Spatial irrigation management to sustain groundwater and economic returns

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Abstract

Expanding irrigated agriculture and drought in the Lower Mississippi River Basin have led to large-scale withdrawals of groundwater and a consequent decline in the Mississippi River Valley Alluvial Aquifer. Conserving the aquifer, while at the same time providing for economic growth, is a challenge for policy makers. We develop a spatially explicit landscape level model for analyzing the aquifer and economic consequences of alternative crop mix patterns. The spatially explicit aquifer model incorporates irrigation needs of the crops grown, initial aquifer thickness, hydro-conductivity of the aquifer, and distance to surrounding grid cells to predict the proportion of groundwater removed from surrounding cells due to pumping on each grid cell. The spatially explicit economic model incorporates site characteristics and location to predict economic returns for a variety of potential crop types. By thinking carefully about the arrangement of activities, we find crop mix patterns that sustain high levels of the aquifer and economic returns. Compared to the crop mix of the current landscape, we show that both aquifer conservation and the value of economic activity could be increased substantially.

Keywords: Aquifer, Irrigation technologies, Agricultural production, Spatial-dynamic optimization

JEL classification: Q25, D62, C61

Introduction

The Mississippi River Valley Alluvial Aquifer (MRVA) is the third most used aquifer in the United States, and its sustainability is vital to maintaining long-term agricultural profitability in the Lower Mississippi River Basin (LMRB), one of the most productive agricultural regions in the country (Maupin and Barber, 2005; Konikow, 2013). The extent of the MRVA covers seven states, and Arkansas is the largest consumer of water from the aquifer (Maupin and Barber, 2005). It is known that the current rate of withdrawals from the aquifer is not sustainable, especially as the number of irrigated acres continues to increase each year (Barlow and Clark, 2011; ANRC, 2012).

Since Arkansas, Louisiana, and Mississippi all have average annual precipitation amounts ranging from 50 to 57 inches per year, the LMRB has often been considered an area rich in water resources (NOAA, 2014). However, there are several key constraints to maintaining agricultural profitability in the Lower Mississippi Region, the first of which is lack of timely rainfall and the increasing need for irrigation. The number of irrigated acres continues to increase in the LMRB in order to maintain and increase yields, avoid risk, and as a result of recurring drought conditions (Vories and Evett, 2010). Moreover, most irrigated acres have resulted from producers privately funding the installation of irrigation wells, with groundwater from the MRVA as the primary source of water for irrigation.

As a result, farmers are now facing marked declines in the supply of water from the MRVA, particularly in years with abnormally dry climatic conditions and lack of timely rainfall. A number of counties in east Arkansas have been designated as critical groundwater areas due to the continued decline in groundwater levels (ANRC, 2012). Studies predict that some parts of the alluvial aquifer will become commercially useless as early as 2015 if current pumping levels continue uncurbed (Sullivan and Delp, 2012). The Delta Sustainable Water Resources Task Force formed in 2011 has been working with other groups and organizations to promote and increase the use of water conservation practices throughout the Mississippi Delta.

Federal programs such as the Mississippi River Basin Healthy Watersheds Initiative, Environmental Quality Incentives Program (EQIP), and now the Regional Conservation Partnership Program (RCPP) provide technical and financial assistance to farmers in the LMRB and have contributed to the voluntary implementation of water conservation practices such as on-farm storage reservoirs, tail-water recovery ditches, and use of sensor technologies, among others. However, there is no landscape level research available about how the adoption of these water conservation measures will reduce the pumping pressure on the MRVA and influence farm profitability. This is a pressing issue, especially as federal incentive programs face increased public scrutiny and farmers try to adapt to changing climatic conditions. We need to know which conservation practices are most likely to be adopted and maintained by farmers and also which practices are most effective at reducing groundwater declines in the MRVA.

Crop type decisions on farm land are based primarily on economic criteria. While crop type decisions based solely on economic returns are often detrimental to the aquifer, securing some economic return from farm land need not be mutually exclusive with aquifer conservation. By thinking carefully about the pattern, extent, and intensity of crop production across the landscape, it may be possible to achieve important aquifer objectives while also generating reasonable economic returns. By adopting water conservation practices, the enhanced efficiency is likely not only to boost the aquifer and economic returns but make the sacrifice of one for the other less severe.

We integrate spatially explicit aquifer and economic models to analyze the consequences of alternative crop type decisions for both aquifer conservation and economic objectives. We develop an aquifer model that evaluates how well groundwater can be sustained on a landscape given a spatially explicit pattern of crop types. We use the aquifer's initial thickness, hydro-conductivity, and distance to surrounding grid cells to generate the proportion of groundwater removed from surrounding cells due to pumping on each grid cell. Using the irrigation needs of the crop types grown and the proportion of groundwater removed from surrounding cells, we estimate the aquifer depletion associated with each grid cell. The aquifer objective is then to sustain the volume of the aquifer which we track by summing the aquifer depletion over all cells.

On the economic side, we develop a model that predicts the economic returns for each grid cell under different crop types, including rice, soybeans, corn, cotton, sorghum, and wheat. Information on location, such as soil characteristics and initial depth to the aquifer, affects the yield for the crops and groundwater pumping cost at each grid cell. The groundwater pumping cost then rises as the aquifer is depleted. Water conservation practices chosen influence the yield, demand for irrigation water, and production cost of the crops. We combine commodity prices data with yields and production costs to generate economic returns for these crop types. The economic objective is the sum of the present value of economic returns of each grid cell given the mix of crop types produced.

We combine results from the aquifer and economic models to search for efficient crop and water conservation practice patterns. An efficient pattern is one that generates the maximum economic returns for a given volume of the aquifer sustained (and vice versa). By maximizing the economic returns over the entire range of possible aquifer volumes we can trace out an efficiency frontier for the landscape. The efficiency frontier illustrates what can be achieved in terms of aquifer and economic objective by carefully arranging the spatial allocation of crops and water conservation practices across the landscape. The efficiency frontier also demonstrates the degree of inefficiency of other crop and irrigation practices not on the frontier.

While there is a large literature on multi-criteria analysis in water resources planning (see Hajkowicz and Collons, 2007, for a recent review), much of this literature focuses on efficient water policy and supply planning. This literature typically does not incorporate analysis of working agricultural lands, either in terms of the landscape's ability to sustain an aquifer or in terms of economic returns. Water supply planning (Joubert et al. 2003) and infrastructure selection (Eder et al. 1997) have impacts on numerous stakeholders and must handle multiple objectives for which multi-criteria analysis is well-suited. Several papers have used multi-criteria analysis to incorporate infrastructure costs and economic returns in water resource planning (e.g. Mimi and Sawalhi, 2003; Karnib, 2004; Raju and Kumar (1999); Cai et al. 2004). Almost all prior work that combines water models of aquifer depletion and economic models to evaluate conservation and economics returns focus on a single irrigation technology or a single crop such as cotton or corn (e.g. Darouich et al. 2012; Gillig et al. 2004; Rodrigues et al. 2013).

The papers closest to our paper in terms of analyzing multiple irrigation technologies and multiple crops while comparing objectives such as aquifer conservation and economic returns are those by McPhee and Yeh (2004) and Xevi and Khan (2005). McPhee and Yeh (2004) derive the tradeoffs among three competing objectives by minimizing the magnitude and extent of drawdown of an aquifer. Xevi and Khan (2005) analyze the conflicts that arise between profitability, variable costs of production, and pumping of groundwater for multiple crops within a network of reservoirs, canals, and irrigation districts. Neither of these papers though considers the optimized configuration of the landscape in their study of sustained aquifer and economic return tradeoffs.

In the next section we describe the land, water, and economic models as well as the optimization algorithm used to find efficient land and water patterns. The section that follows describes the data for the application of the approach to the Arkansas piece of the Mississippi Delta. The last two sections include the results and a conclusion with a discussion of the methods and results.

Methods

Spatial-dynamics of the crops grown in the farm production region of the Arkansas Delta depend on the land suitability and on the supply of water in the underlying aquifer. A grid of *m* cells (sites) represents spatially specific crop yields associated with soil quality and spatially symmetric cones of depression from groundwater pumping with the available groundwater based on the pumping decisions of farms in and around the site weighted by distance. The time frame is the 30 year period from 2013 to 2043.

Spatial-dynamics of land

We track the cumulative amount of land in use *j* for *n* land types for each of the major crops in the region (irrigated corn, irrigated cotton, rice, irrigated soybean, double crop soybean/winter wheat, non-irrigated sorghum, and non-irrigated soybean) using an irrigation technology *k* for the *K* major irrigation technologies of the region (conventional i.e. furrow for crops other than rice and flood for rice, center pivot, computerized poly pipe-hole selection, surge valve, land leveling, alternate wet-dry, multiple-inlet) at the end of period *t* with $L_{ijk}(t)$ site *i*. Another potential land use *j* is on-farm reservoirs for storing surface water to reduce reliance on groundwater and created from existing crop land. We refer to the on-farm reservoir use as $j = R$, and the cumulative amount of land in reservoirs in period *t* is $L_{iRk}(t)$.

