Conjunctive On- and Off-farm Surface Water Investment influence on Crop Mix and Groundwater Use on an Agricultural Landscape

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Abstract

The use of surface water to replace groundwater for irrigation is often viewed as an effective approach for reducing groundwater overdraft on an agricultural landscape. The expected increase in the aquifer volume in the presence of surface water does not occur unless the off-farm water price is low enough to generate a significant shift away from groundwater. There is a change in the crop pattern toward more irrigation intensive crops, and the net effect can be a rise in groundwater extraction.

Keywords: Irrigation, Groundwater conservation, Surface water delivery

JEL Classifications: Q15, Q24, Q25

Introduction

Overdraft of groundwater for irrigation causes the depletion of shallow aquifers, and the rise in groundwater pumping costs causes economic returns to fall. One solution to the problem of groundwater overdraft is the use surface water instead of groundwater for irrigation. However, precipitation that generates surface water often occurs at times of the year when the demand for irrigation is low, and the surface water must then be stored until the demand for irrigation is high. The storage can be a reservoir built on the farm or off-farm storage units that distribute water to the farm through a canal system.

The use of surface water through on- or off-farm sources affects the aquifer volume and irrigation costs, and this influences the crops grown and economic returns from the agricultural landscape. A rise in the aquifer may not occur if the price for surface water is too high to significantly reduce groundwater use and more irrigation intensive crops are grown. Amidst the backdrop of changes in irrigated and non-irrigated crops, we investigate how alternative prices for off-farm surface water in conjunction with on-farm surface water influence the long-run aquifer volume and economic returns.

The model we use has spatially explicit aquifer, irrigation, and economic components to analyze how crop and irrigation source decisions change the demand for off-farm farm water. Other than groundwater, on-farm reservoirs with tail-water recovery that reuse water throughout the season provide a backstop source of water as an alternative to off-farm water. The model allows for more efficient irrigation practice adoption which reduces the per acre irrigation water demand for the crops, and this may shift the off-farm demand curve inward unless irrigated acreage expands significantly. The availability of on- and off-farm surface water and the adoption of efficient irrigation practices affects the mix of irrigated and non-irrigated crops, and this leaves the outcome for the aquifer uncertain. A shift toward an irrigation intensive crop like rice with the availability of surface water may lead to a decline in the aquifer. The aquifer model evaluates how the flow of water within the aquifer due to well pumping at each site responds to aquifer thickness, hydro-conductivity, and proximity to other wells.

Our model is applied to the Lower Mississippi River Basin (LMRB), a region with one of the fastest increases in irrigated acreage (Schaible and Aillery 2012). A number of counties in the LMRB region of Arkansas have experienced declines in groundwater so significant that they are designated as critical groundwater areas, and projections indicate only about 20 percent of irrigation water demand can be met with groundwater by 2050 (ANRC, 2014). Federal cost share programs contribute to the implementation of on-farm storage reservoirs, tail-water recovery ditches, and irrigation practices such as special furrow techniques that modify soil-moisture infiltration.

Previous studies find that the use of on-farm reservoirs in the study region become worthwhile when the depth to the aquifer is greater than sixty feet and the saturated thickness of the aquifer is less than thirty feet (Kovacs and Mancini, 2017; Wailes et al. 2004). Farmers with land over these depleted aquifers are likely to either purchase off-farm water or build on-farm reservoirs. Hill et al. (2006) find that a government cost share program for on-farm reservoirs and irrigation pipeline in conjunction with off-farm water availability is the best policy for maintaining farm incomes on a rice landscape. There is no modeling however of changes in crop choice or the size of the on-farm reservoirs or of the spatial connectivity of the aquifer that could alter these findings.

In the next section we describe the land and irrigation components of the model for the farm net returns optimization used to derive the off-farm water demand curve followed by a description of the sensitivity analyses and policy options. After this, the data for the Arkansas Delta application is presented. Lastly, there is a section with the results of the model scenarios and a conclusion with a summary of key model findings and future research directions.

Methods

The land cover of the agricultural landscape includes crops and on-farm reservoirs. The chosen crops generate economic returns, but irrigation from wells depletes groundwater. The landscape is spatially heterogeneous due to differences in long term investment in farm practices, soil types, and access to water resources. A time horizon T is chosen for a single generation of farmers to observe how depletion of the aquifer influences production decision, and a grid of m cells (sites) represents spatial differences.

The major crops include irrigated rice, soybean, corn, and cotton, non-irrigated sorghum and soybean, and double cropped irrigated soybean with winter wheat. These crops may use any of K irrigation practices of the study region that include conventional (furrow for crops other than rice and flood for rice), center pivot, computerized poly pipe-hole selection, surge, land leveling, alternate wet-dry, and multiple-inlet. There are n possible land cover types j using any of the irrigation practices k at the end of period t as denoted by L_{ijkt} for site i that include each of the crops and reservoirs that have tail-water recovery. We refer to the on-farm reservoir use as $j = R$, and the cumulative amount of land in reservoirs in period t is L_{iRt}. At the end of each period t, which is a 10-year interval, we assume any land cover j can become another crop or an on-farm reservoir with tail-water recovery. A profit maximizing farmer may switch land out of irrigated crops into non-irrigated crops in response to declining groundwater availability at the end of each period.

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

$$\sum_{j}^{n}\sum_{k}^{K} L_{ijkt} = \sum_{j}^{n}\sum_{k}^{K} L_{ijk0} \text{, for } j = \text{crops, on-farm reservoirs} \tag{1}$$

Irrigation

The average annual irrigation that crop *j* receives to supplement precipitation, wd_j, is the crop demand for irrigation in acre-feet. A reduction in the irrigation water applied to the crop, known as deficit irrigation, is not explored since optimization becomes intractable, and there is empirical evidence that perfectly inelastic demand for irrigation water is a reasonable assumption (Wang and Segarra 2011). The groundwater stored in the aquifer beneath site *i* at the end of the period *t* is AQ_{it}. There are three potential sources of irrigation water for producers. Either the producer purchases water from off-farm sources, OFW_{it}, constructs and pumps water from on-farm reservoirs, RW_{it}, or pumps groundwater from wells, GW_{it}. There is recharge of the groundwater, nr_i, that occurs naturally from precipitation, streams, and underlying aquifers each period.

