy}	Annual production cost of irrigated soybean ($/hectare)	863.86
ca_{dsorg}	Annual production cost of dry land sorghum ($/hectare)	668.32
ca_{crp}	Annual maintenance cost of CRP ($/hectare)	64.36
wd_{rice}	Annual irrigation per hectare of rice (cubic-meters)	3083.70
wd_{isoy}	Annual irrigation per hectare of full-season soybean (cubic meters)	1233.48
c^p	Cost to raise an cubic-meter of water by one meter ($/meter)	1.80
δ_t	Discount factor	0.98

Table 3. Crop, water use, and economic conditions for the baseline simulation model at the end of the study period for bathtub and spatial representations of the aquifer for the entire landscape, the rice intensive landscape, and the irrigated soybean intensive landscape

Crop, water use, and economic conditions	**All sites**		**Rice intensive sites**		**Irrigated soybean intensive sites**	
	Bathtub aquifer	**Spatial aquifer**	**Bathtub aquifer**	**Spatial aquifer**	**Bathtub aquifer**	**Spatial aquifer**
Rice (Proportion of total acres in the respective landscape)	0.26	0.15	0.24	0.15	0.24	0.15
Soybeans (Proportion of total acres in the respective landscape)	0.62	0.68	0.40	0.48	0.72	0.74
Non-irrigated sorghum (Proportion of total acres in the respective landscape)	0.09	0.09	0.31	0.29	0.03	0.05
CRP land (Proportion of total acres in the respective landscape)	0.03	0.07	0.06	0.08	0.02	0.06
30-year groundwater use (acre-feet per acre)	36.78	30.20	27.88	22.31	38.36	31.86
Aquifer (thousand acre-feet per acre)[1]	61	67	--[2]	54	--[2]	76
30-year farm net returns ($ per acre)	2,528	2,377	1,764	1,634	2,995	2,840

Note: Number of acres on the entire, rice intensive, and irrigated soybean intensive landscape is 944 thousand, 131 thousand, and 323 thousand. The initial aquifer for all sites, rice intensive sites, and irrigated soybean intensive sites is 84, 62, and 95 thousand acre-feet per acre, respectively. [2] The aquifer beneath the rice and soybean intensive landscapes does not represent the only groundwater available to farmers because the bathtub aquifer model allows groundwater anywhere on the landscape to be available to any site.

Table 4. Percent difference between the bathtub and spatial representations of the aquifer for the crop, water use, and economic conditions for the baseline simulation model for the entire landscape, the rice intensive landscape, and the irrigated soybean intensive landscape

Percent difference between the bathtub and spatial representations of the aquifer	**All sites**		**Rice intensive sites**		**Irrigated soybean intensive sites**	
	Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**
Final period rice (% difference in acres)	33	73	41	68	16	84
Soybeans (% difference in acres)	-16	55	-9	54	-31	57
Non-irrigated sorghum (% difference in acres)	-50	61	-77	49	-17	52
CRP land (% difference in acres)	-74	59	-88	41	-58	66
30-year groundwater use (% difference in acre-feet)	12	38	15	54	1	37
30-year farm net returns (% difference in $)	7	15	8	16	6	16

Note: Number of sites on the entire, rice intensive, and irrigated soybean intensive landscape is 2000, 256, and 734

Table 5. Aquifer representation and the cost-effectiveness of policies to conserve groundwater

Policy	**Aquifer representation**	**Aquifer, 2045 (thousand acre-feet)**	**Farm net returns, 30yr NPV [a] ($ millions)**	**Government revenue, 30yr NPV ($ millions)**	**Groundwater conservation cost [b] ($ per acre-foot)**
Baseline	Bathtub	57,160	2,385	--	--
	Spatial	63,330	2,243	--	--
Cap on groundwater pumping [c]	Bathtub	70,960	2,000	0	27.89
	Spatial	72,250	1,932	0	34.87
Tax on groundwater use [d]	Bathtub	70,600	2,003	354	2.08
	Spatial	72,950	1,855	99	30.04
Subsidy on CRP [d]	Bathtub	70,440	2871	-772	10.87
	Spatial	72,450	2571	-470	15.57

Note: All models use a profit objective, allow on-farm reservoirs and all conservation technologies, and there is no constraint on the aquifer magnitude. [a] The farm net returns include the payments to or receipts from the government because of the policy. [b] Groundwater conservation cost is calculated as the policy cost (which is the farm net returns in the baseline less the farm net returns plus government revenue for each policy scenario) divided by the change in aquifer level between the policy option and the baseline. [c] A cap on groundwater use is chosen that limits groundwater use for the entire study period to 75% of the initial groundwater pumping. [d] We choose a tax on groundwater pumping costs (40% for the bathtub model and 10% for the spatial) and a subsidy on CRP rental payments (120% for the bathtub model and 90% for the spatial) to achieve groundwater conservation similar to the cap on groundwater pumping.

Figure 1. (a) Three eight-digit hydrologic unit code (HUC) watersheds define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. The boundary of the Arkansas Delta is defined as Mississippi river alluvial plain. (b) County lines overlay the gridded study area. Public land and urban areas are excluded. (c) The depth to the alluvial aquifer in 2015 shown in feet. Lighter shades indicate the groundwater resource is more abundant.