Any land use *j* can be chosen in period *t* so long as the cumulative amount of land equals the original amount of land in production at site i (Eq. 1),

$$\sum_j \sum_k L_{ijk}(t) = \sum_j \sum_k L_{ijk}(0) \quad . \tag{1}$$

The land balance equation is constrained by historical crop-specific minimum and maximum acreage ($L\min_j \le \sum_i \sum_k L_{ijk}(t) \le L\max_j$). The constraints reflect historical limits on acreage in the crops associated with land suitability, crop rotation restrictions, availability of capital, and producer knowledge of alternative crop production methods (Popp et al. 2011). The objectives of aquifer or economic returns described in later subsections of the methods are optimized subject to these land constraints.

Spatial-dynamics of water use

Irrigation demand, which varies by crop and irrigation technology k, is given by wd_{jk}, representing average annual irrigation needs excluding natural rainfall. The variable $AQ_i\ (t)$ is the amount of groundwater (acre-feet) stored in the aquifer beneath site i at the end of the period t, and the amount of water pumped from the on-farm reservoirs is $RW_i\ (t)$. The amount of water pumped from the ground is $GW_i\ (t)$ during period t. The natural recharge (acre-feet) of groundwater at a site i from precipitation, streams, and underlying aquifers in a period is nr_i.

The runoff from site i is diverted to reservoirs through a tail-water recovery system. A reservoir, making up a small portion of acres available in site i, can be completely filled from the runoff collected from site i. A larger reservoir occupying a larger fraction of site i is only partly filled because the reservoir receives the same acre-feet of runoff. Hence, the acre-feet of water an acre reservoir can hold at full capacity from runoff throughout site i is $\omega_{\max}$. The water accumulated from rainfall into the reservoir is $\omega_{\min}$ per acre. The values for $\omega_{\max}$ and $\omega_{\min}$ are estimates because evaporation, rainfall, and the timing of rainfall during the season change by year. We define the following function (Eq. 2) for the acre-feet of water stored in an acre reservoir as

$$(2) \qquad \left(\omega_{\max} + \omega_{\min}\right) - \frac{\omega_{\max}}{\sum_j \sum_k L_{ijk}(0)} R_i(t),$$

which depends on the number acres of the reservoir $R_i\ (t)$ and the total acreage at site i, $\sum_j \sum_k L_{ijk}(0)$. The low-end acre-feet of water in each acre of the reservoir is $\omega_{\min}$ when the reservoir occupies the entire site i and only the rainfall fills the reservoir. The high-end is approximately $\left(\omega_{\max} + \omega_{\min}\right)$ when the reservoir is less than an acre in size because runoff water as well as rainfall fills the reservoir.

Typically economic papers suppose a single-cell aquifer that assumes an aquifer responds uniformly and instantly to groundwater pumping at any place in the study area (Ding and Peterson, 2012; Wang and Segarra, 2011; Wheeler et al., 2008). A limited number of papers are beginning to use a spatial aquifer to examine groundwater flow like this paper does (Brozovic, Sunding, and Zilberman, 2010; Pfeiffer and Lin, 2012). We define p_{ik} as the expected proportion of the groundwater in the aquifer that flows underground out of site i into the aquifer of site k when an acre-foot of groundwater is pumped out of site k, where p_{ik} is a negative quadratic function of the distance and the hydraulic diffusivity between sites i and k. The amount of water leaving site i is then $\sum_{k=1}^{m} p_{ik} GW_k(t)$.

The cost of pumping an acre-foot of groundwater to the surface at site i during period t is $GC_i\ (t)$. Pumping costs depend on the cost to lift one acre-foot of water by one foot using a pump, c^p, the initial depth to the groundwater within the aquifer, dp_i, and the capital cost per acre-foot of constructing and maintaining the well, c^c. Note that we assume a producer drills a well deeper than the depth to the aquifer to allow for the eventual decline in the water table. Pumping costs vary by the energy needs required to lift water to the surface. The possibility of new well drilling, either at an existing well or in a new location, if the aquifer level drops below the initial drilled depth is captured in the capital cost per acre foot. We assume the groundwater pumps are uniformly efficient with identical power units that deliver a fixed number of gallons per minute.

The dynamics of irrigation and pumping cost at each site is then represented by:

(3)
$$\sum_j \sum_k wd_{jk} L_{ijk}(t) \le GW_i(t) + RW_i(t)$$

(4)
$$RW_i(t) \le \left(\left(\omega_{\max} + \omega_{\min}\right) - \frac{\omega_{\max}}{\sum_j \sum_k L_{ijk}(0)} \sum_k L_{iRk}(t) \right) \sum_k L_{iRk}(t)$$

(5)
$$AQ_i(t) = AQ_i(t-1) - \sum_{k=1}^{m} p_{ik} GW_k(t) + nr_i$$

(6)
$$GC_i(t) = c^c + c^p \left(dp_i + \frac{\left(AQ_i(0) - AQ_i(t)\right)}{\sum_j \sum_k L_{ijk}(0)} \right)$$

Each period, the total amount of water for irrigating crops grown at the site must be less than the water pumped from the aquifer and the reservoirs (Eq. 3), and the amount of water available from reservoirs must be less than the maximum amount of water that all the reservoirs built on the site can hold (Eq. 4). The cumulative amount of water in the aquifer by the end of period *t* is the amount of water in earlier periods plus the amount of recharge that occurs naturally less the amount of water pumped from the ground of surrounding sites weighted by the proximity to site *i* (Eq. 5). The cost of pumping an acre-foot of groundwater is c^p times the depth to the groundwater, which depends on how depleted the aquifer is under the site *i*, plus c^c (Eq. 6).

The constraints (Equations 3 to 6) on the water availability from the ground or in the reservoirs limit the profits from the agricultural landscape. The objectives of aquifer or economic returns are optimized subject to these water availability constraints.

Aquifer objective

The aquifer objective evaluates how well the volume of the aquifer can sustained on a landscape given the pattern of land use. We keep the groundwater model relatively simple because we are interested in optimization over a large landscape. The aquifer volume beneath site *i* described in Eq. 4 depends on a) the level of groundwater pumping, b) the distance and hydraulic diffusivity between sites, and c) the level of recharge that occurs naturally.

We maximize the volume of the aquifer beneath the study area in the final period, which is defined as sum of the aquifer volumes across sites:

(7)
$$\max_{L_{ijk}(t), RW_i(t), GW_i(t)} : \sum_{i=1}^{m} AQ_i(T)$$

subject to:

(8)
$$L_{ijk}(0) = L_0^{ijk}, R_i(0) = 0, AQ_i(0) = AQ_0^i, L_{ijk}(t) \ge 0, AQ_i(t) \ge 0$$

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

The objective (Eq. 7) is to determine $L_{ijk}(t)$, $RW_i(t)$, and $GW_i(t)$ (i.e. the number of acres in crops and reservoirs, and water use) to maximize the volume of the aquifer at the end of the fixed time horizon *T*. Equation 8 represents the initial conditions of the state variables and non-negativity constraints on land use and aquifer.

Economic returns objective

Several economic parameters are needed to complete the formulation of economic returns objective. The price per unit of the crop is pr_j, which we assume remains constant over time to study how crop, irrigation, and water use decisions respond to a declining aquifer rather than to relative price changes. The cost to produce an acre of the crop excluding the water use costs is ca_{jk}, which depend on the crop *j*, irrigation technology *k*, and are constant in nominal terms. The yield of crop *j* using irrigation technology *k* per acre is y_{ijk} at site *i* and are constant meaning no productivity growth trend. The net value per acre for crop *j* is then $pr_j y_{ijk} - ca_{jk}$ excluding differential water pumping cost between well and reservoir water, and the reservoir construction costs. The discount factor to make values consistent over time is δ_t.

Other costs constant in nominal terms include the annual per acre cost of constructing and maintaining a reservoir, c^r, and the cost of pumping an acre-foot of water from the tail water recovery system into the reservoir and from the reservoir to the field plus the capital cost per acre-foot of constructing and maintaining the pump, c^{rw}. We assume the stationary relift pumps are uniformly efficient with identical power units that deliver a fixed number of gallons per minute.

The problem is to maximize net returns of farm production:

$$(9)\qquad \max_{L_{ijk}(t), RW_i(t), GW_i(t)} : \sum_{t=1}^{T} \delta_t \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \left(pr_j y_{ijk} - ca_{jk} \right) L_{ijk}(t) - c^r L_{iRk}(t) - c^{rw} RW_i(t) - GC_i(t) GW_i(t) \right)$$

subject to the spatial dynamics of land and water use (Eqs. 1-6) and Eq. 8.

The objective (Eq. 9) is to determine $L_{ijk}(t)$, $RW_i(t)$, and $GW_i(t)$ (i.e. the number of acres of each crop and in reservoirs, and water use) to maximize the present value of profits of farm production over the fixed time horizon *T*. Revenue accrues from crop production constrained by the water and other inputs needed for the crops. Costs include the construction and maintenance of reservoirs/tailwater recovery, the capital and maintenance of the pumps, the fuel for the pumping of water from the reservoirs or ground, and all other production costs.