Equation (2) shows the acre-feet of water stored in an acre reservoir (Kovacs et al. 2014) as

$$\left(\omega_{\max} + \omega_{\min}\right) - \frac{\omega_{\max}}{\sum_{j}^{n}\sum_{k}^{K} L_{ijk0}} L_{iRt}, \tag{2}$$

which includes, L_{iRt}, as the acres in reservoirs at time *t*, and the total acreage at site *i*, $\sum_{j}^{n}\sum_{k}^{K} L_{ijk0}$. If the reservoir occupies the entire site *i* and only the rainfall fills the reservoir, then the low-end acre-feet of water that fills each reservoir acres is $\omega_{\min}$. If the reservoir is less than the size of the site, then recovery of the runoff and rainfall fills the reservoir to a high-end capacity in acre-feet per reservoir acre of $\left(\omega_{\max}+\omega_{\min}\right)$.

The water used for irrigation must be less than the water available from off-farm sources, reservoirs, and wells (Eq. 3), and Equation (4) indicates the water stored in the reservoirs must be greater than the water used from the reservoirs. The aquifer volume in the previous period less the spatially weighted proportion of water pumped from the surrounding sites plus natural recharge equals the current aquifer volume (Eq. 5). The cost of pumping groundwater at a site, GC_{it}, depends on the cost to lift an acre-foot of water by one foot, c^p, and the initial depth to the groundwater, dp_i. The depletion of the aquifer volume, $\left(AQ_{i0}-AQ_{it}\right)$, divided by the area of the site, $\sum_j^n\sum_k^K L_{ijk0}$, indicates how much the depth to the aquifer increases. Capital costs per acre-foot for the well, which accounts for new well drilling in response to aquifer decline, is c^c (Eq. 6).

$$\sum_{j=1}^{n} wd_j L_{ijt} \le GW_{it} + OFW_{it} + RW_{it} \tag{3}$$

$$RW_{it} \le \left(\left(\omega_{\max}+\omega_{\min}\right)-\frac{\omega_{\max}}{\sum_j^n\sum_k^K L_{ijk0}}L_{iRt}\right)L_{iRt} \tag{4}$$

$$AQ_{it} = AQ_{i(t-1)} - \sum_k^m p_{ik}GW_{kt} + nr_i \tag{5}$$

$$GC_{it} = c^c + c^p\left(dp_i + \frac{\left(AQ_{i0}-AQ_{it}\right)}{\sum_j^n\sum_k^K L_{ijk0}}\right) \tag{6}$$

Economic returns objective

The cost to produce an acre of the crop *j* with irrigation practice *k*, excluding the irrigation costs, ca_{jk}, and the price per conventional unit of the crop, pr_j, are constant in real terms. We assume no productivity growth trend for the constant yield of crop *j* per acre using irrigation practice *k* at site *i*, y_{ijk}. Excluding the costs of irrigation, the net value for crop *j* with irrigation practice *k* is then $pr_j y_{ijk}$ - ca_{jk} per acre. The constant purchase price for an acre-foot of off-farm water is c^{ofw}. The reservoir pumping cost per acre-foot is c^{rw}, and per-acre capital and maintenance cost of a reservoir each period is c^r. We make monetary values over time comparable using the real discount factor, δ_t.

Equation 7 indicates the economic objective to maximize the present value of farm profits over the fixed horizon *T* by changing the amount of land in each crop, the off-farm water use, the reservoir water use, and groundwater use, namely L_{ijkt}, OFW_{it}, RW_{it}, and GW_{it}. The initial condition of the state variables and the non-negativity constraints on land, water use, and the aquifer are shown in Equation 8.

$$\max_{L_{ijkt},RW_{it},OFW_{it},GW_{it}} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \left(pr_j y_{ijk} - ca_{jk} \right) L_{ijkt} - c^r L_{iRt} - c^{rw} RW_{it} - c^{ofw} OFW_{it} - GC_{it} GW_{it} \right) \tag{7}$$

subject to:

$$L_{ijk0} = L_0^{ijk}, L_{iR0} = 0, AQ_{i0} = AQ_0^i, L_{ijt} \geq 0, RW_{it} \geq 0, OFW_{it} \geq 0, GW_{it} \geq 0, AQ_{it} \geq 0 \tag{8}$$

and the spatial dynamics of land and irrigation (Eqs. 1-6).

Off-farm water demand curve

The demand for off-farm water by the producers on the agricultural landscape is created by varying the price of an acre-foot of off-farm water from $5 per acre-foot to $350 per acre-foot with increments of $5 per acre-foot. The pairing of the quantity demanded and the price per acre-foot of the off-farm water for each $5 per acre-foot increment traces out the demand curve for the off-farm water. The quantity of water demanded from the irrigation water sources for each off-farm price increment indicates how effectively off-farm water can supplant reservoir and groundwater.

To evaluate the availability of off-farm water use and irrigation practice adoption on land, reservoir, and groundwater use, and economic returns, the baseline, which assumes no off-farm and reservoir water use and no irrigation practice adoption (No OFW-No Res-No IP), is compared to the results of the technology and policy scenarios, for off-farm water prices of $50, $125, and $200 per acre-foot.

Policy options

The groundwater conservation policy options we consider are a reservoir construction cost share by modifying c^r, in addition to irrigation practice cost shares for land leveling, pipe hole selection program, surge valve, multiple inlet, and center pivot by modifying ca_{jk}. Another policy is a tax that raises the groundwater pumping cost GC_{it}. The cost share for irrigation reservoir construction is 65%, and the cost share for land leveling, pipe hole selection program, surge valve, multiple inlet, and center pivot is 60% based on the Natural Resource Conservation Service (NRCS) rates (NRCS 2015). A tax that raises groundwater pumping costs by 26% is chosen to achieve groundwater conservation similar to the cost share on reservoir construction.