Optimization and solution methods

The goal of the analysis is to find land and water use patterns that maximize the economic objective (Eq. 9) for a given level of the aquifer (Eq. 7), and vice versa. By finding the maximum economic returns for a fixed volume of the aquifer, and then varying the volume of the aquifer over its entire potential range, we trace out the efficiency frontier. The efficiency frontier illustrates what is feasible to attain from the landscape in terms of the economic and aquifer objectives, and the necessary tradeoffs between the aquifer and economic objectives on the landscape. The efficiency frontier also illustrates the degree of inefficiency of other land and water use patterns not on the frontier, which shows how much the economic returns and/or aquifer could be increased.

The first step for generating points on the efficiency frontier involves finding the maximum potential of the aquifer in the final period. This is any land use patterns that moves all production into non-irrigated land uses and allows the volume of the aquifer to rise at the rate of natural recharge. The second step is to find the lowest level of the aquifer which is found by solving with the economic returns objective with no restriction on the final volume of the aquifer. With the highest and lowest levels of the aquifer known, the remaining aquifer values for the efficiency frontier are chosen from equally spaced intervals between the lowest and the highest amounts of the aquifer.

The final step is to find the land and water use patterns that maximizes the landscape economic scores while maintaining each of the aquifer levels found in the first and second steps. The value of economic returns matched to its corresponding aquifer level gives a combination that rests on the efficiency frontier. We perform the optimization with the Generalized Algebraic Modeling System (GAMS) 23.5.1 using the non-linear programming solver CONOPT from AKRI Consulting and Development.[1]

Sensitivity Analyses

An efficiency frontier is created from a version of the model that does not allow any irrigation technologies. This frontier illustrates, by comparison with the efficiency frontier that allows all irrigation technologies, the magnitude of efficiency gains possible in the form of higher economics returns and/or aquifer volumes from the adoption of irrigation technologies. To evaluate the impact of individual irrigation technologies, the model outcomes from the landscape maximizing economic returns without restriction on the size of the aquifer and that use all the irrigation technologies (baseline) are compared to the outcomes of models that i) do not allow the building of reservoirs; ii) halve the water efficiency; iii) double the water efficiency; iv) double the cost; v) halve the cost of all irrigation technologies other than reservoirs; and v) evaluate policy options for groundwater conservation.

Policy options

Several policy options for groundwater conservation are considered that include cost share for reservoir construction by modifying c^r, as well as cost share for the irrigation technologies including center pivot, land leveling, surge valve, pipe hole selection program, and multiple inlet by modifying ca_{jk}, and taxing groundwater pumping cost GC. The cost share is 65% for irrigation reservoir construction, and 60% for center pivot, land leveling, surge irrigation, multiple inlet, and pipe hole selection based on the rates from the Natural Resource Conservation Service's (NRCS) Agricultural Water Enhancement Program (NRCS 2014). We choose tax on groundwater pumping costs of 10% to achieve groundwater conservation similar to the cost share on reservoir construction.

[1] The problem is not linear because the groundwater pumping cost and the amount of groundwater pumped are both solved as part of the problem and are multiplied together. The CONOPT solver available in GAMS is particularly effective at solving complex non-linear programs.

Data

The study area has three eight-digit HUC watersheds[2] that represent the region of the Arkansas Delta where unsustainable groundwater use is occuring (Fig. 1). The watersheds overlap eleven Arkansas counties: Arkansas, Craighead, Cross, Desha, Lee, Monroe, Phillips, Poinsett, Prairie, St. Francis, and Woodruff. The study area is divided into 2,973 sites to evaluate how farmers make decisions about crop allocation and water use in a spatially differentiated landscape. The 2010 Cropland Data Layer (Johnson and Mueller, 2010) determines the initial acreage of crops in each cell shown in the appendix (Table A-1). The irrigated vs. non-irrigated soybean acreage is allocated on the basis of harvested acreage for 2010-2011 (NASS, 2012). The 2% real discount rate chosen for the analysis corresponds to the average yield of the 30yr Treasury Bond over the last decade of 5% (US Department of the Treasury, 2012) less an inflation expectation of 3%. County crop yield information for the past 5 years is used as a proxy for yields of each of the crops and not adjusted over time. The cost of production for all crops as well as the ownership and maintenance charges for the water-saving irrigation technologies, reservoirs and wells are held constant in inflation adjusted terms.

Groundwater use and recharge

The depth to the water table (from surface to the top of the water table) and initial saturated thickness (height of aquifer) of the alluvial aquifer shown in appendix (Table A-1) come from the Arkansas Natural Resources Commission (ANRC 2012). A thinner aquifer suggests greater depletion of the aquifer has occurred in that area (Fig. 1b). The initial size of the aquifer, $AQ_i(0)$, at site i is computed as the acreage, $\sum_j L_{ij}(0)$, times the saturated thickness of the aquifer.

The natural recharge (nr_i) of the Alluvial aquifer is based on a calibrated model of recharge for the period 1994 to 1998 associated with precipitation, flow to or from streams, and groundwater flow to or from the underlying Sparta aquifer (Reed, 2003). Note that producers do not use the deeper Sparta aquifer because the depth is prohibitively expensive, and municipalities have rights to the Sparta for drinking water.

Pumping of the groundwater reduces the size of the aquifer for the grid cell with the pumped well and for the cells that surround the well. After pumping, some of the water in the aquifer flows from the surrounding cells into the cell with the pumped well. The size of the underground flow of water is based on the distance from the pump and the hydraulic diffusivity of the aquifer. Jenkins (1968) introduced a term that is widely applied in aquifer depletion problems called the "aquifer depletion factor" (or *ADF*) to quantify the relation between these two variables. The depletion factor for pumping at a particular location in an aquifer is defined as

$$ADF = \frac{D}{d^2} \tag{12}$$

where d is the shortest distance between the pumped well and the nearby aquifer, and D is the hydraulic diffusivity of the aquifer. The hydraulic diffusivity is the ratio of the transmissivity and the specific yield of the unconfined alluvial aquifer (Barow and Leake 2012). Specific yield, which does not vary across cells in our study area, is a dimensionless ratio of water drainable by

[2] The HUCs for L'anguille, Big, and the Lower White are 08020205, 08020304, and 08020303.

saturated aquifer material to the total volume of that material. The product of hydraulic conductivity and saturated thickness is the transmissivity, and hydraulic conductivity is the rate of groundwater flow per unit area under a hydraulic gradient (Barlow and Leake, 2012). The hydraulic conductivity in feet per day for the Mississippi River Valley alluvial aquifer come from spatially coarse pilot points digitized in Clark, Westerman and Fugitt (2013).

The depletion of the aquifer beneath the cell is greater (i.e large ADF) if the grid cell is closer to the pumped well and the hydraulic diffusivity is bigger. We use the *ADF* to determine the proportion (or spatial weight) of the acre-feet of water pumped from a well that reduces the aquifer beneath the surrounding cells. The distance from the well and hydraulic diffusivity (based on the saturated thickness and hydraulic conductivity) of the surrounding cells influence the p_{ik} used in the economic model.

Farm production

Table A-1 of the appendix indicates the costs of production by crop from the 2012 Crop Cost of Production estimates (Division of Agriculture, 2012). Variable irrigation costs regardless of water source include fuel, lube and oil, irrigation labor, and poly pipe for border irrigation plus the levee gates for the flood irrigation of rice (Hogan et al., 2007). Capital costs associated with wells, pumps, gearheads and power units are charged on a per acre-foot basis and are incurred whether reservoirs are installed or not as wells remain to cover potential reservoir shortfalls. The average water use over the course of the growing season excluding natural rainfall is about an acre-foot for soybeans and more than three acre-feet for rice (Powers, 2007). Crop prices are the five year average of December futures prices for harvest time contracts for all crops (GPTC, 2012). These model parameters are found in the appendix (Table A-2). Cost of production, crop price and yields do not vary over time to allow groundwater scarcity and the tradeoff of aquifer volume and economic returns to guide crop mix changes.

The cost of pumping water from the ground and/or reservoir depends on the costs of the fuel, maintenance, and capital. The capital cost of the well, pump and gearhead, and power unit is amortized (Hogan et al., 2007) and divided by the acre-feet pumped from the well to calculate a capital cost per acre-foot applied. The reservoir and tail-water recovery system capital cost also is converted to periodic payments and depends on the reservoir acreage. The fuel cost per acre-foot of water from the aquifer depends on the depth to the water table and the corresponding fuel needed to raise water. Diesel use ranges from 13 gallons of diesel per acre foot for a 100 foot well to 26 gallons of diesel per acre foot for a 200 foot well (Hogan et al., 2007). The diesel needed per acre-foot for pumping water to and from the reservoir is 6 gallons (Hogan et al., 2007). We use $3.77 per gallon of diesel fuel (EIA, 2012) and add 10% to fuel cost to account for oil and lube for irrigation equipment (Hogan et al., 2007).

Irrigation technologies

For soybeans, corn, and cotton, the conventional irrigation technique in the Arkansas Delta is to use furrows with irrigation water delivered through polyvinyl chloride plastic irrigation pipe (i.e. poly-pipe). The alternative irrigation techniques for the soybeans, corn, and cotton to reduce water use and potentially raise yield include center pivot, surge irrigation, precision leveling, and poly-pipe with computerized holes selection software. The center pivot is a hanging sprinkler system that rotates circularly around a pivot. Surge irrigation is a variant of furrow irrigation where the water in the poly-pipe is pulsed on and off to advance water down the furrow faster. Precision leveling is to smooth the surface of the field to increase flow and uniformity of water down the furrow. Computerized pipe-hole selection software reduces water by adjusting the size of tubing holes for different row lengths and calculates pressure changes along the tubing.

Flood irrigation is the conventional technique for rice, and the alternative techniques considered for rice are precision leveling, alternate wet-dry, and multiple-inlet flooding. The precision leveling for rice is in fact zero-grading of the paddies to provide uniform flood of the rice. Alternate wetting and drying irrigation of rice is a practice where soils are allowed to drain intermittently during the rice life-cycle rather than having the field continuously flooded. Multiple-inlet irrigation releases flood water with tubing over the whole field evenly and at once through holes or gates in the tubing.

The alterations to crop yields, water use, and production costs associated with the alternative irrigation technologies are shown in the appendix (Tables A3-A5). The alternative technologies' induced changes of the farming parameters are displayed as a percentage of the baseline values for the conventional technology. The literature used to quantify the magnitude of the changes represents the best available information on how the alternative technologies affect yield, water use, and costs. In some instances, there are no studies on a particular irrigation technology for the Mississippi Delta region or the studies are not peer-reviewed. Our best judgment therefore must suffice to estimate how the irrigation technologies could affect the relevant parameters.

There already exist in the study region the use of the alternative irrigation technologies. However to highlight how these technologies matter for the tradeoffs between farm profits and aquifer conservation, we suppose only the conventional irrigation technology is used initially.

Reservoir use and construction

Young et al. (2004) determined 440 acre feet is the maximum a reservoir can be filled using a tail-water recovery system from the average rainfall runoff on a 320 acre farm. This suggests that an acre of land can yield 16.5 acre-inches for holding at the reservoir. This is the minimum amount of water (ω_{min}) we estimate an acre of reservoir can hold without the collection of runoff from a tail-water recovery system. The use of a tail-water recovery system allows a reservoir to fill to an estimated maximum capacity of 11 acre-feet per acre over the course of a year (Smartt et al., 2002). The reservoir's capacity is 1.5 times the storage height less what is lost to evaporation because runoff collected during the year refills the reservoir.

On-farm reservoir/tail-water recovery construction and maintenance costs for various size reservoirs were estimated using Modified Arkansas Off-Stream Reservoir Analysis (MARORA) (Smartt et al., 2002) for different size operations to obtain capital cost estimates. Subsequently, total system cost was regressed against acres occupied by the reservoir to determine per acre investment cost for different size reservoirs. Since a majority of the construction cost for a reservoir rest on the cost to move one cubic yard of soil, this cost was updated from $1 per cubic yard to $1.2 per cubic yard to reflect changes in fuel cost since 2002 when MARORA costs were updated last. The remainder of the investment and maintenance cost is based on estimates provided within MARORA and includes a pump for tail-water recovery and a pump for irrigation.

Note that while reservoirs already exist in the study region, we assume zero reservoirs in the baseline to highlight the potential for reservoirs. This is because of the scarcity of spatially explicit data on existing reservoirs as well as the objective to highlight how construction of surface water reservoirs for irrigation use are important to farm profitability and potential maintenance of groundwater.

Results

Table 1 shows different point along the efficiency frontier that combines economic returns on one side, and volume of the aquifer on the other. Conventional and water-saving irrigation techniques as well as presence or absence of reservoirs have been compared. The volume of the aquifer is maximized for points A and F, whereas economic returns are maximized for points E and J. Points B to D and G to I express intermediate cases along the efficiency frontier. Points A to E show a set of cases in which only conventional irrigation techniques and no reservoirs are permitted, whereas cases from F to J allow for the creation of reservoirs and water-saving irrigation technologies. Point K shows the effects on the aquifer when land uses are constrained over time at the 2013 level. It can be seen that the lowest economic returns and aquifer volumes are observed in case the current landscape pattern remains fixed over time, with an overall negative economic return of 890 million dollars and a loss in the volume of the aquifer equal to 41% compared to the maximum volume reachable. When land is not constrained, the maximizing profit motive with no aquifer constraints results in net economic returns that vary from around 3800 million dollars (no water conservation) to 6619 million dollars (water conservation technologies and reservoirs).

Therefore, when the only objective is to maximize net economic returns, conservation technologies result in almost twice as much profits with about 8% of water saved in comparison to the scenario in which no conservation technologies are adopted. The overall variation in economic returns from the aquifer and the profit maximization motive is 5% when water conserving technologies are allowed, whereas it changes of 70% when no conservation is in place. This corresponds to a 21% (conservation) versus 29% (no-conservation) overall variation in the volume of the aquifer. Point F indicates that it is possible, when conservation technologies are in place, to obtain net economic returns that are almost sixfold in comparison to point A (no conservation in place), while preserving the aquifer at the maximum level. Maximizing the aquifer with conservation technologies still results in economic returns that are 1.6 times higher than the maximum profits reachable in the situation in which no conservation is in place. Figure 2 shows the variation in economic returns versus the variation in the aquifer level and the spatial allocation of crops, and Figure 3 illustrates the spatial configuration of crops for each of the points along the efficiency frontier on the geographical map for the area analyzed.

Table 2 illustrates the allocation of land for each crop and each irrigation technology if conservation is in place. As expected, when no water-conserving technologies are in place, most of the land reallocates to non-irrigated crops in measure that depends on the level of the aquifer conservation goal. When conservation of water is the main goal, in absence of water conservation technologies and reservoirs all land is reallocated into dry sorghum and soybean; when maximizing profits with no constraints on the volume of the aquifer is the goal, the two most grown crop become soybeans (736 thousand acres), corn (248 thousand acres), and the no irrigated crops account for 153 thousand acres. When water conservation technologies and reservoirs are in place, the main change in land allocation resulting from a more profit or conservation oriented goal is the amount of land used for reservoirs (from 74 to 30 thousand acres).

As for the most adopted water saving technologies, the most efficient way of saving water for rice is land leveling, for soybeans is the adoption of surge valves, whereas for corn some variability is observed: surge valves are adopted on most of the landscape, followed by pipe hole selection, land leveling and center pivots. Cotton disappears from the landscape for both scenarios (adoption or not of water-saving technologies), whereas rice disappears only in case of lacking adoption of water-saving irrigation systems. No dryland and wheat are observed when conservation technologies are in place. Among the irrigation systems that can be adopted, center pivots are only observed on a very limited proportion of land (less than 1%), and only for corn. In case there is no change in land use and the 2013 baseline is maintained, irrigated soybeans is the most grown crop, followed by rice, non-irrigate soybeans, corn, wheat, cotton and sorghum. As indicated above, this landscape configuration results in the lowest volumes for the aquifer, and negative overall net returns.

Table 3 represents the economic consequences that emerge from moving from one point to another along and across the efficiency frontier. Greater effects in terms of the increase of net returns can be observed for both cases (absence or presence of water conserving technologies) when diverting from the aquifer maximization goal. The less water becomes a constraint, the more profits increase, resulting in an increasing reduction in the volume of the aquifer that is greater the closer net returns become to the maximum net returns achievable. When water saving technologies are in place, the increase of profits can be obtained through an increase of groundwater extraction, a decrease in the use of water for reservoirs and the reallocation into crops of land previously used for reservoirs. The observed variation for both volume of the aquifer and net returns is greater when no conservation is in place. The maximum variation observed in the aquifer is equal to about 30 thousand acre feet, whereas when conservation is in place the aquifer varies in its volume, when moving along the frontier, of a little above 20 thousand acre feet.

Net returns can vary by a little under 2.7 billion dollars when no conservation is in place, whereas when conservation is in place the maximum variation possible is of little under 350 million dollars. Moving across frontiers (from no conservation to conservation) results in decreasingly increasing net returns (from about 5 billion $ to 2.8 billion $) when increasingly diverting from the aquifer maximization goal. Conservation of the aquifer is mostly achieved through the use of reservoirs (more than 8.6 million acre-feet from A to F). An overall reduction of groundwater use of a little under 4.5 million acre-feet can be observed when water conservation technologies are adopted and the objective is to maximize profits without water use constraints (from E to J). In overall terms, conservation technologies allow for greater increases in profits when the objective is to preserve the volume of the aquifer, whereas they allow for greater reduction in the groundwater use when the objective is to maximize profits. This results in lower variation observed along the efficiency frontier when conservation technologies are used compared to the case in which no conservation technologies are implemented. This can be clearly seen in Fig. 2: the vertical and horizontal variation for points F to J is lower than what observed for points A to E, especially in terms of net returns.