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). Eleven Arkansas counties overlap the watersheds, and 2,724 sites divide the study area to evaluate how farmers make decisions about crop allocation and water use on a spatially differentiated landscape. Table S1 in the supporting information has the acreage of each crop initially by site based on the 2013 Cropland Data Layer (Johnson and Mueller, 2010). The irrigated vs. non-irrigated soybean acreage is based on the harvested acreage for 2010-2011 (NASS, 2012). The estimate of yield for each of the crops comes from the average county crop yields for the past 5 years (Division of Agriculture, 2012). After adjustment for inflation, the ownership and maintenance charges for the irrigation technologies, reservoirs and wells and the costs of production for all crops are constant over time. With a 30yr Treasury Bond yield over the last decade of 5% (US Department of the Treasury, 2012) less a long-run expectation for inflation of 3%, the analysis uses a 2% real discount rate.

Farm production

The farm production model parameters are shown in Table S2. The Division of Agriculture (2012) has the 2012 Crop Cost of Production estimates used for the costs of production by crop excluding irrigation costs. Labor, fuel, lube and oil, and poly pipe for border irrigation plus the levee gates for the flood irrigation of rice all contribute to the costs of irrigation (Hogan et al., 2007). The wells, pumps, gearheads, and power units have purchase and maintenance costs that raise the per acre-foot costs of irrigation water. The Division of Agriculture (2012) 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, 2012). The depth to the water table and the corresponding fuel needed to raise water determines the fuel cost per acre-foot from the aquifer. 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). About 6 gallons of diesel are necessary to pump an acre-foot of water to and from a reservoir (Hogan et al., 2007). EIA (2012) indicates $3.77 per gallon of diesel, and to account for oil and lube for irrigation equipment we add 10% to the fuel costs (Hogan et al., 2007).

Reservoir use and construction

An acre of reservoir can hold about 16.5 acre-inches from natural rainfall (ω_{min}) without the collection of runoff from a tail-water recovery system (NOAA, 2014). With a tail-water recovery system, a reservoir can fill to a maximum capacity of 7.5 acre-feet per acre (ω_{max}) over the course of a year (Smartt et al., 2002). For the low-end and high-end capacity of the reservoirs for the reservoir scenarios, a maximum annual capacity of 4 and 11 acre-feet per acre of reservoir is used, respectively.

The Modified Arkansas Off-Stream Reservoir Analysis (MARORA) (Smartt et al., 2002) tool estimates on-farm reservoir/tail-water recovery construction and maintenance costs for various size reservoirs. Most of the reservoir construction cost is associated with moving soil, and this is updated to $1.2 per cubic yard. The maintenance costs from MARORA include a pump for tail-water recovery and a pump for irrigation. The reservoir and tail-water recovery system capital cost is converted to an annual amortized cost plus maintenance cost of $377 per acre of reservoir. An annual cost at the low-end of $285 and at the high-end of $777 per acre of reservoir for the reservoir scenarios is used.

Groundwater use and recharge

The depth to the water table and initial saturated thickness of the alluvial aquifer shown in Table S1 comes from the Arkansas Natural Resources Commission (ANRC 2012). Overdraft of the aquifer makes the saturated thickness of the aquifer decline. The acreage of each site times the saturated thickness of the aquifer is the initial size of the aquifer under the site. 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.

Well pumping causes groundwater to flow from the surrounding sites in the aquifer into the sites with the depleted aquifer. The distance from the pump and the hydraulic diffusivity of the aquifer determines this underground flow of water. The hydraulic diffusivity divided by the square of the shortest distance between the pumped well and the surrounding sites indicates the proportion, p_{ik}, of the surrounding aquifer i depleted due to pumping at a particular site k (Kovacs et al. 2015). The ratio of the transmissivity and the specific yield of the unconfined alluvial aquifer is the hydraulic diffusivity (Barow and Leake 2012). The dimensionless ratio of water drainable by saturated aquifer material to the total volume of that material is the specific yield. Transmissivity is the product of hydraulic conductivity and saturated thickness, and the rate of groundwater flow per unit area under a hydraulic gradient is the hydraulic conductivity. Clark, Westerman and Fugitt (2013) use spatially coarse pilot points to estimate the hydraulic conductivity.

Alternative irrigation practice adoption

Conventional irrigation for furrow irrigated soybeans, corn, and cotton in the Arkansas Delta delivers irrigation water through equally sized holes punched into polyvinyl chloride plastic irrigation pipe (i.e. poly-pipe). The irrigation water flows from the holes in the poly-pipe laid at the top of the field down each furrow. Alternative irrigation practices for furrow irrigated crops to reduce water use and potentially raise yield are center pivot, surge irrigation, precision leveling, and poly-pipe with computerized hole selection. A hanging sprinkler system that rotates circularly around a pivot is the center pivot. A variation on poly-pipe furrow irrigation is surge irrigation where water flowing from the poly-pipe is pulsed on and off to advance water down the furrow faster. Computerized pipe-hole selection is another variation of poly-pipe furrow irrigation that helps fully irrigate the field with less water by adjusting hole sizes on the tubes for different row lengths based on pressure changes along the tube. By smoothing the surface of the field, precision leveling increases the rate of flow and evenness of water down the furrow.

Flood is the conventional irrigation practice for rice while alternative practices for rice are precision leveling, alternate wet-dry, and multiple-inlet flooding. The zero-grade of rice paddies to provide uniform flood of the rice is the precision leveling. Alternate wetting and drying is a practice where soils drain intermittently during part of the rice life-cycle rather than maintaining a continuous flood on the field. The release of flood water evenly over the whole field through holes or gates in poly-pipe tube is multiple-inlet flooding.

Tables S3, S4, and S5 indicate how crop yield, irrigation water use, and production costs by crop change if producers adopt the alternative irrigation practices. The changes because of the irrigation practice adoptions are shown as adjustment coefficients to the conventional practice values. Within the model the alternative irrigation practices improve farm profitability and lower water pumping costs, and this would make producers adopt them immediately even without cost-share assistance from government. In practice however the rate of adoption takes time because education about the practices occurs gradually, and not all farmers believe alternative irrigation practices can help them. Our baseline rate of adoption allows the percentage of the crop acreage on the landscape using alternative irrigation practices to rise by 20 percent every ten years to 60 percent by the end of the thirty-year study period in 2043.

Results

Tables 1 and 2 present the results of five model scenarios: 1) no off-farm water, reservoirs, or adoption of irrigation practices (No OFW, No Res, No IP); 2) adoption of off-farm water and no adoption of reservoirs or irrigation practices (OFW, No Res, No IP); 3) adoption of off-farm water and reservoirs and no adoption of irrigation practices (OFW, Res, No IP); 4) adoption of off-farm water, no adoption of reservoirs, and adoption of irrigation practices up to 60 percent of the entire landscape area by 2043 (OFW, No Res, IP); and 5) adoption of off-farm water, reservoirs, and irrigation practices up to 60 percent of the crop landscape by 2043 (OFW, Res, IP). The results represent the projected state of land use, water use, and economic returns for year 2043 for each of the scenarios and for selected off-farm water prices of $50/acre-foot, $125/acre-foot, and $200/acre-foot. Figure 2 shows the demand curve for off-farm water by scenario.

For the entire landscape, the results indicate that, if priced competitively, off-farm water has the potential to become a relevant source of irrigation water. At $50/acre-foot, off-farm water becomes a primary source of irrigation water in scenarios without irrigation practice adoption. It provides 948 thousand acre-feet or 57 percent of total water use in 2043 (Table 1), and 526 thousand acre-feet or 45 percent of total water use when irrigation practices are allowed.

The use of reservoirs affects the off-farm water demand only slightly and at high off-farm water prices. Reservoirs become a competitive source of water only at off-farm water prices above $75/acre-foot (Figure 2), reducing the intercept of the off-farm water demand curve to $125/acre-foot from $250/acre-foot (Figures 1 and 2). The adoption of irrigation practices greatly reduces total water demand from all sources (including off-farm water). Moreover, the adoption of irrigation practices affects the off-farm water demand curve in two distinct ways: 1) shifting it to the left at off-farm water prices below $75/acre-foot, and 2) without reservoirs making it very inelastic at higher prices, moving the intercept up to $345/acre-foot. The impact of irrigation practices on the elasticity of off-farm water demand at high prices is explained by the shift in land use generated by the adoption of irrigation practices that favor the expansion of rice, particularly in sites with highly depleted aquifers where off-farm water use persists even at such high prices.

The substitution of off-farm water for groundwater greatly helps alleviate the depletion of aquifers. Without off-farm water, reservoirs, and irrigation practices, we project that the volume of the aquifer will decrease to 57.7 million acre-feet by 2043, marking a 24 percent decrease relative to the initial 2013 level. At an off-farm water price of $125/acre-foot, the adoption of reservoirs slightly decreases the 2043 aquifer to 57.6 million acre-feet without the adoption of irrigation practices because the acreage of irrigated crops increases when reservoirs and off-farm water provides a backstop water source. At an off-farm water price of $50/acre-foot, the capacity of the aquifer in 2043 will be 74.3 million acre-feet and 73.3 million acre-feet with and without adoption of irrigation practices, respectively (Tables 1 and 2). This is an increase in the volume of the aquifer of the landscape by at least 15.6 million acre-feet by 2043, and significantly reduces its depletion, estimated at less 4 percent relative to their 2013 level.

Off-farm water at a competitive price generates important changes in land use, primarily for rice and sorghum, and the adoption of irrigation practices reinforces these changes. Without off-farm water, reservoirs, and irrigation practices, rice acreage by 2043 is estimated at 214.4 thousand acres or 19 percent of the total land used. The adoption of reservoirs increases rice acreage by 19 percent to 255.8 thousand. However, the main boost in rice acres comes if off-farm water has a competitive price such as $50/acre-foot. At that price, rice acreage increases by 91 percent to 410.2 thousand acres, amounting to 36 percent of the total land use by 2043 (Table 1). Sorghum acreage follows an opposite trend than rice, becoming a dominant choice when only groundwater is available, but decreasing as alternative water sources are available to grow irrigated crops. The adoption of irrigation practices changes land use by 2043 in two primary ways: 1) it increases the share of irrigated crops in the landscape to over 90 percent of the total land use; and 2) it stabilizes the crop mix choice at different off-farm price levels. The adoption of irrigation practices results in an expansion of rice acreage up to almost half of the total land used in 2043. All rice and cotton acreage is expected to adopt some form of water-saving irrigation practice (Table 2).

Table 3 presents the influence of water conservation policies when off-farm water and reservoir water are available at baseline adoption rates of irrigation practices (“OFW, Res, IP”). Only three policies, either cost-sharing reservoir construction and land leveling, or the tax on groundwater use, have a modest effect on land and water use, and farm and government returns. The cost share on reservoir construction has a negligible influence on the aquifer and farm and government returns at the off-farm water price of $50/acre-foot since it results in the construction of only 37 acres of reservoirs. At $125/acre-foot for off-farm water, the reservoir cost share program contributes to doubling the reservoir acreage from 11 thousand to 22.1 thousand acres, and the aquifer rises by 3.9 million acre-feet. It also changes land use in favor of irrigated crops, most notably cotton, at the expense of non-irrigated sorghum. The program costs the government $159 million and improves farm returns by $82 million meaning there is a cost to society of the reservoir policy of $77 million. Dividing the cost to society by the 3.9 million acre-feet of groundwater saved means a cost of $19.9/acre-foot.

Land leveling is the only efficient irrigation practice adopted in the baseline. At $50/acre-foot of off-farm water, the cost-share on land leveling is a transfer from the federal government to producers with no impact on land and water uses. At $125/acre-foot of off-farm water the cost-share on land leveling leads to an expansion of irrigated crops, most notably cotton, a modest expansion of total water use supported by reservoir and ground water, and a lower aquifer. Hence, at high off-farm water prices, the cost share on land leveling exerts changes in water use that are a cost to society without any increase in the aquifer. The tax on groundwater use increases the aquifer, decreases farm returns, and raises government revenues. The tax has a stronger influence on the aquifer at low off-farm water prices, resulting in 5.5 million acre-feet of groundwater saved, relative to 3.9 million acre-feet of groundwater saved at $125/acre-foot of off-farm water. The tax on groundwater use reduces farm returns by $93 million and $275 million, and generates $69 million and $243 million in government revenues at $50/acre-foot and $125/acre-foot of off farm water, respectively. This means the tax policy achieves groundwater conservation at a cost to society of $4.3/acre-foot and $8.3/acre-foot at $50/acre-foot and $125/acre-foot of off farm water, respectively.