Table 4 shows the economic value in present terms of each crop for all points along the efficiency frontiers for both presence and absence of water conservation technologies. In case no water conservation technologies are adopted, the profit or conservation objective can be achieved through changes in crops on the landscape. When the objective is the conservation of the aquifer, all land is allocated in non-irrigated crops that result in a value of a little above 1.1 billion dollars. Diverting from the conservation objective, corn and soybeans appear. Rice, which is the most water-demanding crop, is only grown when there are no constraints in the extraction of groundwater. Its presence accounts for 340 million dollars, whereas the most grown crop results soybeans, which appears more water demanding per unit of output than corn: when there is a mixed objective (point C), corn is the crop that produces the highest economic returns (1.3 billion $). When water conserving technologies can be adopted, the profit or conservation objective can be achieved through the differential adoption of irrigation technologies, whereas little changes in crop areas can be observed, and non-irrigated crops do not appear on the landscape. The combination of crops represented by point K is unsustainable both in economic and water conservation terms.

In Table 5 are shown the effects of a variation in water efficiency, water cost and presence or absence of reservoirs in relation to the baseline represented by the scenario driven by the profit maximization rule without water constraints and the adoption of water-saving technologies for irrigation (point J). Water efficiency has an effect on the reallocation of land in particular between soybeans, corn and reservoirs. When water efficiency halves, about 39 thousand acres previously grown with irrigated soybeans switch into reservoirs (+13 thousand acres) and conservation irrigated corn (+29 thousand acres). Moreover, rice surface reduces of about 4 thousand acres, and some conventionally irrigated crops emerge (1 thousand acres). The result of halving water efficiency in terms of groundwater extraction is an increase equal to 102 thousand acre-feet. The amount of land allocated for corn increases (+49 thousand acres) also in case water efficiency doubles. Doubling water efficiency has an effect on rice as well (+15 thousand acres). The increase of area grown with corn and rice balances the loss of land grown with soybeans (-39 acres) and reservoirs (-21 thousand acres). With regard to the baseline, doubling water efficiency reduces groundwater use of 244 thousand acre-feet.

Doubling of halving the cost of water has an effect that can be mostly observed again in terms of reservoirs, irrigated soybeans and irrigated corn. When water costs halve, the amount of land grown with corn increases (+44 thousand acres) as well as the amount of reservoirs (+7 thousand acres), to the expenses of irrigated soybeans (-40 thousand acres). On the other hand, when costs for water double, the land for irrigated soybeans decreases less than the land allocated for corn (-5 vs. -11 thousand acres), whereas reservoirs still increase (+15 thousand acres) and some conventionally irrigated crops appear (+1 thousand acres). Non irrigated crops compare only in case no reservoirs are allowed (+103 thousand acres). The volume of the aquifer varies, for all considered cases, from a minimum of about 66 billion acre-feet (no reservoirs allowed) to a maximum of 81 billion acre-feet (doubled water efficiency). The effect that a variation of water cost has on the aquifer appears to be lower on the aquifer that the effect resulting from variations in efficiency. The same can be observed in terms of total present value for crops: halving water costs results in an increase of the present value with respect to the baseline of 63 million dollars, whereas a doubling in the water efficiency results in an overall present value that is 596 million dollars higher than the baseline. The absence of reservoirs and a reduction of water efficiency in a half are the two conditions that result in the lowest present values.

As far as water conservation policies are concerned (Table 6), the only policy scenario that allows for a moderate increase in rice land is the cost share for land leveling (+8 thousand acres). All policy options result in an increase of irrigated corn (from +35 thousand acres for cost share for reservoir construction, cost share for the pipe hole selection program and tax on groundwater use, to +39 thousand acres for all other policy options), and in a reduction in the irrigated soybeans acreage (from -39 to -47 thousand acres). The most effective policy option to prevent groundwater depletion is cost share for the pipe-hole selection program: this is because it is the policy option that results in the highest farm returns and the third highest aquifer level.

The combination of these two elements balances the cost of implementing the policy, which is the highest observed (79 million dollars), and results in the lowest cost per feet of water conserved ($6.43). The second best policy option is a tax on groundwater extraction: it results in the lowest farm net returns (-82 million dollars compared to the baseline, the only case in which net returns are lower than the baseline), but also in a government revenue (+64 million dollars) and the best result in terms of water conservation (+2.2 billion acre-feet) that both balance farm losses and result in a water conservation cost per acer feet of $8.29. The third best policy option is the cost share for building reservoirs, with a water conservation cost per acre-feet that is equal to 25.14$, almost four times higher than the cost of water conservation in case of the cost share for the pipe-hole selection program is in place. All the other policy options result in partial depletion of the aquifer with respect to the baseline that varies from 50 to 230 thousand acre-feet of water (cost share for respectively center pivots and multiple inlets).

Conclusion

We used aquifer and economic models that utilize crop patterns to explore the joint aquifer and economic impacts of crop decisions at a landscape scale. Considering the joint effects on aquifer and economic consequences of crop decisions in the Arkansas Delta application, we found that it is possible to maintain a high level of the aquifer and generate large economic returns through careful spatial management of crops. It is important to recognize the varying irrigation needs of crops, observing that dry land crops can generate profit with no pressure on the aquifer, rather than an exclusive focus on maintaining one irrigation intensive crop. Doing so gives a more realistic picture of how well an aquifer is likely to do beneath an agricultural landscape and lessens the apparent conflict between an aquifer and economic objectives.

The largely positive findings for the Arkansas Delta, where certain crop patterns can jointly generate high aquifer volume and economic returns, occur because many crops in the Delta require less irrigated water than rice while still delivering high economic returns. The fact that the highest value crop for the Delta recently is corn, which requires less irrigation water than rice, is also important in limiting the degree of conflict between aquifer and economic objectives. In other regions, where the most economically profitable crops are more irrigation intensive, there will likely be much greater conflict between conservation objectives and economic returns. Even in the Arkansas Delta, if the price for rice increases there will be a more apparent tradeoff between aquifer and economic objectives.

In this application we found that aquifer volume and economic returns for crop patterns on the efficiency frontier exceeded those for the 2013 landscape by large margins, indicating that there are large improvements that potentially can be realized by alternative crop management. For example, point C on the efficiency frontier without new irrigation technologies had economic returns $3.8 billion higher than the 2013 land-use pattern represented by point K, while the aquifer volume increased by 24.4 million acre-feet. Both of these increases cover the majority of the gap between the point K 2013 crop pattern and the maximum value found for each objective. There has, in fact, already been some change in crop patterns reflecting the growing groundwater scarcity.

The results also show that maximizing either the economic or aquifer values imposes large losses on the other objective. The efficiency frontier shows that at points close to the economic maximum, further small increases in the economic returns impose large declines in the aquifer volume. At the other end of the efficiency frontier, when the landscape is close to the aquifer maximum, further small increases in the aquifer value come at the expense of large declines in the economic value. Xevi and Khan (2005), who combine aquifer and economic models to evaluate tradeoffs, find that minimizing pumping means only 76% of the maximum economic returns can be achieved.

Because we modeled the present value of agricultural production for a large section of the Arkansas Delta, the total value of economic returns was high (maximum of $3.8 billion and $6.6 billion, respectively without and with new irrigation technologies). For the frontier without new irrigation technologies, a reduction of 40% in economic returns, which is required to raise the percentage of aquifer volume sustained on the landscape to above 90% of the maximum attainable, is a substantial $828 billion. Meanwhile, if the new irrigation technologies are used, a reduction of only 3% in economic returns is required to raise the percentage of aquifer volume sustained on the landscape to above 90% of the maximum attainable, but this is still a significant $200 million. It is not unreasonable to think of making an investment of this size to sustain the aquifer at a regional scale. This amount could be financed through a combination of a government bond issue to support cost-share of irrigation technologies along with investments by non-governmental conservation organizations.

The results in this paper should be viewed as suggestive rather than being prescriptive about particular crops for particular sections of the landscape or irrigation technologies for particular crops. Details of the landscape may preclude certain uses or make certain uses undesirable even though the analysis here indicates those uses are beneficial. Lack of detailed knowledge of irrigation technology effects on crop yields and water use may make this model inappropriate for designing specific irrigation plans. However, the overall pattern of tradeoffs between conservation objectives and economic returns, and the general characteristics of crop mix that will benefit the aquifer should be robust and could help guide conservation planning.

In the application we treated the Arkansas Delta as an island ignoring geographic range lying outside of the basin. In general, aquifer links to other regions will be important in conservation planning at anything less than the full extent of the aquifer. Considering the broader conservation context will also be important for knowing how much aquifer is important to conserve within the planning region and how much aquifer could best be conserved elsewhere. In an important respect, the economic model used in this paper is simpler than the aquifer model. The value of economic returns at a grid cell is solely a function of the grid cell's characteristics. Nearby or adjoining grid cells do not influence the economic return for a grid cell. In doing so, we ignore changes in market prices or the effects of economies of scale from changes in crop decisions.

We also do not include ‘‘externalities’’ from adjacent land uses, such as the positive effect of pollinators on crop yields or the negative effects of pesticide and nutrient runoff.

The aquifer model also contains several important simplifications that deserve mention. We were constrained in the Arkansas Delta application by lack of recharge-specific data from streams and vegetation related evapotranspiration that translates from annual rainfall to the level of recharge on the landscape. More detailed information about recharge would improve the reliability of model predictions. In addition, connections between the shallow alluvial aquifer and the underlying Sparta aquifer are not considered, and this can affect the storage and hydraulic conductivity of the alluvial aquifer which in turn influences the extent of groundwater flow in response to pumping.

We plan to further investigate how much the spatial pattern of crops and the placement of wells matter for aquifer conservation. If there is not much difference between choosing crops based solely on the amount of groundwater pumped and the more complicated approach that takes account of the spatial pattern of pumping and groundwater flow, then simpler approaches focusing on total pumping could be used. Ignoring spatial considerations would considerably simplify the aquifer model and allow for much faster search for efficient solutions. If the way in which spatial pattern is modeled affects results in important ways, then further work on spatial modeling will be required.

Probably the most important set of issues not addressed in this paper are related to crop change and dynamics. We consider the long-run consequences of a landscape in terms of the aquifer and economic objectives. In reality, however, changes to an existing landscape and irrigation technologies will take time to occur. For example, if the current crop is rice but the desired crop is dry land sorghum or soybean, it will take decades for the farmers to adjust to new production practices so that there will be a significant delay between the crop change and the onset of aquifer benefits of a less irrigation intensive crop. Besides the time it takes to make intentional transition between different crops and irrigation technologies, there may be unintentional transitions caused by disturbances such as pest outbreaks or more long-term fundamental changes brought on by climate change. Aquifer levels also take time to adjust. The presence of some water-efficient irrigation in a region may be a function of crop conditions in the past but they may be unable to continue to persist if crop conditions change. On the other hand, some irrigation technologies may not be currently present but might be adopted and persist if suitable policies for adoption are available. In addition, human population changes and shifts in market prices will alter the economic returns of various alternative crops through time resulting in pressures for crop change. Future work should include analysis of these important dynamics and transitions.

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Table 1: Groundwater and economic return values for selected points along the efficiency frontiers and for the 2013 landscape.

Land use pattern	**Present value of economic returns ($ M)**	**Percentage of maximum economic return**	**Volume of the aquifer (thousand acre-feet)**	**Percentage of maximum volume of aquifer**
Efficiency frontier				
Without new irrigation technologies				
A	1146	30	91,710	100
B	2312	61	85,200	93
C	2996	79	78,700	86
D	3481	91	72,200	79
E	3806	100	61,350	71
With new irrigation technologies				
F	6285	95	91,710	100
G	6435	97	86,975	95
H	6535	98	82,240	90
I	6598	99	77,505	85
J	6619	100	72,770	79
2013 land use pattern				
K	-890	-23	54,250	59

Note: The values of economic returns are reported in millions of 2013 constant dollars and the volume of the aquifer in 2043 is reported in thousands of acre-feet.

Table 2. Land-use in 2043 for selected points along the efficiency frontier and the 2013 landscape.

Land use	2013 landscape K	Efficiency frontier points					
		Without new irrigation technologies, 2043			With new irrigation technologies, 2043		
		A	C	E	F	H	J
Rice							
Conventional	221	0	0	0	0	0	0
Alternate wet/dry	--	--	--	--	0	0	0
Multiple inlet	--	--	--	--	0	0	0
Land leveling	--	--	--	--	205	205	206
Full season irrigated soybeans							
Conventional	448	0	32	736	0	0	0
Center pivot	--	--	--	--	0	0	0
Pipe hole selection	--	--	--	--	0	0	0
Surge	--	--	--	--	428	443	460
Land leveling	--	--	--	--	0	0	0
Irrigated corn							
Conventional	142	0	103	248	0	0	0
Center pivot	--	--	--	--	1	1	1
Pipe hole selection	--	--	--	--	129	130	136
Surge	--	--	--	--	279	279	280
Land leveling	--	--	--	--	25	25	28
Irrigated cotton	26	0	0	0	0	0	0
Wheat	129		0	4	0	0	0
Non-irrigated sorghum	20	783	358	72	0	0	0
Non-irrigated soybeans	155	358	648	81	0	0	0
Reservoirs	--	--	--	--	74	59	30

Note: All values are reported in thousands of acres.

Table 3. Change in economic returns, water use, and the aquifer in 2043 along the efficiency frontiers and across efficiency frontiers.

Change in efficiency frontier points	Present value of economic returns	Reservoir water use	Groundwater use	Aquifer
Along efficiency frontier				
Without new irrigation technologies				
A to C	1850	--	1346	-13,010
C to E	810	--	8509	-17,350
With new irrigation technologies				
F to H	250	-1799	1908	-9470
H to J	84	-3405	3602	-9470
Across efficiency frontiers				
A to F	5139	8662	0	0
C to H	3539	6863	562	3540
E to J	2813	3458	-4327	11,420

Note: We report the economic returns in in millions of 2013 constant dollars and water use and the volume of the aquifer in thousand acre-feet.

Table 4: Present value of economic returns by crop for points along the efficiency frontiers and for the 2013 landscape.

Land use pattern	Conventionally irrigated value			Conservation irrigated value			Non-irrigated crop value
	Rice	Soybean	Corn	Rice	Soybean	Corn	
Efficiency frontier							
Without new irrigation technologies							
A	0	0	0	--	--	--	1145
C	4	576	1384	--	--	--	1032
E	340	1542	1513	--	--	--	411
With new irrigation technologies							
F	0	0	0	1695	897	3693	0
H	0	0	0	1726	981	3828	0
J	0	0	0	1763	1010	3846	0
2013 land use pattern							
K	-1211	-128	199	--	--	--	250

Note: The value of economic returns is reported in millions of 2013 constant dollars.

Table 5. Land use, water, and economic conditions in 2043 for sensitivities of the conservation technologies.

Crop and water conditions	Baseline (Point J)	Sensitivity analyses of the conservation technologies*				
		No reservoirs	Halve water efficiency	Double water efficiency	Double cost	Halve cost
Land use (thousand acres)						
Conventionally irrigated crops	0	0	1	0	1	0
Conservation irrigated rice	206	176	202	221	206	206
Conservation irrigated soybeans	460	419	421	417	455	420
Conservation irrigated corn	445	443	474	494	434	478
Non-irrigated crops	0	103	0	0	0	0
Reservoirs	30	0	43	9	45	37
Water conditions (thousand acre-feet)						
Reservoir water use	346	0	492	105	527	427
Groundwater use	553	836	655	309	361	471
Aquifer	72770	65840	69620	80950	76930	74060
Economic conditions ($M)						
Present value conventional irrigated	0	0	0	0	0	0
Present value conservation irrigated	6619	6080	6265	7215	6386	6682
Present value non-irrigated	0	155	0	0	0	0
Total	6619	6235	6265	7215	6386	6682

* All models use the profits objective and exclude changes to the water efficiency and cost of on-farm reservoirs.

Table 6. Water conservation policies influence on crop mix, reservoirs built, aquifer, and economic returns.

Policy	Rice (thousand acres)	Irrigated soybeans (thousand acres)	Irrigated corn (thousand acres)	Reservoirs (thousand acres)	Aquifer, 2043 (thousand acre-feet)	Farm net returns, 30yr NPV [a] ($ millions)	Government revenue, 30yr NPV ($ millions)	Groundwater conservation cost [b] ($ per acre-foot)
Baseline (Point J)	206	460	445	30	72770	6619	--	--
Cost share reservoir construction [c]	206	420	480	35	74600	6631	-58	$25.14
Cost share center pivot [c]	206	421	484	30	72700	6619	-8	No groundwater conserved
Cost share land leveling [c]	214	413	484	30	72620	6638	-60	No groundwater conserved
Cost share surge irrigation [c]	206	421	484	30	72720	6619	-7	No groundwater conserved
Cost share pipe hole selection program [c]	206	421	480	34	74480	6687	-79	$6.43
Cost share multiple inlet [c]	206	421	484	30	72540	6619	-12	No groundwater conserved
Tax on groundwater use [d]	206	421	480	34	74940	6537	64	$8.29

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] The cost share is 65% for irrigation reservoir construction, and 60% for center pivot, land leveling, surge irrigation, multiple inlet, and pipe hole selection based on the rates from the Natural Resource Conservation Service's (NRCS) Agricultural Water Enhancement Program (NRCS 2014). [d] We choose a tax on groundwater pumping costs (10%) to achieve groundwater conservation similar to the cost share on reservoir construction.