An off-farm water price of $50/acre-foot rather than $125/acre-foot raises the aquifer by 13.6 million acre-feet with no tax on groundwater use, and by 15.2 million acre-feet when combined with a tax on groundwater use. This suggests that a government cost-share to make off-farm water available at a price less than $125/acre-foot may be a cost-effective way to preserve the aquifer. The policy scenarios suggest that, if priced at $50/acre-foot, the quantity demanded of off-farm water is significant with the implementation of the cost share policy on reservoir construction and land leveling, and is the main source of irrigation water when there is a tax on groundwater use.

Discussion and Conclusion

The use of off-farm surface water increases both the aquifer and economic returns when the price for the off-farm water is less than a price between $50 and $125/acre-foot. For comparison, the average initial groundwater pumping cost on the landscape is about $44/acre-foot. Without irrigation practice adoption, an off-farm water price of $125/acre-foot and greater raises economic returns slightly, but relative to the baseline without off-farm water (No OFW – No Res – No IP), the aquifer is lower because the share of irrigated crops rises when off-farm water is available. At an off-farm water price of $125/acre-foot, the use of on-farm surface water raises economic returns but also increases groundwater use because of a shift toward irrigated crops, and this makes the aquifer lower compared to the baseline. These findings illustrate how the use of on- and off-farm surface water increase economic returns on an agricultural landscape but may not help to sustain the aquifer. The price of surface water from either on- or off-farm sources needs to be low enough to generate a significant shift away from the groundwater.

The use of efficient irrigation practices substantially raises economic returns and the aquifer. The irrigation practices result in a more pronounced rise in the aquifer when the price for off-farm water is $125/acre-foot or greater. The irrigation practices allow more high valued crops at a low cost to be grown with less burden on the aquifer, and this positively influences economic and aquifer conditions even if off-farm water is cheaply available at $50/acre-foot. The rate of adoption of the irrigation practices has a modest influence on the aquifer volume but the economic returns significantly increase. This is because most of the irrigation practice adoption is in rice where higher yields and lower irrigation costs boost net returns.

The policy options to create an incentive for producers to lower groundwater use indicate that only a tax on groundwater use raises the aquifer at an off-farm water price of $50/acre-foot and that only the cost-share on reservoir construction and the tax on groundwater use raise the aquifer at an off-farm water price of $125/acre-foot. The cost-share on the land-leveling irrigation practice used principally in rice makes rice acreage and groundwater use increase, and the policy is thus not effective for aquifer conservation even though each acre of rice uses less groundwater than before.

Future research could look at the return on investment in off-farm surface water by modeling a supply curve for off-farm water for farmers throughout the landscape. A comparison of long-run return on investment for on- and off-farm water or for more efficient irrigation practices would help policy makers prioritize where to direct scarce conservation funds. These analyses should be careful to account for changes in land use at all margins and to examine the sensitivity to energy and crop price changes. Another extension is to make the rate of adoption of efficient irrigation practices around the landscape based on the spatial proximity to farms that already use the practices. The spatial diffusion of irrigation practices then influences the equilibrium price for off-farm water, and this has repercussions on the level of groundwater extraction and economic returns.

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Table 1. Impact of reservoir construction on land and water use, and economic returns in 2043

	NO OFW NO RES NO IP*	**OFW - NO RES - NO IP**			**OFW - RES[1] - NO IP**		
		Off-farm water prices ($/Ac ft)			**Off-farm water prices ($/Ac ft)**		
Land use (acres)		**50**	**125**	**200**	**50**	**125**	**200**
Rice - conventional irrigation	214,400	410,200	216,700	214,400	410,200	255,800	255,800
Rice - IP		0	0	0	0	0	0
Irrigated soybeans - conventional irrigation	126,100	129,900	126,800	126,100	129,900	127,100	127,100
Irrigated soybeans - IP		0	0	0	0	0	0
Irrigated corn - conventional irrigation	379,800	411,400	402,200	392,300	411,400	406,600	406,600
Irrigated corn - IP		0	0	0	0	0	0
Irrigated cotton - conventional irrigation	94,844	96,613	97,360	94,840	96,613	97,943	97,943
Irrigated cotton - IP		0	0	0	0	0	0
Double crop soybean/wheat - conventional irrigation	11,600	14,599	23,234	12,187	14,599	5,866	5,866
Double crop soybean/wheat - IP		0	0	0	0	0	0
Non-irrigated soybeans	0	0	0	0	0	0	0
Non-irrigated sorghum	314,400	78,395	274,900	301,300	78,395	233,400	233,400
Reservoirs		0	0	0	0	14,353	14,353
Water use (1,000 ac-ft./year)							
Annual water use	1,145	1,674	1,186	1,159	1,674	1,275	1,275
Annual reservoir water use	0	0	0	0	0	115	115
Annual groundwater use	1,145	726	1,139	1,146	726	1,160	1,160
Annual off-farm water use	0	948	47	13	948	0	0
Aquifer	57,720	73,280	57,570	57,700	73,280	57,630	57,630
30 year farm net returns (million $)	**4,469**	**5,024**	**4,500**	**4,472**	**5,024**	**4,546**	**4,546**

* OFW: Off-farm water; RES: reservoirs; IP: irrigation practices. [1] The baseline reservoir cost/capacity is $377 per acre per year and 7.5 acre-feet of storage per acre.

Table 2. Impact of irrigation practices on land and water use, and economic returns in 2043

	NO OFW NO RES NO IP*	**OFW - NO RES – IP[1]**			**OFW – RES[2] – IP[1]**		
		Off-farm water prices ($/Ac ft)			**Off-farm water prices ($/Ac ft)**		
Land use (acres)		**50**	**125**	**200**	**50**	**125**	**200**
Rice - conventional irrigation	214,400	0	0	0	0	0	0
Rice - IP		561,200	560,200	548,100	561,200	560,500	560,500
Irrigated soybeans - conventional irrigation	126,100	52,151	49,823	49,297	52,151	50,177	50,177
Irrigated soybeans - IP		0	0	0	0	0	0
Irrigated corn - conventional irrigation	379,800	342,000	313,300	295,500	342,000	317,500	317,500
Irrigated corn - IP		0	19,200	29,200	0	13,000	13,000
Irrigated cotton - conventional irrigation	94,844	0	0	0	0	0	0
Irrigated cotton - IP		123,500	105,200	107,400	123,500	111,200	111,200
Double crop soybean/wheat - conventional irrigation	11,600	13,566	5,937	3,545	13,566	4,808	4,808
Double crop soybean/wheat - IP		0	0	0	0	0	0
Non-irrigated soybeans	0	0	0	0	0	0	0
Non-irrigated sorghum	314,400	48,747	87,410	108,100	48,747	72,793	72,791
Reservoirs		0	0	0	0	11,133	11,140
Water use (1,000 ac-ft./year)							
Annual water use	1,145	1,174	1,137	1,111	1,174	1,141	1,141
Annual reservoir water use	0	0	0	0	0	91	91
Annual groundwater use	1,145	648	1,040	1,048	648	1,050	1,050
Annual off-farm water use	0	526	97	63	526	0	0
Aquifer	57,720	74,290	60,730	60,850	74,290	60,700	60,700
30 year farm net returns (million $)	**4,469**	**7,091**	**6,748**	**6,672**	**7,091**	**6,783**	**6,783**

* OFW: Off-farm water; RES: reservoirs; IP: irrigation practices. [1] The baseline rate of irrigation practice adoption is 60% of the crop landscape by 2043. [2] The baseline reservoir cost/capacity is $377 per acre per year and 7.5 acre-feet of storage per acre.

Table 3. Water conservation policies influence on reservoir construction, aquifer capacity, and economic returns by 2043.

	Off-farm water price $50/acre-foot				**Off-farm water price $125/acre-foot**			
Land use (acres)	**OFW-RES-IP**[1]	**CS RES**[2]	**CS LL**[3]	**GWT**[4]	**OFW-RES-IP**[1]	**CS RES**[2]	**CS LL**[3]	**GWT**[4]
Rice – IP	561,200	561,200	561,200	561,200	560,500	561,300	560,800	558,000
Irrigated soybeans - conventional irrigation	52,151	52,114	52,151	51,963	50,177	50,143	50,177	49,403
Irrigated corn - conventional irrigation	342,000	342,000	342,000	342,000	317,500	329,300	324,500	299,500
Irrigated corn – IP	0	0	0	0	13,000	3,400	5,500	20,200
Irrigated cotton - IP	123,500	123,500	123,500	123,500	111,200	120,000	118,400	106,500
Double crop soybean/wheat - conventional irrigation	13,566	13,566	13,566	13,634	4,808	3,413	2,331	2,211
Non-irrigated sorghum	48,747	48,747	48,747	48,867	72,793	51,525	68,099	91,435
Reservoirs	0	37	0.0	0.0	11,133	22,099	11,326	13,897
Water use (1,000 ac-ft./year)	0				0			
Annual water use	1,174	1,174	1,174	1,174	1,141	1,152	1,146	1,119
Annual reservoir water use	0	0.3	0	0	91	182	92	115
Annual groundwater use	648	648	648	511	1,050	970	1,054	1,004
Annual off-farm water use	526	526	526	662	0	0	0	0
Aquifer	74,290	74,290	74,290	79,750	60,700	64,580	60,660	64,600
30 year farm net returns (million $) [5]	7,091	7,091	7,159	6,998	6,783	6,866	6,851	6,509
30 year government revenue (million $)	--	-0.1	-67.8	69.4	--	-159.4	-67.5	242.6
Groundwater conservation cost ($/acre-foot) [6]	--	No groundwater conserved	No groundwater conserved	4.3	--	19.9	No groundwater conserved	8.3

[1] OFW: Off-farm water; RES: reservoirs; IP: irrigation practices; [2] The cost share is 65% for irrigation reservoir construction (NRCS 2014). [3] The cost share is 60% for land leveling (NRCS 2014). [4] A tax on groundwater pumping costs (26%) is chosen to achieve groundwater conservation similar to the cost share on reservoirs at an off-farm water price of $125. [5] The farm net returns include the payments to or receipts from the government because of the policy. [6] 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.