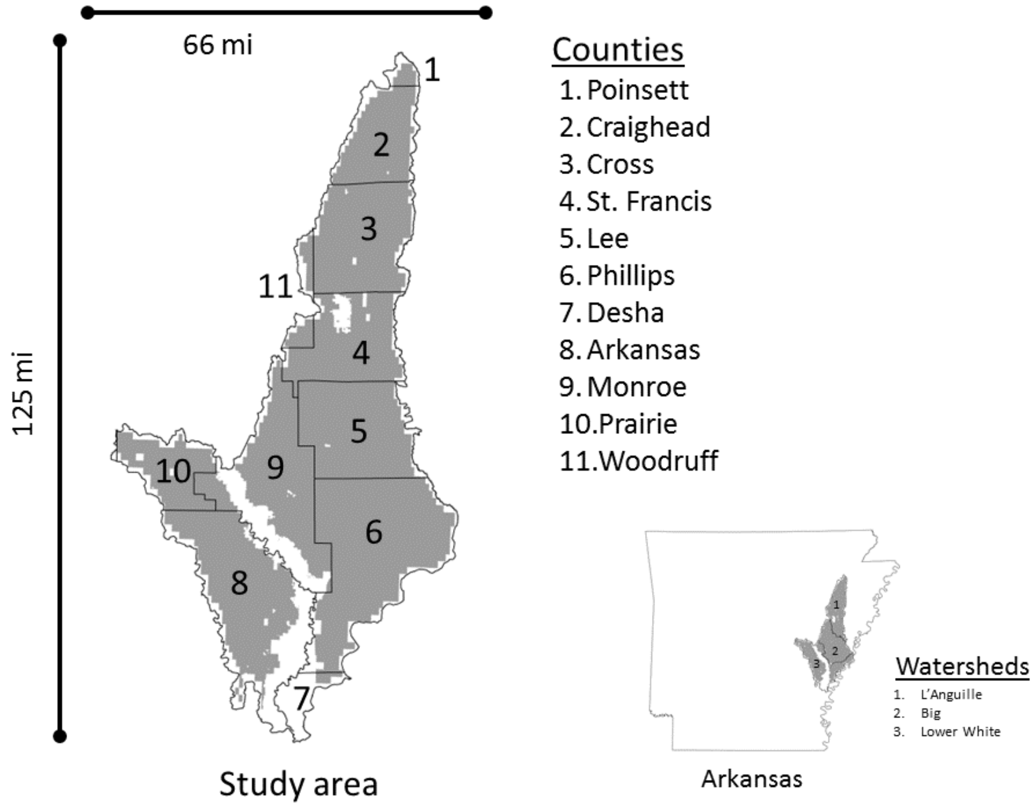

Figure 1. Three eight-digit HUC watersheds in the Mississippi Delta region of eastern Arkansas define the outer boundary of the study area. An eight-digit HUC defines the drainage area of the sub-basin of a river. County lines overlay the study area. Public land and urban areas are excluded. The location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

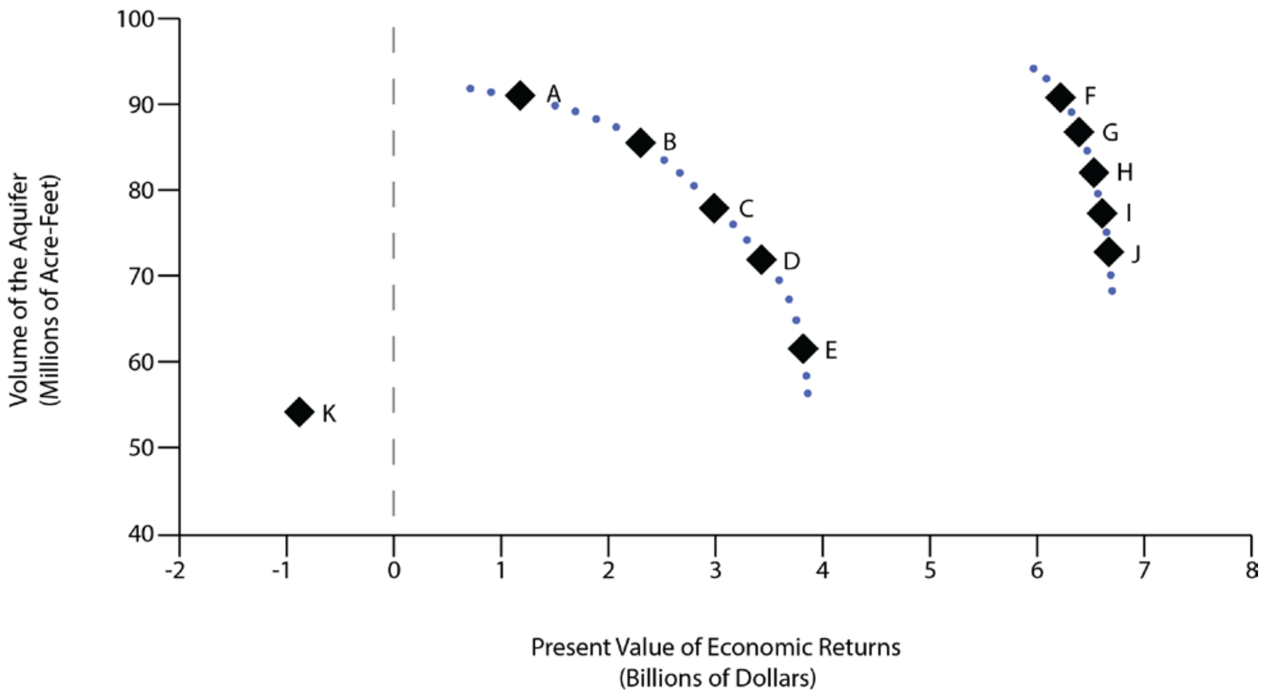

Figure 2. Efficiency frontiers. The present value of economic activity generated by a crop mix pattern is shown on the horizontal axis. The volume of the aquifer sustained by a crop mix pattern is shown on the vertical axis. The efficiency frontiers are outlined by circles. The lettered diamonds represent specific crop mix patterns along the frontier. Point A represents the highest volume of the aquifer found when there is no groundwater pumping. Only non-irrigated crops are grown because no reservoirs or new irrigation technologies are available. Point E represents the maximum economic returns possible without new irrigation technologies available. Point F represents the highest volume of the aquifer when there is no groundwater pumping, but reservoirs are available to provide surface water and new irrigation technologies make irrigation water use more efficient. Point J represents the maximum economic returns possible with new irrigation technologies available. Point K represents the volume of aquifer and economic returns when the crop mix pattern is constrained to be the 2013 crop mix pattern for the entire study period.

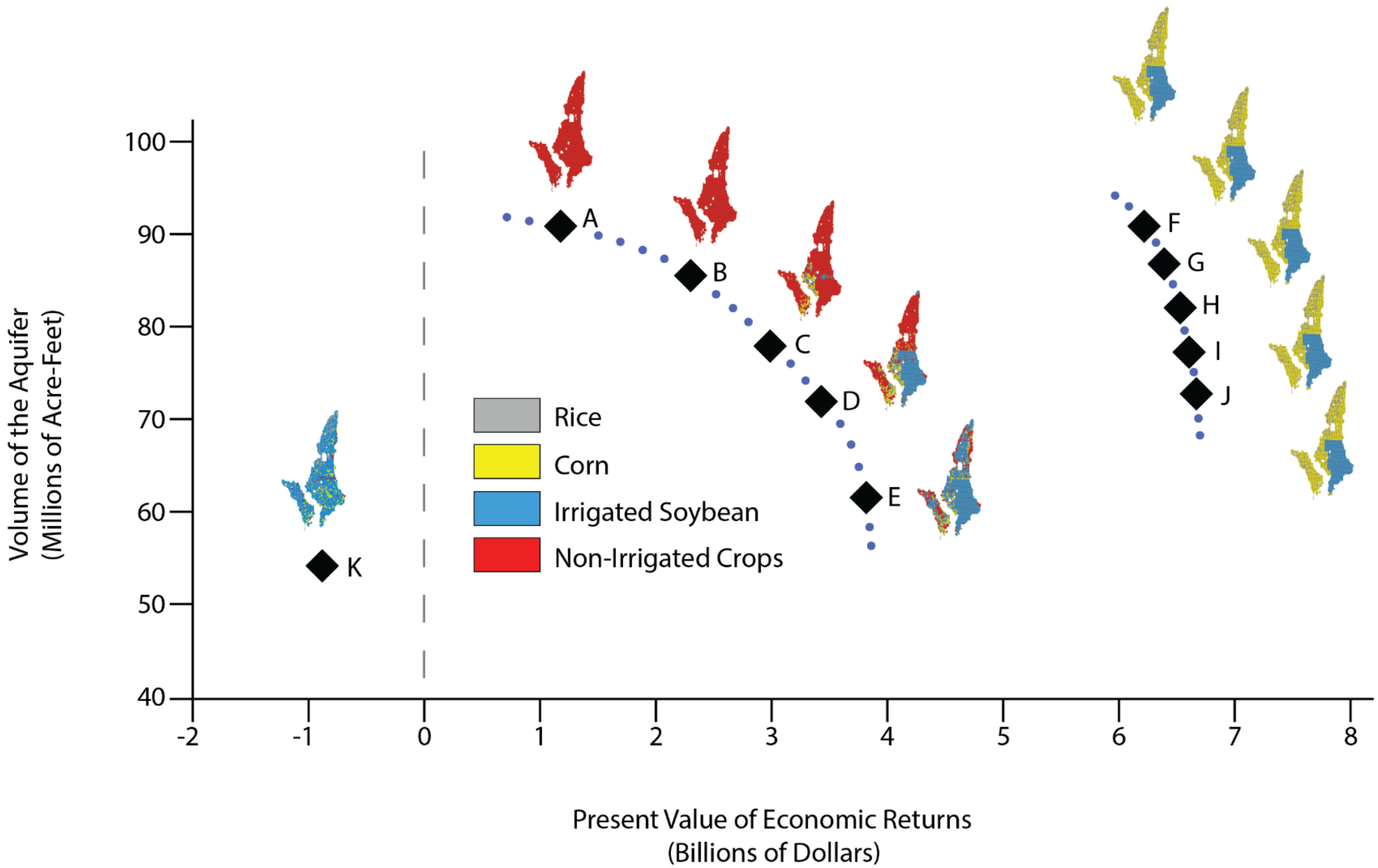

Figure 3. Crop mix patterns associated with specific points along the efficiency frontiers and the current landscape. Each crop mix pattern shown outside of the efficiency frontiers correspond to a lettered point on the frontiers. The current crop mix pattern is also shown. Compared to the current landscape, points on the efficiency frontier without new irrigation technologies available have less soybeans and more non-irrigated crops, and points on the efficiency frontier with new irrigation technologies available have less soybeans and more corn and rice. When no new irrigation technologies are available, there is a shift from predominantly irrigated crops toward non-irrigated crops as the aquifer objective is emphasized more relative to the economic objective. With the new irrigation technologies available, irrigated crop mix pattern is largely unchanged along the efficiency frontier.

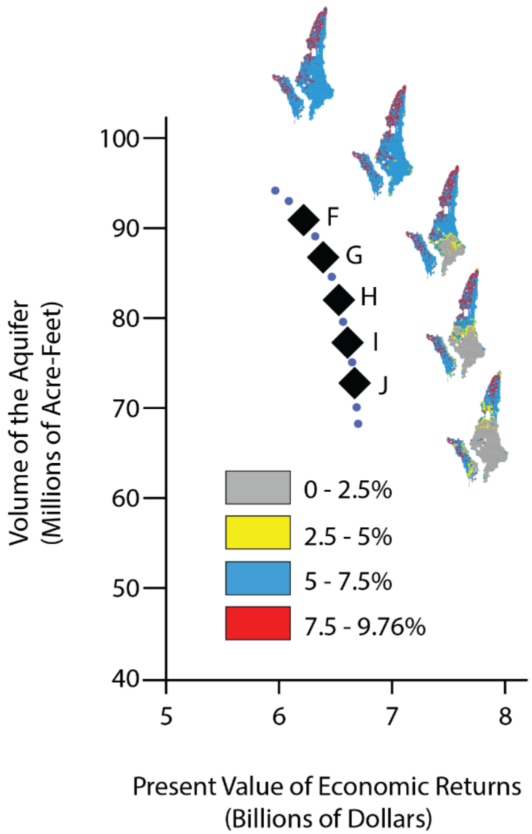

Figure 4. Percentage of land in reservoirs associated with specific points along the efficiency frontier with new irrigation technologies available. Each reservoir intensity pattern shown outside of the efficiency frontiers correspond to a lettered point on the frontier. There is a shift from reservoirs largely in the northern and western sections of the study area toward reservoirs present throughout the study area as the aquifer objective is emphasized more relative to the economic objective.

Appendix

Table A-1 indicates the initial crop mix and aquifer conditions for the study area. Table A-2 indicates the economic and reservoir parameters for the model.

Table A-1. Descriptive statistics of the model data across the sites of the study area

Variable	Definition	Mean	Std. Dev.	Sum (thousands)
$L_{i,rice}$, $L_{i,corn}$, $L_{i,cotton}$, $L_{i,isoy}$, $L_{i,dsoy}$, $L_{i,dsorg}$, $L_{i,dbl}$	Initial acres of rice, corn, cotton, irrigated soybean, dry land soybean, dry land sorghum, double crop irrigated soybean and winter wheat	81, 52, 10, 165, 57, 7, 47	99, 77, 40, 97, 49, 23, 73	220,624; 142,632; 25,891; 448,469; 154,946; 20,017; 128,552
$y_{i,rice}$, $y_{i,cotton}$, $y_{i,corn}$, $y_{i,isoy}$, $y_{i,dsoy}$, $y_{i,dsorg}$, $y_{i,dbl}$, $y_{i,wheat}$	Annual rice yield (cwt per acre), cotton yield (pounds per acre), corn, irrigated soybean, dry land soybean, dry land sorghum, double crop irrigated soybean, and winter wheat yields (bushels per acre)	71, 954, 163, 43, 26, 75, 34, 59	3, 12, 9, 3, 3, 6, 1, 4	-
dp_i	Depth to water (feet)	57	31	-
AQ_i	Initial aquifer size (acre-feet)	27,587	12,514	82,016
K	Hydraulic conductivity (feet per day)	226	92	-
nr_i	Annual natural recharge of the aquifer per acre (acre-feet)	0.001	0.04	547

Note: Number of sites is 2,724.

Table A-2. Value of model parameters.

Parameter	Definition	Value
pr_{rice} , pr_{cot} , pr_{corn} , pr_{soy} , pr_{sorg} , pr_{wht}	Price of rice ($/cwt), cotton ($/lbs), corn, soybeans, sorghum, and wheat ($/bushel)	14.00, 0.88, 5.50, 11.99, 5.23, 6.39
ca_{rice} , ca_{corn} , ca_{cotton} , ca_{isoy} , ca_{dsoy} , ca_{dsorg} , ca_{dbl}	Annual production cost of rice, corn, cotton, irrigated soybean, dry land soybean, dry land sorghum, and double crop irrigated soybean and winter wheat ($/acre)	646, 632, 742, 349, 289, 270, 656
wd_{rice} , wd_{corn} , wd_{cotton} , wd_{isoy} , wd_{dbl}	Annual irrigation per acre of rice, corn, cotton, full-season soybean, and double crop irrigated soybean (acre-feet)	3.3, 1.2, 0.8, 1.0, 0.8
$\omega_{\min}$, $\omega_{\max}$	Annual minimum and maximum capacity of a one acre reservoir (acre-feet)	1.4, 11
c^r	Estimated annual per acre cost of reservoir ($/acre)	96.7[a]
c^{rw}	Cost to re-lift an acre-foot to and from the reservoir ($/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 amortized cost to construct an additional acre of reservoir. The first acre of the reservoir constructed is more expensive, and the last acre of reservoir constructed is less expensive.

The next three tables indicate the percentage adjustments for the alternative irrigation techniques in relation to the conventional irrigation approach. Table A-3 shows the percentage adjustments to crop yield. Table A-4 reports the percentage adjustments for the irrigation requirements of the crops, and Table A-5 indicates the percentage adjustments to production costs.

Table A-3. Conservation technologies and adjustment coefficients for yields relative to standard irrigation.

Crop	Conventional[1]	Center Pivot	Pipe hole selection	Surge	Precision grading	Alternate wet-dry	Multiple inlet
Irrigated corn	1 .000	1 .014 [2]	1 .050 [3]	1 .050 [4]	1 .020 [3]	--	--
Rice	1 .000	0.961[6]	--	--	1 .170 [5,7]	1 .000 [8]	1 .036 [9,10]
Irrigated cotton	1 .000	1.083	1.000 [11]	1.030	1.200 [3-,2]	--	--
Full season irrigated soybeans	1 .000	1 .014 [2]	1 .050 [3]	1 .050 [4]	1 .020 [3]	--	--
Non-irrigated soybeans	1 .000	--	--	--	--	--	--
Non-irrigated sorghum	1 .000	--	--	--	--	--	--
Double crop winter wheat and irrigated soybeans	1 .000	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 A-4. Conservation technologies and adjustment coefficients for water use relative to standard irrigation.

Crop	Conventional[1]	Center Pivot	Pipe hole selection	Surge	Precision grading	Alternate wet-dry	Multiple inlet
Irrigated corn	1 .000	0.750 [1, 3]	0.775 [4]	0.705 [5]	0.750 [1]	--	--
Rice	1 .000	0.594 [6]	--	--	0.489 [2,6]	0.785 [7]	0.755 [6]
Irrigated cotton	1 .000	0.900 [1,8]	0.775 [9,10]	0.735 [5]	0.675 [11]	--	--
Full season irrigated soybeans	1 .000	0.750 [1]	0.775 [4]	0.705 [5]	0.750 [1]	--	--
Non-irrigated soybeans	1 .000	--	--	--	--	--	--
Non-irrigated sorghum	1 .000	--	--	--	--	--	--
Double crop winter wheat and irrigated soybeans	1 .000	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 A-5. Adjustment coefficients for costs of conservation technologies for selected crops.

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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