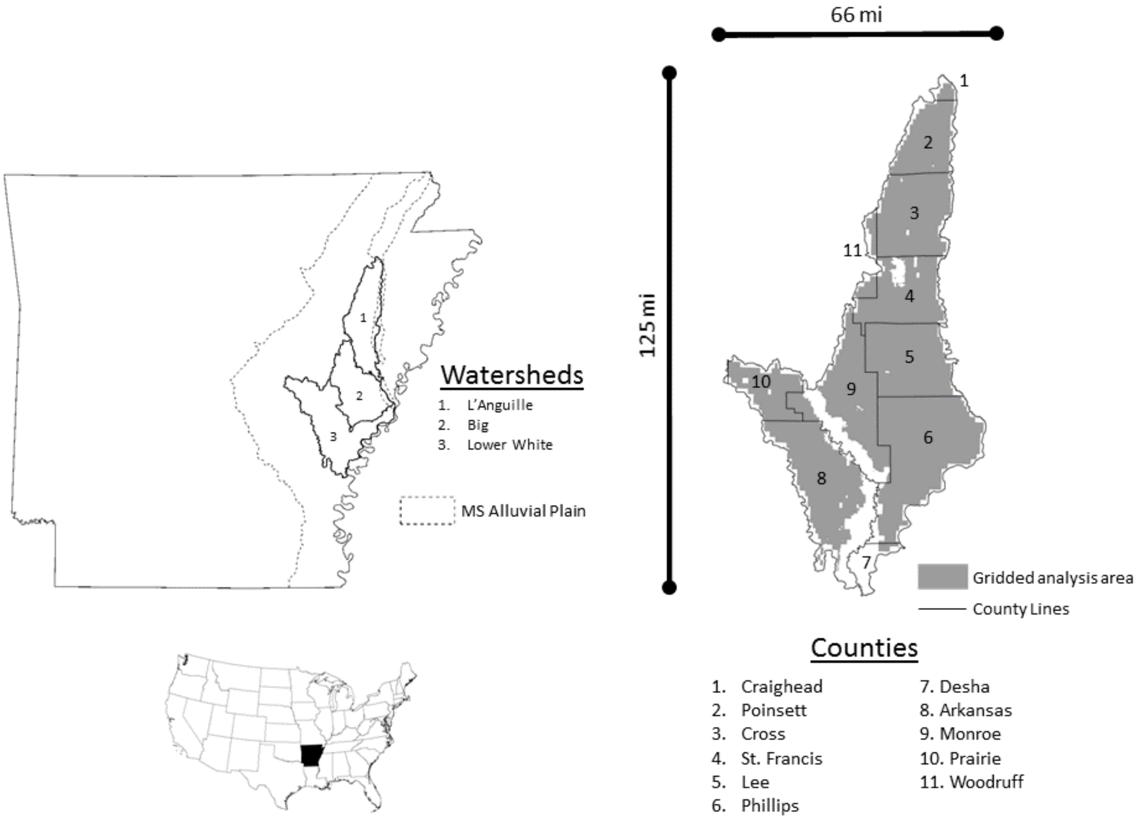

Figure 1. Three eight-digit hydrologic unit code (HUC) watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. County lines overlay the study area. Public land and urban areas are excluded. The location of the study area within the State of Arkansas is shown.

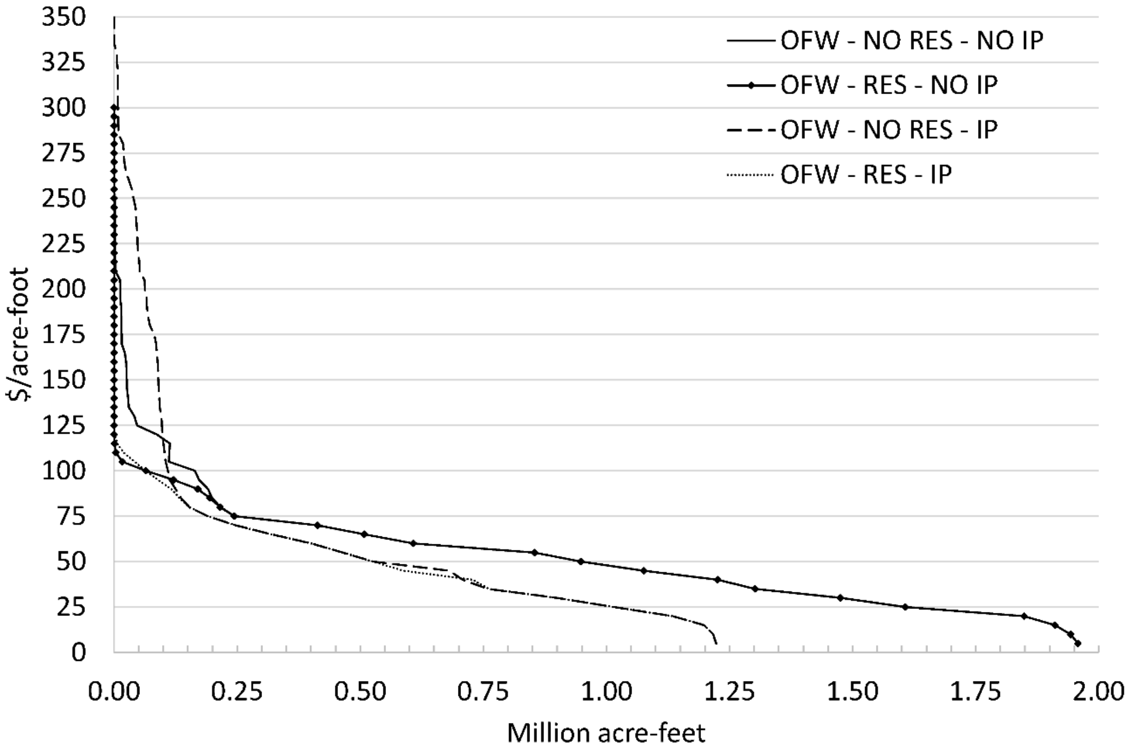

Figure 2. Off-farm water demand curves for four scenarios for the study area in 2043.

Supporting information

The initial crop acres and aquifer conditions in 2013 for the study area are shown in Table S1. The parameters for the economic and irrigation components of the model are in Table S2. The adjustment coefficients for crop yield, irrigation water use, and production costs for the alternative irrigation practices relative to conventional irrigation are in Tables S3, S4, and S5, respectively.

Table S1. Descriptive statistics of the model data across the sites of the study area

Variable	**Definition**	**Mean**	**Std. Dev.**	**Sum (thousands)**
$L_{i,rice}$	Initial acres of rice	81	99	221
$L_{i,corn}$	Initial acres of corn	52	77	143
$L_{i,cotton}$	Initial acres of cotton	10	40	26
$L_{i,isoy}$	Initial acres of irrigated soybean	165	97	449
$L_{i,dsoy}$	Initial acres of dry land soybean	57	49	155
$L_{i,dsorg}$	Initial acres of dry land sorghum	7	23	20
$L_{i,dbl}$	Initial acres of double crop irrigated soybean and winter wheat	47	73	129
$y_{i,rice}$	Annual rice yield (cwt per acre)^1	71	3	-
$y_{i,cotton}$	Annual cotton yield (pounds per acre)^1	1012	148	-
$y_{i,corn}$	Annual corn yield (bushels per acre)^1	166	11	-
$y_{i,isoy}$	Annual irrigated soybean yield (bushels per acre)^1	42	4	-
$y_{i,dsoy}$	Annual dry land soybean yield (bushels per acre)^1	25	3	-
$y_{i,dsorg}$	Annual dry land sorghum yield (bushels per acre)^1	69	12	-
$y_{i,dbl}$	Annual double crop irrigated soybean yield (bushels per acre)^1	34	1	-
$y_{i,wheat}$	Annual winter wheat yields (bushels per acre)^1	57	5	-
dp_i	Depth to water (feet)	57	31	-
AQ_i	Initial volume of the aquifer (acre-feet)	28,047	11,972	76,398
K	Hydraulic conductivity (feet per day)	226	92	-
nr_i	Annual natural recharge of the aquifer per acre (acre-feet)	0.45	0.19	1.22

Note: Number of sites is 2,724. ^{1} The mean and the standard deviation of the county yields come from the 11 counties of the study area.

Table S2. Value of economic and irrigation model parameters.

Parameter	**Definition**	**Value**
pr_{rice}	Price of rice ($/cwt)	14.00
pr_{cot}	Price of cotton ($/lbs)	0.88
pr_{corn}	Price of corn ($/bushel)	5.50
pr_{soy}	Price of soybeans ($/bushel)	11.99
pr_{sorg}	Price of sorghum ($/bushel)	5.23
pr_{wht}	Price of wheat ($/bushel)	6.39
ca_{rice}	Annual production cost of rice ($/acre)	646
ca_{corn}	Annual production cost of corn ($/acre)	632
ca_{cotton}	Annual production cost of cotton ($/acre)	742
ca_{isoy}	Annual production cost of irrigated soybean ($/acre)	349
ca_{dsoy}	Annual production cost of dry land soybean ($/acre)	289
ca_{dsorg}	Annual production cost of dry land sorghum ($/acre)	270
ca_{dbl}	Annual production cost of double crop irrigated soybean and winter wheat ($/acre)	656
wd_{rice}	Annual irrigation per acre of rice (acre-feet)	2.5
wd_{corn}	Annual irrigation per acre of corn (acre-feet)	1.0
wd_{cotton}	Annual irrigation per acre of cotton (acre-feet)	1.0
wd_{isoy}	Annual irrigation per acre of full-season soybean (acre-feet)	1.0
wd_{dbl}	Annual irrigation per acre of double crop soybean (acre-feet)	0.75
ω_{min}	Low-end annual capacity per acre of reservoir (acre-feet)	4.0
ω_{base}	Baseline annual capacity per acre of reservoir (acre-feet)	7.5
ω_{max}	High-end annual capacity per acre of reservoir (acre-feet)	11.0
c'_{min}	Low-end annual per acre cost of reservoir ($/acre)[a]	285
c'_{base}	Baseline annual per acre cost of reservoir ($/acre)[a]	377
c'_{max}	High-end annual per acre cost of reservoir ($/acre)[a]	777
c^{rw}	Cost to re-lift an acre-foot to and from the reservoir ($/acre-foot)	22.62
c^{p}	Cost to raise an acre-foot of water by one foot ($/foot)	0.55
δ_t	Discount factor	0.98

[a] This is the annual amortized construction cost and maintenance cost for each acre of reservoir.

Table S3. Adjustment coefficients to yield by crop relative to conventional for alternative irrigation practices

Crop	**Conventional**[1]	**Center Pivot**	**Pipe hole selection**	**Surge**	**Precision grading**	**Alternate wet-dry**	**Multiple inlet**
Irrigated corn	1.00	1.014[2]	1.050[3]	1 .050[4]	1.020[3]	--	--
Rice	1.00	0.961[6]	--	--	1.170[5,7]	1.000[8]	1.036[9,10]
Irrigated cotton	1.00	1.083[2]	1.000[11]	1.030[4]	1.200[2,3]	--	--
Full season irrigated soybeans	1.00	1.014[2]	1 .050[3]	1.050[4]	1.020[3]	--	--
Non-irrigated soybeans	1.00	--	--	--	--	--	--
Non-irrigated sorghum	1.00	--	--	--	--	--	--
Double crop winter wheat and irrigated soybeans	1.00	1.014[2]	1.050[3]	1.050[4]	1.020[3]	--	--

[1] Univeristy of Arkansas 2013; [2] O'Brien *et al.* 2001; [3] Henggeler 2006; [4] Preston 1992; [5] Watkins 2007. [6] Vories 2011; [7] Reba 2013; [8] Massey 2010; [9] Vories 2005; [10] Tackler and Vories 2013; [11] Young *et al.* 2006; [12] Ayer and Wright 1986.

Table S4. Adjustment coefficients to water use by crop relative to conventional for alternative irrigation practices

Crop	Conventional[1]	Center Pivot	Pipe hole selection	Surge	Precision grading	Alternate wet-dry	Multiple inlet
Irrigated corn	1.00	0.750 [1, 3]	0.775 [4]	0.705 [5]	0.750 [1]	--	--
Rice	1.00	0.594 [6]	--	--	0.489 [2,6]	0.785 [7]	0.755 [6]
Irrigated cotton	1.00	0.900 [1,8]	0.775 [9,10]	0.735 [5]	0.675 [11]	--	--
Full season irrigated soybeans	1.00	0.750 [1]	0.775 [4]	0.705 [5]	0.750 [1]	--	--
Non-irrigated soybeans	1.00	--	--	--	--	--	--
Non-irrigated sorghum	1.00	--	--	--	--	--	--
Double crop winter wheat and irrigated soybeans	1.00	0.750 [1]	0.775 [4]	0.705 [5]	0.750 [1]	--	--

[1] Univeristy of Arkansas 2013; [2] Watkins 2007. [3] Yazoo Mississippi Delta Joint Water Management District 2007; [4] Massey 2011; [5] Texas Project for Agricultural Water Efficiency 2013; [6] Henry *et al.* 2013; [7] Kongchum 2005; [8] Amosson *et al.* 2011; [9] Ray 2014; [10] University of Arkansas 2014; [11] Advanced Agrotech

Table S5. Adjustment coefficients to the costs of production by crop relative to conventional for alternative irrigation practices

Crop	Conventional[1]	Center Pivot[2]	Pipe hole selection[3]	Surge[4]	Precision grading[4]	Alternate wet-dry[3]	Multiple inlet[3]
Irrigated corn	1 .000	1.029	1.036	1.001	1.018	--	--
Rice	1 .000	1.029	--	--	1.017	1.049	1.035
Irrigated cotton	1 .000	1.025	1.031	1.001	1.015	--	--
Full season irrigated soybeans	1 .000	1.053	1.065	1.002	1.032	--	--
Non-irrigated soybeans	--	--	--	--	--	--	--
Non-irrigated sorghum	--	--	--	--	--	--	--
Double crop winter wheat and irrigated soybeans	1 .000	1.028	1.035	1.001	1.017	--	--

[1] University of Arkansas 2013; [2] NRCS MS442 2012; [3] NRCS MS449 2012; [4] NRCS MO464 2012

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